Annual phytoplankton dynamics in the Gulf Saint Vincent, South Australia, in 2011

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Abstract

Phytoplankton communities are the basis of many marine and freshwater food webs. Their composition fluctuates depending on hydrochemical conditions, such as light,

temperature, salinity, pH, nutrients and turbulence. This study investigates the effect of changing environmental conditions on the coastal phytoplankton community of the Gulf St Vincent in South Australia. This is the first study simultaneously investigating the phytoplankton communities and their environment in this area and is essential to set up the baseline of future studies. In total, 179 phytoplankton species were identified and enumerated between January and December 2011. Phytoplankton communities were numerically dominated by chlorophytes during 6 months of the survey and an intense bloom (representing 62% of the overall phytoplankton community) of the diatom *Cylindrotheca closterium* was observed in February. Our results suggest that in the coastal waters of the Gulf St Vincent, the variability in environmental conditions is driven by temperature, wind speed/direction and the changing levels of phosphorus. However, the variability observed during autumn and winter months seems to be driven by changing levels of nitrogen and silica. In this shallow environment, the wind speed is proportional to the stress at the ocean floor and should directly influence the resuspension of sediment and associated nutrients. Nutrient ratios were observed to investigate potential phytoplankton nutrient limitation patterns. These ratios indicated that nitrogen was usually the limiting nutrient, which is typical of marine systems. Since nutrient enrichment is generally the main factor driving the succession and composition of phytoplankton communities in coastal waters, further work is now needed to identify the sources of nutrients in this region where river runoff is limited and evaporation is high relative to precipitation.

1. Introduction

Phytoplankton communities are the basis of many marine and freshwater food webs (Huertas et al. 2011). Their composition fluctuates depending on hydrological conditions, such as light, temperature, salinity, pH, nutrients and turbulence (Legendre & Demers 1984, Smayda 1990, Leterme et al. 2005, 2006). Typically, diatoms dominate coastal marine communities. However, other groups of phytoplankton can dominate depending on the combination of hydrological conditions and climatic variability (Margalef 1975, Leterme et al. 2006). Changes in dominant base groups/species often propagate up the food chain, impacting on fish, marine mammals and birds (Donnelly et al. 2007). Phytoplankton are known to exhibit rapid responses to changes in environmental conditions (Furnas 1990) and are therefore commonly acknowledged as excellent bio-indicators of the impact of natural and seasonal changes in coastal ecosystems (Harris 1986, Rimet & Bouchez 2012). Their susceptibility to environmental change is usually expressed by morphological and/or behavioural changes as well as by persistent or seasonally atypical differences in abundance and distribution (Margalef 1975, Leterme et al. 2010, 2013). Where mono- or class-specific blooms are observed on an annual basis, they often vary significantly in magnitude and/or duration between years (Ji et al. 2006). These

seasonal fluctuations in biomass can be explained by (i) a generally positive correlation between phytoplankton biomass, day length and temperature, (ii) the patterns of upwelling/downwelling-favourable conditions impacting on nutrient ratios and (iii) the ability of phytoplankton to rapidly metabolise nutrients (Lips & Lips 2010). In coastal ecosystems, the capacity of phytoplankton populations and biomass to fluctuate in response to changing environmental conditions is often highly amplified when compared to the open ocean (Cloern 1996, Carter et al. 2005). These changes range from temperature changes, over naturally occurring nutrient fluctuations caused by upwelling/downwelling-favourable conditions, to biochemical input from natural and anthropogenic land run-off (Justic et al. 1995).

The oceanography of Gulf St Vincent (GSV) has recently been described by Pattiaratchi et al. (2006) and Bye & Kämpf (2008). They showed that the key processes affecting the currents and mixing of the GSV are (1) astronomical tides with a strong spring neap cycle, (2) wind-driven flows (i.e. coastal trapped waves and storm surges), (3) seasonal changes in the heating/cooling and evaporation cycles that affect water temperature and salinity and (4) Southern Ocean swells that propagate into the GSV. However, there is still a big gap in understanding the biology of the Gulf. This study investigates the monthly fluctuations of the phytoplankton communities of the GSV. Biological, chemical and physical properties of the ecosystem were monitored over twelve months in order to assess and explain changes in species composition in relation to environmental conditions. This is the first study of its kind, simultaneously investigating the phytoplankton communities and their environment in this area and is essential to establish a baseline for future studies.

2. Material and methods

This study took place in the vicinity of the recently built desalination plant off Port Stanvac (Figure 1), 30 km south of Adelaide (South Australia), on the coast of the GSV.

The GSV is a large, relatively shallow (< 40 m deep) inverse estuary with well mixed dense waters. Its main water circulation moves in a clockwise direction, with most open-ocean water entering through Investigator Strait and being expelled from the Gulf through the Backstairs Passage (Figure 1, Bye & Kämpf 2008). Shallow depths support broad subtidal seagrass meadows, intertidal sandflats, mangrove woodlands, samphire-algal marshes and supratidal flats (Barnett et al. 1997). Depending on seasonal patterns, wind direction, temperature and salinity gradients, the flushing time of the entire volume of the Gulf is approximately four months (Pattiaratchi et al. 2006, Bye & Kämpf 2008). The GSV has restricted water exchange

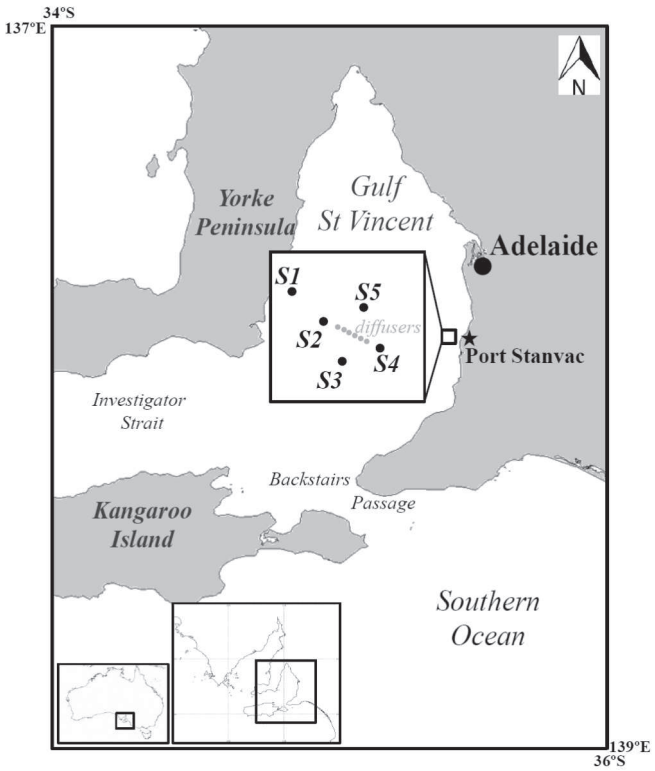

Figure 1. Map of the sampling area in the Gulf St Vincent (South Australia). Samples were taken at the intake pipe (S1) and at 100–150 m from the outfall diffusers (S2–S5) of the desalination plant. The intake pipe and the outfall saline concentrate diffusers are located 1500 m and 1100 m respectively away from the coastline where the desalination plant was built

with the open ocean due to the dense upwelling of shelf waters at the mouth of the Gulf and Kangaroo Island that acts as a physical barrier, protecting the Gulf from high wave action (Middleton & Bye 2007).

Between January and December 2011, monthly samples were taken at the intake pipe (S1) and around the outfall saline concentrate diffusers (S2–S5) of the Adelaide Desalination Plant (ADP), with a total of 5 sites being sampled. The intake pipe and the outfall are located at a depth of 20 m and at a distance of 1300 m and 900 m from the edge of the shore respectively. At each site, samples were collected in triplicate at two depths, sub-surface (i.e. 1 m below the surface) and bottom (i.e. 1 m from the bottom $\sim$ 18–19 m depth depending on weather and tide conditions). Vertical profiles of salinity (Practical Salinity Units, PSU) and temperature [°C] were obtained using

a multi-parameter probe (66400-series YSI Australia, Morningside QLD) calibrated to a standard salinity solution before deployment.

The concentration of dissolved silica, ammonium, orthophosphate and the combined concentrations of nitrate and nitrite (nitrate/nitrite) were measured simultaneously every month, using a Lachat Quickchem Flow Injection Analyser (FIA, Lachat, Loveland USA) and carried out following published methods (Hansen & Koroleff 2007). Three replicates of seawater (100 mL) were sampled at each site and depth and filtered through bonnet syringe Minisart filters (0.45 μm pore size, Sartorius Stedim, Dandenong, Australia) to remove large particles. Filtrates were then stored at -20°C until further analysis. Prior to analysis, the samples were thawed and mixed before injecting approximately 10 mL of each sample into the FIA in duplicate for a total of 6 replicates per sample. The detection limits were 40 nM for dissolved silica species, 70 nM for ammonium, 30 nM for orthophosphate and 70 nM for nitrate/nitrite. The method was calibrated using standard solutions prepared in 0.6 M sodium chloride, corresponding to typical seawater salinity values of 35 PSU.

The concentration of chlorophyll *a* (Chl *a*) was measured every month using methanol extraction and subsequent fluorometric determination (Welschmeyer 1994). Seawater (600 mL) was filtered in triplicate through 47 mm, glass microfibre filters (1 μm pore size, Filtech, Fairy Meadow, Australia), using a vacuum pump and a filtration ramp. The filters were then wrapped in aluminium foil and stored at -20°C. For analysis, the filters were placed in methanol (5 mL) for 24 h at 4°C in the dark, and the concentration of the Chl *a* dissolved in the methanol was determined using a Turner 450 fluorometer, previously calibrated with Chl *a* extracted from *Anacystis nidulans* (Sigma Chemicals, St Louis, MO, USA).

At each site and depth, 1 L samples of seawater were taken and preserved with Lugol's iodine added to each bottle (0.5% final concentration, Hajdu et al. 2007) for identification and enumeration of phytoplankton species (>5 μm). Identification and enumeration of phytoplankton was carried out every two weeks by Microalgal Supply Service (Ormond, Victoria, Australia). The cells were identified up to the genus or species level based on their key taxonomic features (Tomas 1997, Hallegraef et al. 2010) and grouped according to their size and shape.

Wind speed [m s^{-1}] and direction data [i.e. northerly/southerly (NS) and easterly/westerly (EW)] were provided by the Australian Bureau of Meteorology and measured by the Adelaide airport weather station. The average wind was entered into a coordinate system where positive NS components indicated upwelling-favourable wind conditions and negative NS components indicated downwelling-favourable wind conditions

and corresponded to the dimensionless empirical drag coefficient over 14 days prior to the date of sampling. Upwelling- or downwelling-favourable conditions were determined on basis of the Ekman transport associated with northerly and southerly wind conditions along the coast of the Gulf.

All environmental and biological data were tested for normality using the Kolmogorov-Smirnov test (Zar 1999). As none of the data were normally distributed, non-parametric tests were applied to determine temporal correlations (Spearman's rho rank correlation coefficient ρ; Zar 1999) between phytoplankton communities and environmental parameters over time and depth (combining all 5 sites as replicates) using IBM SPSS Statistics v19. In order to identify seasonal and/or spatial patterns in the environmental data, the data were $\log(x+1)$ transformed and principle component analyses (PCA) performed on the whole dataset.

3. Results and discussion

The range, average and standard error of the hydrological and biological data for the twelve months period are listed in Table 1. Over the twelve months of the study, the YSI profiles for temperature and salinity did not exhibit any vertical changes along the water column, suggesting that the water column was well mixed. This was reflected in the hydrological and biological data as there was no significant difference between the surface and bottom samples. In addition, there was no difference between the temperature, salinity, nutrients and the biological parameters measured at the ADP intake pipe (S1) and outfall (S2–S5).

Table 1. Averages and standard errors of the hydrological and biological data for the 12-month period

Factor	Autumn (average ± SE)	Winter (average ± SE)	Spring (average ± SE)	Summer (average ± SE)
salinity [PSU]	37.11 ± 0.02	37.45 ± 0.06	37.05 ± 0.06	37.02 ± 0.04
temperature [°C]	18.7 ± 0.3	13.5 ± 0.1	16.8 ± 0.3	20.8 ± 0.3
wind speed [m s^{-1}]	13.4 ± 0.5	12.1 ± 0.5	13.7 ± 0.3	15.5 ± 0.1
N [μmol l^{-1}]	1.55 ± 0.33	0.78 ± 0.14	0.39 ± 0.07	0.30 ± 0.04
P [μmol l^{-1}]	0.05 ± 0.01	0.11 ± 0.04	0.09 ± 0.06	0.03 ± 0.04
Si [μmol l^{-1}]	4.08 ± 0.29	2.79 ± 0.18	1.92 ± 0.10	2.32 ± 0.08
N:P	26.6 ± 4.5	8.56 ± 1.43	5.53 ± 0.96	8.14 ± 0.77
N:Si	0.31 ± 0.03	0.26 ± 0.05	0.22 ± 0.04	0.17 ± 0.02
Si:P	71.3 ± 6.6	33.1 ± 4.2	37.7 ± 7.8	42.9 ± 3.3
Chl *a* [mg L^{-1}]	0.11 ± 0.01	0.08 ± 0.01	0.09 ± 0.01	0.09 ± 0.01

In order to summarise the weight of each environmental parameter in setting the environmental conditions of the study, a PCA was applied. The PCA revealed clear clustering along the primary (PC1) and secondary (PC2) axes, explaining a total of 57.4% of the variance observed during the survey period (Figure 2). The first principal component (PC1: 41.3% of variance) was related to temperature, wind speed/direction and phosphorus content, while the second principal component (PC2: 16.1% of variance) was related to salinity, silicate and nitrogen. The main environmental drivers of the temporal variability of the Gulf therefore seem to be temperature, wind speed/direction and phosphorus levels. However, the variability observed during autumn and winter months is driven by changing levels of salinity, nitrogen and silica. The water temperature exhibited a clear austral-seasonal pattern with a maximum of 22°C in January (summer) and

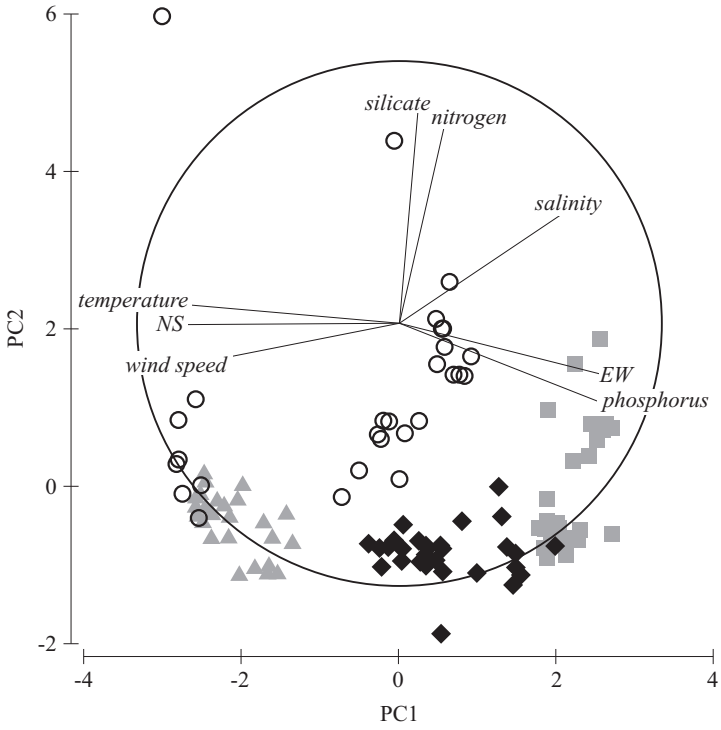

Figure 2. Principal Component Analysis (PCA) of the environmental data. The clustering of the data along the primary (PC1: 41.3% of the variance) and secondary (PC2: 16.1% of the variance) axes represent 57.4% of the total variance. The seasons have been used as factors to illustrate the clusters: summer (grey triangles), autumn (open circles), winter (grey squares) and spring (black diamonds). Wind direction is indicated as northerly/southerly (NS) and easterly/westerly (EW)

a minimum of 13°C in July (winter; Figure 3). Salinity did not show any clear seasonal pattern, with an average [± standard error (SE)] of 37.17 (± 0.03) PSU (Figure 3). Currents along the Adelaide metropolitan coastline generally flow parallel to the shore, but are seasonally influenced by a variety of factors, including wind direction, temperature and salinity gradients

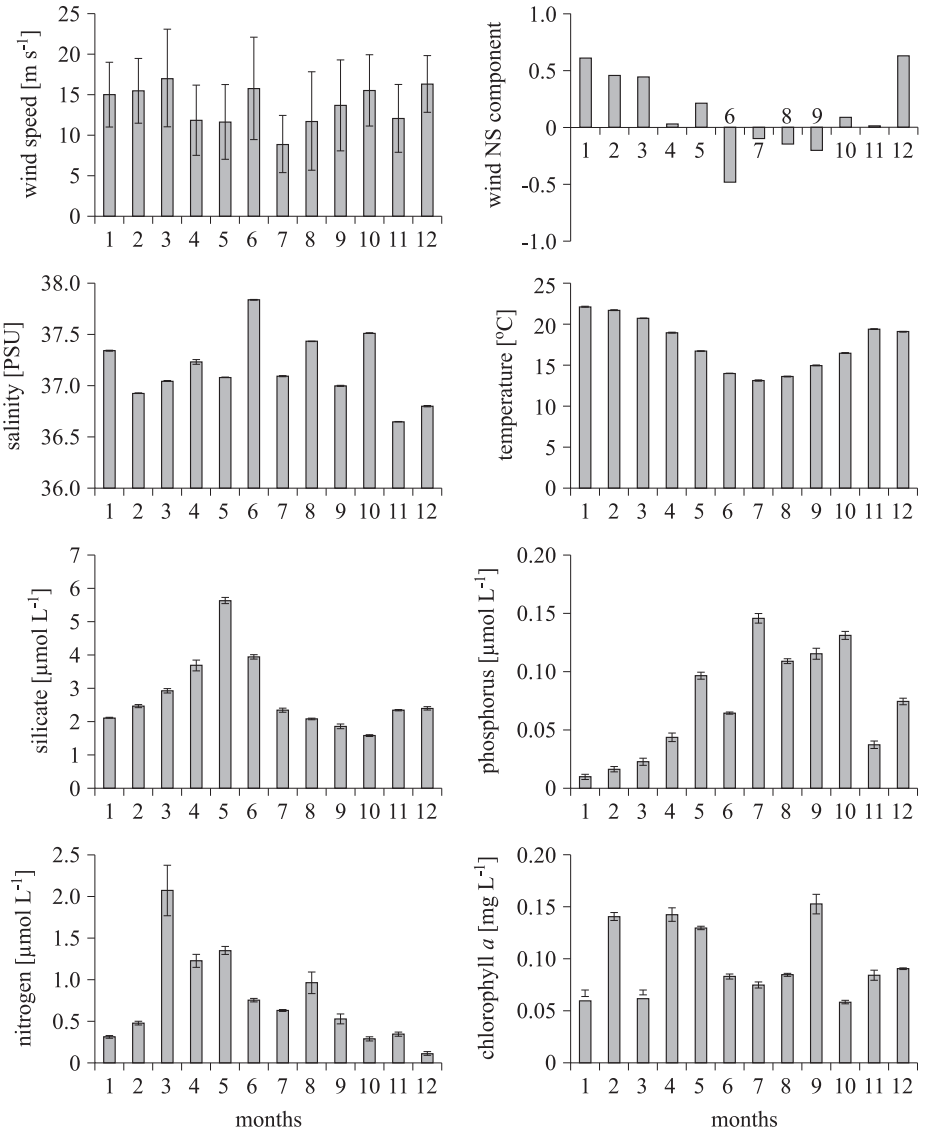

Figure 3. Annual cycle in 2011 of the environmental variables averaged over the five sampling sites. Wind direction is indicated as (NS) northerly/southerly. The error bars represent the standard error from the mean

(Pattiaratchi et al. 2006). In particular, the north-south (NS) wind direction showed a seasonal pattern, with upwelling-favourable conditions prevailing in summer and autumn and downwelling-favourable conditions prevailing in winter (Figure 3).

All nutrients (i.e. nitrogen, phosphorus and silicate) exhibited a seasonal cycle with lower concentrations during summer (Figure 3). During spring and summer, ammonium was the most abundant source of nitrogen, while nitrate and nitrite were the prevalent source of nitrogen during autumn and winter (data not shown). Since the sampling area is impacted by stormwater and wastewater outflows, the increase of nitrate and nitrite during autumn and winter might be related to an increase in precipitations and water run-offs. The concentration and elemental ratios of nitrogen (N), phosphorus (P) and silicate (Si) such as N:P:Si (typical nomenclature used in ecology) are known to strongly influence phytoplankton communities (Harris 1986). Redfield et al. (1963) proposed that growing phytoplankton take up nutrients from the water column in fixed proportions, namely C:N:P:Si ratios of 106:16:1:15. Deviations in nutrient concentrations from these proportions have been used as indicators of the limitation of primary production in pelagic systems. However, the role of nutrient limitation and N:P ratios in structuring the phytoplankton communities has been suggested to vary considerably, both spatially and temporally, among different systems (Lagus et al. 2004). For example, a C:N:P:Si ratio of 62:11:1:24 was proposed for the Southern Ocean by Jennings et al. (1984). Here, we observed N:P ratios between 0.3 and 107 with an annual average of 12.3 ± 1.5 which was close to the 11 nominated for phytoplankton growth by Jennings et al. (1984). In addition, our winter to summer ratios (Table 1, Figure 4) were similar to the observed N:P spring ratio of 8.3 ± 5.4 in the Polar Frontal zone at 140°E (Lourey & Trull 2001) and at 64°S, 141°E (Takeda 1998). Like the N:P ratios, N:Si ratios were variable: this was expected, since they depend on the abundance of diatoms which can show both temporal and spatial variations. N:Si ratios were in the range of 0.01 to 1.52 with an annual average of 0.25 ± 0.02. This compares well with suggested values of 0.45 (Jennings et al. 1984). The values observed during spring (0.95) and autumn (0.82) correspond to the expected ratio of 0.95 for planktonic diatoms (Brzezinski 1985) and match the blooming periods observed for diatoms in this study. Furthermore, the Si:P ratios were highly variable between 5 and 171 with an annual average of 44.5 ± 3.25. Smayda (1990) suggested that changes in Si:P ratios would affect planktonic assemblages, with a possible shift from diatom to flagellate when a decline in Si:P ratios was observed. These ratios indicate that N was usually the limiting nutrient in the GSV, which is typical of marine systems (Hecky & Kilham

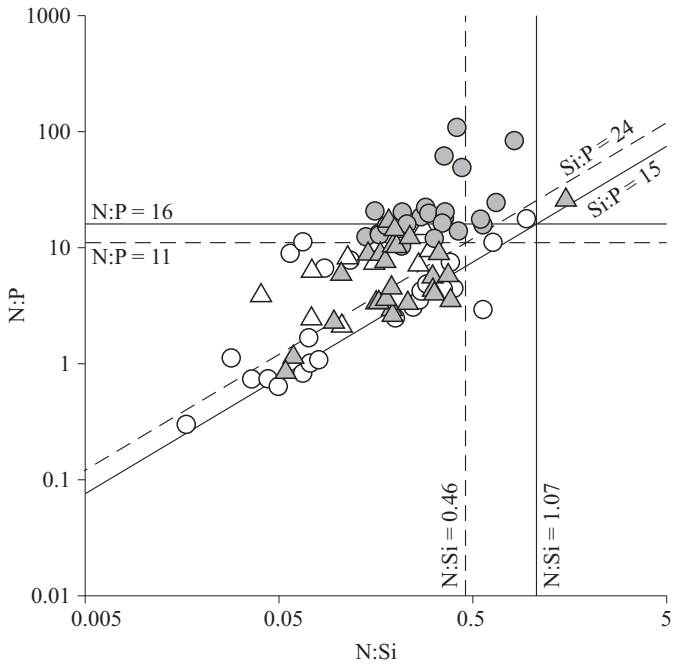

Figure 4. Dissolved nutrient ratio relationships for each season: spring (open circles), summer (open triangles), autumn (grey circles) and winter (grey triangles). Solid lines indicate Redfield ratios and dashed lines indicate the ratios following Jennings et al. (1984)

1988, Elser et al. 2007). All ratios were the highest in autumn with N:P ratios of 26.6 ± 4.5, N:Si ratios of 0.31 ± 0.03 and Si:P ratios of 71.3 ± 6.61 (Figure 4). Previous work showed that N:P ratios greater than 20–30 suggest P limitation (Dortch & Whitledge 1992, Justic et al. 1995), which should not happen in the GSV except in autumn when the ratio exceeds those values. In addition, since both N:Si and Si:P ratios showed that Si was in excess compared to N and P, the diatom-zooplankton-fish food web should not be compromised.

Levels of Chl *a* revealed higher phytoplankton biomass during autumn (Figure 3) which was significantly correlated to N:P ($\rho = 0.309$, $p < 0.05$) and Si:P ($\rho = 0.283$, $p < 0.05$) ratios. In their experiments, Lagus et al. (2004) showed that changes in N levels explained most of the phytoplankton biomass variation, even though P levels also contributed to the biomass increase. Here, we suggest that, depending on the time of the year, either N and/or P control the phytoplankton biomass in the coastal waters of the GSV.

In total, 179 phytoplankton species (i.e. 68 diatoms, 62 dinoflagellates, 14 flagellates, 10 haptophytes, 9 chlorophytes, 6 cryptophytes and 10

other groups) were identified and enumerated over the twelve-month study (Table 2). While diatoms and dinoflagellates have previously been described as the most abundant phytoplankton classes in coastal ecosystems (Carter et al. 2005), our study identified a dominance of chlorophytes during six of the twelve months of the survey period and of haptophytes in October. However, there was a clear dominance of diatoms in February, with a bloom of *Cylindrotheca closterium* that constituted 62.31% of the overall phytoplankton community. In general, the phytoplankton communities were numerically dominated by chlorophytes, with its contribution varying between 17 to 41% of the total abundance (Figure 5). The mean dinoflagellate contribution varied from 5 to 37%, the diatom contribution varied between 6 to 62%, the mean haptophyte contribution varied between 3 and 28%, while the mean cryptophyte contribution varied between 7 and 24% (Figure 5). The most abundant species from those groups were *Pyramimonas* spp., *Hemiselmis* sp., *Gyrodinium* sp., *Heterocapsa rotunda*, *C. closterium*, *Chaetoceros* spp., *Chrysochromulina* spp. and *Emiliania huxleyi* (Figure 6).

For the chlorophytes, *Pyramimonas* spp. were positively correlated to N ($\rho = 0.264$, $p < 0.05$) and N:P ($\rho = 0.254$, $p < 0.05$) while for the cryptophytes, *Hemiselmis* sp. was positively correlated to Si ($\rho = 0.567$, $p < 0.001$) and Si:P ($\rho = 0.400$, $p < 0.001$). Suikkanen et al. (2007) observed that *Pyramimonas* spp., which formed the bulk of the chlorophyte biomass in the Gulf of Finland, preferred high N concentrations and a high temperature with its biomass increasing in summer. Similarly, the biomass of *Pyramimonas* spp. in the GSV increased in summer and autumn. Finally, *Hemiselmis* sp. and *Pyramimonas* spp. were positively correlated to Si, which could be explained by the timing of their bloom compared to the blooms of diatoms. In particular, their annual cycle showed late spring/early summer and autumn blooms, while diatoms showed late summer and winter blooms. Ansotegui et al. (2003) found that after diatom blooms, a drastic change in the size and structure of the phytoplankton, as well as in the specific composition of the community could be observed, with chlorophytes becoming the dominant group.

Dinoflagellates, like chlorophytes, have also been observed to bloom during late spring/early summer and autumn. With regard to the most abundant dinoflagellate species, *Gyrodinium* sp. was positively correlated to N:P ($\rho = 0.262$, $p < 0.05$) and to *Hemiselmis* sp. ($\rho = 0.567$, $p < 0.001$). Some *Gyrodinium* species can potentially cause toxic blooms (Li et al. 2000) but an important feature of this phototrophic dinoflagellate species is its capability to eat other protists. Mixotrophy appears common among

Table 2. Phytoplankton species list of the Gulf St Vincent (SA). Diatoms (DIAT, 68 spp.), dinoflagellates (DIN, 62 spp.), flagellates (FLA, 14 spp.), haptophytes (HAP, 10 spp.), chlorophytes (CHL, 9 spp.), cryptophytes (CRYP, 6 spp.), chrysophytes (CHRYS, 4 spp.), dictyochophytes (DIC, 4 spp.), euglenoids (EUGL, 2 spp.) and raphydophytes (RAPH, 1 spp.)

Acanthoceras sp.	DIAT	*Fallacia* sp.	DIAT	*Plagioselmis prolonga*	CRYP
Akashiwo sanguinea	DIN	*Fragilaria* sp.	DIAT	*Plagiotropis* sp.	DIAT
Alexandrium catenella/fundyense	DIN	*Gephyrocapsa oceanica*	HAP	*Pleurosigma* sp.	DIAT
Alexandrium minutum	DIN	*Gomphonema* sp.	DIAT	*Podolampas* sp.	DIN
Alexandrium peruvianum/ostenfeldii	DIN	*Goniodoma* sp.	DIN	*Polykrykos schwartzii*	DIN
Alexandrium pseudogonyaulax	DIN	*Goniomonas truncata*	FLA	*Preperidinium meunieri*	DIN
Alexandrium sp.	DIN	*Gonyaulax* spp.	DIN	*Proboscia alata*	DIAT
Amphidinium sp.	DIN	*Grammotophora marina*	DIAT	*Proboscia alata*	DIAT
Amphora sp.	DIAT	*Grammotophora serpentina*	DIAT	*Pronoctiluca spinifera*	DIN
Amylax sp.	DIN	*Guinardia delicatula*	DIAT	*Prorocentrum compressum*	DIN
Anaulus australis	DIAT	*Guinardia flaccida*	DIAT	*Prorocentrum cordatum*	DIN
Apedinella spinifera	DIC	*Guinardia striata*	DIAT	*Prorocentrum dentatum*	DIN
Ardissonea crystallina	DIAT	*Gymnodinioid* spp.	DIN	*Prorocentrum emarginatum*	DIN
Asterionellopsis glacialis	DIAT	*Gyrodinium* spp.	DIN	*Prorocentrum gracile*	DIN
Asteromphalus sarcophagus	DIAT	*Gyrosigma* spp.	DIAT	*Prorocentrum lima*	DIN
Attheya sp.	DIAT	*Halosphaera* sp.	CHL	*Prorocentrum micans*	DIN
Bacillaria paxillifera	DIAT	*Hemiaulus* sp.	DIAT	*Prorocentrum rhathymum*	DIN
Bacteriastrum elegans	DIAT	*Hemidiscus* sp.	DIAT	*Prorocentrum* sp.	DIN
Calciopappus caudatus	HAP	*Hemiselmis* sp.	CRYP	*Prorocentrum triestinum*	DIN
Calycomonas sp.	CHRYS	*Heterocapsa rotundata*	DIN	*Protoperidinium bipes*	DIN
Cerataulina sp.	DIAT	*Heterocapsa triquetra*	DIN	*Protoperidinium mesoporos*	DIN
Ceratium furca	DIN	*Heterosigma* sp.	DIAT	*Protoperidinium minutum*	DIN
Ceratium fusus	DIN	*Imantonia* sp.	HAP	*Protoperidinium* spp.	DIN
Ceratium lineatum	DIN	*Karenia mikimotoi*	DIN	*Protoperidinium* steinii	DIN

Table 2. (*continued*)

Ceratium macroceros	DIN	*Karenia papillionacaea*	DIN	*Prymnesium* sp.	HAP
Ceratium pentagonum	DIN	*Karenia* spp.	DIN	*Pseudo-nitzschia delicatissima group*	DIAT
Ceratium tenue	DIN	*Karlodinium* sp.	DIN	*Pseudo-nitzschia fraudulenta/australis*	DIAT
Ceratium tripos	DIN	*Katodinium* sp.	DIN	*Pseudo-nitzschia heimii*	DIAT
Ceratoneis closterium	DIAT	*Leptocylindrus danicus*	DIAT	*Pseudo-nitzschia pungens/multiseries*	DIAT
cf. *Pachysphaera* sp.	CHLO	*Leptocylindrus minimus*	DIAT	*Pseudo-nitzschia turgidula*	DIAT
cf. *Strombomonas* sp.	EUGL	*Leucocryptos marina*	CRYP	*Pseudopedinella pyriforme*	FLA
Chaetoceros spp.	DIAT	*Licmophora* sp.	DIAT	*Pseudoscourfieldia* sp.	FLA
Chattonella spp.	RAPH	*Lioloma* sp.	DIAT	*Pseudosolenia calcar-avis*	DIAT
Chlamydomonas sp.	HAP	*Mamiella* sp.	CHL	*Pterosperma* sp.	FLA
Chrysochromulina spp.	HAP	*Mastogloea* sp.	DIAT	*Pyramimonas* spp.	CHL
Climacodium sp.	DIAT	*Meringiosphaera mediterranea*	CRYP	*Resultor micron*	FLA
Cocconeis spp.	DIAT	*Micromonas pusilla*	CHL	*Rhizosolenia setigera*	DIAT
Cochlodinium spp.	DIN	*Minidiscus trioculatus*	DIAT	*Rhizosolenia* spp.	DIAT
Corymbellus sp.	HAP	*Minutocellus* sp.	DIAT	*Rhodomonas salina*	CRYP
Coscinodiscus spp.	DIAT	*Monoraphidium* sp.	CHL	*Scrippsiella* spp.	DIN
Cyclotella spp.	DIAT	*Naviculoid* spp.	DIAT	*Skeletonema costatum/pseudocostatum*	DIAT
Cylindrotheca closterium	DIAT	*Nephroselmis* sp.	CHL	*Staurastrum* sp.	CHL
Cymbella sp.	DIAT	*Nitzschia longissima*	DIAT	*Stauroneis* sp.	DIAT
Cymbomonas sp.	FLA	*Nitzschia sigmoidea*	DIAT	*Stephanoeca* sp.	FLA
Dactyliosolen fragilissimus	DIAT	*Nitzschia* spp.	DIAT	*Stephanoeca* sp.	FLA
Dactyliosolen sp.	DIAT	*Noctiluca scintillans*	DIN	*Striatella unipunctata*	DIAT
Dictyocha fibula	DIC	*Oblea* sp.	DIN	*Synedra* sp.	DIAT
Dictyocha octonaria	DIC	*Ochromonas* spp.	CHRYS	*Takayama pulchella*	DIN
Dinobryon sp.	CHRYS	*Odontella* sp.	DIAT	*Teleaulax acuta*	CRYP

Table 2. (*continued*)

Dinophysis acuminata	DIN	*Ostreopsis* sp.	DIN	*Telonema subtilis*	CRYP
Dinophysis fortii	DIN	*Oxyphysis oxytoxoides*	DIN	*Tetraselmis* spp.	CHL
Dinophysis tripos	DIN	*Oxyrrhis marina*	DIN	*Thalassionema* sp.	DIAT
Dinophysis/Phalachroma mitra	DIN	*Oxytoxum scolopax*	DIN	*Thalassiosira* cf. *mala*	DIAT
Diploneis sp.	DIAT	*Paralia sulcata*	DIAT	*Thalassiosira* sp.	DIAT
Dunaliella sp.	FLA	*Paraphysomonas* sp.	FLA	*Thalassiothrix* sp.	DIAT
Ebria tripartita	CHRYS	*Pedinella* sp.	DIC	*Torodinium* sp.	DIN
Emiliania huxleyi	HAP	*Peridinium* sp.	DIN	*Trachelomonas* spp.	FLA
Encyonema sp.	DIAT	*Phaeocystis pouchetii cells*	HAP	*Tryblionella* sp.	DIAT
Entomoneis sp.	DIAT	*Phaeocystis* sp.	HAP	*Warnowia* sp.	DIN
Eutreptiella spp.	EUGL	*Phalochromium rotunda*	DIN		

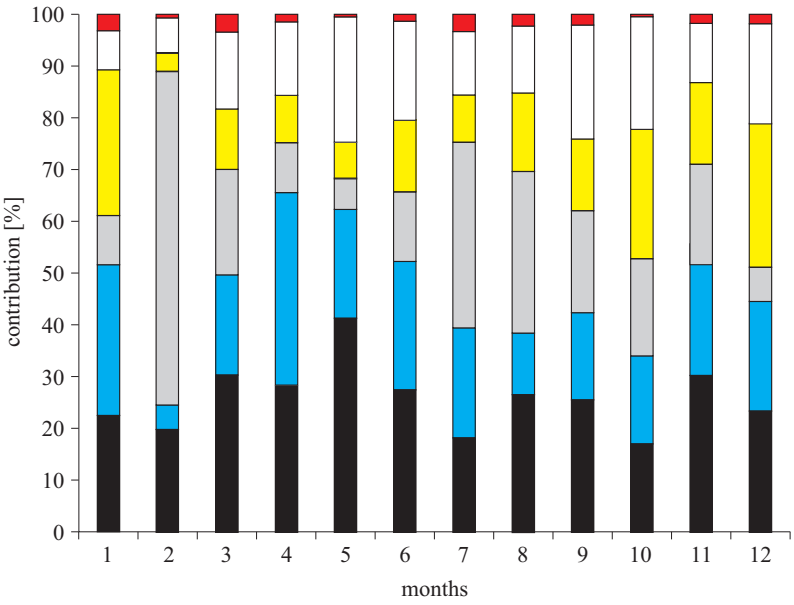

Figure 5. Average contribution of phytoplankton groups: chlorophytes (black), dinoflagellates (blue), diatoms (light grey), haptophytes (yellow), cryptophytes (white) and others (red) to the total abundance for the 12-month period of study in 2011. Data have been averaged over the five sampling sites

dinoflagellates (Sanders & Porter 1988, Li et al. 1996) and has been proposed to contribute to their success under varying nutrient conditions (Stoecker et al. 1997). For example, *Gyrodinium galatheanum* has been observed eating cryptophytes in Chesapeake Bay (Li et al. 1996). Here, the strong temporal correlation between *Gyrodinium* sp. and *Hemiselmis* sp. demonstrates their co-occurrence in the GSV and suggests that *Hemiselmis* sp. could be part of the diet of *Gyrodinium* sp. in the coastal waters of the GSV.

For diatoms, *C. closterium* was negatively correlated to salinity ($\rho = -0.259$, $p < 0.05$) and NS wind direction ($\rho = -0.350$, $p < 0.001$). During February, the community was dominated by the diatom *C. closterium*, a meroplanktonic species that can exploit a half-planktonic, half-benthic existence (Round 1981). These species are resuspended in the water column by mixing events and return to the sediment under calm conditions (Kingston 2009). *C. closterium* usually attains high densities in the water column following wind mixing events. In our study, the bloom of *C. closterium* corresponds to strong wind events (i.e. 15.44 ± 3.99 m s^{-1}). Since the growth rate of this species has been observed to be much higher than that of many other diatom species (Tanaka 1984), this could explain why it prospered

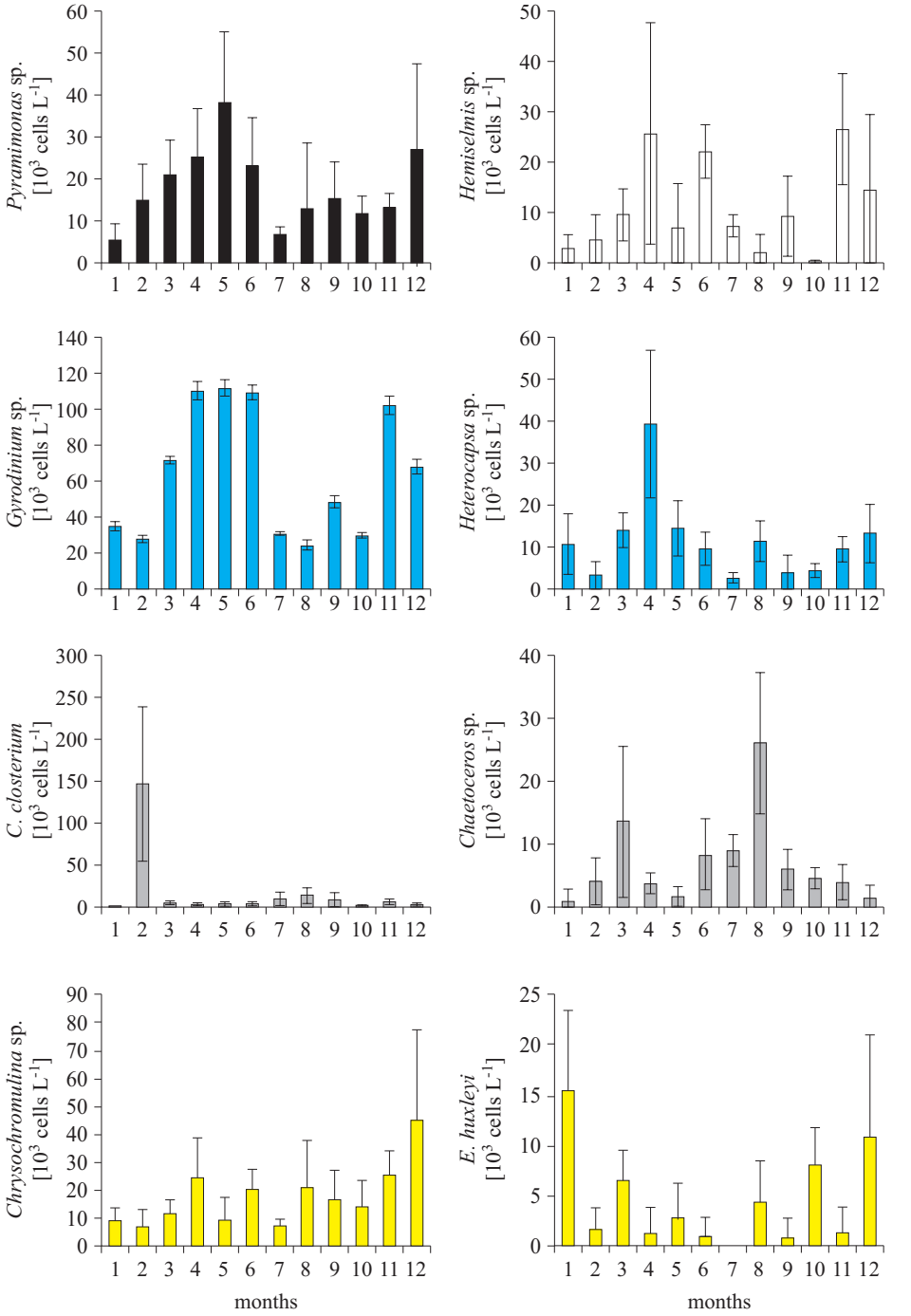

Figure 6. Annual cycle of the phytoplankton species identified as the most abundant within each phytoplankton group in 2011. The error bars represent the standard error from the mean

in the favourable conditions and dominated the community in February. In contrast, *Chaetoceros* spp. bloomed in autumn and winter. It was positively correlated to the EW wind direction ($\rho = 0.298$, $p < 0.05$) and N ($\rho = 0.310$, $p < 0.05$) and negatively correlated to temperature ($\rho = -0.551$, $p < 0.001$) and NS wind direction ($\rho = -0.616$, $p < 0.001$). Species of the genus *Chaetoceros* may be harmful to fish, should their spines become lodged within gills. This diatom indeed has siliceous spikes and barbs which characterise its genus and can penetrate the gill membranes of fish. The penetration of the spikes and barbs of the gill membranes would cause a reduction of gas exchange in the gills, caused by mucus production when the gill epithelium is irritated by the spines (Rensel 1993). In 2013, a fish kill event occurred in the GSV and was related partly to species of the genus *Chaetoceros* (PIRSA report 2013).

Finally, for the haptophytes, *Chrysochromulina* spp. were negatively correlated to N ($\rho = -0.280$, $p < 0.001$) but positively correlated to wind speed ($\rho = 0.261$, $p < 0.05$) and EW wind direction ($\rho = 0.360$, $p < 0.001$). On the other hand, *Emiliania huxleyi* was negatively correlated to N ($\rho = -0.364$, $p < 0.001$), N:P ratio ($\rho = -0.375$, $p < 0.001$) and EW wind direction ($\rho = -0.405$, $p < 0.001$), and positively correlated to temperature ($\rho = 0.381$, $p < 0.001$), wind speed ($\rho = 0.353$, $p < 0.001$) and NS wind direction ($\rho = 0.591$, $p < 0.001$). Here, *E. huxleyi* was negatively correlated to the N:P ratio. Previously, Lessard et al. (2005) showed that for a bloom to occur, *E. huxleyi* requires high P concentrations relative to N: this is what we observed in our study. *E. huxleyi* is a cosmopolitan species, widely distributed in both oceanic and coastal waters (Balch et al. 1991). *E. huxleyi* may have an unusually high affinity for P uptake and can also use alkaline phosphatase to access dissolved organic P sources (Riegmann et al. 2000). Here, the main environmental drivers of the phytoplankton communities were wind speed/direction and nutrient ratios. We propose that wind speed has a strong impact on this coastal ecosystem based on the principle that in a shallow water column (i.e. 20 m), the wind speed is proportional to the bottom stress on the ocean floor and then to the resuspension of sediment and associated nutrients.

4. Conclusion

Over the course of twelve months, this study demonstrated a typical austral-seasonal pattern in water temperature, accompanied by a similar annual cycle in phytoplankton. The main species contributing to the Chl *a* signal were *Pyramimonas* spp., *Hemiselmis* sp., *Gyrodinium* sp., *Heterocapsa rotunda*, *Cylindrotheca closterium*, *Chaetoceros* spp., *Chrysochromulina* spp. and *Emiliania huxleyi*. The different phytoplankton groups showed shifts

in species dominance between summer and winter, with a dominance of chlorophytes during six months of the year. It became apparent that wind speed and direction played an important role in setting the environmental conditions off Port Stanvac and subsequently on the distribution and abundance of phytoplankton species in this coastal area. In summary, our results show that in the coastal waters of the GSV, phytoplankton communities are affected by wind conditions and by changing nutrient levels on a seasonal basis, which is typical of coastal environments. Nutrient enrichment of coastal waters is generally the main factor driving the succession and composition of phytoplankton communities, and further work is now needed to identify the sources of nutrients in this region, where river run-off is limited and evaporation is high relative to precipitation. This is particularly relevant in the light of environmental studies on the impact of the Adelaide Desalination Plant, which became fully operational in early December 2012.

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References

Ansotegui A., Sarobe A., Trigueros J. M., Urrutxurtu I., Orive E., 2003, *Size distribution of algal pigments and phytoplankton assemblages in a coastal-estuarine environment: contribution of small eukaryotic algae*, J. Plankton Res., 25 (4), 341–355, http://dx.doi.org/10.1093/plankt/25.4.341.

Balch W. M., Holligan P. M., Ackleson S. G., Voss K. J., 1991, *Biological and optical properties of mesoscale coccolithophore blooms in the Gulf of Maine*, Limnol. Oceanogr., 36 (4), 629–643, http://dx.doi.org/10.4319/lo.1991.36.4.0629.

Barnett E. J., Harvey N., Belperio A. P., Bourman R. P., 1997, *Sea-level indicators from a Holocene, tide-dominated coastal succession, Port Pirie, South Australia*, T. Roy. Soc. South Aust., 121, 125–135.

Brzezinski M. A., 1985, *The Si:C:N ratio of marine diatoms: interspecific variability and the effect of some environmental variables*, J. Phycol., 21 (3), 347–357, http://dx.doi.org/10.1111/j.0022-3646.1985.00347.x.

Bye J. A., Kämpf J., 2008, *Physical oceanography*, [in:] *Natural history of GSV*, S. A. Shepherd, S. Bryars, I. Kirkegaard, P. Harbison & J. T. Jennings, Roy. Soc. South Austr. Inc., Adelaide, 56–70.

Carter C. M., Ross A. H., Schiel D. R., Howard-Williams C., Hayden B., 2005, *In situ microcosm experiments on the influence of nitrate and light on phytoplankton community composition*, J. Exp. Mar. Biol. Ecol., 326 (1), 1–13, http://dx.doi.org/10.1016/j.jembe.2005.05.006.

Cloern J. E., 1996, *Phytoplankton bloom dynamics in coastal ecosystems: a review with some general lessons from sustained investigation of San Francisco Bay, California*, Rev. Geophys., 43 (2), 127–168, http://dx.doi.org/10.1029/96RG00986.

Donnelly A., Jones M., O'Mahony T., Byrne G., 2007, *Selecting environmental indicator for use in strategic environmental assessment*, Environ. Impact Asses., 27 (2), 161–175, http://dx.doi.org/10.1016/j.eiar.2006.10.006.

Dortch Q., Whitledge T. E., 1992, *Does nitrogen or silicon limit phytoplankton production in the Mississippi River plume and nearby regions?*, Cont. Shelf Res., 12 (11), 1293–1309, http://dx.doi.org/10.1016/0278-4343(92)90065-R.

Elser J. J., Bracken M. E. S., Cleland E. E., Grune D. S., Harpole W. S., Hillebrand H., Ngai J. T., Seabloom E. W., Shurin J. B., Smith J. E., 2007, *Global analysis of nitrogen and phosphorus limitation of primary producers in freshwater, marine and terrestrial ecosystems*, Ecol. Lett., 10 (12), 1135–1142, http://dx.doi.org/10.1111/j.1461-0248.2007.01113.x.

Furnas M. J., 1990, *In situ growth rates of marine phytoplankton: approaches to measurement, community and species growth rates*, J. Plankton Res., 12 (6), 1117–1151, http://dx.doi.org/10.1093/plankt/12.6.1117.

Hajdu S., Höglander H., Larsson U., 2007, *Phytoplankton vertical distributions and composition in Baltic Sea cyanobacterial blooms*, Harmful Algae, 6 (2), 189–205, http://dx.doi.org/10.1016/j.hal.2006.07.006.

Hallegraef G. M., Bolch C. J. S., Hill D. R. A., Jameson I., Leroi J. M., McMinn A., Murray S., de Salas M. F., Saunders K. M., 2010, *Algae of Australia: phytoplankton of temperate coastal waters*, CSIRO Publ., Melbourne, 432 pp.

Hansen H., Koroleff F., 2007, *Determination of nutrients*, [in:] *Methods of seawater analysis*, K. Grasshoff, K. Kremling & M. Ehrhardt (eds.), Wiley-VCH Verlag GmbH, Weinheim, 41–73, http://dx.doi.org/10.1002/9783527613984.ch10.

Harris G. P., 1986, *Phytoplankton ecology: structure, function and fluctuation*, Chapman & Hall, New York, 384 pp., http://dx.doi.org/10.1007/978-94-009-4081-9.

Hecky R. E., Kilham P., 1988, *Nutrient limitation of phytoplankton in freshwater and marine environments: A review of recent evidence on the effects of enrichments*, Limnol. Oceanogr., 33 (4, Pt. 2), 796–822, http://dx.doi.org/10.4319/lo.1988.33.4_part_2.0796.

Huertas I. E., Rouco M., López-Rodas V., Costas E., 2011, *Warming will affect phytoplankton differently: evidence through a mechanistic approach*, Proc. Roy. Soc. B: Biol. Sci., 278 (1724), http://dx.doi.org/10.1098/rspb.2011.0160.

Jennings J. C., Gordin L. I., Nelson D. M., 1984, *Nutrient depletion indicates high primary productivity in the Weddell Sea*, Nature, 309, 51–54, http://dx.doi.org/10.1038/309051a0.

Ji R., Chen C., Franks P. J. S., Townsend D. W., Durbin E. G., Beardsley R. C., Lough R. G., Houghton R. W., 2006, *Spring phytoplankton bloom and associated lower trophic level food web dynamics on Georges Bank: 1-D and 2-D model studies*, Deep-Sea Res. Pt. II, 53 (23–24), 2656–2683, http://dx.doi.org/10.1016/j.dsr2.2006.08.008.

Justic, D., Rabalais N. N., Turner R. E., 1995, *Stoichiometric nutrient balance and origin of coastal eutrophication*, Mar. Pollut. Bull., 30 (1), 41–46, http://dx.doi.org/10.1016/0025-326X(94)00105-I.

Kingston M. B., 2009, *Growth and motility of the diatom Cylindrotheca closterium: implications for commercial applications*, J. North Carolina Acad. Sci., 125, 138–142.

Lagus A., Suomela J., Weithoff G., Heikkila K., Helminen H., Sipura J., 2004, *Species-specific differences in phytoplankton responses to N and P enrichments and the N:P ratio in the Archipelago Sea, northern Baltic Sea*, J. Plankton Res., 26 (7), 779–798, http://dx.doi.org/10.1093/plankt/fbh070.

Legendre L., Demers S., 1984, *Towards dynamic biological oceanography and limnology*, Can. J. Fish. Aquat. Sci., 41, 2–19, http://dx.doi.org/10.1139/f84-001.

Lessard E. J., Merico A., Tyrrell T., 2005, *Nitrate: phosphate rations and Emiliania huxleyi blooms*, Limnol. Oceanogr., 50 (3), 1020–1024, http://dx.doi.org/10.4319/lo.2005.50.3.1020.

Leterme S. C., Edwards M., Seuront L., Attrill M. J., Reid P. C., John A. W. G., 2005, *Decadal basin-scale changes in diatoms, dinoflagellates, and phytoplankton colour across the North Atlantic*, Limnol. Oceanogr., 50 (4), 1244–1253, http://dx.doi.org/10.4319/lo.2005.50.4.1244.

Leterme S. C., Ellis A. V., Mitchell J. G., Buscot M. J., Pollet T., Schapira M., Seuront L., 2010, *Morphological flexibility of Cocconeis placentula (Bacillariophyceae) nanostructure to changing salinity levels*, J. Phycol., 46 (4), 715–719, http://dx.doi.org/10.1111/j.1529-8817.2010.00850.x.

Leterme S. C., Prime E., Mitchell J. G., Brown M. H., Ellis A. V., 2013, *Diatom adaptability to environmental change: a case study of two Cocconeis species from high salinity areas*, Diatom Res., 28 (1), 29–35, http://dx.doi.org/10.1080/0269249X.2012.734530.

Leterme S. C., Seuront L., Edwards M., 2006, *Differential contribution of diatoms and dinoflagellates to phytoplankton biomass in the NE Atlantic Ocean and the North Sea*, Mar. Ecol.-Prog. Ser., 312, 57–65, http://dx.doi.org/10.3354/meps312057.

Li A., Stoecker D. K., Coats D. W., 2000, *Spatial and temporal aspects of Gyrodinium galatheanum in Chesapeake Bay: distribution and mixotrophy*, J. Plankton Res., 22 (11), 2105–2124, http://dx.doi.org/10.1093/plankt/22.11.2105.

Li A., Stoecker D. K., Coats D. W., Adam E. J., 1996, *Ingestion of fluorescently-labeled and phycoerythrin-containing prey by photosynthetic dinoflagellates*, Aquat. Microb. Ecol., 10 (2), 139–147, http://dx.doi.org/10.3354/ame010139.

Lips I., Lips U., 2010, *Phytoplankton dynamics affected by coastal upwelling events in the Gulf of Finland in July–August 2006*, J. Plankton Res., 32 (9), 1269–1282, http://dx.doi.org/10.1093/plankt/fbq049.

Lourey M. J., Trull T. W., 2001, *Seasonal nutrient depletion and carbon export in the Subantarctic and Polar Frontal Zones of the Southern Ocean, south of Australia*, J. Geophys. Res., 106 (C12), 31463–31488, http://dx.doi.org/10.1029/2000JC000287.

Margalef R., 1975, *Assessment of the effects on plankton*, [in:] *Marine pollution and marine waste disposal*, Proc. 2nd Int. Cong., San Remo, 17–21 December, 1973, E. A. Pearson & E. De Fraja Frangipane (eds.), Pergamon Press, Oxford, New York, Toronto, Sydney, Paris, Braunschweig, 487 pp.

Middleton J. F., Bye J. A. T., 2007, *A review of the shelf-slope circulation along Australia's southern shelves: Cape Leeuwin to Portland*, Prog. Oceanogr., 75 (1), 1–41, http://dx.doi.org/10.1016/j.pocean.2007.07.001.

Pattiaratchi C., Newgard J., Hollings B., 2006, *Physical oceanographic studies of Adelaide coastal waters using high resolution modelling, in-situ observations and satellite techniquest – Sub Task 2 Final Technical Report*, 20, ACWS Tech. Rep.

PIRSA Report, 2013, *Fish and dolphin mortalities in South Australia*, 75 pp.

Redfield A. C., Ketchum B. H., Richards F. A., 1963, *The influence of organisms on the composition of sea water*, [in:] *The sea*, Interscience, New York, 26–77.

Rensel J. E., 1993, *Severe blood hypoxia of Atlantic salmon Salmosalar exposed to the marine diatom Chaetoceros concavicornis*, [in:] *Toxic phytoplankton blooms in the sea*, Proc. 5th Int. Conf. 'Toxic Marine Phytoplankton', Elsevier, New York, 625–630.

Riegmann R., Stolte W., Noordeloos A., Slezak D., 2000, *Nutrient uptake and alkaline phosphatase EC 3:1:3:1 activity of Emiliania huxleyi (Prymnesiophyceae)*, J. Phycology, 36 (1), 87–96, http://dx.doi.org/10.1046/j.1529-8817.2000.99023.x.

Rimet F., Bouchez A., 2012, *Biomonitoring river diatoms: implications of taxonomic resolution*, Ecol. Indic., 15 (1), 92–99, http://dx.doi.org/10.1016/j.ecolind.2011.09.014.

Round F. E., 1981, *The ecology of algae*, Cambridge Univ. Press, Cambridge, 653 pp.

Sanders R. W., Porter K. G., 1988, *Phagotrophic phytoflagellates*, Adv. Microb. Ecol., 10, 167–192, http://dx.doi.org/10.1007/978-1-4684-5409-3_5.

Smayda T. J., 1990, *Novel and nuisance phytoplankton blooms in the sea: evidence for a global epidemic*, [in:] *Toxic marine phytoplankton*, E. Granéli, B. Sunström, L. Edler & D. M. Anderson (eds.), Elsevier Sci. Ltd., New York, 554 pp.

Stoecker D. K., Li A., Coats D. W., Gustafson D., Nannen M. K., 1997, *Mixotrophy in the dinoflagellate Prorocentrum minimum*, Mar. Ecol.-Prog. Ser., 152, 1–12.

Suikkanen S., Laamanen M., Huttunen M., 2007, *Long-term changes in phytoplankton communities of the open northern Baltic Sea*, Estuar. Coast. Shelf Sci., 71 (3–4), 580–592, http://dx.doi.org/10.1016/j.ecss.2006.09.004.

Takeda S., 1998, *Influence of iron availability on nutrient consumption of diatoms in the oceanic water*, Nature, 393, 774–777, http://dx.doi.org/10.1038/31674.

Tanaka I., 1984, *Distribution of chlorophyll a at the frontal region formed in the water adjacent to Funka Bay, Hokkaido*, Bull. Japanese Soc. Fish. Oceanogr., 46, 9–17.

Tomas C. R., 1997, *Identifying marine phytoplankton*, Acad. Press, San Diego, 855 pp.

Welschmeyer N. A., 1994, *Fluorometric analysis of Chlorophyll-a in the presence of Chlorophyll-b and pheopigments*, Limnol. Oceanogr., 39, 1985–1992, http://dx.doi.org/10.4319/lo.1994.39.8.1985.

Zar J. H., 1999, *Biostatistical analysis*, Prentice-Hall, Upper Saddle River, 663 pp.