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Estimating lake carbon fractions from remote sensing data

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ABSTRACT

Issues like monitoring lake water quality, studying the role of lakes in the global carbon cycle or the response of lakes to global change require data more frequently and/or over much larger areas than the *in situ* water quality monitoring networks can provide. The aim of our study was to investigate whether it is feasible to estimate different lake carbon fractions (CDOM, DOC, TOC, DIC, TIC and pCO_2) from space using sensors like OLCI on future Sentinel 3. *In situ* measurements were carried out in eight measuring stations in two Swedish lakes within 2 days of MERIS overpass. The results suggest that the MERIS CDOM product was not suitable for estimating CDOM in lakes Mälaren and Tämnaren and was not a good proxy for mapping lake DOC and TOC from space. However, a simple green to red band ratio and some other MERIS products like the total absorption coefficient, turbidity index, suspended matter and chlorophyll-a were correlated with different carbon fractions and could potentially be used as proxies to map these lake carbon fractions (CDOM, DOC, TOC, DIC, TIC and pCO_2) from space.

1. Introduction

Knowing the lake carbon content is important from several aspects. For example, the increase in the amount of dissolved organic matter in lakes used as drinking water resources increases the cost of water treatment (Matilainen, Vepsalainen, & Sillanpää, 2010) and the risk of cancer (McDonald & Komulainen, 2005). Moreover, recent studies (Tranvik et al., 2009) show that lakes play an important role in the global carbon cycle. It is obvious that remote sensing has to be used in order to get spatial and temporal coverage needed for water management, and there is no other option to clarify the role of lakes in the global carbon cycle than by means of remote sensing.

First attempts to map lake carbon content with remote sensing were made already in the 1980s. For example Vertucci & Likens (1989) estimated dissolved organic carbon (DOC) and absorbance at 360 nm (CDOM) in Adirondack lakes from reflectance measured with a hand held spectrometer from a boat. Different airborne and satellite sensors have been used in mapping lake dissolved organic matter or its coloured component CDOM (coloured dissolved organic matter) since then (Kallio et al., 2008, 2001; Kutser, Herlevi, Kallio, & Arst, 2001; Kutser, Pierson, Kallio, Reinart, & Sobek, 2005; Kutser, Pierson, Tranvik, et al., 2005; Kutser, Tranvik, & Pierson, 2009; Shuchman et al., 2013; Zhu et al., 2014). The sensors used in these studies (Landsat, ALI, and Hyperion) were not suitable for operative monitoring and/or global studies due to either low spatial coverage, low temporal coverage or low radiometric sensitivity. MERIS provided global coverage and high temporal coverage, had sufficient radiometric sensitivity and was shown to provide reliable CDOM estimates in boreal lakes (Zhu et al., 2014). The only disadvantage of this sensor was 300 m spatial resolution which was suitable only for relatively large lakes while the majority of the lakes on Earth are too small to be studied with sensors with such spatial resolution. The situation with sensors potentially suitable for lake carbon studies is changing now. Landsat 8 and planned Sentinel-2 missions will provide data for smaller lakes and Sentinel-3 will provide data for larger lakes. Therefore, it is now timely to evaluate what satellite sensors can actually provide for lake carbon studies.

Most of the carbon in lakes is usually in dissolved form (Wetzel, 2001). Therefore, there is often good correlation between the dissolved organic carbon and total organic carbon (TOC). Some studies have shown that the lake TOC can be mapped with remote sensing (Chang & Vannah, 2012; Song et al., 2006). Both of these studies used Landsat TM imagery and data from one lake. Although Landsat imagery has been used in some other studies for lake carbon mapping (Kallio et al., 2008; Kutser, 2012) it is generally known that the low signal to noise ratio and 8-bit radiometric resolution (256 gray levels) are suboptimal for aquatic studies because just a few of the gray levels in each band have to describe the whole possible variations in optical properties of water bodies.

Stramski, Reynolds, Kahru, and Mitchell (1999) have shown that particulate organic carbon (POC) can be estimated with remote sensing in Southern Ocean waters. The algorithm was based on a good correlation between the particulate backscattering coefficient at 510 nm and

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POC. However, this relationship varied in different parts of the ocean and the correlation was good for log-transformed variables. Hadjimitsis & Clayton (2011) used hand-held spectrometer data, recalculated it to Landsat bands and developed a statistical POC retrieval algorithm for water treatment reservoirs. Backscattering was not measured in these water bodies. Therefore, it is not known whether the backscattering from organic particles made their quantitative mapping with remote sensing feasible. It must be noted that both of these studies use the term particulate organic carbon (POC), but neither of them measured actually carbon. The actual measured parameter was suspended particulate organic matter (SPOM) which was determined as the difference between the dry weight of total suspended solids (TSS) and suspended particulate inorganic matter (SPIM) that is left after combustion of the TSS filters.

Sobek, Algesten, Bergström, Jansson, and Tranvik (2003) have shown that pCO_2 and DOC are correlated ($R^2 = 0.51$) during ice free season in many boreal lakes. This should allow us to estimate roughly pCO_2 from space if we can estimate DOC with sufficient accuracy. We measured pCO_2 in both Mälaren and Tämnaren in order to test this hypothesis.

The aim of our study was to carry out a small scale experiment and test which lake carbon fractions could potentially be mapped with remote sensing. In this pilot study we tried to estimate from remote sensing data both the parameters that have direct impact on water colour (like CDOM), but we tested also the possibility of estimation of characteristics which do not have known direct impact on water colour (like pCO_2). The only satellite sensor suitable for lake carbon studies that was available during our pilot study was MERIS. However, the results of this study allow us to test the potential of future OLCI sensor onboard Sentinel-3 as this sensor will be MERIS follow up.

2. Study sites and data

Most of the measurements were carried out in Lake Mälaren (Fig. 1) on September 14–18, 2011 while one sampling station was in Lake Tämnaren. Lake Mälaren is the third largest lake in Sweden. Its surface area is 1140 km^2. It is a gemorphologically very complicated lake and its basins behave quite differently from optical point of view (Köhler et al., 2013; Kutser, 2012). Lake Tämnaren is a much smaller (32.6 km^2) and a very shallow (max 1.7 m) lake. Lake Mälaren was chosen as a study object because of its optical variability while Lake Tämnaren was the main study site during 2011 in the Colour of Water project in the frame of which our pilot study was carried out. The lake is located about 50 km north of Uppsala and was equipped with a flux tower and underwater instrumentation for continuous carbon flux studies during 2011 ice free period.

Weather conditions were quite variable throughout the fieldwork week. During the first day we experienced strong wind and rain showers while during the last days the conditions were nearly perfect from remote sensing point of view — calm and cloud free. The conditions were most extreme in Lake Tämnaren as strong wind and very shallow water depth caused resuspension of considerable amount of sediments. This, however, guaranteed that the water was optically deep as the Secchi depth was just 0.3 m in the sampling station while the water depth was 1.5 m.

The *in situ* reflectance measurements were performed with Trios Ramses spectrometers (spectral range of 350–900 nm). The measurements were carried out in two different ways. At first we measured reflectance as a ratio of upwelling radiance to downwelling irradiance while both sensors were above the water surface. Second set of measurements was carried out having upwelling radiance sensor (which is equipped with a 5 cm black plastic tube) just below the water surface. Ten spectra were measured and averaged in both cases. The first measurements gave us reflectance with sky and sun glint while the second series gave true reflectance without glint.

Absorption, attenuation and scattering coefficient measurements were carried out *in situ* with WetLabs AC-S, volume scattering measurements with WetLabs ECO-VSF3, and backscattering measurements with Wetlabs ECO-BB3 and ECO-VSF3 for which the wavelengths were chosen complementary to cover the visible part of spectrum (BB3 412 nm, 595 nm and 715 nm; VSF3 460 nm, 532 nm, and 660 nm). *In situ* pCO_2 measurements were performed with SAMI by Sunburst Sensors.

The carbon fractions measured in the laboratory were dissolved organic carbon (DOC), dissolved inorganic carbon (DIC), total organic carbon (TOC) and total inorganic carbon (TIC). The carbon samples were collected in acid-rinsed (10% HCl) plastic vials by filling the bottle almost to the top. The sample set was not preserved with acid at the time of collection. The samples were packed in ice and frozen gel packs and delivered to laboratory within hours where most of the analysis where performed immediately. Water chemistry samples were divided into subsamples in the laboratory and thus for analysing dissolved

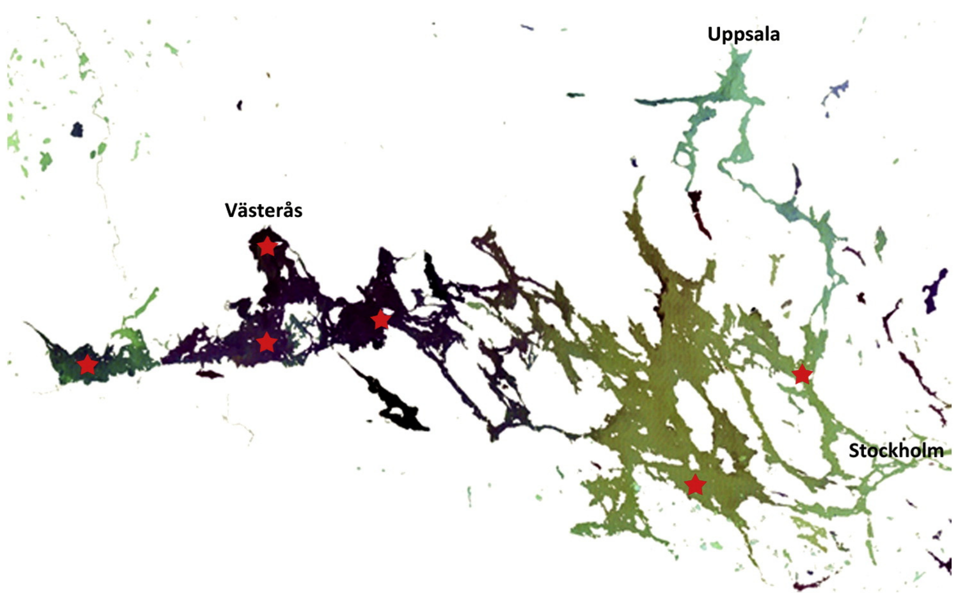

Fig. 1. Landsat image of Lake Mälaren showing the sophisticated geomorphology of the lake. Sampling stations are indicated with red stars. Lake Tämnaren is located 50 km north from Uppsala and is not shown in this map.

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