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Microphytobenthos interannual variations in a north-European estuary (Loire estuary, France) detected by visible-infrared multispectral remote sensing

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A B S T R A C T

Estuarine intertidal sediments are colonized by photosynthetic microorganisms grouped under the generic term of microphytobenthos (MPB). These microbial assemblages form transient biofilms at the sediment surface and have important ecosystem functions. MPB biofilms are well known to exhibit high microscale patchiness whereas meso- and macroscale spatio-temporal structures are little known. In this work, satellite remote sensing was used to map MPB assemblages at such scales. MPB interannual distribution was investigated in the poly- and mesohaline domain of the north-European estuary (Loire estuary), using a multispectral SPOT image time series (1991–2009). The Normalized Difference Vegetation Index (NDVI) was calculated from two SPOT channels, XS2 and XS3, (red and near-infrared wavelengths, respectively). MPB biofilms were identified by NDVI values between 0 and 0.3. At the scale of the whole intertidal area, the results showed that MPB biofilms in the Loire estuary exhibited perennial structures in both the polyhaline and mesohaline sectors, occupying nearly 90% of the mudflat surfaces. MPB biofilm density was closely associated with intertidal position, with thicker biofilms developing mostly in the upper and middle shore, and formed kilometric longitudinal structures parallel to the shoreline. Mean NDVI values showed a strong positive correlation with mean seasonal air temperature ($\tau = 0.714$, $p < 0.05$ in the polyhaline domain and $\tau = 0.810$, $p < 0.05$ in the mesohaline domain), with a strong correlation in the upper intertidal mudflat (between +3 and 4 m isobaths). Negative wind effect was mainly detected in the upper intertidal areas, particularly between the +3 and 4 m isobaths ($\tau = -0.810$, $p < 0.05$ in the polyhaline domain and $\tau = -0.910$ in the mesohaline).

1. Introduction

Estuarine ecosystems are characterized by a high variability of environmental parameters. Located at the interface between oceans and rivers, estuarine water is submitted to complex tidal and fluvial influences, producing strong spatio-temporal variations in salinity, pH, temperature and desiccation. Estuarine food webs rely overall on detrital organic matter, and benthic and planktonic microalgae (Baretta and Ruardij, 1989) but water turbidity frequently limits phytoplankton growth (Monbet, 1992). Thus, in some estuaries, benthic microalgae can represent up to 50% of the total primary production (Underwood and Kromkamp, 1999) and they can contribute significantly to the total amount of chlorophyll-a biomass present in the water column (De Jonge and Van Beusekom, 1995). These benthic species may be resuspended by physical processing, such as waves and tidal currents, responsible for the erosion of the sediment (e.g. De Jonge and Van Beusekom, 1992; Le Hir et al., 2008). Other environmental factors that can affect benthic microalgae include salinity (Admiraal and Peletier, 1980; Admiraal et al., 1984; Underwood et al., 1998; Thornton et al., 2002), temperature (e.g. Blanchard et al., 1997; Guarini et al., 1997) and most importantly the sediment composition (e.g. Brotas et al., 1995; Lucas and Holligan, 1999; Paterson and Hagerthey, 2001; Méléder et al., 2007; Jesus et al., 2009; Ribeiro et al., 2013). Benthic photosynthetic microorganisms are

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collectively known as microphytobenthos (MPB) and are composed of unicellular algae (mainly diatoms and euglenids), cyanobacteria and other photosynthetic bacteria (e.g. MacIntyre and Cullen, 1996). MPB typically develops transient biofilms forming at the sediment surface during diurnal low tide periods (e.g. Pinckney and Zingmark, 1991). These biofilms are a complex mixture of cells, sediments and extracellular polymeric substances (EPS) exuded by diatoms as a result of cellular movement on and within the sediment (e.g. Smith and Underwood, 1998; Tolhurst et al., 2003). MPB biofilm EPS have been shown to play an important role in intertidal mudflats by reducing erosive processes leading to less sediment resuspension and the stabilization of mudflats (Decho, 2000). MPB colonizes sediments at different depths depending on the sediment type and particle size, two parameters that strongly affect light penetration of sediment (Kuhl et al., 1994). In muddy sediments (cohesive), the photic zone is estimated to be less than 1 mm in depth (Paterson et al., 1998). To map MPB at an estuarine scale using the conventional field sampling methods would require extensive sampling programs that would be impossible in most estuaries. Thus, the majority of the studies dealing with MPB spatio-temporal variability are based on MPB biomass estimation from a limited set of field sites and on measuring the amount of chlorophyll extracted from the sediment (e.g. Höpner and Wonneberger, 1985; Underwood, 1994), sometimes followed by spatial interpolation (e.g. Garrigue, 1998; Guarini et al., 1998, 2000; Riaux-Gobin and Bourgoin, 2002; Jesus et al., 2005). Therefore, remote sensing, offers an efficient alternative method for mapping microphytobenthos in large areas, e.g. >1 km^2(e.g. Méléder et al., 2003; Combe et al., 2005; Brito et al., 2013). The presence of photosynthetic pigments and cellular accessories causes MPB biofilm to be colored differently depending on the type of dominant pigment. Thus, biofilms can be characterized by their reflectance spectra (e.g. Paterson et al., 1998; Jesus et al., 2008) and detected by satellite or airborne sensors (e.g. Méléder et al., 2003). Currently, most of the data using this type of sensor has been used to describe MPB spatial distribution at macroscale (Roelfsema et al., 2002; Méléder et al., 2003; Combe et al., 2005; van der Wal et al., 2008; Kazemipour et al., 2012), and only few studies have dealt with biofilm temporal dynamics at such a scale (Méléder et al., 2003; van der Wal et al., 2010; Brito et al., 2013). Some studies showed a correlation between chlorophyll *a* and temperature (e.g. Blanchard et al., 1997). This trend was observed in northern Europe and we hypothesized that it could be detected at macroscale in another large north-European estuary using spatial remote sensing.

The objective of the current study was to analyze MPB interannual variations at an estuarine ecosystem scale using multispectral visible-infrared remote sensing. Images were selected for their spatial resolution enabling the observation of small mudflats across poly- and mesohaline domains. In this work, we used SPOT satellite images combined with *in situ* spectroradiometric field measurements to map MPB biofilm dynamics over an 18-year period from 1991 to 2009 in the Loire estuary (France). Finally, we tested correlations between time series of Normalized Difference Vegetation Index (NDVI) and meteorological conditions.

2. Materials and methods

2.1. Study site

The Loire estuary (Fig. 1), located on the French Atlantic coast (47°17′34.42″N, 2° 4′21.28″O), is the longest river in France (1012 km), with a drainage basin of 118,000 km^2, covering about one fifth of the French territory. The flow rate ranges from 80 to 5500 m^3 s^{-1} with an average of 800 m^3 s^{-1}. Input of fine material from the river to the estuary is about 10^9 kg year^{-1} (Figueres et al., 1985). A MPB spatio-temporal analysis was carried out on the poly- and mesohaline domains of the Loire estuary (Fig. 1), covering 1000 and 200 ha, respectively, of intertidal areas. Most of the calculations were done at the level of each entire domain but, to illustrate MPB distribution, we focused on one of the main mudflats of the polyhaline domain (Brillantes) and one from the mesohaline domain (Lavau) (Fig. 1).

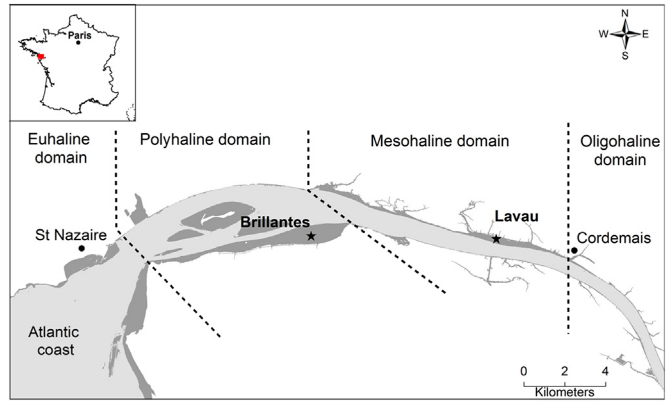

Fig. 1. The Loire estuary with its intertidal flats shown in dark gray. Field data were obtained at two sites in the polyhaline (Brillantes mudflat) and mesohaline (Lavau mudflat) domains.

2.2. Satellite imagery and atmospheric correction

Eight SPOT multispectral images acquired at low tide during the summer period between 1991 and 2009 were analyzed (Table 1). Two criteria were used for image selection: 1) an acquisition time close to spring low tides when mudflats are most exposed; 2) all images were acquired in cloud-free conditions (<10%) with an almost zenithal sun. SPOT images were calibrated to reflectance with FLAASH correction (Fast Line of sight Atmospheric Analysis of Spectral Hypercubes), using ENVI® software and MODTRAN4 transfer codes for the atmospheric corrections (Matthew et al., 2000). For the Loire estuary, the middle latitude winter and summer atmospheric models were used, respectively, with a maritime aerosol model with an initial visibility of 80 km. Atmospheric correction consistency was checked by comparing the spectral signatures of the main vegetation types (micro- and macroalgae, seagrass, perennial saltmarsh plants) with reference signatures from previous studies (Méléder et al., 2003; Barillé et al., 2010). The scenes were registered in the WGS 84 UTM 30N coordinate system.

The normalized difference vegetation index (NDVI; Tucker, 1979) was calculated using the reflectance calibrated images (ρ), using red (XS2: 610–680 nm) and near-infrared (XS3: 780–890 nm) SPOT spectral bands: NDVI = $[\rho(XS3) - \rho(XS2)]/[\rho(XS3) + \rho(XS2)]$. This index was chosen among various multispectral vegetation indices to

Table 1
Satellite imagery used to assess microphytobenthos spatial distribution and inter-annual variations in the Loire estuary.

Acquisition date	Satellite scene	Acquisition time (UT)	Low tide (UT)	Tidal coefficient	Pixel resolution
28/08/1991	SPOT 2	11:36	11:39	90	20 × 20 m
20/08/1993	SPOT 2	11:33	11:35	111	20 × 20 m
16/09/1996	SPOT 2	11:33	11:47	87	20 × 20 m
21/09/1998	SPOT 1	11:32	10:24	89	20 × 20 m
06/09/2006	SPOT 2	10:58	08:37	77	20 × 20 m
02/06/2007	SPOT 2	11:23	10:38	74	20 × 20 m
22/07/2008	SPOT 2	11:13	12:28	80	20 × 20 m
08/09/2009	SPOT 5	11:22	11:58	87	10 × 10 m