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Evaluating the portability of satellite derived chlorophyll-*a* algorithms for temperate inland lakes using airborne hyperspectral imagery and dense surface observations

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ABSTRACT

This study evaluated the performances of twenty-nine algorithms that use satellite-based spectral imager data to derive estimates of chlorophyll-*a* concentrations that, in turn, can be used as an indicator of the general status of algal cell densities and the potential for a harmful algal bloom (HAB). The performance assessment was based on making relative comparisons between two temperate inland lakes: Harsha Lake (7.99 km^2) in Southwest Ohio and Taylorsville Lake (11.88 km^2) in central Kentucky. Of interest was identifying algorithm-imager combinations that had high correlation with coincident chlorophyll-*a* surface observations for both lakes, as this suggests portability for regional HAB monitoring. The spectral data utilized to estimate surface water chlorophyll-*a* concentrations were derived from the airborne Compact Airborne Spectral Imager (CASI) 1500 hyperspectral imager, that was then used to derive synthetic versions of currently operational satellite-based imagers using spatial resampling and spectral binning. The synthetic data mimics the configurations of spectral imagers on current satellites in earth's orbit including, WorldView-2/3, Sentinel-2, Landsat-8, Moderate-resolution Imaging Spectroradiometer (MODIS), and Medium Resolution Imaging Spectrometer (MERIS). High correlations were found between the direct measurement and the imagery-estimated chlorophyll-*a* concentrations at both lakes. The results determined that eleven out of the twenty-nine algorithms were considered portable, with r^2 values greater than 0.5 for both lakes. Even though the two lakes are different in terms of background water quality, size and shape, with Taylorsville being generally less impaired, larger, but much narrower throughout, the results support the portability of utilizing a suite of certain algorithms across multiple sensors to detect potential algal blooms through the use of chlorophyll-*a* as a proxy. Furthermore, the strong performance of the Sentinel-2 algorithms is exceptionally promising, due to the recent launch of the second satellite in the constellation, which will provide higher temporal resolution for temperate inland water bodies. Additionally, scripts were written for the open-source statistical software R that automate much of the spectral data processing steps. This allows for the simultaneous consideration of numerous algorithms across multiple imagers over an expedited time frame for the near real-time monitoring required for detecting algal blooms and mitigating their adverse impacts.

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1. Introduction

Over the last several decades, there has been a noticeable increase in the frequency and extent of freshwater harmful and nuisance algal blooms (HNABs) in the United States (Reif, 2011; USEPA, 2012). Exact environmental mechanisms have yet to be determined (Graham, 2006; Linkov et al., 2009), although, high nutrient concentrations and algae available insolation appear to be significant contributing factors (Dokulil and Teubner, 2000). Freshwater HNABs have become a global concern affecting forty-five countries worldwide and have resulted in animal deaths in at least twenty-seven US states (Graham, 2006, USEPA, 2012; WHO, 2003). What makes these blooms “harmful” is that the algae comprising the bloom can produce toxic compounds including, dermatoxins, hepatoxins, and neurotoxins, which may be dangerous to both humans and animals if inhaled or ingested (USEPA, 2012). Although the World Health Organization and state agencies such as, the Ohio Department of Health, have set safety standards for the consumption and contact of these toxins (ODH, 2017), their monitoring in small to mid-sized water bodies is difficult, time intensive, and costly (Backer, 2002; Pitois et al., 2000). Remote sensing using satellite imagers for the detection of HNABs is possible because of photoreactive pigments produced by algae. These pigments have reflective properties that can be ‘sensed’ by analyzing the images. The toxins produced by algae are not directly detectable by the imagery, but toxin concentration is often correlated with algal biomass density, which in turn, is directly related to the concentration of photopigments (Gitelson et al., 1986, 2003; Kudela et al., 2015; Morel and Prieur, 1977; Stumpf et al., 2012, 2016; Vos et al., 1986; Wynne et al., 2012). One of the most abundant photopigments produced by all types of algae is chlorophyll-*a*, which is detectable by satellite imagery, therefore, can serve as an indicator of the presence of an algal bloom (Morel and Prieur, 1977; Vos et al., 1986; Gitelson et al., 1986, 2003; Wynne et al., 2012; Stumpf et al., 2012; Kudela et al., 2015) and is a reliable proxy for water quality (Verdin, 1985; Ekstrand, 1992; Reif, 2011; Mishra and Mishra, 2012). So, while satellite imagery allows for remote sensing of a proxy for algal density, subsequent water sampling for toxin analysis would still be necessary to validate a high signal from the satellite and to evaluate the nature of the bloom to determine toxicity.

To reduce costs and increase coverage of algal bloom monitoring the use of remote sensing, especially from satellite platforms, are currently being utilized to address the risk management challenges associated with HNABs including, the monitoring of smaller fresh water lakes, rivers, and reservoirs, long-term studies of individual bodies of water, and the development of techniques for early detection (Shen et al., 2012). The most effective way to accomplish these goals are through the continual use of high temporal resolution satellites with spatial resolutions significantly less than the size of the water body being observed (Beck et al., 2016). Temporal resolution is of the utmost importance, especially in temperate regions where freshwater HNABs typically occur during the summer, corresponding to the most frequent chances of heavy cloud cover which can influences satellite imager’s effectiveness. Therefore, the ability to maximize the number of satellites to image algal blooms in inland water bodies is important (Veryla, 1995). Ideal remote imaging systems would allow for quicker turnaround time for water safety officials to notify the public about potential HNAB occurrence (Blondeau-Patissier et al., 2014; Klemas, 2012; Stumpf and Tomlinson, 2005).

There has been some success in the global monitoring of algal blooms using satellites systems with high return times and swath widths of sensors such as the Moderate Resolution Imaging Spectroradiometer (MODIS), Ocean and Land Colour Instrument (OLCI) or the Medium Resolution Imaging Spectrometer (MERIS) (Augusto-Silva et al., 2014; Blondeau-Patissier et al., 2014; Klemas, 2012; Stumpf et al., 2012). Since MERIS is no longer operational, the similarly configured sensor, OLCI on the European Space Agency’s (ESA) Sentinel-3, takes MERIS’s place for data after the launch date of February 16th, 2016 (ESA, 2018). Unfortunately, these imagers are less useful for the monitoring of small to mid-sized inland lakes that typically have widths of less than a few kilometers. Satellites with better spatial resolution typically have too long return times to monitor HNABs whose growth dynamics in surface waters may have sub-daily response times (Hunter et al., 2008). Beck et al. (2016) suggested the use of a suite of sensors in order to optimize the successful acquisition of a cloud-free scene and provide effective monitoring of small freshwater lakes for minimal cost. This study evaluates the efficacy and portability of the 29 airborne and synthetic satellite-based reflectance algorithms studied by Beck et al. (2016) for quantification of chlorophyll-*a* in two temperate reservoirs. It further extends the work of Augusto-Silva et al. (2014), as well, by using airborne hyperspectral imagery and dense coincident in-situ observations for a direct comparison between the performances of these algorithms across two lakes.

Augusto-Silva et al. (2014) reviewed the satellite reflectance algorithms, including two-band-algorithm (2BDA) (Dall'Olmo and Gitelson, 2005), three band-algorithm (3BDA) (Gitelson et al., 2003), and the Normalized Difference Chlorophyll Index (NDCI) algorithm (Mishra and Mishra, 2012), while Beck et al. (2016) added the Fluorescence Line Height algorithms (FLH) for the approximation of chlorophyll-*a* concentrations in inland lakes. The findings of these studies demonstrate the accuracy of sensor-based chlorophyll-*a* estimates (Sauer et al., 2012). Where accuracy was based on how close the imager-based proxy was to observed chlorophyll-*a* concentration sampled directly from the water body and determined using a laboratory extraction method.

Due to differing band spacing and sensor configurations, it is important to note that not all algorithms can be applied to all sensors, and direct measurements of chlorophyll-*a* and phytoplankton communities in surface waters are highly variable due to nutrient, wind, and temperature fluxes, as well as a host of other bio-physical factors (Hunter et al., 2008; Sawaya et al., 2003; Stumpf et al., 2016; Wang et al., 2004). The comparison of multiple sensors is again complicated by the varying atmospheric and surface conditions that result from differing return times (Thonfeld et al., 2012). This issue is mitigated in this study by upscaling and spectral binning one hyperspectral image, the airborne-CASI. The advantage of this was we only needed to collect one set of coincident surface observations.

Another issue conflating the direct detection of harmful algae blooms (HABs), which in temperate freshwaters are most often caused by cyanobacteria, is that most current sensors lack the narrow spectral band centered at 620 nm corresponding to the phycocyanin absorption feature. Phycocyanin is more directly related to risk because it is a pigment produced by only cyanobacteria. Here the focus was solely on chlorophyll-*a* algorithms as proxies for any algal bloom. Given the current concern over HABs in general, and the evolving understanding of toxicity attributed algal communities, water safety professionals will likely want to acquire direct samples of any lake that the satellite imagery suggests is experiencing high chlorophyll-*a* concentrations.

In addition to assessing how the 29 algorithm-imager combinations perform between our study lakes, we also examined the site-specific variations that may impact imager performance for the following imagers: Compact Airborne Spectrographic Imager (CASI), WorldView-2, Sentinel-2, Landsat-8, MODIS, and MERIS. Finally, we apply an automated approach to image processing using the open-source software, R, (R Core Team, 2017). This approach significantly decreases the time it takes to derive chlorophyll-*a* estimates so that multiple estimates may be considered simultaneously.

2. Methods

2.1. Study area

The study focuses on two temperate lakes roughly 150 kilometers apart: Taylorsville Lake in Central Kentucky and Harsha Lake (aka East Fork Lake) in Southwest Ohio. Taylorsville Lake has an approximate