MACROALGAL BLOOM DYNAMICS IN A COASTAL LAKE: A MULTIDISCIPLINARY APPROACH

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Abstract

Worldwide, the effects of anthropogenic nutrient loading into estuaries include a shift from sea grass to macroalgae, particularly the "bloom and bust" cycle of the ephemeral Chlorophyta. Macroalgal blooms only occur in spring and summer when rainfall prior to and during this time is low. This study uses a multidisciplinary approach to determine temporal and spatial dynamics of nuisance macroalgal blooms in Avoca Lake, an intermittently closed and open lagoon lake (ICOLL) in NSW, Australia and investigates the factors influencing algal growth in the lake. A major macroalgal bloom was monitored temporally and spatially using digitised aerial photographs and cellular automata modelling. The results indicated that water depth and availability of suitable substrate such as is found at lake edges, within fringing wetland vegetation, and among submerged aquatic vegetation are important in determining the extent to which macroalgae can cover the lake. Nutrient levels in water column and sediment, rainfall, substrate conditions and temperature all contribute to the extent of algal cover. Further experiments will investigate the effects of frequency and timing of entrance openings on algal bloom dynamics. The data will be used to develop recommendations for the management of the lake.

Introduction

The shift from seagrass-dominated to macroalgae-dominated estuaries is a world-wide trend caused by eutrophication (Duarte, 1995; Short & Wyllie-Echeverria, 1996; Valeila et al. 1997). Higher nutrient loads benefit opportunistic benthic algae and drift algae over seagrasses because, unlike seagrasses and other perennial macrophytes, they are capable of quick uptake of nutrients and subsequent rapid increase in biomass leading to their domination in the system (Pederson and Borum, 1997; Valiela et al. 1997; Nelson et al. 2008). As a result, high density algal mats can block out light from seagrass and cause hypoxia through respiratory processes and lead to seagrass decline (Duarte, 1995: Pederson and Borum, 1997; Rivers and Peckol, 1995), invertebrate and fish kills (Rosenberg, 1985; Raffaelli et al. 1989) and other drastic changes in community composition (Ahern et al. 1995).

Drift algae tend to undergo 'boom and bust' cycles by growing very fast in favourable conditions and dying off when nutrient resources are exhausted. Thus, when algae are in decline the sediment is supplied with rapidly decomposing organic material. Although green algae (Chlorophyta) are the main contributors to macroalgal blooms, some Rhodophtya and Phaeophyta have also been associated with macroalgal blooms in seagrasses and coral turfs (Cummins, 2004). During spring and summer actively growing macroalgae almost completely assimilate nutrients from the water column under aerobic conditions. After the die-off decomposing macroalgae release large amounts of nutrients that may accumulate in the sediments.

Plant performance and species composition in shallow coastal waters are highly influenced by availability of nutrients, so, generally, slow-growing species dominate nutrient poor areas and fast-growing ephemeral species are more successful in nutrient-rich conditions. The ephemeral species have the ability to uptake, assimilate and store large amounts of nitrogen in areas of high N loading, which results in low water column N concentrations. The availability and supply of nitrogen can vary hourly and monthly leading to an asynchrony of external N availability and macroalgal growth demand. For example, in times of high nutrient availability macroalgae may take up and store excess N usually in pools of nitrate and ammonia and simple organic compounds (McGlathery et al. 2001). Such conditions are likely to be met in south-eastern Australia, where light is not limited and input of nitrogen can lead to excessive growth of opportunistic algae. Interestingly, most of the bloom-forming species of macroalgae are common in estuaries world-wide, although the types of water bodies and degree of eutrophication may differ substantially. For example, species such as *Enteromorpha (Ulva) intestinalis, Ulva lactuca, Chaetomorpha linum* were major contributors to macroalgal blooms in estuaries in North America (Valiela et al.1997), Europe (Scanlan et al. 2006; Canal-Verges et al. 2014), China (Fu et al. 2008) and Australia (Cummins et al. 2004). The common characteristic of these algae is their ability to take advantage of available nutrients by rapid uptake followed by rapid growth in biomass. Although nutrient enrichment is commonly considered the main cause of algal blooms (e.g. Lowthion et al. 1985), other factors may play an important role.

Salinity and temperature, for example, can have a profound influence on algal growth. In some estuaries, salinity can range from almost freshwater to excessively saline conditions, thus reflected in differences in ionic concentration, density of seawater and osmotic pressure. Many studies have reported salinity effects on the growth of *Enteromorpha intestinalis,* one of the common contributors to algal blooms. In particular, hypo- and hypersaline conditions can cause physiological stress in *E. intestinalis* (Martins et al. 1999). On the other hand, *Ulva expansa* and *E. intestinalis* have been considered euryhaline due to the dominance of these species throughout the year in the water bodies with fluctuating salinity regimes (Kamer and Fong, 2000). For example, *E. intestinalis* can maintain cell turgor and regulate turgor pressure when external salinity conditions fluctuate (Young et al. 1987) however the cost to the alga of maintaining turgor pressure is reflected in decreasing productivity (Fong, 1996). Fong et al. (1996) and Martins et al. (2001) found that lowered salinity negatively affected growth and nutrient uptake in the genus *Ulva*, a common blooming alga worldwide.

The coast of New South Wales is characterised by large numbers of coastal lakes and lagoons, many of which are located in urbanised or agricultural areas. The Central Coast of NSW has four lagoons with intermittently opening and closing entrances (ICOLLs): Wamberal, Terrigal, Avoca and Cockrone. Avoca Lagoon experiences regular blooms, during which macroalgae cover most of the lake surface. The blooms are commonly perceived as both an environmental and economic hazard. They may profoundly impact the ecosystem through oxygen depletion and increased turbidity, which, in turn, may lead to changes in benthic invertebrate assemblages (Norkko and Bondsdorff, 1996; Cummins et al. 2004) and decline of seagrasses (McGlathery, 2001). Macroalgal blooms also negatively affect recreational activities and, specifically, prevent people from swimming and boating on the lake. Strong odours from decomposing algae at the time of bloom decline create additional cause of concern for locals and a strong deterrent forvisitors. Yet, dynamics of the macroalgal blooms in Avoca Lake has not been documented in detail and factors causing the blooms are not understood. Such an understanding is, however, necessary for successful management of the lake.

The main aim of this study was to document algal blooms in Avoca lagoon and identify any causative factors using both mathematical modelling and empirical studies. Specifically, we describe temporal dynamics of the blooms and carry out direct field measurements of environmental conditions associated with them. This, in turn, will be used to calibrate and fine-tune a mathematical model that will be developed as a predictive tool for use by mangement agencies for understanding when algal blooms are likely to occur.

Methods

Avoca lagoon, classified as an Intermittently Closed and Open Lagoon Lake (ICOLL) is located about 90 km north of Sydney. The catchment to Avoca lagoon is located within the Gosford City Council Local Government area and covers approximately 11.6 km^2, while the surface area of the lagoon is approximately 0.63 km^2. The lake is roughly star-shaped, comprising four irregular arms and has a considerable area of wetlands around its perimeter. Bareena Island is approximately the centre of the lake. Much of the upper catchment is rural land, comprising predominantly farmland or undeveloped forest. The lower slopes in the vicinity of the lagoon contain significant urban development. The outlet to the ocean is generally closed by the beach berm, which can be breached naturally during high sea surge events and also be opened artificially, thereby providing a free connection between the lagoon and the ocean. The artificial opening of the entrance is based on water level data at the lagoon monitoring station and is utilised as a flood mitigation measure for surrounding residences.

The observations of algal bloom dynamics was conducted through aerial photographs of the lake surface during blooms. The photographs were taken with a Nikkon D3100 SLR Camera with a polarising lens from a plane at an average height of 1600 metres on four occasions, on October 17, October 30, November 15 and December 2 in 2012. GIS data files obtained from Gosford City Council (GCC) were used with the digitised aerial photographs for GIS mapping to determine spread of the macroalgal bloom. Using data provided by GCC, NSW Department of Lands, digitisation of Avoca lagoon was made using Excel and ArcGIS (V10) software (ESRI Inc.). ArcCatalog and ArcMap (V10) (ESRI Inc.) were used to create a visual representation of the outline of Avoca lake. The lake was partitioned into cells of 10m by 10m and the resultant grid was superimposed over the perimeter of the extracted outline of the lake in ArcGIS. Excel was used to create a table of "x" and "y" values and a third column, "a", indicating the presence (1) or absence (0) of algae.

A cellular automata discrete model was based on a model developed by McArthur et al. (2006) to determine the spread and growth of an invasive green alga *Caulerpa taxifolia*. Although, unlike blooming species, *Caulerpa* is attached to the sediment surface, the general dynamics of its spread can be described by similar methods. The model divides the area into cells of uniform size, and allocates a state depending on what the cell contains. In the current model the state is defined as "-1" for land, "0" - for no algae, or "1" indicating the presence of algae. Once the model is initialised, a set of rules is determining the state of each cell after each timestep is applied. The rules are based upon Conway's Game of Life, and allow growth if neighbour cells contain the algae, and do not allow growth if they are clear. The model was validated by comparison with the aerial photographs of the lake during the spring-summer bloom. The model was programmed in the computer package MATLAB (MathWorks Inc.) and initiated by spontaneous appearance of algae along the edge of the lake. The model uses data assuming algal growth is initiated at the edges of the lake (with the exception of Bareena Island) and validated with the four subsequent aerial data sets.

Water quality (temperature - ºC, dissolved oxygen – mg/L and % saturation, pH, salinity – expressed according to the practical salinity scale, turbidity - NTU, conductivity - m*S*/cm, available nitrate and phosphate – mg/L) was measured at ten or more (when possible) sites throughout the lagoon, at edges and at various depths, on at least a twice weekly basis since early spring 2012 that coincided with mapping the bloom.

After macroalgae growth was established, the measurements were taken in the middle of the water column within the bloom (in the breaks of algal cover). Physico-chemical variables (temperature, salinity, pH, DO and turbidity) were measured using YeoKal water quality monitoring unit, and then 1 litre sample of water was collected from each site to test for nitrate-nitrogen and orthophosphate using a La Motte colorimeter. Nitrate was measured using the cadmium reduction method and phosphate by ascorbic acid reduction. Water quality was measured at least once a week at two sites - one near the saltmarsh where macroalgae were first detected in 2012 and one at the jetty where Gosford City Council do their monthly monitoring.

We also used water quality data collected by Gosford City Council; a range of variables, water depth, salinity, pH, dissolved oxygen, total N, ammonia, oxidised N, soluble phosphorus, total phosphorus, turbidity, chlorophyll-a, faecal coliform bacteria and zooplankton were measured by the Council once a month at one site in Avoca lagoon. The lake water level data were also obtained from Gosford City Council in the lake at 15 minute intervals using a data logger. These data were plotted to determine entrance opening events for 2011, 2012 and 2013 (2014 data not yet available). Total monthly rainfall for 2011, 2012, 2013 and 2014 was obtained from Bureau of Meteorology and plotted. We were specifically interested in the period leading up to and including spring and early summer so we compared July to October, over the 4 years since we commenced the study.

Results and Discussion

The aerial photographs collected over the 2012 spring bloom, included the early stages, pre-peak, peak and decline of the bloom. The bloom began in September and was virtually gone by the end of December. The algal spread simulated by model runs for the four sampling times was very close to the observed pattern with more than 92% similarity between observed and simulated data on two-dimensional macroalgal cover of the lake. Normally, the algae grow, subsequently die and then the tissue rises to the surface as it decomposes. The algae grow where the light conditions are sufficient for active photosynthesis. The presence of seagrass encourages algal growth by providing the surface for the attachment. Algae that are attached to seagrasses are therefore higher in the water column and can take advantage of available light, especially in deeper areas. Other external factors may inhibit or encourage the spread of macroalgae. The macroalgal bloom of 2012 is the first time that a bloom has been quantified spatially and temporally in Avoca lagoon, and the results indicate that the macroalgal bloom will not spread to areas where the water is too deep or too turbid for active photosynthesis. However, the presence of submerged aquatic vegetation i.e. the seagrasses, *Zostera capricorni* and *Ruppia* spp. can facilitate the spread to deeper areas by providing a substrate that enabled the macroalgae to be at sufficiently illuminated depth in the mid-sections of the lake. Further development of the model will see inclusion of the factors contributing to the bloom (e.g. presence of submerged vegetation) and identified through this study. This will be achieved once data from the next bloom has been collected.

Total monthly rainfall in 2011 was higher than in 2012 with the exception of January and February (Figure 1). In fact, total monthly rainfall from March to December 2011 (except for June) was between 25 mm and 205 mm higher than the corresponding months of 2012. Such high rainfall should be reflected in the differences in water salinity and turbidity levels. Although water salinity was found low (5.2) in April 2011 following high monthly rainfall (>200mm) and entrance opening in March, turbidity (11 NTU) was not. Water salinity was also low (8.1) in December 2011 (Gosford City

Council data). Salinity affects ionic concentration, density of seawater and osmotic pressure; thus, when salinity is outside intermediate levels, macroalgal cell wall membranes can be compromised. For example, in years of high precipitation characterised by a significant increase of freshwater into the Mondego estuary in western Portugal, no *Enteromorpha* blooms were observed even though it is an eutrophic estuary with seasonal macroalgal blooms (Martins et al, 1999). The authors concluded that salinity is an important factor in controlling growth of *E. intestinalis* at their study location and that macroalgal blooms are dependent upon the rainfall of each year (Martins et al, 1999). Their laboratory experiments showed the highest growth rates for *Enteromorpha intestinalis* at salinities between 15 – 20 psu (Martins et al, 1999). In contrast to the high rainfall and non-bloom year of 2011, during the macroalgal bloom of 2012, salinity in Avoca lagoon stayed within 15 to 20, the optimum range for *E. intestinalis* as reported by Martins et al. 1999).

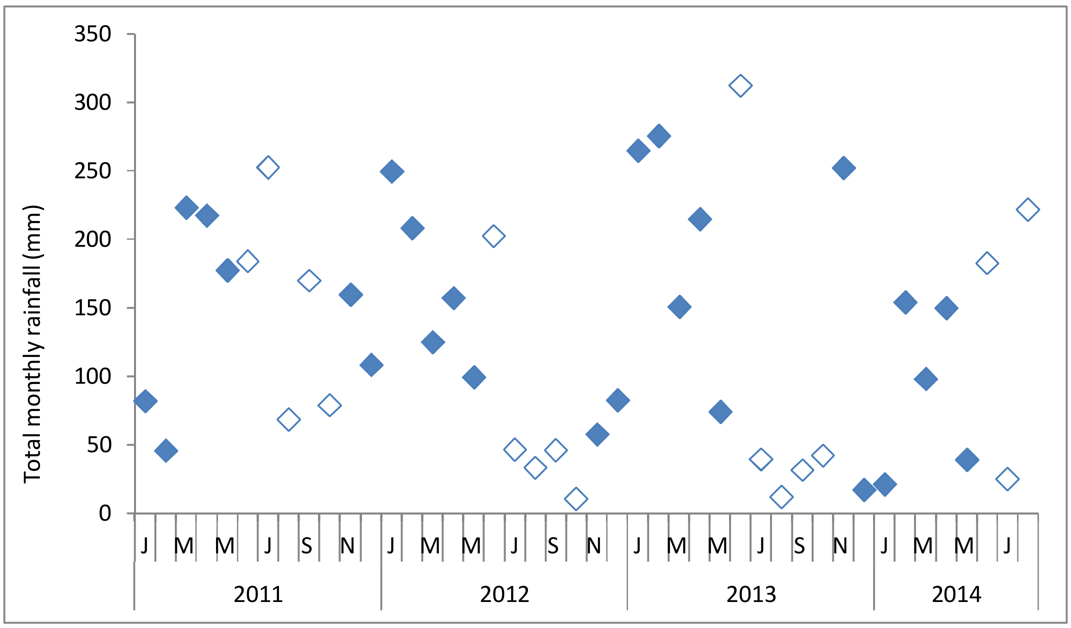

Figure 1: Total monthly rainfall for 2011, 2012, 2013 and 2014 to Aug (open diamonds show months leading up to and including spring (Source BOM)

The entrance was opened 4 times (April, May, July and October) in 2011 and twice (January and May) in 2012. After the entrance closed, water levels remained low during the spring-summer bloom in 2012. There was, however, no bloom in 2013. Total monthly rainfall was high in June (312mm) but was low during July to October (Figure 2). The entrance remained closed July to December 2013, and the water levels relatively low.

It seems that an important feature of the lagoon is the irregular opening of the entrance, though so far, no data have been collected on the effects of entrance opening on bloom dynamics, patterns of water movement in and out of lagoon from tides and the fate of nutrients (i.e. whether they are removed from lagoon with tidal water and/or through the movement of sediment). It has been noted, for example, that in non-bloom years openings of the lagoon were more frequent than when the bloom occurred. Frequent flushing is likely to lead to the removal of excess nutrients and, possibly, propagules and/or juvenile fronds of the algae. The timing of opening may be even more important than the frequency in such case. For example, it is possible that opening of the lagoon before the bloom season might prevent the bloom occurring by draining water rich in nutrients and algal propagules from the lagoon. At the same time, frequent openings can have negative consequences for lagoons such as increased exposure and death of perennial aquatic vegetation (e.g. seagrasses) and increased risk of low dissolved oxygen and incidence of fish kills as a consequence. One way to test the effect of entrance opening on bloom dynamics would be experimentally opening the entrance at pre-determined times to observe the changes in nutrient concentrations in water and sediments before and after the opening, as well as effects on algal biomass.

If Avoca lagoon was to experience an algal bloom this spring-summer there would be some evidence by now, however, as of October 30, 2014 no bloom has yet been observed. Total monthly rainfall was high in June, August and September (although BOM data not yet available for September) (Figure 1). Following the high rainfall, salinity decreased from over 30 in July and early August to 20 at the end of August and to less than 15 during September. Water column turbidity increased from less than 10 NTU in July and early August to over 35 NTU in late August. The entrance was also kept open during September (water level data not obtained from GCC for this year).

Conclusions

There have been no blooms in Avoca lagoon since the mapping and modelling in 2012, so we have been unable to determine whether improvements to the algorithm enhanced the model. However, the amount of the rainfall and presence of seagrasses are identified as important factors influencing bloom dynamics. They will be included in the next version of the model, which will be verified during the next bloom event.

In 2014, water level has been low as the entrance was kept open during August and September for undertaking the new sewage works. During this time, water level was, in fact, so low that beds of *Zostera muelleri (capricorni)* and *Ruppia* spp in the shallower edge regions were exposed to desiccation. If these seagrass beds have suffered then the substrate they provide for macroalgae may not be available this spring/summer, so any occurring algal growth would be limited to the edges of the lake.

Predicting macroalgal blooms in lakes is particularly problematic due to the number of factors contributing to and influencing bloom formation and is often complicated by the irregular entrance openings. Future experimental studies will focus on the effects of frequency and timing of entrance openings on the nutrient dynamics and algal growth testing the potential role of entrance opening for bloom prevention.

Acknowledgements

Funding for this study was provided by Gosford City Council Ecological Research Grant. Laboratory and field equipment were provided by University of Newcastle and Community Environment Network Waterwatch program. We are grateful to Michael Kilpie of Aqua Fun Avoca for providing kayaks.

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