

Temporal and Spatial Patterns of *Cladophora* Biomass and Nutrient Stoichiometry in Lake Michigan

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Introduction

Although there has been a noticeable increase in the amount of benthic algae fouling beaches on the western shoreline of Lake Michigan in recent years, there have been no quantitative studies of the distribution of benthic algal biomass, or the temporal fluctuations in biomass abundance. Such studies can provide useful information regarding factors that may potentially influence benthic algal growth. For example, the distribution of biomass in relation to river mouth location and prevailing nearshore currents may help to determine whether river nutrient inputs have a direct influence on algal abundance, while depth distribution will reflect the significance of light as a controlling factor.

In the 1970s, when *Cladophora* also grew to nuisance levels in parts of all the Great Lakes except Lake Superior, a large amount of research was conducted to determine the causes of this excessive growth. There was no consensus in these studies, with different emphasis being given to the role of light (Adams and Stone 1973; Mantai 1974; Graham et al. 1982), temperature (Bellis 1968; Moore 1978; Taft 1975; Mantai 1974), nitrogen (Hopkins and Carney 1972; Mantai 1976), inorganic carbon (Wood 1968), and phosphorus (Neil and Owen 1964; Herbst 1969; Lin and Blum 1973; Gerloff and Muth 1979) as controlling factors. In fact, more than one of these factors may operate simultaneously to control *Cladophora* growth. Perhaps the most definitive studies were those of Auer, Canale and colleagues (Auer and Canale 1982; Canale and Auer 1982; Graham et al. 1982), who used experimental data to develop calibrated models to simulate the combined influence of temperature, light and phosphorus on *Cladophora* growth.

To determine which factors might be responsible for the recent resurgence in *Cladophora* abundance on the western shores of Lake Michigan, we monitored *Cladophora* abundance, *Cladophora* nutrient content, and environmental conditions at a 10 m deep station immediately north of Milwaukee during the summer and fall of 2004. In addition, on one occasion we measured *Cladophora* abundance at 5 m intervals between 5 and 20 m, and we conducted a shoreline survey to compare abundance and nutrient composition at nine locations. Our objective was to compare measurements of biomass, nutrient content, temperature, and irradiance with the results of earlier experimental and modeling exercises cited above to determine which factors may be responsible for the recent resurgence of *Cladophora* in Lake Michigan. In addition, by comparing *Cladophora* biomass among sites, and comparing *Cladophora* nutrient demand with river nutrient

input, we attempted to determine the relative importance of river nutrient input as a factor controlling *Cladophora* growth.

Temporal Fluctuations in Biomass and Phosphorus Content

In considering measurements of *Cladophora* biomass and nutrient content, it needs to be noted that throughout the study period, large amounts of epiphytic diatoms were observed on *Cladophora*. At times, diatom biomass exceeds *Cladophora* biomass (see Fig. 1). These diatoms are included in all measurements of biomass and nutrient content presented below.



Fig. 1. *Cladophora* filament with epiphytic diatoms. Diatoms have not yet grown on the faster growing filament branches, but on the main filament diatom biomass is greater than *Cladophora* biomass.

Cladophora phosphorus content, expressed as μg of P per mg of *Cladophora* dry weight, decreased from early June into late June and July, but then increased on sampling dates between early August and October (Fig. 2). A comparison with the experimental data of Auer and Canale (1982) indicates that P content in late June and July were near the minimum quota to permit growth (Q_0), while P content on other dates, while still suboptimal, was sufficient to support growth, providing temperature and irradiance were sufficient. A comparison of *Cladophora* P content with water temperature (Fig. 2) indicates that the June-July decline in P content coincided with a temperature increase to levels that are optimal for *Cladophora* growth (Graham et al. 1982). *In situ* irradiance data (which are only available for dates after mid-July) suggest that irradiance at 10 m during July was suboptimal for growth, but was sufficient for growth for much of August and September. Despite the low irradiance in late July, we suggest that the increase in temperature in June – July allowed *Cladophora* to grow more rapidly, exhausting its internal phosphorus supply and becoming more P limited. *Cladophora* growth at 10 m was likely temperature- and light-limited prior to June, and P limited later in the summer. Biomass measurements during the study period varied between 30 and 70 g m^{-2} (dry weight). Lowest biomass was recorded in mid-July, when *Cladophora* P content was lowest. Hence, while growth rate likely increased with temperature in late June, it appears that sloughing rate also increased, resulting in a net loss of biomass.

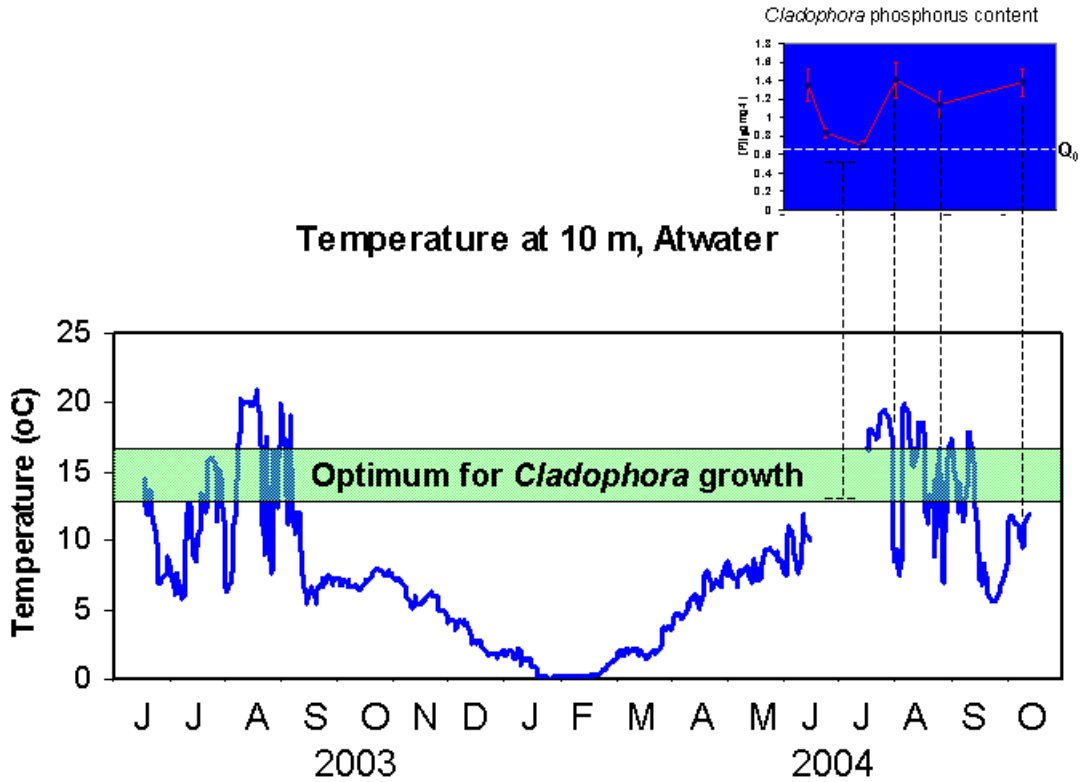


Fig. 2. Temperature and *Cladophora* phosphorus content at the Atwater station.

Cladophora Depth Transect

The depth transect of *Cladophora* biomass and P content indicated a large decline in biomass between 10 and 15 m, and a significant increase in *Cladophora* P content over the same depth interval (Fig. 3). Using the minimum P quotas of Auer and Canale (1982), *Cladophora* at depths of 10 m or shallower appeared to be P limited, while *Cladophora* at depths of 15 m or greater are not P limited, but are likely limited by low irradiance. The growth rate of *Cladophora* at depths greater than 10 m will respond positively to any further increases in water clarity in Lake Michigan.

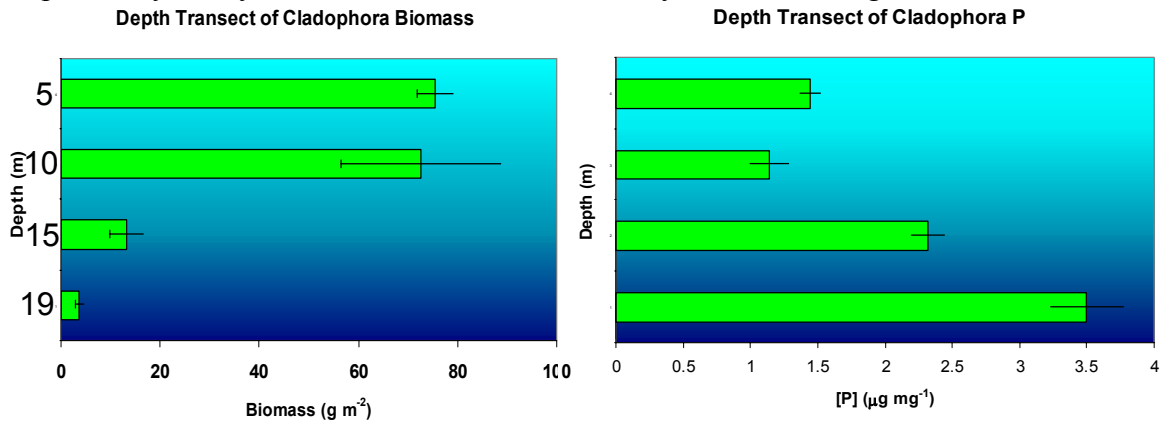


Fig. 3. Depth transect of *Cladophora* biomass and P content, August 2004.

Cladophora Shoreline Survey

A September 2003 survey of *Cladophora* abundance at four 10 m deep sites in the Milwaukee region indicated that biomass was greater near the Milwaukee Harbor than at a location approximately 15 km north of the city (Fig. 4a). This suggested that nutrient output from the harbor may have a significant influence on *Cladophora* biomass. However, a second transect conducted in September 2004 indicated that *Cladophora* abundance north of the city was greater than that south of the city (Fig. 4b). This was not expected, since current in this part of Lake Michigan are generally from the north to the south (Beletsky et al. 1999), carrying nutrients released from Milwaukee harbour south along the western shoreline of Lake Michigan.

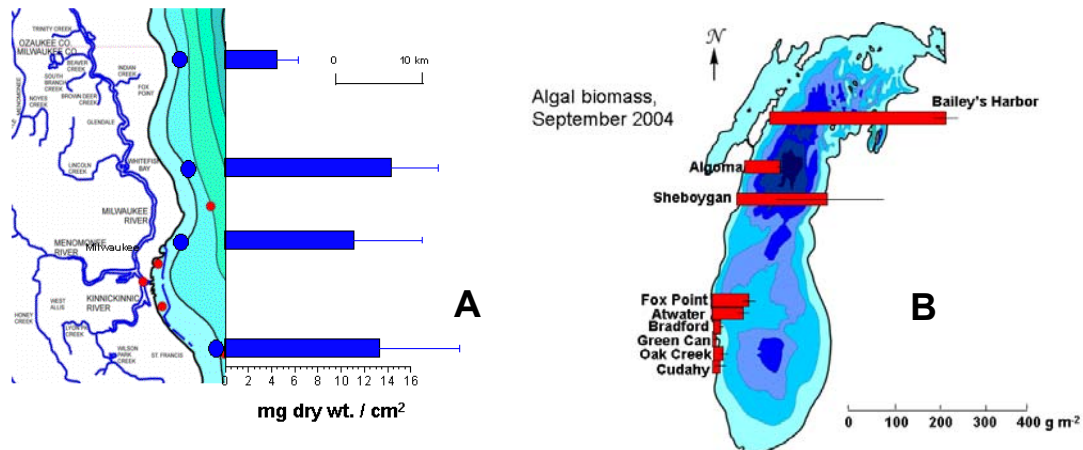


Fig. 4. *Cladophora* biomass distribution near Milwaukee in September 2003 (A) and between Cudahy and Door Peninsula in September 2004 (B). Bailey's Harbor sample dominated by *Chara* sp.

Cladophora biomass at other stations further to the north was also high, although biomass at the Bailey's Harbor on the Door Peninsula was dominated by another green alga, *Chara* sp. (probably due to the soft substratum at this sampling site).

Despite the lower biomass south of Milwaukee, *Cladophora* P content was generally higher in this area, supporting the hypothesis that the Milwaukee Harbor outflow serves as a nutrient source to regions south of the harbor outflow. We suspect that sloughing in this region prior to the sampling date may have resulted in the low biomass measurements, and further measurements both north and south of the harbor will be required to confirm the potential effect of harbor discharge on *Cladophora* growth and abundance.

River Phosphorus Loading and *Cladophora* Phosphorus Demand

A second approach to assess the importance of river input as a nutrient supply for *Cladophora* is to compare estimates of *Cladophora* P requirements with P loading from rivers. Between April and October 2004, samples were collected from the three major rivers that converge in Milwaukee (Milwaukee River, Menomonee River, Kinnickinnic

River), as well as from the inflow to Milwaukee Harbor (immediately below the Hoan Bridge) and the three gaps connecting the outer harbor to the open lake. Nutrient concentrations measured at the inlet to the harbor, as well as water discharge (determined as the combined discharge of the three rivers as reported by the USGS) are shown in Fig. 5. The large rain events of May 2004 were accompanied by high particulate P concentrations, but there was a lag in the concentration of dissolved P, which peaked in June. In all months, P loads were dominated by soluble reactive phosphorus (primarily phosphate), which is the form of P most available for uptake by algae, and most of the P load originated from the Milwaukee River. Note that these data do not allow us to reach any conclusions regarding the source of these nutrients, which will be an unknown mixture of urban runoff, agricultural non-point sources, and other point sources. These measurements simply allow us to estimate how much P is entering the lake from all sources via the three rivers and Milwaukee harbor.

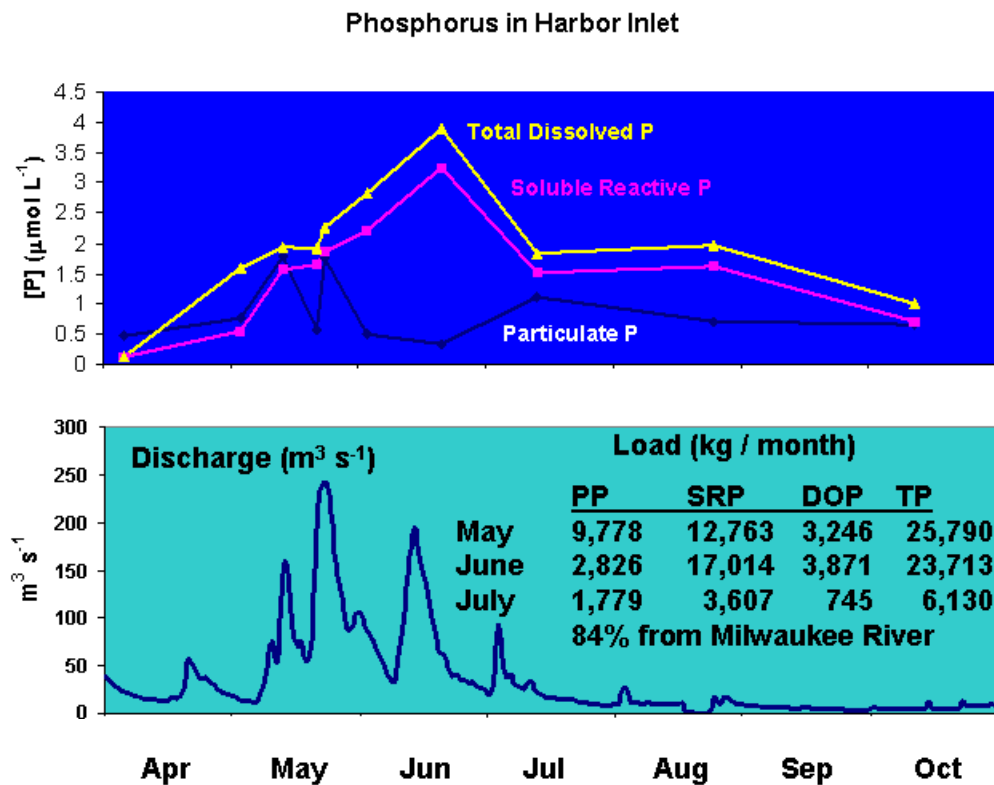


Fig. 5. Water discharge rate and nutrient concentrations measured at the confluence of the Milwaukee, Menomonee and Kinnickinnic Rivers prior to entering Milwaukee Harbor.

A comparison of phosphorus concentrations in the water flowing into the harbor (harbor inlet) with that flowing out of the harbor’s main gap to the lake indicates that there was a retention of both particulate and dissolved P in the harbor. These data suggest that the harbor is serving as a net sink for phosphorus, most likely due to phosphorus burial in harbor sediments.

In order to determine the importance of the river P load in supporting *Cladophora* growth in Lake Michigan, an estimate of *Cladophora* P demand is necessary. An approximate estimate was derived by selecting an area that is potentially influenced by outflow from the Milwaukee Harbor, and determining the amount of P that is required to support *Cladophora* growth within that area. We selected an area spanning a distance from approximately 15 km north of Milwaukee to 25 km south of the city. The only other tributary within this area is Oak Creek, but its discharge and P load are very small compared to that of the Milwaukee Harbor. Using bathymetric charts and aerial imagery to determine the distribution of *Cladophora*, assuming that mean biomass within the area is equal to the mean measured at the regular monitoring station north of Milwaukee, and applying the mean P content of $1.1 \mu\text{g mg}^{-1}$, we derived a conservative estimate of *Cladophora* P mass of 20,680 kg for the 0 to 10 m depth range (area = 188 km²). P demand was determined as total P mass multiplied by the *Cladophora* growth rate. Auer and Canale (1982) observed that at a P content of between 1 and $2 \mu\text{g mg}^{-1}$, *Cladophora* growth rate is generally between 0.1 and 0.25 day^{-1} . Using the conservative estimate of 0.1 day^{-1} and the above estimate of 20,680 kg of P in *Cladophora* within this area, the P supply required to support *Cladophora* growth in the area is approximately $2,068 \text{ kg day}^{-1}$. In comparison, the average P load from the Milwaukee Harbor to the lake for the period April – October 2004 was 249 kg day^{-1} . This comparison suggests that P loading from the rivers near Milwaukee can only provide a fraction of the P required to support *Cladophora* growth. The above estimate of river P supply is likely conservative, since it does not account for P retention in Milwaukee Harbor. These comparisons strongly suggest that internal P recycling processes within the lake are providing much of the P to support *Cladophora* production.

The above analysis does not mean that river P inputs have no influence on *Cladophora* growth. Depending on the rate of dispersion of river plumes after entering the lake, river nutrient input may have a significant local effect, and the higher P content of *Cladophora* observed south of Milwaukee in September suggests that there is some river influence. But on a larger spatial scale there must be other processes within the lake that affect nutrient supply to benthic algae. An obvious possibility is nutrient excretion / egestion by dreissenid mussels. Two questions requiring further investigation regarding the role of mussels are: 1) What is the *in situ* nutrient supply rate from mussels relative to allochthonous nutrient input rate? and 2) To what degree do mussels rely directly on allochthonous nutrient inputs as opposed to the existing large nutrient pool within the lake? The answers to these questions are necessary to determine whether reduction of nutrient loads from rivers will have any impact on *Cladophora* growth.

The earlier work of Auer and Canale (1982) demonstrated that *Cladophora* growth responds strongly to internal P concentrations between 1 and $2 \mu\text{g mg}^{-1}$, similar to those measured in this study. Within this range, a small increase in *Cladophora* P content may result in a relatively large increase in growth rate, and *vice versa*. Therefore, while reduction of P input from rivers may have a small effect on total P availability, it may have a significant effect on *Cladophora* growth rate. Likewise, any changes in the lake's internal nutrient cycle that result in a small increase in *Cladophora* P content may result in significant increases in *Cladophora* growth rate and abundance.

Conclusions

1. At depths of less than 10 m, *Cladophora* will respond to changes in P availability, irradiance and temperature.
2. At depths greater than 10 m, *Cladophora* is light and / or temperature limited.
3. Lakeshore surveys suggest that river nutrient discharge does not strongly influence *Cladophora* abundance on a large scale.
4. While river phosphorus input may support *Cladophora* production near river mouths, a comparison of estimated *Cladophora* phosphorus demand with river phosphorus inputs suggests that most *Cladophora* production is supported by phosphorus cycling processes within Lake Michigan. Future research needs to focus on identifying and quantifying these internal cycling processes.

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