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# Associations between county-level land cover classes and cyanobacteria blooms in the United States

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ABSTRACT

Cyanobacteria blooms can cause public health concerns related to drinking water quality and water recreation. The rapidly changing global climate is anticipated to bring about an increased frequency of extreme weather events (e.g. stronger storms, more extensive droughts), which are expected to promote more frequent cyanobacteria blooms that persist for longer durations in freshwater. Land use planning, landscape management, and ecological engineering may present mitigation opportunities for decreasing the occurrence and intensity of current and future cyanobacteria blooms through improved nutrient management strategies thereby reducing eutrophication of watersheds. To examine the potential impacts of various land cover classes (and their relative density) on cyanobacteria bloom coverage, county-level data were obtained or generated from the National Land Cover Database and the national nutrient inputs to the land surface database. These data were paired with county-level estimates of cyanobacteria bloom area obtained by satellite-based MERIS (Medium Resolution Imaging Spectrometer). Multivariable zero-inflated beta regression models were constructed for the U.S. and five U.S. regions for assessing the relationships between the proportion of county area experiencing a cyanobacteria bloom, county land cover types, and nutrient loading. The land cover type associated with the greatest decreases in bloom area in the national model was deciduous forest ($p < 0.001$). Open water extent ($p = 0.001$) and nitrogen loading from manure ($p = 0.002$) and fertilizer ($p < 0.001$) were positively associated with the proportion of water characterized as experiencing a cyanobacteria bloom. A significant interaction ($p < 0.001$) was observed between cultivated crop coverage and open water extent. Overall, increasing cultivated crop coverage was associated with increasing proportions of cyanobacteria blooms. Low intensity, medium intensity, and high intensity development land uses were not associated with bloom coverage in the national model, although development land uses were positively associated in several regional models. Ultimately, there is evidence that county-level land cover and nutrient loading, notably N in the national model, can impact county-level cyanobacteria bloom coverage. Given regional model differences, additional remote sensing-based studies that examine watershed-based effects on cyanobacteria coverage are needed to establish watershed-specific associations. Studies that transcend county boundaries may provide greater utility than this correlational study for better characterizing land uses and mitigation measures that impact or could impact cyanobacteria bloom coverage in U.S. surface waters.

## 1. Introduction

### 1.1. Societal impacts of harmful cyanobacteria blooms

Natural and anthropogenic land uses influence nitrogen (N) and phosphorus (P) loading in aquatic ecosystems (Foley et al., 2005). The combined effect of N and P in aquatic systems influences the likelihood for cyanobacteria (blue-green algae) populations to bloom (Paerl et al., 2016a,b). During blooms, public health and aquatic ecosystems may be imperiled due to the formation of health-relevant cyanotoxins (Carmichael, 1997; Carmichael and Boyer, 2016; Brooks et al., 2016), carcinogenic disinfection byproducts (Delpla et al., 2009), and

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dissolved oxygen depletion (Scavia et al., 2014). Bloom events have downstream effects to local economies through harm to fisheries, livestock, land values, recreation/tourism, and drinking water treatment costs (Carmichael, 2008; Cunha et al., 2016). Changes in the global climate enhance the likelihood of more cyanobacteria blooms (Paerl and Huisman, 2009). Accordingly, efforts to mitigate and minimize cyanobacteria bloom development in aquatic ecosystems are timely.

### 1.2. *Cyanobacteria blooms and public health*

Cyanobacteria present significant public health concerns when densities of toxin-producing genera are elevated and producing toxins in waters used as a source for drinking water and recreation. Cyanotoxins produced during harmful bloom events may act as potent hepatotoxins, neurotoxins, cytotoxins, irritants, and/or gastrointestinal toxins (Carmichael, 1997). Several cyanotoxins are produced by cyanobacteria (e.g. anatoxin, saxitoxin, cylindrospermopsin, microcystin, etc.), however, guidelines are typically based upon microcystin. Elevated levels of microcystin, have been linked to liver cancer (Yu, 1995) and in an extreme case, the death of 76 dialysis patients in Brazil (Carmichael et al., 2001). Cyanobacteria bloom intensity as measured via remotely sensed phycocyanin pigment concentrations has been positively associated with liver disease in the U.S. (Zhang et al., 2015). Mouse and pig toxicity studies have demonstrated harmful effects (Fawell et al., 1994; Falconer et al., 1994) and these animal studies informed the World Health Organization (WHO) in setting provisional drinking water and moderate recreational water risk guidelines of 1.0 μg-microcystin/L and 20 μg-microcystin/L, respectively (WHO, 2003). WHO recommends advisory signage for water recreators at 20,000 cyanobacteria cells/mL (WHO, 2003), which approximates to 4 μg/L of microcystin.

### 1.3. *U.S. geographic distribution of microcystins*

Cyanobacteria are ubiquitous and their production of cyanotoxins suggests elevated densities of cyanobacteria compared to areas where toxins are not detected. Overall, microcystins (a group of commonly measured cyanotoxins) were readily detected in inland waters in the most recent 2012 National Lake Assessment for the U.S. (U.S. EPA, 2016). Microcystins, which typically become more common as cyanobacteria densities increase (Marion et al., 2012), were observed in 39% of all U.S. lakes and reservoirs. In the most agriculturally-dense ecoregions, microcystins were more frequently observed. Specifically, 76% of Northern Plains lakes, 79% of Southern Plains lakes, and 66% of Temperate Plains lakes had detectable microcystins. Additionally, 6% of Northern Plains lakes had microcystin levels > 20 ppb; compared to 1.6% and 0.2% for Temperate Plains and Southern Plains lakes, respectively. Furthermore, the Northern Plains lakes also led the nation in the frequency of water quality impairment related to N and P (U.S. EPA, 2016). Human population densities and urban development are low in this region. Agricultural impacts are major drivers for elevated N, P, and cyanobacteria in the U.S. and for inland and coastal waters worldwide (Bennett et al., 2001). The 2012 National Lake Assessment findings in regards to regions with elevated N, P, and cyanotoxins were similar to 2007 National Lake Assessment. In both cases, land use practices, N, and P, are linked to cyanotoxins in lakes (Beaver et al., 2014).

### 1.4. *Nutrient reduction strategies and land use impacts on cyanobacteria*

In the midst of a changing global climate anticipated to enhance the frequency and duration of cyanobacteria blooms, mitigation measures for controlling terrestrial releases of N and P are recommended before they enter receiving waters (Hamilton et al., 2016). In cases where N and P enter aquatic systems, nutrient reduction strategies have been proposed or utilized through the promotion of aquatic macrophyte growth including wetland development (Paerl et al., 2016a,b; Paerl, 2014; Dunne et al., 2015). Assessments of whether or not wetlands remove nutrients have indicated that the majority do reduce nutrients loads (Fisher and Acreman, 2004); however, such assessments have not been widely performed on their ability to reduce cyanobacteria bloom frequency.

Recent attempts to assess large-scale landscape factors for predicting microcystin concentrations determined that local influences were most influential in predicting elevated toxin levels (Taranu et al., 2017). The land use adjacent to lakeshores, distances from nature preserves, and within-watershed land uses have all been implicated as major drivers of cyanobacteria bloom frequency (Doubek et al., 2015; Marmen et al., 2016; Katsiapi et al., 2012).

### 1.5. *Remote sensing for cyanobacteria bloom and land use determination*

For broad scale monitoring of cyanobacteria blooms when field measurements are not possible or not existent, remote sensing offers an opportunity for estimating blooms and bloom intensity. Since the phycocyanin pigment is unique to cyanobacteria and is positively associated with elevated levels of microcystins in inland waters (Marion et al., 2012), phycocyanin may serve as an indicator of bloom conditions. Estimates of phycocyanin concentrations in water have been determined remotely with satellite imagery and these results have been positively correlated with *in-situ* measurements of phycocyanin and genetic markers indicative of cyanobacteria and cyanotoxin-producing genes in near shore environments (Lee et al., 2015). Recent application has also occurred for estimating cyanobacteria blooms within the state of Ohio's inland lakes, ponds, quarries, and rivers that are 300 m or greater in width (Gorham et al., 2017).

Remote sensing for determining different land uses at different spatial and geographical levels has been occurring for over a half century, and remotely sensed land cover data have been classified using a common classification system since 1976 (Anderson et al., 1976). Modern studies on land use categories and water quality are common; however, U.S. studies on cyanobacteria occurrence as it relates to remotely sensed land cover are not as common (Doubek et al., 2015). At the time of Doubek et al. (2015) and since that time, no other study has examined the geospatial relationships between phytoplankton (including cyanobacteria) and land uses on such a broad national scale. In Doubek et al., the land use determinations were made using 200 m wide perimeters around 236 natural U.S. lakes from the 2007 National Lake Assessment (U.S. EPA, 2009). The land uses were quantified from the 2006 National Land Cover Dataset (Fry et al., 2011). Collectively, land uses (notably agricultural and human development) coupled with nutrients and temperature influenced cyanobacteria density and N-fixing cyanobacteria dominance (Doubek et al., 2015).

### 1.6. *Study objectives*

General estimations are needed regarding the role and importance of various land uses in regulating cyanobacteria bloom occurrence in U.S. waters and abroad. Furthermore, county-level estimates may provide understanding as to whether or not and to what extent local (county-level) land uses impact cyanobacteria bloom potential in their own surface water supplies. The research questions investigated were (1) which land uses and (2) which type of nutrient (N or P) contributes the most to cyanobacteria bloom risks? To accomplish study objectives, remotely sensed cyanobacteria bloom coverage was determined for counties in the conterminous United States and then paired with data sources for county-level land cover and nutrient loading.