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A review of microalgae as indicators in South African estuaries

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ABSTRACT

Microalgae are one of the most important components of estuarine ecosystems, providing the fuel required to sustain higher trophic levels. Being at the base of aquatic food webs, these communities are generally the first to respond to anthropogenic disturbances – particularly opportunistic species – and can often be used effectively as indicators of ecosystem health. The purpose of this review is to assess the status of estuarine microalgal research in South Africa and to highlight the shortcomings of past research and identify priorities for future research. What became apparent during a synthesis of South African literature on the topic, was that the broad ecology of microalgae – both phytoplankton and microphytobenthos – has been well addressed. Generally speaking, the interaction between freshwater inflow and microalgal communities has formed the basis for the majority of this research. This trend was logical due to South Africa being a relatively arid country, where demand for freshwater often exceeds supply. In terms of microalgal studies however, numerous shortcomings can be identified, including the lack of: (1) thorough assessments of microalgal community composition; (2) conclusive demonstration of the role of suggested indicator species; (3) adequate sampling periods and/or intensity; and (4) fine-scale experimental research – both *in situ* and laboratory. A concern on a broader scale, and in stark contrast to Europe and the United States, is the lack of explicit assessment of what comprises eutrophication in South African estuaries. Finally, and perhaps the most pertinent theme identified in this review is the necessity for adopting 'hypothesis-driven research'.

1. Introduction

Due to their importance as primary producers and indicators of ecosystem health, estuarine microalgal research is an ever-growing and advancing field of research on the global scale. As such, it is imperative that South African research aligns with global trends on this topic in order to remain relevant. The purpose of this review was to take stock of the current state of knowledge, identify shortcomings, and highlight the way forward for microalgal research in South African estuaries.

1.1. Phytoplankton

Phytoplankton play a pivotal role in sustaining the ecological functioning of aquatic ecosystems, being largely responsible for fuelling food webs, directly or indirectly, through primary production. Furthermore, phytoplankton is a key factor in global biogeochemical processes, contributing to the transformation and cycling of key elements (Domingues et al., 2008). Consequently, it is important to understand and monitor phytoplankton dynamics in order to prevent losing the valuable ecosystem services these communities provide. This task has become progressively more pertinent due to the ever-increasing anthropogenic pressure placed on estuarine and coastal ecosystems over recent decades (Cloern, 2001). This pressure has been attributed to the demands of an ever-increasing population, which have subsequently lead to an increase in waste production from domestic and industrial sources, and from agriculture and aquaculture (Brito et al., 2012a, 2012b; Schallenberg et al., 2010).

The primary outcomes of these activities are increased nutrient loading (especially nitrogen [N] and phosphorus [P]) and reduced and/or altered freshwater flow patterns within estuarine and coastal ecosystems (Coutinho et al., 2012; Snow and Adams, 2007; Snow et al., 2000a). Increased nutrient loading has led to alterations in the ratio of nutrients, N:P and N:Si, that subsequently impact on phytoplankton production, both in terms of biomass and community composition (Borja et al., 2012; Snow and Adams, 2007). Generally speaking, it is expected that during periods of low freshwater inflow there will be a shift from P to N limitation (Nozais et al., 2001; Snow et al., 2000a, 2000b). The combination of nutrient enrichment and altered water residence times in estuaries often results in enhanced net algal growth rates and biomass accumulation, which may lead to a disturbance where the desirable balance of organisms shifts and water quality is degraded (Brito et al., 2012a, 2012b; Coutinho et al., 2012). Notably, high algal biomass is associated with the visible symptoms of eutrophication, and is generally the primary cause leading to the practical issues (~ loss of ecosystem services) that arise in eutrophic systems. Disturbances such as these

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are central to the definition of what constitutes eutrophication, i.e. deterioration of ecosystem health (Brito et al., 2012b; Coutinho et al., 2012).

Broadly speaking, the process of eutrophication in estuaries generally entails a shift from systems dominated by submerged macrophytes (e.g. seagrasses) and perennial macroalgae to bloom-forming, opportunistic macroalgae and eventually dominance by phytoplankton (Coutinho et al., 2012; Valiela et al., 1997). Phytoplankton blooms in the pelagic environment can lead to shading of benthic primary producers (i.e. reduced light penetration). Following bloom formation the subsequent decomposition processes can lead to oxygen depletion and elevated nutrient effluxes (N and P) to the water column from the sediment (Borja et al., 2012; Brito et al., 2012a, 2012b; Cloern, 2001; Coutinho et al., 2012; Silva et al., 2013). Furthermore, because an increase in algal biomass often leads to a single species dominating the community, the likelihood of harmful algal bloom (HAB) formation is amplified (Brito et al., 2012a, 2012b; Coutinho et al., 2012).

Water column chlorophyll *a*, used as a proxy for phytoplankton biomass, has been widely implemented as an indicator with which to assess ecological state and change in aquatic ecosystems (Boyer et al., 2009; Brito et al., 2012a, 2012b; Domingues et al., 2008; Garmendia et al., 2013). Factors influencing the duration, density, composition and spatial extent of phytoplankton biomass in estuaries include: external nutrient loading, internal nutrient cycling, light availability, temperature, water residence time, sedimentation, and grazing (i.e. both benthic and pelagic) (Boyer et al., 2009; Brito et al., 2012a; Domingues et al., 2008; Valiela et al., 1997). Because of its sensitivity and rapid rate of response to these ecosystem drivers, as well as its value as an integrative indicator (i.e. close linkages with estuarine processes and components), phytoplankton biomass provides a sensitive and pertinent indicator of water quality (Boyer et al., 2009; Domingues et al., 2008; Garmendia et al., 2013). In stating this however, one of the foremost shortcomings associated with measuring phytoplankton biomass, by means of chlorophyll-*a* assessment, is the variability of cellular chlorophyll content which exists between species – reported to range from 0.1 to 9.7% of fresh algal mass (Boyer et al., 2009).

The incorporation of both spatial and temporal trends of phytoplankton biomass along the length of estuaries is pertinent to obtaining an accurate assessment of their condition. For example, regarding spatial variability, even in severely impacted estuaries the phytoplankton biomass levels can exhibit a broad range, with low minimum ($\pm$ 1 μg chl-*a* l^{-1}) and high maximum (>100 μg chl-*a* l^{-1}) values (Coutinho et al., 2012; Silva et al., 2013; Snow et al., 2000a; Thomas et al., 2005). A high level of temporal variability is exemplified by the noticeable differences between biomass levels associated with the open (~ wet seasons) and closed (~ dry seasons) mouth phases of temporarily open systems (Coutinho et al., 2012; Kaselowski and Adams, 2013).

Another useful indicator regarding phytoplankton relates to community structure. This is an important component to consider since changes in phytoplankton community composition can lead to large shifts in the ecosystem food web and nutrient cycling dynamics (Devlin et al., 2007). For example, if more easily grazed functional groups (e.g. diatoms) are replaced by less palatable groups (e.g. dinoflagellates and cyanobacteria) during periods of increased nutrient loading, the level of trophic transfer and nutrient cycling in the water column will decrease leading to altered food chains (Devlin et al., 2007; Domingues et al., 2005; Gordon et al., 2011). A variety of characteristics related to phytoplankton communities can be explored to identify ecosystem function and changes linked to nutrient enrichment, including: biomass, abundance, taxon diversity, seasonal succession and indicator species, e.g. the colonial flagellate, *Phaeocystis* sp. and the cyanobacteria genus, *Microcystis*. For example, due to variations in surface area to volume ratio, it has been reported that small cells are more efficient at growing under oligotrophic conditions, whilst larger cells, such as diatoms and dinoflagellates, are more competitive during eutrophic conditions (Gordon et al., 2011; Guenther et al., 2015; Snow and Adams, 2007). Phytoplankton biomass measurements have been recommended as a proxy with which to assess phytoplankton abundance (Devlin et al., 2007); yet this approach should be utilised with caution due to the variability that exists within and between the various functional groups (i.e. related to biovolume, carbon/chlorophyll *a* ratios, and environmental preferences) (Devlin et al., 2007; Domingues et al., 2008).

The direct assessment of phytoplankton community composition can be achieved using a variety of methods, such as traditional microscopy, pigment analysis, fluorescence based methods of photosynthetic activity and size spectra analysis (Garmendia et al., 2013). The determination of community composition has inherent advantages over the widely employed biomass approach (Garmendia et al., 2013). One such advantage is the inclusion of heterotrophic species that would otherwise be overlooked using chlorophyll *a* measurements (Domingues et al., 2008). Additionally, an increase in phytoplankton biomass due to eutrophication is usually accompanied by shifts in the abundance, evenness and species richness of the phytoplankton community structure (Garmendia et al., 2013); thus providing greater detail and value to possible indicator parameters. Each of the phytoplankton functional groups has been reported to indicate specific environmental conditions (Table 1).

There are, however, numerous difficulties that hinder the application and development of community composition indicators, such as the time-consuming identification process, the high spatio-temporal variability and complexity of the communities, the difficulties in setting reference conditions and boundaries, as well as the lack of a standardized methodology (Garmendia et al., 2013). Ultimately, a community composition indicator should be incorporated into a multi-metric index that considers as many fundamental attributes of phytoplankton as possible (e.g. biomass, abundance, structure and bloom frequency), as this enables a more sensitive and robust assessment of ecosystem state (Ferreira et al., 2011; Garmendia et al., 2013).

1.2. Microphytobenthos

Benthic microalgae populations are made up predominantly by diatoms (> 90%), with chlorophytes, euglenophytes and cyanobacteria also present, but to a lesser degree (Jesus et al., 2009; Underwood, 2010). These assemblages are collectively termed microphytobenthos (MPB), and inhabit the surface layer of sediment in marine and freshwater

Table 1
Summary of the indicator properties of each of the phytoplankton functional groups present in marine and fresh waters.

Dominant functional group	Controlling factors	References
Chlorophytes	Freshwater conditions; Low residence time (high flow); Cool temperatures (winter); High N:P, but low Si	Cloern, 2001 Domingues et al., 2005; Paerl et al., 2006; Paerl et al., 2010; Domingues et al., 2011; Gordon et al., 2011; Kotsedi et al., 2012; Kaselowski and Adams, 2013; Pinto and O'Farrell, 2014
Cyanobacteria	High optimum temperature; Elevated nutrient input; Low N:P, and low Si High residence time (low flow)	
Diatoms	Present in marine and freshwater; Low residence time (high flow); High N:P ratio, and high Si	
Dinoflagellates	High residence time (low flow); Stable, stratified conditions; Warm temperatures (spring and summer); High nutrients, but low Si	
Flagellates	High flow conditions; Reduced temperatures; Cosmopolitan distribution along estuaries	

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