Estuaries and Coasts (2015) 38:165–178
DOI 10.1007/s12237-014-9811-8

Characterization of the *Microcystis* Bloom and Its Nitrogen Supply in San Francisco Estuary Using Stable Isotopes

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Received: 28 May 2013 / Revised: 12 March 2014 / Accepted: 26 March 2014 / Published online: 3 May 2014

Abstract A suite of particulate and dissolved organic and inorganic stable isotopes were needed to determine the source of the nutrients and cells that initiate and sustain the toxic cyanobacteria bloom of *Microcystis* in San Francisco Estuary. Particulate and dissolved inorganic and organic matter in water and plankton samples were collected biweekly during *Microcystis* blooms in 2007 and 2008. Stable isotopes for particulate and dissolved organic matter, nitrate, and water (POM-δ^{13}C, POM-δ^{15}N, DOC-δ^{13}C, C/N ratio, NO_3-δ^{15}N, NO_3-δ^{18}O, H_2O-δ^{18}O and H_2O-δ^{2}H) were compared with *Microcystis* cell abundance, dissolved organic carbon, chlorophyll *a*, and toxic total microcystins concentration, as well as physical and chemical water quality variables, including streamflow. The isotopic composition of particulate organic matter, nitrate, and water differed for the Sacramento and San Joaquin Rivers and varied along the salinity gradient. The variation of particulate organic matter and water isotopes suggested *Microcystis* primarily entered the estuary from the San Joaquin and Old Rivers, where it was most abundant. Nitrate isotopes along with streamflow variables indicated that the San Joaquin River was a source of nitrate to the estuary. However, stable isotope comparison of the nitrogen in *Microcystis* cells with the dissolved inorganic nitrate in the San Joaquin River indicated that nitrate was not the primary source of nitrogen that supported the bloom. Instead, ammonium from the Sacramento River was the likely sole source of the nitrogen for most of the bloom. Selective uptake of ammonium may have further contributed to the magnitude of the *Microcystis* bloom which increased with the percent of ammonium within the total dissolved inorganic nitrogen pool.

Keywords *Microcystis* · Stable isotopes · Nutrients · Cyanobacteria bloom · Estuary · Streamflow

Communicated by Hans W. Paerl

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Introduction

Summertime blooms of the toxic cyanobacteria *Microcystis aeruginosa* (*Microcystis*) have occurred regularly in San Francisco Estuary (SFE) since 1999 (Lehman et al. 2005). *Microcystis* is the only harmful algal bloom that consistently occurs in the estuary and begins once water temperature reaches above 19°C, total suspended solids drop below 40 mg l^{-1} and net streamflow is low during the summer and fall, usually between June and October (Lehman et al. 2013). These blooms are a threat to SFE because *Microcystis* cells often contain toxic microcystins, which promote tumors and liver cancer in humans and wildlife (Zegura et al. 2003; International Agency for Research on Cancer 2006; Ibelings and Havens 2008) and impact the health and survival of the phytoplankton, zooplankton, and the native fish in the estuary (Lehman et al. 2010; Ger et al. 2010; Acuña et al. 2012a, b). Importantly, the onset of these blooms in 2000 coincided with a decline in fish of interest to SFE, including the endangered delta smelt, longfin smelt, threadfin shad, and striped bass

Table 1 Median and standard deviation of environmental variables measured in the Sacramento (1), San Joaquin (2) and Old (3) Rivers during the summer of 2007 and 2008

Variable	Sacramento River	San Joaquin River	Old River	Significance
Ammonium (mg l^{-1})	0.05±0.01	0.03±0.02	0.03±0.02	1>2, 3 and 2>3
Nitrate (mg l^{-1})	0.35±0.07	0.30±0.15	0.20±0.15	1>3
Soluble reactive P (mg l^{-1})	0.06±0.02	0.06±0.02	0.06±0.02	ns
Silica (mg l^{-1})	14.00±1.19	14.50±1.33	12.70±2.82	ns
Chloride (mg l^{-1})	1570±1533	44±28	122±67	1>2, 3 and 3>2
Specific conductance (μS cm^{-1})	4778±5502	305±116	483±314	1>2, 3 and 3>2
Dissolved oxygen (mg l^{-1})	8.80±0.44	8.50±0.59	8.80±1.19	ns
pH	7.90±0.15	8.10±0.30	8.10±0.59	ns
Secchi disk depth (cm)	60±30	108±50	104±53	2, 3>1
Water temperature (°C)	21.30±1.04	23.10±1.93	23.50±1.33	2, 3>1
Dissolved organic carbon (mg l^{-1})	2.00±0.44	2.20±0.44	2.30±0.30	2, 3>1
Total organic carbon (mg l^{-1})	2.10±0.44	2.30±0.30	2.40±0.30	2, 3>1
Total suspended solids (mg l^{-1})	16.50±9.63	4.00±4.45	6.00±2.96	1>2, 3 and 2>3
Volatile suspended solids (mg l^{-1})	3.00±1.48	1.00±1.48	1.00±1.48	1>2, 3

Significant differences among the rivers at the 0.05 level or higher are indicated (e.g., 1>2, 3 means that river #1 (the Sacramento River) has a significantly higher value for the variable than rivers #2 and #3)

cooler than the San Joaquin and Old Rivers by about 2°C. Water transparency (Secchi disk depth) was a factor of 2 lower in the Sacramento River and accompanied by a factor of 4 greater suspended and volatile solids than the San Joaquin or Old Rivers. In contrast, the San Joaquin and Old Rivers had greater TOC and DOC than the Sacramento River. All rivers had relatively high and similar soluble reactive phosphorus and silica concentrations; only nitrate and ammonium concentrations were greater in the Sacramento River.

Chlorophyll *a* concentration and *Microcystis* cell abundance were negatively correlated with chloride (r=−0.35 and −0.30, respectively) and total suspended solids concentration (r=−0.32 and −0.35, respectively) and positively correlated with water temperature (r=0.34 and 0.35, respectively, p<0.01). Elevated specific conductance and chloride concentration characterized the Sacramento River and was accompanied by greater suspended and volatile solids than in the San Joaquin or Old Rivers, where *Microcystis* was abundant (Table 1). Both chlorophyll *a* concentration and *Microcystis* cell abundance were greater in the San Joaquin and Old Rivers, where water temperature was relatively high (Table 1).

Microcystis cell abundance (r=−0.30, p<0.05), chlorophyll *a* concentration (r=−0.42, p<0.01), and total microcystins concentration (r=−0.38, p<0.01) increased in the San Joaquin River when the net streamflow was low. High POM-δ^{13}C values, which characterized the *Microcystis* bloom in the San Joaquin and Old Rivers, were also unexpectedly correlated with a coincident decrease in the percentage of San Joaquin River water at each station (r=−0.41, p<0.01). The association between low San Joaquin River flow and high POM-δ^{13}C values was supported by the correlation between POM-δ^{13}C and the percentage of Sacramento River water at each station (r=0.32, p<0.05; Fig. 5).

DOC concentration did not increase with *Microcystis* cell abundance (r=−0.47), chlorophyll *a* concentration (r=−0.51), or microcystin concentration (r=−0.52) in the San Joaquin River (p<0.01; Table 1). Instead, DOC concentration increased with the percentage of San Joaquin River water at stations in the Sacramento, San Joaquin, and Old Rivers

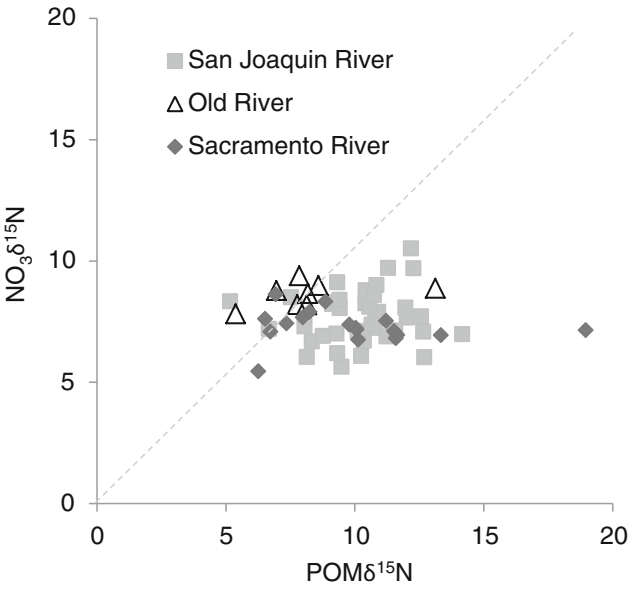

Fig. 4 Plot of NO_3-δ^{15}N versus POM-δ^{15}N at stations within the Sacramento (*diamond*), San Joaquin (*square*), and Old (*triangle*) Rivers during the *Microcystis* blooms of 2007 and 2008. The *dotted line* indicates the 1:1 ratio