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# Impact of iron associated to organic matter on remote sensing estimates of lake carbon content

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ABSTRACT

There is a strong need to develop remote sensing methods for mapping lake carbon content on regional to global scales. The use of in situ methods is impractical for monitoring lake water quality over large geographical areas, which is a fundamental requirement to understand the true role of lakes in the global carbon cycle. The coloured component of dissolved organic carbon (DOC), called CDOM, absorbs light strongly in the blue part of the visible spectrum and can be used as a proxy for mapping lake DOC with remote sensing. However, iron associated to organic matter can cause extra browning of waters. Consequently, the remote sensing signal we interpret as DOC may partially be attributed to the presence of iron associated to organic matter, potentially hampering our ability to estimate carbon concentrations.
A thorough analysis of biogeochemical parameters was carried out on Lake Mälaren on August 23, 2010, and a MERIS full resolution image was acquired simultaneously. MERIS standard, Case 2 Regional, and Boreal processors were used to calculate remote sensing products, which were compared with different lake water characteristics.
The carbon to iron ratio was different from the rest of the lake in one of the basins. MERIS standard and Case 2 Regional processors were sensitive to this difference as the correlation between MERIS CDOM product and DOC was low ($R^2 = 0.43$) for all sampling stations and increased to 0.92 when the one basin was excluded. The Boreal Lakes processor results were less disturbed by the different carbon–iron ratios found in one basin and produced reasonably good results ($R^2 = 0.65$).
We found MERIS products (e.g. total absorption) that provided good correlation ($R^2 = 0.80$) with DOC-specific absorbance at 254 nm, called SUVA, which is a metric commonly used to assess drinking water treatability. However, none of the MERIS products were suitable for mapping the total organic carbon in Lake Mälaren. MERIS total suspended matter product was a good ($R^2 = 0.73$) proxy for particulate iron, meaning that the particulate iron content in Mälaren can be mapped from space.


## 1. Introduction

Recent studies indicate that lakes play an important role in the global carbon cycle (IPCC, 2013; Tranvik et al., 2009). In addition, over recent decades there has been an increase in the amount of dissolved organic matter (DOM) and browning of many surface waters, at least in boreal and hemiboreal zones for which long time data series exist (Weyhenmeyer, Prairie, & Tranvik, 2014). DOM is an important substrate for microorganisms including bacteria and algae (Tranvik, 1992), and hence in some cases can promote fouling of water, causing problems of taste, odour, and hygiene. Moreover, disinfection of water still containing DOM may result in the formation of carcinogenic chlorinated organic by-products (McDonald & Komulainen, 2005). The need for higher doses of chlorine can enhance the risk of bladder and rectal cancers (Koivusalo, Pukkala, Vartianen, Jaakola, & Hakulinen, 1997). Likewise, excess DOM in source water results in the need to add higher doses of costly flocculants (Eikebrokk, Vogt, & Liltved, 2004; Matilainen, Vepsalainen, & Sillanpää, 2010).

Despite efforts to remove DOM, the efficiency of DOM removal is highly variable between drinking water treatment plants, which is largely attributed to the varying qualities of DOM (Valade, Becker, & Edzwald, 2009). An easy to measure proxy for DOM quality is the carbon specific UV absorbance (SUVA), which is a useful way of predicting the general chemical characteristics of DOM, particularly the aromatic content of DOM (Weishaar et al., 2003). For several decades, water treatment plants have routinely monitored the SUVA of source waters to

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detect changes in its treatability, particularly the potential ease of DOM removal (Edzwald, Becker, & Wattier, 1985). For these reasons, developing a means of estimating the SUVA of surface waters remotely would be highly valuable to the drinking water industry.

Lake monitoring programmes have detected increasing DOM content over the past several decades (Weyhenmeyer et al., 2014). However, lake monitoring is expensive and requires large field crews and the extent of field sampling is limited, both spatially and temporally. There is a strong need to develop remote sensing methods for mapping lake carbon content at larger regional and global scales. Current estimates on the role of lakes in the global carbon cycle (Tranvik et al., 2009) were obtained by upscaling in situ measurements from a few thousand lakes to a statistical estimate of the global distribution of lakes. However, Seekel and Pace (2011) have shown that the Pareto distribution used to produce the global lake abundance estimates (Downing et al., 2006; Lehner & Döll, 2004) contains very large uncertainty, especially in the case of small lakes that comprise the majority of the lakes on Earth. To determine the true role of lakes at a global scale, one needs more accurate numbers on both the abundance of lakes in the world, and better estimates of lake carbon concentrations. Mapping tens of millions of small lakes and collection of in situ data about carbon content in majority of them is not feasible. Recently, mapping of lakes on a global scale was achieved. Verpoorter, Kutser, and Tranvik (2012) developed a methodology to recognise water bodies from 14.25 m spatial resolution Landsat GeoCover mosaics covering practically the whole Earth "land" surfaces and a map of all water bodies greater than 0.2 ha (Verpoorter, Kutser, Tranvik, & Seekel, 2014). Developing more reliable carbon retrieval algorithms is also a work in progress (Brando, Dekker, Park, & Schroeder, 2012; Kallio et al., 2001; Kallio et al., 2008; Kutser, Pierson, Kallio, Reinart, & Sobek, 2005; Kutser, Tranvik, & Pierson, 2009; Kutser et al., 2005; Shuchman et al., 2013). However, there is a need to validate the developed algorithms before the global lake carbon estimate can be produced. There are potentially confusing factors for lake carbon remote sensing (like high concentration of phytoplankton or strongly absorbing sediment) that remote sensing scientists are aware of, but one of the unknown factors is the presence of iron associated to organic matter in lake waters. Our aim was to address this issue in the present study.

The MEdium Resolution Imagining Spectrometer, MERIS, was the best sensor to be used in large lake monitoring over the previous decade, with a 300 m spatial resolution, nearly daily coverage in higher latitudes, and some spectral bands designed for remote sensing of optically complex coastal and inland waters. MERIS was launched on March 1, 2002 and was operational until April 8, 2012. A follow-up instrument OLCI (Ocean and Land Colour Instrument) with a few extra spectral bands is due to be launched on Sentinel-3 in 2015. MERIS had several processors (standard Ground Segment — MEGS, Case 2 Regional, Boreal Lakes, etc.) and each of them with products (yellow substances (CDOM), the diffuse attenuation coefficient of light at 490 nm — $K_d(490)$, turbidity index, etc.) that may be suitable for mapping lake carbon content.

In many areas of the world, 90–95% of organic carbon in lakes is in the dissolved form as DOC (Wetzel, 2001). Therefore, both determining the true role of lakes in the global carbon cycle and monitoring water quality require reliable estimates of lake DOC. Only the visible part of electromagnetic radiation can penetrate the water surface and provide us with information about water properties. Consequently, the parameter we want to measure from space or airborne sensors must affect optical water properties (e.g. reflectance), or correlate directly with water characteristics that affect the optical water properties. For example, suspended matter concentration in lakes can be measured with remote sensing (Kallio et al., 2001) because it has direct impact on reflectance whereas optically "invisible" total phosphorus concentration has been estimated from remote sensing data due to close correlation between the phosphorus and water transparency (Kutser, Arst, Miller, Käärmann, & Milius, 1995) in the studied lake.

DOC contains a coloured component called yellow substances or CDOM (Coloured (or Chromophoric) Dissolved Organic Matter). There is typically a strong correlation between DOC and CDOM in boreal lakes, as well as in many other water bodies (Kallio, 1999; Tranvik, 1990; Yacobi, Alberts, Takacs, & McElvaine, 2003; Zhang, Qin, Zhu, Zhang, & Yang, 2007). For example, a study including 983 boreal lakes distributed across Sweden found that absorbance at 254 or 420 nm was very good predictors of DOC concentration, with $R^2$ values of 0.95 and 0.96, respectively (Erlandsson, Futter, Kothawala, & Köhler, 2012). However, there is generally a lack of data about the CDOM–DOC relationship around the world. DOM absorbance properties tend to change in lakes with longer retention time (Dillon & Molot, 1997; Köhler, Kothawala, Futter, Liungman, & Tranvik, 2013; Kothawala et al., 2013; Meili, 1990). Validating existing algorithms in some of the more complicated systems is thus potentially a challenge for existing MERIS CDOM products. Furthermore, there may be other MERIS products that are better proxies for DOC than CDOM. For example, characteristics that describe the total effect of phytoplankton, CDOM and TSM on the reflectance (like Secchi depth, beam attenuation coefficient, diffuse attenuation coefficient) or the effect of just two components (like turbidity) may perform better than the algorithms that have been designed to retrieve concentration of just one optically active substance. Water transparency, turbidity and other similar characteristics are robust parameters that are relatively straightforward to estimate from remote sensing data (Kallio et al., 2001; Kutser et al., 1995; Olmanson, Bauer, & Brezonik, 2008). It may happen that remote sensing algorithms are wrong in partitioning the signal caused by the phytoplankton, CDOM and TSM, but perform much better in estimating their sum — transparency/turbidity. If a parameter under investigation (e.g. DOC) is in correlation with one of the transparency/turbidity products, then these products may provide better information about lake DOC concentrations than CDOM products. For example, we have found that MERIS total absorption coefficient product may be a better predictor of DOC and TOC than MERIS CDOM absorption product (Kutser, Verpoorter, Paavel, & Tranvik, 2014). There may be good correlations between some of the water characteristics and some remote sensing products that do not have direct cause–result relationships as far as we know. Therefore, it is worth studying all possible correlations between the water characteristics under investigation and different MERIS products.

The absorbance of filtered water, usually considered as a measure of CDOM concentration, depends also on the amount of iron associated to organic matter in water (Köhler et al., 2013; Weishaar et al. (2003); Xiao, Sara-Aho, Hartikainen, & Vähätalo, 2013). Iron passing the filter can exist as truly dissolved monomeric inorganic iron complexes, or as one of two colloidal forms, 1) as ferrihydrate and 2) iron that is bound to organic matter (Jensen, Mulder, & Verstraten, 2003; Lofts, Tipping, & Hamilton-Taylor, 2008). Rising Fe concentrations with DOC have been observed recently in some landscapes (Evans, Monteith, & Cooper, 2005), however, it has been noted that this rise in Fe is not proportional to the rise in DOC (Kritzberg & Ekström, 2011). If part of the water colour is due to colloidal iron associated to organic matter and part due to dissolved organic matter itself (Köhler et al., 2013; Xiao et al., 2013) and their relative contributions vary, then it may be difficult to develop remote sensing products for mapping lake carbon content.

The aim of this study is to understand whether the variable iron concentration in lake waters hampers our capacity to estimate lake CDOM and DOC contents by means of remote sensing. We test whether any MERIS products are suitable for mapping lake water characteristics such as SUVA or the iron associated to organic matter concentration in lake waters.

## 2. Study site and methods

Mälaren is the third largest lake in Sweden (Fig. 1). Its surface area is 1140 $km^2$ and it provides drinking water to approximately 1.5 million people in Stockholm and surrounding communities. Mälaren has a