Harmful Algae 63 (2017) 94–108

Contents lists available at ScienceDirect

Harmful Algae

journal homepage: www.elsevier.com/locate/hal

Impacts of the 2014 severe drought on the *Microcystis* bloom in San Francisco Estuary

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ARTICLE INFO

Article history:
Received 2 July 2016
Received in revised form 21 January 2017
Accepted 29 January 2017
Available online xxx

Keywords:
Microcystis
Drought
Microcystins
Cyanobacteria
Climate
Water quality
qPCR

ABSTRACT

The increased frequency and intensity of drought with climate change may cause an increase in the magnitude and toxicity of freshwater cyanobacteria harmful algal blooms (CHABs), including *Microcystis* blooms, in San Francisco Estuary, California. As the fourth driest year on record in San Francisco Estuary, the 2014 drought provided an opportunity to directly test the impact of severe drought on cyanobacteria blooms in SFE. A field sampling program was conducted between July and December 2014 to sample a suite of physical, chemical, and biological variables at 10 stations in the freshwater and brackish reaches of the estuary. The 2014 *Microcystis* bloom had the highest biomass and toxin concentration, earliest initiation, and the longest duration, since the blooms began in 1999. Median chlorophyll *a* concentration increased by 9 and 12 times over previous dry and wet years, respectively. Total microcystin concentration also exceeded that in previous dry and wet years by a factor of 11 and 65, respectively. Cell abundance determined by quantitative PCR indicated the bloom contained multiple potentially toxic cyanobacteria species, toxic *Microcystis* and relatively high total cyanobacteria abundance. The bloom was associated with extreme nutrient concentrations, including a 20-year high in soluble reactive phosphorus concentration and low to below detection levels of ammonium. Stable isotope analysis suggested the bloom varied with both inorganic and organic nutrient concentration, and used ammonium as the primary nitrogen source. Water temperature was a primary controlling factor for the bloom and was positively correlated with the increase in both total and toxic *Microcystis* abundance. In addition, the early initiation and persistence of warm water temperature coincided with the increased intensity and duration of the *Microcystis* bloom from the usual 3 to 4 months to 8 months. Long residence time was also a primary factor controlling the magnitude and persistence of the bloom, and was created by a 66% to 85% reduction in both the water inflow and diversion of water for agriculture during the summer. We concluded that severe drought conditions can lead to a significant increase in the abundance of *Microcystis* and other cyanobacteria, as well as their associated toxins.

1. Introduction

Harmful cyanobacteria blooms (CHABs) are expected to increase worldwide with the frequency and intensity of drought conditions produced by either anthropogenic or climatic conditions (IPCC, 2007; Elliott, 2012; O'Neil et al., 2012; Paerl and Paul, 2012; Paerl and Scott, 2010). Increased water temperature, salinization, duration of the summer season, water stratification, evaporation and hydraulic residence time, associated with drought conditions, are expected to favor development of freshwater CHABS, particularly *Microcystis*, the most cosmopolitan freshwater CHAB worldwide (Van Gremberghe et al., 2011; Mosley, 2015). *Microcystis* can cause a harmful algal bloom, because it often contains hepatotoxic microcystins, which promote liver cancer in humans and wildlife across ecosystems, (Zegura et al., 2003; International Agency for Research on Cancer, 2006; Ibelings and Havens, 2008; Miller et al., 2010), and lipopolysaccharide endotoxins, which inhibit ion transport in fish gills, as well as fish embryo development (Codd, 2000). The potential of *Microcystis* blooms to increase during drought is greater than for most freshwater CHABs, because its tolerance of salinity enables it to survive and expand into brackish and marine water environments

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http://dx.doi.org/10.1016/j.hal.2017.01.011
1568-9883/

(Paerl, 1988; Sellner et al., 1988; Rocha et al., 2002; Robson and Hamilton, 2003). In addition, *Microcystis* out-competes phytoplankton and other cyanobacteria at elevated water temperature, a common condition during drought (Paerl and Paul, 2012). However, relatively little is known about how *Microcystis* varies directly with severe drought conditions.

Microcystis spp. (*Microcystis*) blooms have occurred yearly in San Francisco Estuary (SFE) since 1999 (Lehman et al., 2005, 2013). The bloom occurs over a four month period and peaks in the summer during August and September. On average, about 20% of the cells during *Microcystis* blooms in SFE contain microcystins, which occur in *Microcystis* colonies, dissolved in the water column and aquatic animal tissue (Lehman et al., 2005, 2013; Baxa et al., 2010). *Microcystis* grows well in SFE where nutrients are in excess (Jassby, 2008). Both isotope and nitrogen uptake studies indicated *Microcystis* rapidly took up ammonium, which was the primary nitrogen source for the bloom (Lee et al., 2015; Lehman et al., 2015). Conditions characteristic of drought, warm water temperature and low streamflow, were correlated with the increase in *Microcystis* biomass and toxin content (Lehman et al., 2008, 2013). Although some data are available on the variation of *Microcystis* blooms with wet and dry conditions in SFE, no data are available on the impact of severe drought conditions on the amplitude, toxin content, duration or causal factors associated with *Microcystis* blooms. Because 2014 was the fourth largest drought year on record in California, information on the *Microcystis* bloom amplitude, toxin content and controlling factors in 2014 provided an opportunity to gain insight into the potential impact of future severe climate or anthropogenic induced droughts on CHABS in SFE, needed to develop management strategies.

The purpose of this study was to characterize the amplitude, species composition and toxin concentration of the *Microcystis* bloom in SFE and its association with environmental conditions during the severe drought of 2014. The study addressed the hypotheses that during severe drought conditions the *Microcystis* bloom biomass and toxin concentration will 1) increase significantly and 2) be controlled by similar environmental factors, compared with previous wet and dry conditions. These hypotheses were evaluated by comparing the *Microcystis* bloom and associated conditions during the 2014 severe drought with two previous wet (2004–2005) and dry (2007–2008) years. Information on the impacts of drought on *Microcystis* blooms is critically needed to develop strategies for managing CHABs in the highly urbanized SFE. Here drought impacts from both climate change and water management affect the quantity and quality of water used for drinking, agriculture, recreation, industry and urbanization of over 25 million people, as well as habitat needed for threatened and endangered estuarine fish species (Sommer et al., 2007).

2. Materials and methods

2.1. Site description

SFE is the largest estuary on the west coast of North America and is located in central California, USA. The estuary contains an inland delta of 2990 km^2 with 1100 km of waterways, is bounded by the Sacramento River on the north and the San Joaquin River on the south, and is commonly referred to as the Sacramento-San Joaquin Delta (Delta; Fig. 1). The Delta extends upstream to the head of the tide at Freeport on the Sacramento River and Vernalis on the San Joaquin River. Water from these two major rivers converge near Antioch and flow into a chain of downstream marine bays – Suisun, San Pablo and San Francisco. The water year 2014 was the fourth driest year on record in SFE (http://www.water.ca.

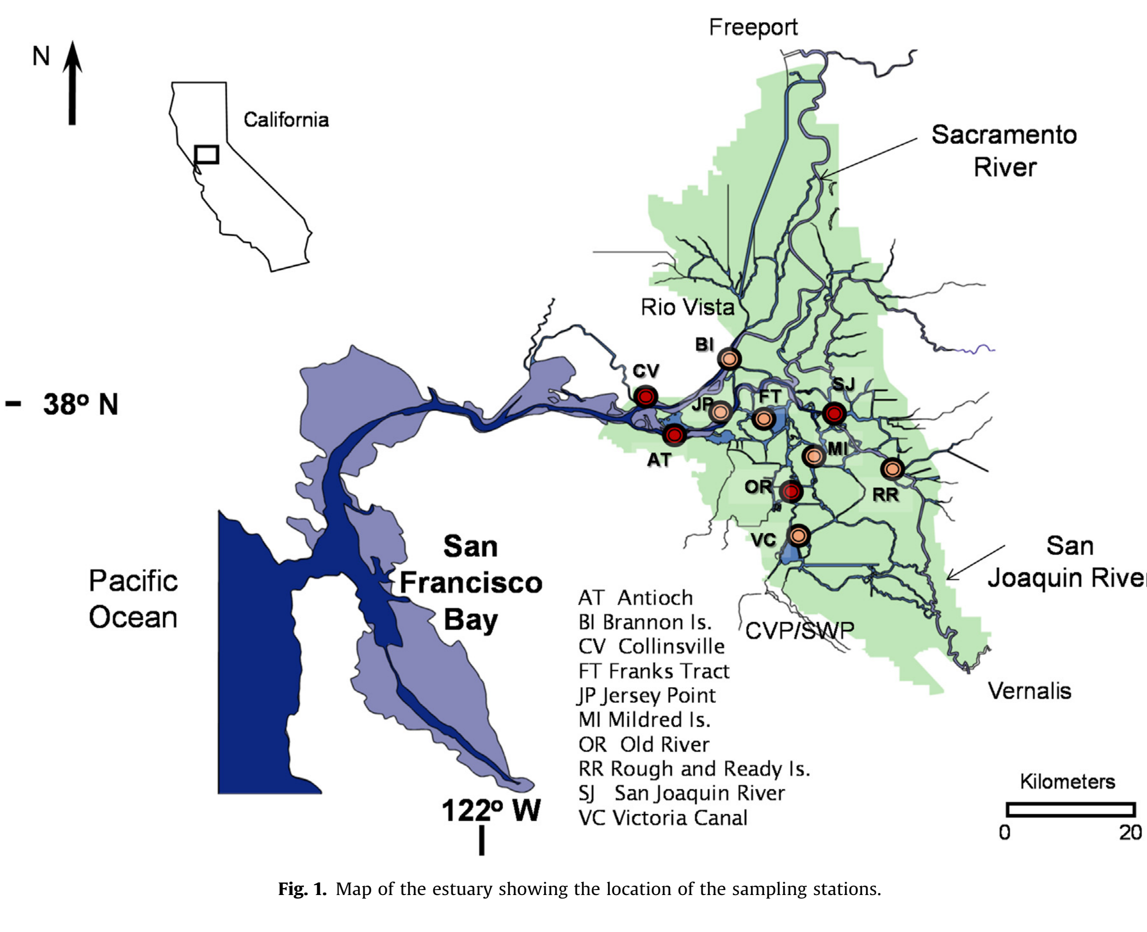

Fig. 1. Map of the estuary showing the location of the sampling stations.