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Spatio-temporal variations of CDOM in shallow inland waters from a semi-analytical inversion of Landsat-8

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ABSTRACT

Bottom reflectance is often the main cause of high uncertainty in Colored Dissolved Organic Matter (CDOM) estimation for optically shallow waters. This study presents a Landsat-8 based Shallow Water Bio-optical Properties (SBOP) algorithm to overcome bottom effects so as to successfully observe spatial and temporal CDOM dynamics in inland waters. We evaluated the algorithm via 58 images and a large set of field measurements collected across seasons of multiple years in the Saginaw Bay, Lake Huron. Results showed that the SBOP algorithm reduced estimation errors by as much as 4 times (RMSE = 0.17 and R^2 = 0.87 in the Saginaw Bay) when compared to the QAA-CDOM algorithm that did not take into account bottom reflectance. These improvements in CDOM estimation are consistent and robust across broad range CDOM absorption. Our analysis revealed: 1) the proposed remote sensing algorithm resulted in significant improvements in tracing spatial-temporal CDOM inputs from terrestrial environments to lakes, 2) CDOM distribution captured with high resolution land-viewing satellite is useful in revealing the impacts of terrestrial ecosystems on the aquatic environment, and 3) Landsat-8 OLI, with its 16 days revisit time, provides valuable time series data for studying CDOM seasonal variations at land-water interface and has the potential to reveal its relationship to adjacent terrestrial biogeography and hydrology. The study presents a shallow water algorithm for studying freshwater or coastal ecology, as well as carbon cycling science.

1. Introduction

The assessment of Colored Dissolved Organic Matter (CDOM) in lake waters help the scientific community better understand both global/regional carbon cycling and aquatic ecosystem biogeochemistry. CDOM can be used as a surrogate for terrestrially derived dissolved organic carbon (DOC) assessment (Kutser et al., 2015). The export of terrestrial DOC to lakes and oceans represents a significant carbon exchange at the land-water interface (Roulet and Moore, 2006; Tian et al., 2013). This carbon flux is a key pathway leading to widespread CO_2 supersaturation in aquatic environments (Butman et al., 2016; Jonsson et al., 2003; Raymond et al., 2013). Inland waters also play a significant role in the sequestration, transport and mineralization of terrestrially sourced organic carbon (Bastviken et al., 2011; Battin et al., 2009; Tranvik et al., 2009). In addition, soil carbon loss to rivers and lakes has an important impact on net terrestrial carbon budgets (Davidson et al., 2010). CDOM in inland waters also influences the aquatic ecosystem in a variety of ways (Williamson et al., 1999). CDOM in inland water absorbs short wavelength incoming light, and this absorption will further affect the growth of plankton communities (Diehl, 2002; Williamson et al., 1996). Moreover, terrestrial DOC transportation to inland waters represents a very important nutrient exportation pathway from land to water (Cole et al., 2007). These terrestrial carbon inputs will ultimately impact the food webs within the lake environment (Brezonik et al., 2015; Cole et al., 2006).

Remotely sensed satellite imagery provides an efficient solution for monitoring CDOM dynamics (Keith et al., 2016). The remote sensing estimation of water biogeochemistry is based on observation of water bio-optical components, including CDOM, which influence the underwater light field (Hoge and Lyon, 1996; Yu et al., 2010), and therefore lead to changes in water leaving radiance received by the satellite sensor (Zhu et al., 2011). Previous research on inland and coastal water CDOM estimation by high-resolution satellite data often relied on empirical band ratios algorithms, in which model coefficients are specific

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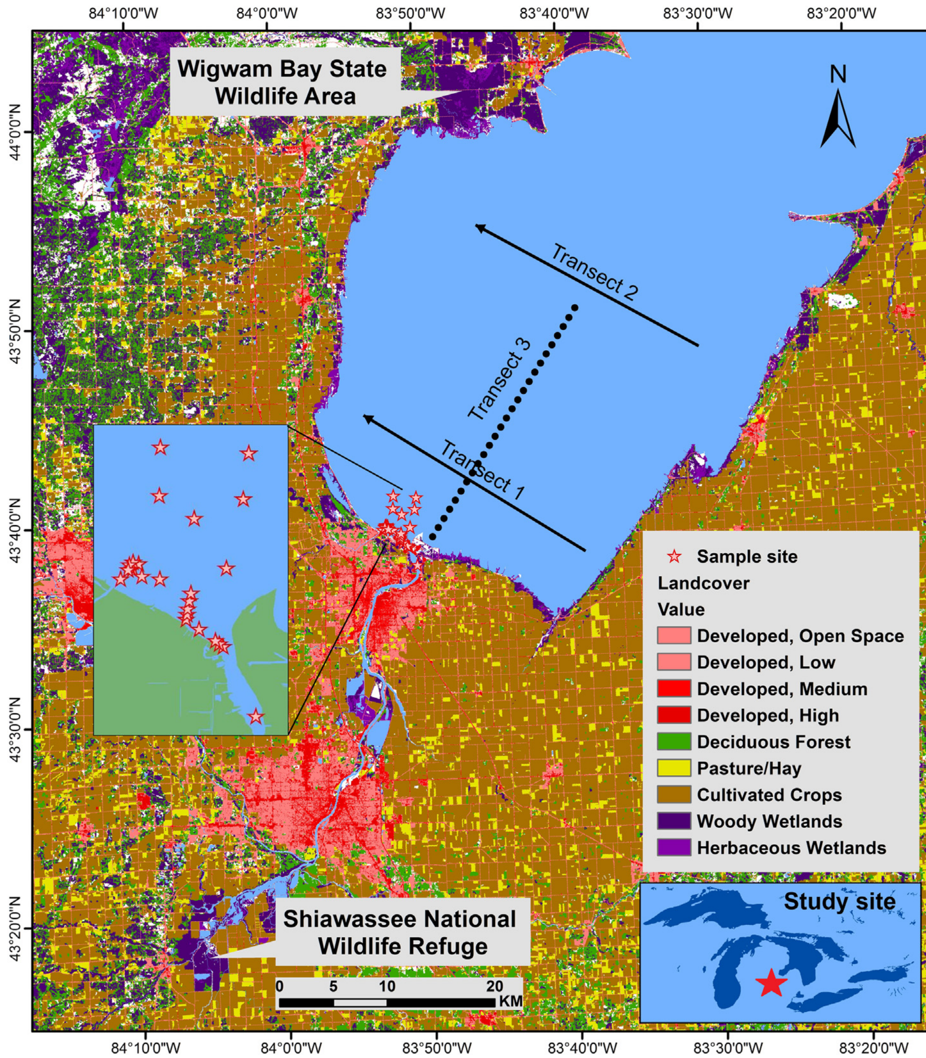

Fig. 1. The study area of Saginaw Bay, Lake Huron. The surrounding area contains varied landcover types, including wetlands, agricultural cropland, and forest. Red stars marked the filed samplings locations. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

to site and satellite sensors. It often requires additional tuning when applied to other waterbodies (Kutser et al., 2005; Mannino et al., 2008). Sensor-independent semi-analytical algorithms based on bio-optical water radiative transfer models have been developed to improve the retrieval of water biogeochemistry, particularly chlorophyll absorption (Carder et al., 1999; Kahru and Mitchell, 2001; Le et al., 2013; Lee et al., 2002). In addition, the need to better estimate carbon amounts in coastal regions resulted in the development of several semi-analytical algorithms designed to retrieve CDOM absorption in optically deep waters (Matsuoka et al., 2013; Shanmugam, 2011; Zhu and Yu, 2013). Unfortunately, these semi-analytical CDOM algorithms are not applicable to optically shallow waters, which limit using remote sensing techniques for assessing carbon dynamics at the land-water interface. An algorithm specific to the estimation of CDOM in inland, optically shallow waters is needed.

Growing interest in inland water CDOM observation via remote sensing requires suitable satellite images with both the proper spectral wavelengths and finer spatial resolution (Brezonik et al., 2015; Palmer et al., 2015). The semi-analytical algorithms take advantage of better atmospheric correction and water properties estimation (e.g. chlorophyll) aids by an "ultra-blue" band (e.g. from 435 nm to 450 nm) to build the bio-optical model in the coastal region or temperate lake (Lee et al., 2007a; Lee et al., 2002). Consequently, the studies using semi-analytical algorithms are mainly based on the ocean-viewing satellites (MODIS, SeaWiFS) or hyperspectral satellite sensor (EO-1 Hyperion) that record data in this wavelength range (Cuthbert and Del Giorgio, 1992; Kutser et al., 2005; Miller and McKee, 2004; O'Reilly et al., 1998;). However, these images are not applicable to studies involving smaller inland lakes and rivers because of coarse spatial resolutions (e.g., MODIS) or narrow coverage (e.g., Hyperion). Rivers, that are important pathways for transporting terrestrial CDOM, typically have a width narrower than two kilometers (Allen and Pavelsky, 2015). The spatial resolution or pixel size of most ocean-viewing sensors such as MODIS are far too coarse to observe inland waters, and much uncertainty is introduced when these images contain land-water mixed pixels (Zhu et al., 2013a). In contrast, the recently decommissioned high resolution hyperspectral sensor Hyperion had provided the spatial resolutions needed for inland waters, but its utility was very limited with respect to terrestrial CDOM estimation due to its narrow coverage and limited acquisition (Zhu and Yu, 2013). In recent years, several multispectral land-viewing satellite sensors have offered new promise for the retrieval of inland water bio-optical properties with the addition of an ultra-blue band, such as Landsat-8 and Sentinel-2 (Roy et al., 2014). In this study, we selected Landsat-8 to derive the CDOM absorption in lake waters. With its relatively high spatial resolution, Landsat 8 is able to effectively capture images of the lower reaches and plumes of rivers, thereby increasing its potential for observing inland water biogeochemistry (Pahlevan et al., 2014). Several empirical