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Biophysical control of intertidal benthic macroalgae revealed by high-frequency multispectral camera images

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ABSTRACT

Intertidal benthic macroalgae are a biological quality indicator in estuaries and coasts. While remote sensing has been applied to quantify the spatial distribution of such macroalgae, it is generally not used for their monitoring. We examined the day-to-day and seasonal dynamics of macroalgal cover on a sandy intertidal flat using visible and near-infrared images from a time-lapse camera mounted on a tower. Benthic algae were identified using supervised, semi-supervised and unsupervised classification techniques, validated with monthly ground-truthing over one year. A supervised classification (based on maximum likelihood, using training areas identified in the field) performed best in discriminating between sediment, benthic diatom films and macroalgae, with highest spectral separability between macroalgae and diatoms in spring/summer. An automated unsupervised classification (based on the Normalised Differential Vegetation Index NDVI) allowed detection of daily changes in macroalgal coverage without the need for calibration. This method showed a bloom of macroalgae (filamentous green algae, *Ulva* sp.) in summer with >60% cover, but with pronounced superimposed day-to-day variation in cover. Waves were a major factor in regulating macroalgal cover, but regrowth of the thalli after a summer storm was fast (2 weeks). Images and in situ data demonstrated that the protruding tubes of the polychaete *Lanice conchilega* facilitated both settlement (anchorage) and survival (resistance to waves) of the macroalgae. Thus, high-frequency, high resolution images revealed the mechanisms for regulating the dynamics in cover of the macroalgae and for their spatial structuring. Ramifications for the mode, timing, frequency and evaluation of monitoring macroalgae by field and remote sensing surveys are discussed.

1. Introduction

Benthic macroalgae (seaweeds) are important for ecological functioning of coastal ecosystems: as a habitat for other organisms, as a primary producer in nutrient cycling (see Raffaelli et al., 1998 for a review), and as a physical structure modifying hydrodynamic forcing and sediment transport (Carey, 1987; Madsen et al., 2001; Venier et al., 2012). Excessive growth of opportunistic macroalgae, particularly *Ulva* spp., may lead to anoxia and sulphide poisoning of the benthic species underneath the algal blanket (Lopes et al., 2000; Soulsby et al., 1982).

As macroalgae respond strongly to eutrophication, they are being used as indicator for water quality (Juanes et al., 2008). They are one of the biological quality elements to assess the status of estuarine and coastal waters, for example for the EU Water Framework Directive (Guinda et al., 2008; Scanlan et al., 2007). Both human modifications (e.g., eutrophication, changes in turbidity from coastal engineering works), and climate change (e.g., temperature, sea level, storm frequency and intensity) alter these water bodies (Harley et al., 2006), with consequences for intertidal macroalgal biomass and production (Chung et al., 2011; Harley et al., 2012).

The ability to assess and understand the extent and development of macroalgal mats and blooms is thus important for assessing coastal productivity and quality and for the ecologically sound management of estuaries and coasts. Rapid assessment and quantification of macroalgal mats can be problematic, due to the poor accessibility of the areas over which they may occur, and to their spatiotemporal variability (Nedwell et al., 2002). Field surveys are time-consuming and costly, generally precluding a high frequency of visits. False colour aerial photographs (e.g., Meulstee et al., 1986; Nezlin et al., 2007) and multispectral and hyperspectral airborne and satellite imagery (e.g., Bajjouk et al., 1996; Casal et al., 2011; Guillaumont et al., 1993; Kutser et al., 2006) have been used to map algal cover and to distinguish different algal groups or species at various spatial resolutions. While these studies succeeded in assessing the *spatial distribution* of benthic macroalgae, few studies addressed the *temporal variability* of benthic algal biomass

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using remote sensing. Van der Wal et al. (2010) used MODIS Aqua satellite imagery to assess the seasonal and interannual variability of benthic algae, but their method was not well suited to differentiate between benthic microalgae (e.g., diatoms) and macroalgae. The increasing availability of inexpensive digital cameras in recent years offers the potential to remotely monitor the dynamics of macroalgae using repeat (time-lapse) photography. Mounting these systems on towers provides data at an intermediate scale of observation, referred to as 'near-surface remote sensing' (Ahrends et al., 2008; Richardson et al., 2009). The techniques are particularly used in agriculture and forestry, with a focus on phenology of vegetation (see Crimmins and Crimmins, 2008 for an overview).

In this paper, we aim to assess and understand the extent and development of mats formed by macroalgae using this novel technology with unprecedented temporal resolution. The objective of this study is: (1) to identify and quantify relevant time-scales (seasonal, day-to-day) of changes in cover of these macroalgae on tidal flats and (2) to assess the role of abiotic and biotic factors that regulate the spatial distribution patterns and dynamics (settlement, growth and loss) of these macroalgae at appropriate time-scales. We discuss ramifications of these findings for optimizing the monitoring of macroalgae and for ecosystem structuring and functioning in tidal systems.

2. Material and methods

2.1. Study site

The study focuses on a typical tidal flat (Galgeplaat, surface area ca 1000 ha) in the Oosterschelde estuary in the southwest of the Netherlands, i.e., 51.56°N, 3.95°E (Fig. 1a–b). Following major flooding during the North Sea surge in 1953, a large civil engineering scheme, the Delta works, was conceived to guarantee safety in this region. Reduction of the tidal energy due to construction of a storm surge barrier and reduction of freshwater input due to damming caused a levelling of spatial estuarine gradients and erosion of tidal flats since the 1980s. Thus, the Oosterschelde estuary became a mesotidal, mesotrophic, clear water system, with low freshwater input (ca 25 m^3/s), weak tidal currents (<1 m/s), and a low level of pollution (Nienhuis and Smaal, 1994). At present, the mean spring tidal range is ca 3.1 m, salinity is ca 31 and the average attenuation coefficient Kd is 0.9 m^{-1} (Van der Wal et al., 2010). Samples of the sediment in the study area consist of sand with a median grain size of 0.180 mm and a fraction <0.063 mm (mud content) of 2%. The elevation of the study site is ca −0.7 m NAP (Dutch ordnance datum).

Filamentous green algae of the genus *Ulva* (formerly classified within the *Enteromorpha* genus (Hayden et al., 2003)) dominate the summer blooms on the tidal flats in the Oosterschelde (Fig. 2). In addition, (rare) abundance of the red algae *Gracilaria* sp., the green algae *Cladophora* sp., and *Ulva lactuca*, and the red algae *Ceramium* sp., *Polysiphonia* sp., and *Dasysiphonia* sp. are observed.

Fig. 2. Filamentous green algae (*Ulva* sp.) on the Galgeplaat, Oosterschelde, with oyster beds in the background, 25 June 2008.

2.2. Field set-up and field measurements

A set of cameras with hardware for power supply and wireless communication was mounted on a ca 15 m high platform on the tidal flat (Fig. 1c). This includes a multispectral camera (model Grasshopper GRAS-14S5C, Point Grey) and two monochrome cameras (model Grasshopper GRAS-14S5M, Point Grey) with a resolution of 1.4 MP (1384 by 1036 pixels). The set has 3 CCD imaging sensors (Sony ICX285, size 2/3′, 4.65 μm/pixel) in total: one sensor detecting in the visible part of the electromagnetic spectrum (400–700 nm, with a Bayer filter to extract information in the red, green, and blue (RGB), respectively) and 2 near-infrared (NIR) sensors (centred at wavelengths of 775 nm, 46 nm FWHM for NIR1 and 860 nm, 50 nm FWHM for NIR2, respectively). More information on the cameras and on the spectral sensitivity of the imaging sensors can be found in Point Grey Research (2011). The set-up was used in 2011 and 2012, focusing, in oblique view, on a fixed study site of ca 4 by 4 m (Fig. 1d), resulting in a pixel footprint (spatial resolution) of ca 0.5 cm. Images were stored automatically every 3 (during field campaigns) to 30 min, provided water level and light conditions were favourable. A water level sensor was installed at the base of the tower to automatically detect low tide.

In 2009, a RGB camera (network dome surveillance camera, model Axis 232D+) with pan–tilt–zoom function was operational on the

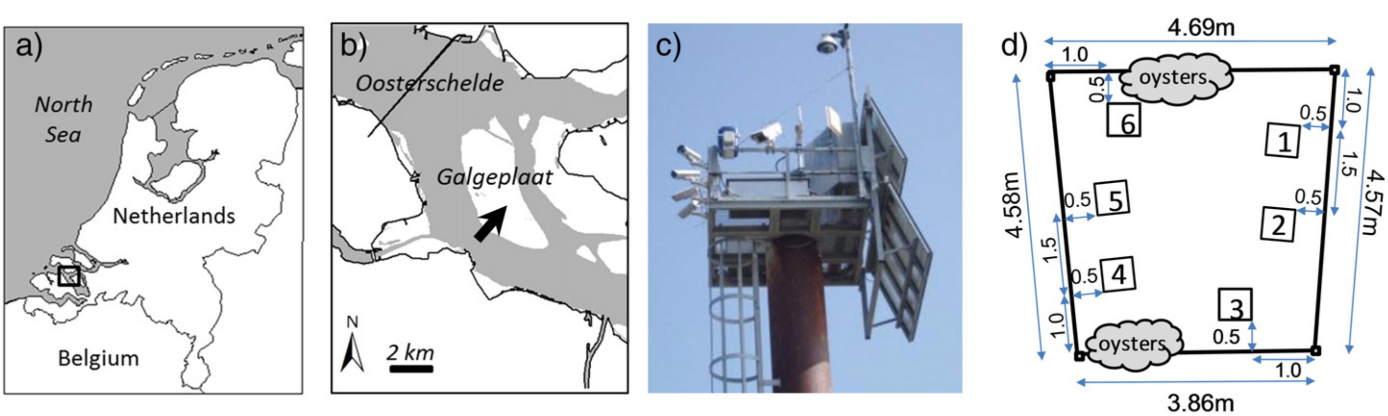

Fig. 1. (a) Oosterschelde estuary in the southwest of the Netherlands, (b) location of the measurement pole (indicated by arrow) on the tidal flat Galgeplaat, Oosterschelde, (c) detail of the measurement pole with camera set-up and (d) study area with the six sampling plots.