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Application of hyperspectral remote sensing to cyanobacterial blooms in inland waters

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ABSTRACT

Cyanobacterial blooms are increasingly posing a severe threat to inland waters, particularly at the land-sea interface where toxins can be transported downstream with subsequent impacts to both terrestrial and marine organisms. These blooms are relatively easy to detect optically because of the surface concentration of cells, the presence of phycocyanin pigments, and the elevated backscatter associated with cell size and the presence of gas vacuoles. Major challenges limiting the use of remote sensing have been, first, that many of these water bodies are small relative to the spatial resolution of ocean color satellites, and second, even with a bright algal target, the spectral resolution, signal-to-noise ratio, and repeat time for terrestrial satellites is often inadequate. The next generation of multispectral and hyperspectral sensors begin to address these issues with both increased spatial and spectral resolution. Weekly monitoring of Pinto Lake, California has demonstrated that this small water body provides an ideal testbed for development and application of algorithms applicable for legacy and next-generation sensors. Pinto Lake experiences seasonal nearly monospecific blooms with a pronounced species succession. Biomass (as chlorophyll) within Pinto Lake seasonally ranges from ~1 to 1000 μg/L. Pinto Lake has been within the flight lines for several recent airborne missions, including the HyspIRI Preparatory Flight Campaign, and is often targeted for HICO acquisitions. Using these data we demonstrate that spectral-shape algorithms requiring minimal atmospheric correction can be used across a range of legacy sensors to detect cyanobacterial blooms and that, with the availability of high spectral resolution data and appropriate atmospheric correction, it is possible to separate the cyanobacterial genera *Aphanizomenon* and *Microcystis*. In California *Aphanizomenon* is typically non-toxic and blooms prior to toxin-producing *Microcystis*, thus leading to the potential for an early warning system based on the identification of algal types.

1. Introduction

In California, there is increasing evidence that freshwater cyanobacteria (blue-green algae) are a growing problem in lakes and rivers. *Microcystis aeruginosa* in particular is considered a cyanobacterial harmful algal bloom (CyanoHAB) organism because it can impede recreational use of waterbodies, reduce esthetics, lower dissolved oxygen concentration, and cause taste and odor problems in drinking water, as well as produce microcystins, powerful hepatotoxins associated with liver cancer and tumors in humans and wildlife (Carmichael, 2001). Extensive *Microcystis* blooms with toxin production occur during summer and fall in impaired waterways in Washington, Oregon and California (Gilroy, Kauffman, & Hall, 2000; Johnston & Jacoby, 2003) and *Microcystis* contamination has been documented at the marine outflows of the Klamath and San Francisco estuaries (Fetcho, 2007; Lehman, Boyer, Hall, Waller, & Gerhrts, 2005) as well as from river inputs to Monterey Bay (Gibble & Kudela, 2014; Miller et al., 2010). The direct impact to the threatened California Sea Otter (*Enhydra lutris*) has promoted these blooms and toxins from predominantly a freshwater issue to potentially a land–sea problem, with concomitant risk because of the lack of monitoring in brackish and marine waters (Miller et al., 2010). Other common bloom-forming pelagic cyanobacteria

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include *Aphanizomenon, Anabaena*, and (less common, but present, in California) *Lyngbya* (Kurobe et al., 2013); however, since toxicity is primarily associated with *Microcystis*, these other CyanoHABs are generally considered nuisance blooms rather than acutely dangerous to humans and wildlife (Backer et al., 2010; Kudela, 2011; Lehman, Marr, Boyer, Acuna, & Teh, 2013).

Both toxigenic (capable of producing toxin) and non-toxic strains of *Microcystis* are present in California (Baxa, Kurobe, Ger, Lehman, & The, 2010; Lehman et al., 2013; Moisander, Lehman, Ochiai, & Corum, 2009). *M. aeruginosa* bloom formation and consequent toxin generation is influenced by environmental variables such as high nutrient supply, elevated light levels, and warm temperatures (Davis, Berry, Boyer, & Gobler, 2009; Jacoby, Collier, Welch, Hardy, & Crayton, 2000; Paerl & Huisman, 2008; Paerl & Otten, 2013; Tsuji et al., 1994; Welker & Steinburg, 2000; Zehnder & Gorham, 1960). The prevalence of CyanoHABs and subsequent toxic events may be intensified by a warming climate in tandem with increases in environmental degradation and eutrophication (Davis et al., 2009; Guo, 2007; Kudela, 2011; O'Neil, Davis, Burford, & Gobler, 2012; Paerl & Huisman, 2008; Welker & Steinburg, 2000; Zehnder & Gorham, 1960).

While toxin events are primarily associated with *M. aeruginosa*, other potentially toxic genera, including *Aphanizomenon*, *Anabaena*, and *Planktothrix* are frequently present in impacted water bodies (Kudela, 2011). These genera often produce dense surface blooms (Lehman et al., 2013; Paerl, 2008; Sellner, 1997), making satellite detection of potentially harmful cyanobacterial blooms possible (e.g. Kahru, 1997; Simis, Peters, & Gons, 2005, Simis et al., 2007; Vincent et al., 2004; Wynne et al., 2008). One issue with these methods is that not all cyanobacterial genera are toxic, nor is toxin always produced by toxigenic species. Thus while it is possible to identify potential CyanoHABs, it is desirable to separate potentially toxic and non-toxic blooms.

Many of the optical detection methods for identification of cyanobacterial blooms rely on algorithms targeting phycocyanin (reviewed by Kutser, 2009 and Ogashawara, Misra, Mishra, Curtarelli, & Stech, 2013), a characteristic pigment associated with freshwater cyanobacteria. Phycocyanin is a pigment-protein complex with a broad absorption feature at ~620 nm, often detected from remote sensing data using a wavelength range of 615–630 nm (Ogashawara et al., 2013). Potential issues with these approaches include the necessity to acquire data at sufficiently fine enough spatial and spectral resolution to identify the phycocyanin absorption feature in remote sensed data, the sensitivity to poor remote sensing data due to (for example) inadequate atmospheric correction (Wynne, Stumpf, Tomlinson, & Dyble, 2010), and the lack of a "universal" algorithm applicable to all sensors (Kutser, 2009).

One approach that avoids issues with atmospheric correction and is more easily extensible to multiple sensors involves the use of spectral shape, rather than identification of specific absorption features. In particular, Wynne et al. (2008, 2010) demonstrated that spectral shape (or the second derivative of the remote sensing reflectance spectrum) is insensitive to atmospheric correction when applied to surface-intensified blooms of cyanobacteria. Those authors developed a Cyanobacterial Index (CI) that relies on changes in the shape between 665, 681, and 709 nm caused by the strong scattering by cyanobacteria at around 709 nm (c.f. Wynne et al., 2008). The CI has been successfully applied to the detection of blooms in the Laurentian Great Lakes using the Medium Resolution Imaging Spectrometer (MERIS; Wynne et al., 2008), and later in conjunction with other environmental data such as wind speed (Wynne et al., 2010). A similar spectral shape approach was taken by Matthews, Bernard, and Robertson (2012). Those authors developed the Maximum Peak Height (MPH) algorithm and applied MPH to inland and coastal waters in South Africa with MERIS data. More recently, another generalization of spectral shape algorithms resulted in the Adaptive Reflectance Peak Height (ARPH) algorithm, applied to coastal waters of Monterey Bay, California, using the Hyperspectral Imager for the Coastal Ocean (HICO) by Ryan, Davis, Tufillaro, Kudela, and Gao (2014). All of these algorithms employ spectral shape and demonstrate reduced sensitivity to noisy data, such that they can even be applied to top-of-atmosphere radiances, a method pioneered by Gower, Doerffer, and Borstad (1999) in the development of the Maximum Chlorophyll Index (MCI) for MERIS.

Despite advances in development of both semi-analytical phycocyanin methods and spectral shape methods (Ogashawara et al., 2013), remote-sensing methods for detection of cyanobacterial HABs are still limited by the relative unavailability of sensors with both fine spectral and spatial resolution. Planned sensors such as the European Space Agency's Ocean Land Color Instrument (OLCI) aboard Sentinel-3 and NASA's Hyperspectral Infrared Imager (HyspIRI) will provide both greatly improved spectral and spatial resolution, but are not yet available. This limitation has hindered the application of remote sensing for routine monitoring and detection of CyanoHABs in California, despite widespread interest by monitoring and management agencies. To address these issues, and in preparation for the routine availability of data products from OLCI, HyspIRI, and other sensors, we took advantage of airborne data from the NASA Student Airborne Research Program (SARP, 2009 and 2011) and the HyspIRI Airborne Campaign (2013) collected over central California. Flights routinely imaged Pinto Lake, a small, hyper-trophic water body located adjacent to Monterey Bay, California. Pinto Lake is well characterized in terms of CyanoHAB events (Kudela, 2011) and makes an ideal testbed for development and testing of remote sensing algorithms. As with other inland waters, Pinto Lake also exhibits a regular successional pattern with increases in the (generally non-toxic) organism *Aphanizomenon* preceding blooms of the highly toxic *Microcystis aeruginosa*. Here we demonstrate that a two-step approach, first identifying the presence of potential CyanoHABs, and second, separating *Aphanizomenon* from *Microcystis*, may provide an early-warning capability for detection of potentially harmful blooms.

2. Materials and methods

2.1. Study area and sampling strategy

The primary study area was Pinto Lake, California (36.95° N, 121.77° W). Pinto Lake is a shallow natural lake located 8.3 km inland from Monterey Bay (Fig. 1). This spring-fed lake has a maximum depth of ~10 m and covers 37 surface hectares. Pinto Lake includes parks operated by the City of Watsonville and Santa Cruz County, and is regularly used for recreational activities including fishing and boating. Two other water bodies were used as qualitative validation for the algorithm development. Kelly Lake is immediately adjacent to Pinto Lake (36.94° N, 121.74° W). It covers 36 surface hectares and has a maximum depth of ~6 m. There is no public access, which precluded routine monitoring. A third water body, Campus Lagoon at the University of California Santa Barbara (34.40° N, 119.84° W) was also sampled opportunistically as part of the field effort.

Of the three study areas, Kelly Lake and Campus Lagoon were sampled a single time, and were included as verification sites for the algorithms, which were developed with the more extensive data available from Pinto Lake. The latter has been sampled approximately weekly since August 2009. Data include relative cell abundance determined by microscopy, surface chlorophyll concentration, temperature, and toxin as both whole-water "grab" samples and integrated toxin using the Solid Phase Adsorption Toxin Tracking (SPATT) methodology. While microcystins include more than 90 chemical congeners, the most common and routinely reported form is microcystin LR (MCY-LR); we therefore used the concentration of MCY-LR (ppb) in this analysis. Details of the time-series are provided in Kudela (2011). For part of the time series phycocyanin was measured by fluorescence using an Algae Torch (BBE). The fluorescence was converted to equivalent μg/L concentration using discrete samples that were extracted and analyzed