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A novel earth observation based ecological indicator for cyanobacterial blooms

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ABSTRACT

Cyanobacteria form spectacular mass occurrences almost annually in the Baltic Sea. These harmful algal blooms are the most visible consequences of marine eutrophication, driven by a surplus of nutrients from anthropogenic sources and internal processes of the ecosystem. We present a novel Cyanobacterial Bloom Indicator (CyaBI) targeted for the ecosystem assessment of eutrophication in marine areas. The method measures the current cyanobacterial bloom situation (an average condition of recent 5 years) and compares this to the estimated target level for 'good environmental status' (GES). The current status is derived with an index combining indicative bloom event variables. As such we used seasonal information from the duration, volume and severity of algal blooms derived from earth observation (EO) data. The target level for GES was set by using a remote sensing based data set named Fraction with Cyanobacterial Accumulations (FCA; Kahru & Elmgren, 2014) covering years 1979–2014. Here a shift-detection algorithm for time series was applied to detect time-periods in the FCA data where the level of blooms remained low several consecutive years. The average conditions from these time periods were transformed into respective CyaBI target values to represent target level for GES. The indicator is shown to pass the three critical factors set for marine indicator development, namely it measures the current status accurately, the target setting can be scientifically proven and it can be connected to the ecosystem management goal. An advantage of the CyaBI method is that it's not restricted to the data used in the development work, but can be complemented, or fully applied, by using different types of data sources providing information on cyanobacterial accumulations.

1. Introduction

Recurring harmful phytoplankton blooms can be found in many of the world's largest estuarine, coastal and freshwater areas (Paerl and Otten, 2013). In the Baltic Sea, the observed increase in cyanobacterial blooms is attributed to severe eutrophication and a subsequent change in nutrient balance caused by anthropogenic nutrient enrichment, in particular from urban areas, agriculture and industry (Vahtera et al. 2007; Conley et al. 2009; HELCOM 2009; Andersen et al., 2011). Cyanobacterial mass occurrences are considered harmful in two fundamental ways; through their toxicity and through high biomass accumulation that have multitude effects on ecosystem functioning (Glibert et al., 2005). Cyanobacterial toxins can affect organisms both through indirect and direct exposure. As well as being transferred through the food web, they can be acutely poisonous for protists, invertebrates and vertebrates, including humans (Landsberg, 2002; Karjalainen et al., 2007). On the other hand, high biomass blooms can potentially degrade ecological habitats, decrease biodiversity and increase bottom anoxia. Furthermore, through their unique ability to utilise dissolved molecular nitrogen, they may introduce new biologically available nutrients and carbon into the system in otherwise nitrogen-limited conditions (e.g. Paerl and Otten, 2013).

The EU Marine Strategy Framework Directive (MSFD; Anonymous, 2008) is the main initiative to protect the seas of Europe. It requires that "*human-induced eutrophication is minimized, especially adverse effects thereof, such as losses in biodiversity, ecosystem degradation, harmful algae blooms and oxygen deficiency in bottom waters*" (Anonymous, 2008, p. L 164/34). However, even though the increase of algal blooms are in the MSFD noted among the main adverse effects of eutrophication, the development of quantitative bloom assessment methods is lagging

Abbreviations: AB, algae barometer value; CSA, cyanobacterial surface accumulation; CyaBI, cyanobacterial bloom indicator; ECDF, empirical cumulative distribution function; EO, earth observation; FCA, fraction with cyanobacterial accumulations; GES, good environmental status; HELCOM, Baltic Marine Environment Protection Commission; MSFD, EU marine strategy framework directive; SYKE, Finnish Environment Institute

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behind. The challenges encountered in the development are common for many biological indicators: the inherent complex characteristics of the phenomenon and its complicated relationship to environmental pressures, as well as challenges in setting target values for GES in the absence of quantitative historical information (Borja et al. 2011, 2012). These issues have hindered phytoplankton indicator development work and to the best of our knowledge, an indicator on harmful algae blooms with identified target levels, has so far not been developed.

The central objective of the MSFD is to achieve or maintain GES in marine areas. The environmental indicators involved in the MSFD are binomial; good environmental status is either reached or not. The boundary value between these two classes defines the environmental target value to which current status is compared. Quantitative series of spatially extensive cyanobacterial bloom observations that reach back in time to the period when the Baltic Sea ecosystem was unaffected by anthropogenic pressures do not exist. A paleolimnological study of sediment pigments provides information on the occurrence and intensity of cyanobacterial blooms in the past century (Poutanen and Nikkilä, 2001), but this study is restricted to a few distinct sampling locations and does not provide sufficient spatial coverage for our purpose. Kahru and Elmgren (2014) present the longest spatially extensive time series on the quantity of cyanobacterial surface accumulations in the Baltic Sea, based on satellite images. Their time series covers the years 1979–2014 and constitutes the most suitable data source for the target setting of cyanobacterial bloom indicators in the area in question.

Cyanobacterial blooms in the Baltic Sea can be rapid or prevailing, and their occurrence may vary from local to basin-wide scales (e.g. Kutser et al., 2006; Reinart and Kutser, 2006; Kahru et al., 2007). Blooms are thus difficult to describe with conventional phytoplankton sampling methods, i.e. by collecting discrete water samples. Earth observation data are considered to have great potential for cyanobacterial bloom monitoring due to its extensive spatial and temporal coverage (e.g. Ferreira et al., 2011; Mouw et al., 2015; Palmer et al., 2015). However, converting images of this visually distinctive phenomenon into direct quantitative information usable in environmental assessments is challenging (cf. Kahru and Elmgren, 2014). This is mainly because the satellite sensors such as MODIS (MODerate Resolution Imaging Spectroradiometer by NASA) suitable for operative large scale monitoring, have spectral band configurations too coarse or inappropriately located to facilitate the separation of cyanobacterial biomass measurements from other phytoplankton groups (Kutser et al., 2006). The MERIS instrument (MEdium Resolution Imaging Spectrometer by European Space Agency; lifespan 2002–2012) showed potential to measure biomass of cyanobacteria by using the absorption of cyanobacteria-specific pigment phycocyanin (Simis et al., 2007; Wynne et al., 2008; Binding et al., 2011). Even though, Woźniak et al. (2016) presented a phycocyanin algorithm adapted to spectral bands of the recently launched Ocean Land Color Imager (OLCI) in the Sentinel-3 satellite by European Space Agency, a generally applicable algorithm exclusive to cyanobacterial biomass that is independent from the satellite instrument has so far not been developed. The cyanobacterial bloom characteristics, typically presented as the areal and temporal coverage or intensity of blooms, have proven to be useful in ecosystem assessment studies (e.g. Kahru et al., 2007; Klemas, 2012; Öberg, 2013; Huang et al., 2015; Palmer et al., 2015). These characteristics, typically presented as the areal and temporal coverage or intensity of blooms are mainly based on the measurements of chlorophyll a concentration or the increased turbidity from the satellite images. The use of cyanobacterial bloom characteristics in describing the cyanobacteria blooms has certain benefits. This information can be estimated not only from majority of optical EO data, but also from other environmental observations including automated measurements, transect data or citizen observations.

In this study, we describe the novel Cyanobacterial Bloom Indicator (CyaBI). The indicator evaluates the current ecological status by combining information on cyanobacterial blooms into an index. The indicator is presented applying seasonal algal bloom characteristics information derived from satellite images. In the target level setting for GES, we applied the satellite based FCA data by Kahru and Elmgren (2014) that has different approach for interpreting bloom accumulations when compared to CyaBI method.. The assessment of the ecosystem state, compares the current status and set target levels. The CyaBI method was tested in four of the open sea sub-basins covering the central and north-eastern parts of the Baltic Sea. We evaluate the indicator according to three general requirements set for marine indicators (Samhouri et al., 2012), namely 1) the ability of the used measurements to describe the current status, 2) the suitability of the GES boundary setting, and 3) how the indicator articulates with ecosystem management goals. The indicator is demonstrated by using satellite derived data, but can be complemented, or even fully applied, with other data sources. The indicator was originally referred to as the Cyanobacterial Surface Accumulation (CSA) index during its development (e.g. Anttila et al., 2015).

2. Study area and materials

2.1. Study area

The Baltic Sea, a non-tidal, semi-enclosed brackish water estuary in northern Europe, is one of the most nutrient-enriched seas in the world. Starting with deforestation and agriculture, anthropogenic activities have affected the Baltic Sea with nutrient inputs for almost 2000 years (Zillén and Conley, 2010), possibly even longer (cf. Odén, 1980; Wassmann, 2004). However, as shown by sediment investigations, the drastic increase in nutrients and productivity started only in the 1950s–1960s (Struck et al., 2000; Poutanen and Nikkilä, 2001).

Blooms of nitrogen-fixing cyanobacteria are considered to be a natural feature of the Baltic Sea, dating as far back as about 7000 years ago (Bianchi et al., 2000; Poutanen and Nikkilä, 2001; Westman et al., 2003). Early phytoplankton investigations show that already in the early 1900s, cyanobacteria occasionally occurred in great quantities in both the coastal (e.g. Levander, 1908) and the open Baltic Sea (Ostenfeld, 1931). However, during the 20th century, their occurrence became extensive and frequent, and since the 1960s cyanobacterial blooms have become common in the Baltic Proper and the Gulf of Finland (Finni et al., 2001; cf. Poutanen and Nikkilä, 2001). Today large-scale surface blooms are an annually occurring phenomenon (Reinart and Kutser, 2006; Kahru and Elmgren, 2014). The predominant bloom type during the warm water period (July–August) in the Baltic Sea is caused in particular by the filamentous nitrogen-fixing species *Aphanizomenon flos-aquae* and *Nodularia spumigena* (Hällfors, 2007). Several other phytoplankton groups may also form surface accumulations or visible discoloration of the water in summer, but these blooms are usually confined to coastal waters and are more local and transient in character (Lindholm, 1995).

The CyaBI indicator is presented by using data from four sub-basins of the Baltic Sea, namely the Gulf of Finland, Northern Baltic Proper, Western Gotland Basin and Eastern Gotland Basin (Fig. 1). The delineation of the sub-basins is based on the open sea assessment areas of the Baltic Marine Environment Protection Commission (HELCOM, 2014).

2.2. Data sets

The main data source used in the indicator development was the satellite data based daily algal bloom product of the Finnish Environment Institute (SYKE), which is in turn derived from the respective chlorophyll *a* and water turbidity products (Appendix A). All of the products constitute a part of the Finnish operative EO monitoring of the Baltic Sea (www.syke.fi/earthobservation). Since cyanobacterial blooms typically occur in the Baltic Sea during the warm water period, the earth observation data sets for years 2003–2015 constituted data