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Review

Phycocyanin concentration retrieval in inland waters: A comparative review of the remote sensing techniques and algorithms

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A B S T R A C T

Phycocyanin (PC), as a characteristic pigment, is more suitable for monitoring cyanobacterial blooms and toxic cyanobacteria than chlorophyll-*a* (Chl-*a*). Because the absorption peak of PC is about ~620 nm, the application of remote sensing using a wavelength range of 615–630 nm becomes very attractive for the implementation of PC-targeted inversion algorithms. Numerous researchers have applied empirical and semi-analytical algorithms to derive PC concentration as proxies for cyanobacterial blooms. However, in contrast to Chl-*a*, the remote sensing estimation of PC concentration at the larger scale is still limited by the scarcity of data with sufficient spatial and spectral resolution. Therefore, this review attempts to provide a comprehensive overview of remote sensing techniques and retrieval algorithms as applied to the PC monitoring. The main emphasis is on the PC inversion algorithms and their realization via the available and perspective remote sensors. Based on the above analysis of state-of-the-art techniques and algorithms, the overall challenges and potentials of remote sensing-based cyanobacterial PC pigment retrieval are discussed in detail.

Contents

Introduction

The fragile balance of freshwater ecosystems is jeopardized by freshwater eutrophication. In particular, the latter phenomenon manifests

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itself by cyanobacterial blooms, which frequently occur in inland and coastal waters, causing a serious hazard to the ecosystem and human health all over the world (Kudela et al., 2015; Sivonen and Jones, 1999). Cyanobacteria are known to produce a variety of toxins (referred to as cyanotoxins), including cytotoxins, hepatotoxins, and neurotoxins (Pearson et al., 2016). Global warming is likely to affect the physiological and molecular changes in cyanobacteria, which enhance the toxin production (El-Shehawy et al., 2012). However, the lack of quantitative surveys on cyanotoxin makes it difficult to estimate the cyanotoxin-related potential hazards to drinking and irrigation water supplies, as well as fishing and recreational use of surface waters worldwide. A recent study has shown that cyanotoxin content could be estimated through surrogate pigments of cyanobacteria such as chlorophyll-*a* (Chl-*a*) and phycocyanin (PC) (Stumpf et al., 2016). Therefore, the effective and accurate monitoring of cyanobacteria blooms is necessary for analyzing the cyanotoxin generation mechanism. Nowadays, remote sensing has become a must-have tool for cyanobacteria monitoring at the local and global scales, due to its cost-effectiveness, as well as temporally repetitive nature of monitoring capabilities.

For remote sensing applications, a commonly used proxy for cyanobacteria blooms is Chl-*a*, being the primary and dominant photosynthetic pigment in phytoplankton (Chorus and Bartram, 1999). The Chl-*a* inversion of remote sensing is relatively mature. However, recent findings (Ma et al., 2009a) have proved that Chl-*a* fails to be an accurate indicator of cyanobacteria, due to its presence in other phytoplankton species. In freshwater, PC is mainly associated with cyanobacteria and, thus, can be used as an alternative marker pigment of cyanobacterial biomass (Dekker, 1993). Earlier studies have demonstrated the potential of PC for the estimation of cyanobacteria biomass or abundance (Brient et al., 2008). The absorption peak of PC being about 620 nm, it can be easily detected and identified by the remote sensing reflectance spectra range between 610 and 630 nm, forming a basis for the development of PC-based algorithms (e.g., Simis et al., 2005; Matthews, 2011; Ruiz-Verdú et al., 2008; Varunan and Shanmugam, 2017). However, as compared to Chl-*a*, the PC retrieval is less user-friendly for measurements or estimation due to the difficulty of PC extraction in the laboratory and its low specific absorption in inland waters. Moreover, the large-scale PC estimation in inland waters is inhibited by the lack of standards methods to extract PC and the applicable satellite sensors with the suitable spectral band at 620 nm (Stumpf et al., 2016).

For a further implementation of remote sensing techniques into PC monitoring and research, this paper presents an overview of the available state-of-the-art methods, to get a deeper insight into the problem and derive the basis for further improvements in this domain. To this end, a brief description of PC absorption is given, followed by a section reviewing the PC retrieval algorithms and comparing their advantages and drawbacks, with a final discussion of the practical PC monitoring via the available satellite sensors.

Phycocyanin absorption properties

PC is a functional protein found in cyanobacteria with a high intracellular variability. There are two PC pigments, namely Cyanophyceae PC (C-PC) and Rhodophyceae PC (R-PC) with distinguished absorption features. C-PC has the maximum absorption at about 620 nm, while the R-PC absorption peak is about 550 nm (Jiang et al., 2001). Biologically, C-PC exists in the blue-green cyanobacteria group, while R-PC appears in the harmful red algae. Rhodophyceae are relatively rare in freshwater so ereafter the abbreviation PC is used to refer to C-PC.

Light absorption features of PC make it attractive for optical remote sensing detection. PC absorbs the orange and red light wavelengths (between 610 and 630 nm) and emits fluorescence at about 650 nm, depending on the community type (Dekker, 1993; Jupp et al., 1994). PC peaks near 620 nm with a prominent shoulder (which means a change in the derivative of a spectral function without a change in sign) extended to the blue wavelengths (MacColl and Guard-Friar, 1983). However, the specific absorption of PC at 620 nm is lower by about 0.075 $m^2\ mg^{-1}$ than that of Chl-*a* for the range between 665 and 681 nm (0.15–0.20 $m^2\ mg^{-1}$) (Simis et al., 2005). Consequently, a higher concentration of PC, as compared to Chl-*a*, is required to get the equivalent signal of remote sensing reflectance. The absorption of Chl-*a* and other accessory pigments near 620 nm strongly affect the signal of PC retrieval due to its weak production of optical signals (Dekker, 1993; Hunter et al., 2010; Mishra et al., 2009; Simis et al., 2005, 2007). For example, Chl-*a* exhibits a significant absorption shoulder at about 623 nm (Ficek et al., 2004). A broad peak of chlorophyll-*b* (Chl-*b*) is observed at 650 nm and 600 nm, while the second peak of chlorophyll-*c* (Chl-*c*) corresponds to 590 nm and 640 nm (Ficek et al., 2004; Sathyendranath et al., 1987). Similarly, the absorption by suspended non-algal particle and colored dissolved organic matters cannot be ignored when PC concentration is quantified through the absorption or reflectance spectra (Simis et al., 2007).

Phycocyanin concentration modeling

The elaboration of an accurate model of water quality parameter inversion for inland waters is quite problematic (Ma et al., 2009b). As compared to Chl-*a*, the inversion model of PC concentration is more cumbersome due to the unique absorption band and low specific absorption. Up till now, researchers have developed empirical, semi-empirical, and semi-analytical models by taking advantage of the PC absorption feature between 615 and 630 nm (Ogashawara et al., 2013). Most models are based on the reflectance spectral shape or relationships between the reflectance band ratio and the PC absorption, but these models are location-specific. More detail on these models can be found elsewhere (Ruiz-Verdú et al., 2008; Varunan and Shanmugam, 2017), while this paper is focused on the main algorithms of PC retrieval and the comprehensive analysis of their advantages and drawbacks.

Empirical algorithms

Empirical models are developed based on the direct statistical relationships between the parameters obtained from remote sensing or in situ optical data and measured PC concentration. For example, Vincent et al. (2004) used the reflectance band ratio from the Landsat Thematic Mapper (TM) sensor (which operated on the board of Landsats 4 and 5 from July 1982 to May 2012) to estimate PC concentrations in Lake Erie in North America. Sun et al. (2015) developed a multivariate band-ratio regression model to estimate the PC concentration using visible and near-IR bands with their band ratios, and thee model performed well. Ma et al. (2009b) elaborated a 6-term polynomial model to estimate the PC concentration using the reflectance data of Moderate Resolution Imaging Spectroradiometer (MODIS) onboard the Terra spacecraft. Dash et al. (2011) quantified PC concentration using the spectral slopes of R_{rs} at the 556 and 511 nm bands of the Ocean Color Monitor (OCM) onboard the Indian Remote Sensing Satellite IRS-P4 in a small lake. Wozniak et al. (2016) designed the multilinear regression using the band ratio of 620/665 nm and 620/708.25 nm for OLCI radiometer and showed its potential in monitoring large-scale changes in PC concentration ($R^2 = 0.77$, RMSE = 0.23).

With the development of hyperspectral sensors, empirical models are able to focus more on the optical features of some pigments. For the case of PC, these algorithms mainly exploit the unique absorption feature near 620 nm. Single bands (~620 nm) and band ratios such as 620/650 nm have been used (e.g., by Dekker, 1993; Mishra et al., 2009; Ruiz-Verdú et al., 2008; Schalles and Yacobi, 2000). Dekker (1993) constructed a reference baseline between two wavelengths (600 and 648 nm) for the reflectance subtraction at 624 nm ($PC \propto (R(600) + R(648))/2) - R(624)$ and reported its strong correlation ($R^2 > 0.99$) with PC concentration in turbid lakes.