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Semi-automatic analysis and interpretation of sediment profile images

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ABSTRACT

Sediment Profile Images (SPIs) are widely used for benthic ecological quality assessment under various environmental stressors. The processing of the information contained in SPIs is slow and its interpretation is largely operator dependent. We report here on a new software: SpiArcBase, which allows for a semi-automatic analysis of SPIs and facilitates the interpretation of observed features. SpiArcBase enhances the objectivity of the information extracted from SPIs, especially for the assessment of the apparent Redox Potential Discontinuity (aRPD). This new software also allows the user to create and manage a database containing original SPIs and corresponding derived pieces of information. Examples of the use of SpiArcBase for SPIs collected during a case study carried out within the Rhône River Prodelta are provided. Correlations between: (1) visually and automatically assessed aRPD and Benthic Habitat Quality Index (BHQ), and (2) automatically assessed aRPD and BHQ and surface sediment organic carbon support the use of this new software.

Software availability

Name: SpiArcBase
Developed by: Alicia Romero Ramirez and Jean-Claude Duchêne
First available: 2011
Language: Microsoft Visual C#
Requirements: -Hardware: Pentium PC or equivalent with at least 2 GB of RAM
-Software: Microsoft Windows XP, Vista or 7.
Software size: 7.5 M
Availability: http://spiarcbase.epoc.u-bordeaux1.fr/
Free for research and educational purposes.

1. Introduction

The need for assessment of the Ecological Quality Status of European marine waters is increasing due to policy requirements associated with the Water Framework Directive (WFD, 2000/60/EC) and the Marine Strategy Framework Directive (MSFD, (2008/56/EC). The overall aim of MSFD is for to insure a good status to all marine water masses included in the European Economic exclusion Zone (i.e., within 200 nautical miles of the coastline versus only 1 nautical mile for the surface waters considered in the WFD) by 2020 (versus 2015 for the WFD). The principles used to define what is a good ecological status have evolved from a deconstructing structural approach of several independently assessed (ecological and chemical) status (WFD) to a holistic functional approach where indicators of 11 descriptors (components/processes/services) together summarize the way in which the whole ecosystem functions (MSFD) (Borja et al., 2009). In addition to the description of an initial state, both WFD and MSFD require the realization of periodic monitoring surveys. Besides, the geographical extension associated with the emergence of MSFD, this enhances the need for automatic, or at least semi-automatic, assessments of biological compartments and processes. Image analysis techniques have a strong potential regarding this particular point since they have for example already been used to: (1) automatize the taxonomic classification of phytoplankton (Sosik and Olson, 2007), (2) facilitate the acquisition and classification of zooplankton images (Gorsky et al., 2009), (3) study coastal dynamics by video observations (Almar et al., 2009) and satellite images (Sánchez-Carnero et al., 2011).

The analysis of benthic macrofauna is used in both WFD and MSFD and several biotic indices have been recently developed to infer sound ecological quality assessments (Borja et al., 2000, 2003; Muxika et al., 2007; Rosenberg et al., 2004). Macrofauna analysis is

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long and tedious and does not provide information regarding the functioning of benthic ecosystems, which makes its use problematic within the MSFD and to a lesser extent in the monitoring part of the WFD. Sediment Profile Imaging was developed in the late 1960s (Rhoads and Cande, 1971; Rhoads and Young, 1970; Young and Rhoads, 1971). It consists in collecting *in situ* 2D images of vertical profiles of the sediment column most often using a specifically designed piece of equipment (i.e., a sediment profiler). The so-collected sediment profile images (SPIs) constitute 2D "optical cores" of the upper part (typically 30 cm) of the sediment column (Germano et al., 2011). Sediment Profile Imaging can provide an efficient tool for rapid and cost-effective assessments of both the structure and functioning of benthic habitats (Rosenberg et al., 2009) providing that its performances are well established (see (Grémare et al., 2009; Josefson et al., 2009; Teixeira et al., 2010) for a similar problem regarding macrobenthic indices) for example through comparisons with other approaches (Labrune et al., 2012; Rosenberg et al., 2003, 2000).

Sediment Profile Imaging has been applied to a variety of problems and disciplines (see review by Germano et al., 2011). Corresponding applications are numerous and first relate to the assessment of the ecological quality of benthic habitats (Diaz et al., 2004) based on the secondary succession models describing the response of benthic macrofauna to organic enrichment (Pearson and Rosenberg, 1978) and physical disturbance (Rhoads and Germano, 1982). This mostly includes the analysis of the impact of various disturbances such as: (1) oxygen deficiency (Nilsson and Rosenberg, 2000; Rosenberg et al., 2001, 2002, 2009; Rosenberg and Nilsson, 2005), (2) dredging and bottom trawling (Nilsson and Rosenberg, 2003; Rosenberg et al., 2003; Smith et al., 2003), (3) aquaculture (Karakassis et al., 2002; Oconnor et al., 1989), (4) drilling and oil spill (Germano, 1995; Ruhmohr and Schomann, 1992), (5) dredging disposal (Wilson et al., 2009) and (6) organic enrichment (Grizzle and Penniman, 1991; Labrune et al., 2012; Wildish et al., 2003).

Sediment Profile Imaging has also been used to examine specific processes taking place at the sediment–water interface and within the top of the sediment column. This includes: (1) the study of animal–sediment-relationships (Diaz and Cutter, 2001), (2) benthic macrofauna activity (Solan and Kennedy, 2002), and (3) bioturbation (O'Reilly et al., 2006a; Solan et al., 2004; Teal et al., 2008). Sediment Profile Imaging has proven to constitute an efficient technique in research. It is now largely spreading as indicated by recent raises in the numbers of: (1) sediment profilers available worldwide, and (2) published scientific papers involving the use of this technique (Germano et al., 2011).

The information contained in SPIs is a rich combination of complex biological, physical and chemical processes that are often difficult to analyze. Moreover its interpretation requires specific knowledge relative to processes taking place at the sediment–water interface (Germano et al., 2011). Diaz and Schaffner (1988), proposed a list of parameters to be measured from SPI. From a biogeochemical standpoint, the information contained in SPIs is mostly indicative of:

(1) the presence of benthic macrofauna (living organisms and/or tubes),
(2) macrofauna activity through the presence and the vertical positioning of several kinds of biogenic structures such as: feeding pits, feeding mounds, burrows and oxic voids,
(3) the interaction of a large variety of biogeochemical processes taking place at the sediment–water interface, which is documented through differences in color between surface and subsurface sediments. The corresponding parameter is the thickness of the layer of the red–brown colored surface sediment overlying the apparent Redox Potential Discontinuity (aRPD; Lyle, 1983) later called Mixing Depth (MD_i; Teal et al., 2010).

Given such a level of complexity, the question of the comparability and therefore of the subjectivity (i.e., operator-dependency) of the interpretation of SPIs has been raised (Ghita et al., 2003). This led Germano et al. (2011) to state in their recent review that "A challenge for the future is to use a more standardized and objective means of analysis that reduces the subjective evaluation of the operator and relies more on actuarial methodologies". The development of appropriate image analysis techniques will certainly strongly contribute to meet this objective.

Recent years have seen the development of computer-assisted procedures for SPI analysis. However, most of them consist in using standard image processing software such as Adobe Photoshop® (Rosenberg et al., 2003) or Image Analyst® (Solan and Kennedy, 2002) or Image J® (Birchenough et al., 2012; de Moura Queirós et al., 2011; Godbold and Solan, 2009). Overall, the lack of specificity of such generic software and the absence of a well-established standard procedure limits the usefulness of Sediment Profile Imaging (Germano et al., 2011). To our knowledge, there has been no attempt to automate the drawing of the sediment water-interface and most biogenic structures. Conversely several semi-automated procedures have been proposed to assess the aRPD (e.g., de Moura Queirós et al., 2011; Ghita et al., 2004; Teal et al., 2010) and burrows (Ghita et al., 2004). However, all these procedures are based on fixed threshold applied either to a grayscale image (Teal et al., 2010) or to the red layer of the image (de Moura Queirós et al., 2011). One major limitation of this approach is that the threshold value is strongly depending on sites (see de Moura Queirós et al., 2011) and is not accounting for the fact that light distribution is not even within each individual SPI.

To our knowledge, there has been only one attempt to produce a software specifically designed for SPI processing (i.e., the MRS software by Ghita et al. (2004); http://www.vsg.dcu.ie/code.html; Feb. 2012). This software allows for an easy semi-automatic drawing of the sediment–water interface and burrows, but also suffers from some drawbacks: (1) the user interface requires image-analysis knowledge; (2) the software is only processing one image at a time; (3) the assessment of the oxidized layer is based on image clustering but still highly user dependent with a choice between three different procedures, some of them including a pre-setting of the number of clusters; (4) SPI variables cannot be visualized as overlays over the original image; and (5) there is no associated database. Moreover, we were not able to find any reference of the practical use of the MRS software in the scientific literature.

We report here on SpiArcBase software specifically designed to process SPIs. Its main original features include: (1) automatic drawing of the sediment–water interface using two algorithms based on two types of edge detection filters, (2) automatic computation of the aRPD using several algorithms based either on a split-merge (Cheevasuvit et al., 1986; Horowitz and Pavlidis, 1974) or a growing seed approach (Adams and Bischof, 1994), (3) semi-automatic detection, analysis and classification of biogenic structures based on the study of gray-scale gradients, and (4) a database for storing all SPI variables.

2. Software description

SpiArcBase presents a graphical user interface designed to enhance the selection of features observed on SPIs (Fig. 1) and to facilitate storage of SPI data via a Microsoft® Access format database, which also includes the meta-information related to individual SPI. The list of images stored within a database is available