Estuarine, Coastal and Shelf Science 172 (2016) 1–12

Contents lists available at ScienceDirect

Estuarine, Coastal and Shelf Science

journal homepage: www.elsevier.com/locate/ecss

Hyperspectral remote sensing of wild oyster reefs

Anthony Le Bris [a], [b], [*], Philippe Rosa [b], Astrid Lerouxel [b], Bruno Cognie [b], Pierre Gernez [b], Patrick Launeau [c], Marc Robin [a], Laurent Barillé [b]

[a] *Université de Nantes, Institut Universitaire Mer et Littoral (FR_C 3473), LETG-Géolittomer (UMR 6554, CNRS), Campus Tertre, BP 81227, 44312, Nantes Cedex 3, France*
[b] *Université de Nantes, Institut Universitaire Mer et Littoral (FR_C 3473), Mer Molécules Santé (EA 2160), Faculté des Sciences et des Techniques, BP 92208, 44322, Nantes Cedex 3, France*
[c] *Université de Nantes, Institut Universitaire Mer et Littoral (FR_C 3473), Laboratoire de Planétologie et Géodynamique (UMR 6112, CNRS), Faculté des Sciences et des Techniques, BP 92208, 44322, Nantes Cedex 3, France*

ARTICLE INFO

Article history:
Received 10 July 2015
Received in revised form
17 December 2015
Accepted 23 January 2016
Available online 28 January 2016

Keywords:
Benthos
Crassostrea gigas
Hyperspectral
Oyster reefs
Remote sensing
Tidal flats

ABSTRACT

The invasion of the wild oyster *Crassostrea gigas* along the western European Atlantic coast has generated changes in the structure and functioning of intertidal ecosystems. Considered as an invasive species and a trophic competitor of the cultivated conspecific oyster, it is now seen as a resource by oyster farmers following recurrent mass summer mortalities of oyster spat since 2008. Spatial distribution maps of wild oyster reefs are required by local authorities to help define management strategies. In this work, visible-near infrared (VNIR) hyperspectral and multispectral remote sensing was investigated to map two contrasted intertidal reef structures: clusters of vertical oysters building three-dimensional dense reefs in muddy areas and oysters growing horizontally creating large flat reefs in rocky areas. A spectral library, collected *in situ* for various conditions with an ASD spectroradiometer, was used to run Spectral Angle Mapper classifications on airborne data obtained with an HySpex sensor (160 spectral bands) and SPOT satellite HRG multispectral data (3 spectral bands). With HySpex spectral/spatial resolution, horizontal oysters in the rocky area were correctly classified but the detection was less efficient for vertical oysters in muddy areas. Poor results were obtained with the multispectral image and from spatially or spectrally degraded HySpex data, it was clear that the spectral resolution was more important than the spatial resolution. In fact, there was a systematic mud deposition on shells of vertical oyster reefs explaining the misclassification of 30% of pixels recognized as mud or microphytobenthos. Spatial distribution maps of oyster reefs were coupled with *in situ* biomass measurements to illustrate the interest of a remote sensing product to provide stock estimations of wild oyster reefs to be exploited by oyster producers. This work highlights the interest of developing remote sensing techniques for aquaculture applications in coastal areas.

1. Introduction

Pacific oyster (*Crassostrea gigas*) is the main bivalve species cultivated worldwide (FAO, 2006; Forrest et al., 2009). This species was introduced into European waters in the seventies to replace the Portuguese oyster (*Crassostrea angulata*) which had been greatly reduced by a large-scale epizootia outbreak (Grizel and Héral, 1991). With the increase of water temperature, spawning and larval survival were gradually observed toward northern latitudes, and oysters progressively colonized intertidal areas, forming dense reefs (Diederich, 2005; Dutertre et al., 2010). Feral *C. gigas* is now considered as an invasive species with different impacts on receiving communities (Troost, 2010). Among these impacts, the most obvious is a direct spatial and trophic competition with local species such as the blue mussel (*Mytilus edulis*) (Diederich, 2005, 2006; Schmidt et al., 2008; Troost, 2010; Markert et al., 2013; Green et al., 2013). Wild oysters also became trophic competitors with cultivated conspecifics causing slower growth and economic losses for the oyster farmers (Cognie et al., 2006). In France, they were considered as a pest by the oyster industry. However since 2008, recurrent mass summer mortalities of oyster spat were

---

[*] Corresponding author. Université de Nantes, Institut Universitaire Mer et Littoral (FR_C 3473), LETG-Géolittomer (UMR 6554, CNRS), Campus Tertre, BP 81227, 44312, Nantes Cedex 3, France.
E-mail address: anthony.le-bris@univ-nantes.fr (A. Le Bris).

http://dx.doi.org/10.1016/j.ecss.2016.01.039

observed along the European coasts with a subsequent decline of the cultivated stock (Cotter et al., 2010; Pernet et al., 2012; Girard and Pérez Agúndez, 2014). As a consequence, the status of the wild oyster changed radically and in some areas oyster producers envisaged exploiting their population as a resource to compensate for their losses. This situation induced conflicts with recreational and professional fishermen generating a need to map and manage wild oyster reefs. However, in many areas of the west European Atlantic coast, these reefs grow in rocky areas within large intertidal mudflats notoriously inaccessible and hard to sample. Traditional ground surveys are therefore time-consuming, expensive and require a substantial human effort in these areas (Cognie et al., 2006). Thus, there is a growing interest and need for the development of reliable remote sensing tools to provide a synoptic view of wild oyster reefs in coastal areas.

Aerial photography has been used to detect live and dead oyster reefs using brightness differences (Grizzle et al., 2002; Kater and Baars, 2004). However, the specific spectral properties related to reflected electromagnetic radiations at different wavelengths cannot be exploited with panchromatic photographs. A preliminary investigation with a multispectral resolution was tested for oyster mapping in South Carolina (NOAA, 2003). More recently, microwave remote sensing with synthetic aperture radar (SAR) was used to map bivalve beds (mussels and oysters) in intertidal areas (Choe et al., 2012; Gade et al., 2014; Nieuwhof et al., 2015). Choe et al. (2012) showed that polarimetric characteristics of SAR images can be used to distinguish surface roughness of oyster reefs from that surrounding mudflat. However, this technique did not permit the discrimination of bivalve species (Gade et al., 2014; Nieuwhof et al., 2015), and was not tested to discriminate distinct tridimensional configuration (e.g. horizontally vs. vertically developed oysters) as can be observed for oyster reefs. Additional optical data in visible and near-infrared domains could improve classifications of intertidal mudflats (Van der Wal and Herman, 2007) and oyster reefs detection (Dehouck et al., 2011). Visible-near infrared (VNIR) data are very useful to map intertidal vegetation such as seagrass (Pasqualini et al., 2005; Barillé et al., 2010) or microphytobenthic biofilms (Brito et al., 2013; Benyoucef et al., 2014) but the richness of absorption bands due to photosynthetic and accessory pigments cannot *a priori* be exploited for bivalve beds. Moreover, the broadband resolution of many multispectral VNIR sensors may be a limit for their detection (Girouard et al., 2004). This restriction could be overcome by using high resolution hyperspectral data. Surprisingly, this technique has only been tested by Schill et al. (2006) to map eastern oyster reefs (*Crassostrea virginica*) based on their spectral reflectance. They suggested that hyperspectral remote sensing could be useful for mapping shellfish resources but observed a high spectral variability within the oyster habitat. Therefore, evaluating the efficiency of hyperspectral data remains to be assessed and generalized to different ecosystems, species and reef typology. For instance, none of the studies previously cited using radar data considered the common situation in western Atlantic bays where oyster reefs can be found in intertidal flats but also in adjacent rocky areas growing with a distinct configuration.

This study aimed to produce spatial distribution maps of wild oyster reefs for two contrasted reef typologies found in mudflats and rocky areas using hyperspectral data from the airborne sensor HySpex. A comparison was performed between HySpex data and SPOT satellite HRG multispectral data to evaluate the role of the sensor's spectral resolution. HySpex maps were spatially and spectrally degraded to compare overall accuracy at different resolutions. In this study, spectral signatures of oyster shells have been analyzed using *in situ* spectroradiometric measurements obtained for different conditions. Finally, we propose a simple method using reef distribution maps and *in situ* measurements of oyster biomass to illustrate the interest of a remote sensing product for the management of this resource at the scale of a shellfish ecosystem.

2. Materials and methods

2.1. Study area

Bourgneuf Bay, located south of the Loire estuary on the French Atlantic coast (47°02′ N, 2°07′ W) (Fig. 1), is a macrotidal bay with a maximum tidal amplitude of 6 m. 100 km^2 of the total bay area (340 km^2) is intertidal. It is a site of extensive aquaculture of the oyster *C. gigas* (Thunberg), ranking fifth in France with a production of 7000 metric tons on 1000 ha of on-bottom cultures. The intertidal zone comprises large mudflats and rocky areas but smaller rocky spots are found in the middle of the mudflat. Two types of wild oyster reefs can be observed: reefs situated in rocky spots within the mudflat which are hardly accessible (Fig. 1, Site 1) and those found in the large rocky areas with a much easier access (Fig. 1, Site 2).

2.2. Typology of wild oyster reefs

Two distinct forms of colonization can be observed: clusters of vertical oysters building three-dimensional dense reefs in the muddy area (Fig. 2A, B) and oysters growing horizontally creating large flat reef structures in rocky areas (Fig. 2D, E). The first form is very similar to the one described for South-Carolina's oyster reefs (NOAA, 2003). A further distinction can be made according to the mud deposition. In the muddy area, oyster shells were dark and partially covered by mud, while in rocky areas, in the absence of any mud deposition, oyster shells had a brighter color. Spectral responses of each reef were obtained with a field portable spectroradiometer ASD FieldSpec3®, measuring the radiance (mW cm^{-2} nm^{-2} sr^{-1}) between 350 and 2500 nm with a spectral sampling interval of 1.4 nm up to 1050 nm and 2 nm up to 2500 and a spectral resolution from 3 to 10 nm. Surface reflectance was determined by measuring the light reflected by a ~99% reflective Spectralon® reference panel (Fig. 2C, F).

2.3. Image pre-processing

Bourgneuf bay was imaged by a HySpex VNIR 1600 camera on September 21st, 2009, during an airborne campaign. This sensor provides a spectral resolution of 4.5 nm in 160 contiguous channels between 400 and 1000 nm. A mosaic of around 20 flight lines over the study area was obtained for a high spatial resolution of 1 m^2 per pixel. A multispectral image was also acquired by the HRG sensor of SPOT-5 satellite on September 8th, 2009. It is characterized by 4 wide bands (500–590; 610–680; 780–890; 1580–1750 nm) and a spatial resolution of 100 m^2 per pixel. Both hyperspectral and multispectral images were acquired at low tide, in cloud-free conditions (<10%). Images were calibrated to ground reflectance using the FLAASH (Fast Line-of-sight Atmospheric Analysis of Spectral Hypercubes) atmospheric corrections module, incorporating the MODTRAN4 transfer code (Matthew et al., 2000). For Bourgneuf Bay, a middle latitude summer atmospheric model was used combined with a maritime aerosol model. MNF (Minimum Noise Fraction) transformations combined with a band-pass filter of 9 nm were applied to the images to remove noise and redundant information. A geographical mask of the terrestrial part and a radiometric mask of the water were applied to identify the intertidal area. Within this area, another mask was applied to distinguish all rocky surfaces from the mudflat itself since wild oysters do not develop directly in the mud, and are systematically associated to a hard substrate. This mask was performed using an X-band SAR