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Tracking the Response of Phytoplankton following Gyttja Disturbance: a Mesocosm Field Study in Myall Lakes, New South Wales, Australia

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Abstract This study determined whether artificially mixing gyttja, an organic sediment that contains high levels of NH4, with its overlying waters, affected phytoplankton abundance and species composition in Myall Lake (NSW, Australia). A series of mesocosms was employed, with three mesocosms being designated as controls, i.e. no gyttja mixing, and three others termed impact mesocosms, i.e. in which gyttja was mixed with the overlying waters. Sampling was undertaken during a 5 day period in sediment disturbance, and phytoplankton community variables were recorded at seven intervals, i.e. just prior to disturbance and 30 minutes, 3 hours, 1, 2, 3, 4 and 5 days after gyttja disturbance. Comparisons of these community variables among treatments and over time convincingly demonstrated that overall phytoplankton abundance rose from 20,000 cells/mL just prior to disturbance to between 30,000 cells/mL and 55,000 cells/mL 2 to 4 days after gyttja mixing. This rise in abundance was attributable to a substantial increase in the cyanophycea over the same period. In contrast to the cyanophyceae, the abundance of bacillariophyceae increased sharply following disturbance from 150 to >1000 cell/mL and did not exceed 1000 cell/mL for the duration of the experiment. This supported the hypothesis that gyttja mixing does introduce benthic microalgae into the water column. Sediment disturbance caused differences in species composition in time, with cyanobacteria being mostly influenced taxa. Each period of disturbance between mesocosm have different assemblages of species.
Keywords Phytoplankton; Sediment disturbance; Mesocosm; Community structure

1 Introduction

In shallow coastal lakes, such as the Myall Lake in Australia, wind, tidal action and anthropogenic activities, such as boating or jetskiing, can cause water turbulence which results in mixing of the water column and occasionally resuspension of the bottom sediments into overlying waters. Such mixing will therefore act to increase the water turbidity, which in turn decreases the attenuation of light. Mixing of the water column with bottom sediments can also increase nutrient availability as a result of nutrient release from the substrates. Changes in light attenuation and nutrient availability have been recorded to have a significant effect on the abundance, biomass and species composition of phytoplankton in such coastal lakes (Carrick et al., 1993; Huisman et al., 1999; Kiorboe, 1993, Olrik and Nauwerek, 1993). For example, Carrick et al., 1993) showed that intermittent turbulence in a small lake influences phytoplankton biomass and species composition by directly resuspending phytoplankton cells in particular silicate cell type from the lake sediments.

The processes that occur during sediment resuspension have also been shown to be related to the presence of blooms of phytoplankton in certain environments (Hansson et al., 1994; Huisman et al., 1999; Garstecki et al., 2002). For example, phytoplankton blooms occur mainly during the low mixing periods in neap tides of South San Francisco Bay, a large marine embayment (Cloern, 1991).

Although there is some understanding of the effect of mixing of the water column on phytoplankton biomass in estuaries and lakes (Huismann et al, 1999; Olrik et al, 1993; Lauria et al 1999), the changes in phytoplankton composition and abundance with water column mixing in coastal lakes are not well understood. Such information would be essential information for managers who are developing plans for management of such coastal lakes.

Myall Lake, in central New South Wales, is a shallow coastal lake that is subject to considerable water

turbulence and thus sediment re-suspension through mixing of the water column. The effects of sediment re-suspension are likely to be marked in this lake due to the presence of the NH4-rich sediment "gyttja", fine sediment which would presumably be particularly susceptible to re-suspension. Since the species composition of the phytoplankton in this lake are well understood, this lake would provide an ideal opportunity to determine the ways in which mixing of the water column and sediment re-suspension will affect the phytoplankton communities.

The present study deployed artificial mesocosms within a location in Myall Lakes to determine the effect of re-suspension of gyttja on phytoplankton cell abundance and species composition and to understand the relationship between water quality parameters and the abundance and composition of phytoplankton following a mixing event. The hypothesis tested in this study is that gyttja mixing directly introduces benthic microalgae into the water column, thereby altering the species composition of phytoplankton, (2) raised levels of NH4 produced by gyttja mixing stimulate growth of certain phytoplankton at different rates, and (3) the combination of the above will result in marked changes in the phytoplankton communities.

2 Materials and Methods
2.1 Study site
The study was carried out at Neranie Bay, which lies at the most northern part of the Myall Lake system in central NSW, Australia (Figure 1). This lake system is
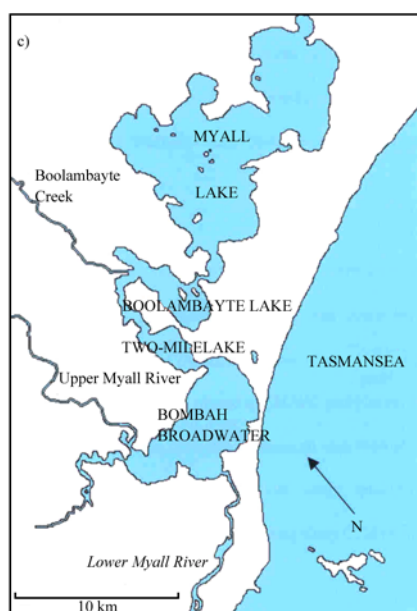

Figure 1 Location of study in Myall Lake on the Coast of NSW

typically <2 m in water depth and is supplied by the Myall River, in which the lower regions can be up to 8 m in depth (Atkinson et al., 1981). Although Myall Lake and the lower reaches of Myall River are subject to some tidal influence, fluctuations of average water depth 2.8 m are mainly attributed to the seasonal rainfall in this area (Thorn, 1965).

2.2 Mesocosms and sampling procedure
The study used 6 purpose-built mesocosms, which incorporated pieces of transparent; polycarbonate sheeting that were joined together with lengths of timber and wood screws (Figure 2). The circumference of each mesocosm was 3.1 m and the diameter was approximately 1 m.
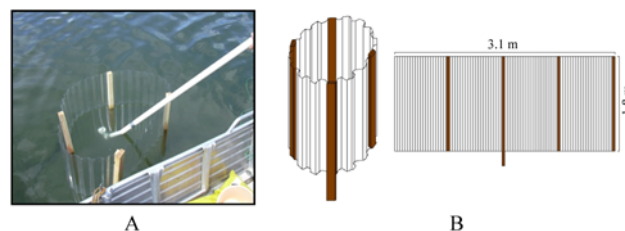

Figure 2 Experimental mesocosm: A: water sample collection, and B: structure and dimensions of the mesocosms (polycarbonate sheeting with wood framing) (from Sampaklis, 2003)

An *in situ* experiment was carried out between 6th and 13th February 2003 at Neranie Bay, which consisted of 3 control (CM) and 3 impacted (IM) mesocosms and a further three replicate (C) sites located outside but nearby to the mesocosms. All sites were located in areas that contained extensive areas of gyttja.

Water samples (containing phytoplankton) were collected from the water column using a PVC pipe with a U-pipe adaptor at six sites just prior to the installation of the mesocosms. At the same time, three water samples were collected from three sites nearby. Within 1 hour of placing the mesocosms, the top 20 cm of gyttja in the IM was manually mixed using a garden rake (termed disturbance) for a 5 min period of mixing. Water samples were collected using the PVC pipe and U-pipe adaptor from all nine sites at time intervals of 30 min, 3 h and 1, 2, 3, 4 and 5 days following the disturbance.

From each sample, water quality (DO, Temperature, pH and salinity) was measured and 30 ml water samples for available nutrients (orthophosphate, NO$_x$,

NH$_4$ and SiO$_4$) were filtered and immediately stored on ice before being frozen for later analysis.

Each water sample was then placed in 200 ml containers and preserved with Acidified Lugols solution. One hundred ml of the Lugols fixed sample was then settled out in the laboratory for 48 hours using a 100 mL graduated cylinder. After 48 hours, 90 ml from the top layer of water in the settling tube was removed and the remaining 10 ml was placed into a vial, which was capped and kept in the dark prior to counting.

Examination of the phytoplankton samples used the Lund cell method, which involved counting 3 traverses for each sample. An upright light microscope with white light achromatic objective of 400× magnification was used to identify and count the phytoplankton cells. The cell abundances for each species (expressed as number of cells per mL) and thus the cell abundances for each of the major groups and of the total sample were determined using the formula as described by Hotzel and Croome (1999).

2.3 Data analysis
A series of one-way Analysis of Variances (ANOVAs) was used to determine whether the total cell abundance and abundance of the Cyanophyceae, Bacillariophyceae, Chlorophyceae and the overall total number of species differed significantly among treatments, i.e. control, control mesocosms and impact mesocosms (SPSS, Inc). Thus, ANOVA's were run separately for each time period, i.e. 30 min, 3 h, and 1, 2, 3, 4 and 5 (day) after disturbance, with treatment being the main factor. If ANOVA detected a significant difference, the *a posteriori* LSD test was used to determine where any significance differences revealed.

Non-metric multi-dimensional scaling (MDS) ordinations were employed on log-transformed (n + 1) data to determine whether the species composition of the phytoplankton differed among times and treatments (PRIMER5, Clarke and Gorley, 2001). Thus, the log-transformed abundance data for each phytoplankton species were calculated for the three treatments in each time interval. These data were then subjected to the Bray-Curtis measure and the resultant similarity matrices ordinated. The stress levels on all plots were < 0.2 and thus provide an accurate representation

of the relationships between the data (Clarke and Warwick, 1994).

3 Results
3.1 Effects on water quality and nutrient concentrations
During the 5 day mesocosm experiment in Neranie Bay, there was no rainfall, salinity was constant at 3 ppt and water temperature was 24-26 ℃ . Due to a non-functioning oxygen probe during the early part of the study, Dissolved Oxygen (DO) measurements were only available from Day 2 onwards; they showed mean DO levels of >8.8 mg/L in the control area, >9 mg/L in the control mesocosms and a marked increase in DO from 6.8 mg/L on Day 2 to 10.1 mg/L on Day 5 in the impact mesocosms. The lack of DO data during the first 2 days of this mesocosm experiment was addressed by Sampaklis (2003), who tested the effects of mixing known amounts of gyttja with known volumes of lake water; when the volume of gyttja in mixed samples was 20%, DO levels dropped to about 6 mg/L but recovered to 8 mg/L within 3 days. Other water quality data in which effects were noted (turbidity and pH) are plotted in Figure 3.

Initial turbidity readings in the study area (prior to any gyttja disturbance) were low (< 2 NTU) (Figure 3a). In the case of the control sites (no mesocosms), the turbidity never exceeded 2 NTU throughout the experiment. The installation of the control mesocosms (CMs) into the sediments resulted in a short-term minor increase in turbidity to 4-6 NTU, followed by a decline to ~ 3 NTU within one day. Thirty minutes after gyttja in the IMs was mixed with overlying water, turbidity levels were 18-24 NTU; they declined to ~ 6.5 NTU after 1 day and stayed at or below this level for the remainder of the experiment. A one-way ANOVA showed a significant difference in turbidity among treatments at all times following disturbance, with turbidity in IMs consistently higher than both control sites and the CMs up until Day 4 (Table 1).

Prior to disturbance, pH levels in the study area were ~ 8.5 and remained between 8 and 9 throughout in the control mesocosms (Figure 3b). The impact of mixing gyttja into overlying water was immediate, with pH levels dropping from 8.5 to 6.5, but steadily increasing thereafter to a near normal pH levels of ~ 8 on Day 5. The one-way ANOVA result showed a significant difference in pH between treatments for all periods of
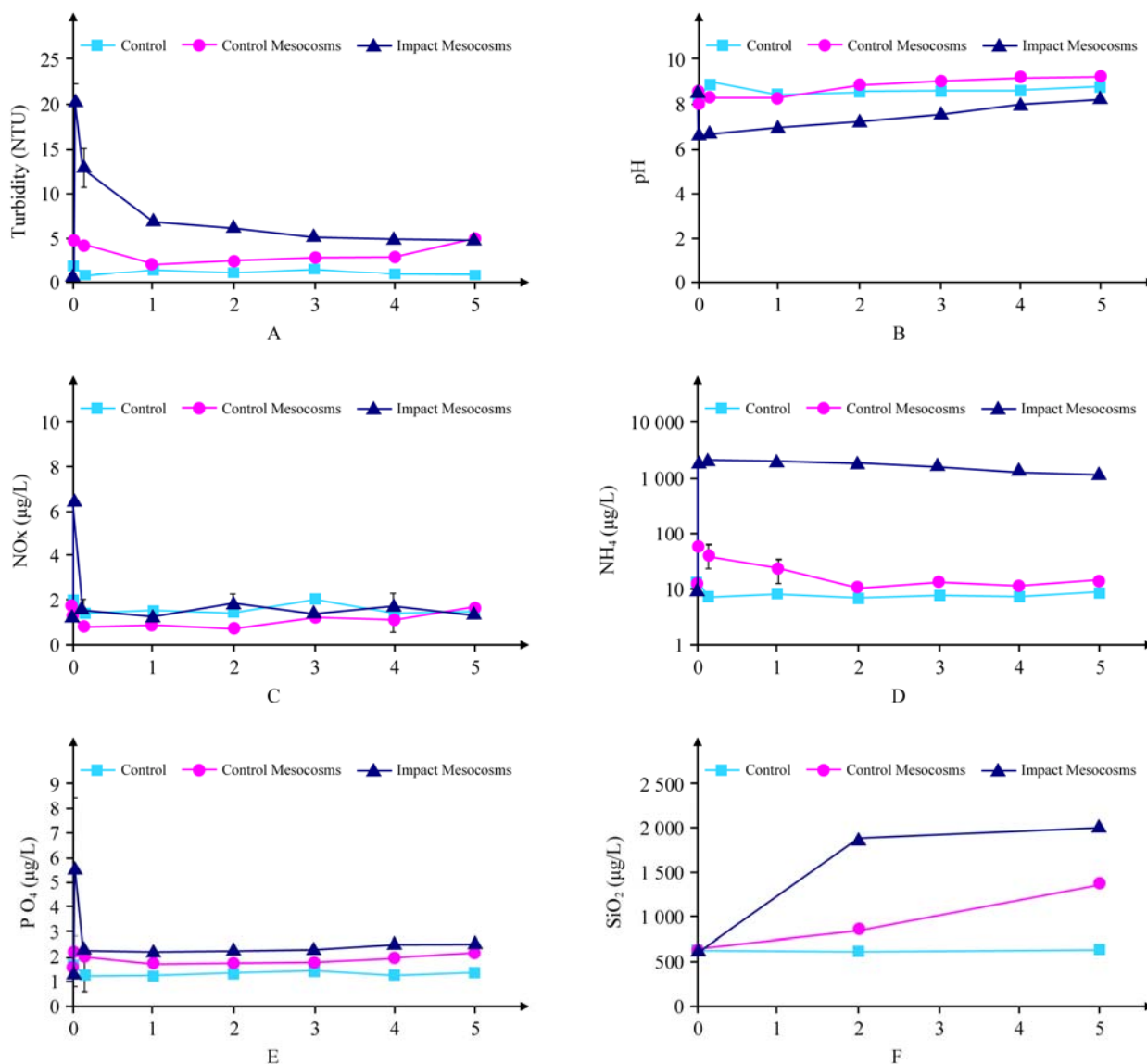
Figure 3 Turbidity, pH, NO_X, NH_4, PO_4 and SiO_2 concentrations (mean ± SE; n = 3) for the three treatments prior to and following mesocosm installation and sediment disturbance. In many cases, the SE bars are very small and thus not visible

disturbance, with pH values in CMs being higher than in control sites and IMs (Table 1).

Nitrate plus nitrite (NO_x) concentrations were low and < 2 µg/L for all samples except for a slight increase immediately following gyttja disturbance in the IMs (Figure 3c). Despite this short-lived effect, there was no significant difference in NO_x levels among treatments, during the entire experiment (Table 1).

Water column concentrations of NH_4^+ at control sites were low and < 20 µg/L prior to and following the deployment of the mesocosms (Figure 4d). While CMs experienced a minor increase in NH_4^+ (about 50 µg/L) following deployment, IMs showed a very large

injection of NH_4^+ (≈ 2000 µg/L) into the water column, with levels remaining above 1000 µg/L for the duration of the experiment. ANOVA detected a significant difference with treatment; LSD post hoc tests showed that concentrations of NH_4^+ in IMs were always significantly greater than in the other two treatments (Table 1).

Mean concentrations of PO_4 were low (1-6 µg/L) and near detection levels (1 µg/L) throughout the experiment (Figure 3e). PO_4 mirrored trends in NO_x levels, which increased slightly in the IMs upon sediment disturbance. Although levels were low, ANOVAs indicated significant differences between

Table 1 Mean squares and their significance values derived from one-way ANOVA of turbidity, pH, NO_x, PO_4 and NH_4 between treatments for each time sampled. NH_4 data were $Log_{10}(n+1)$ transformed. N.B. * = $p<0.05$; ** = $p<0.01$; *** = $p<0.001$. Bolded LSD results are shown where treatments are significantly different

Time interval	df	Sources of variation	Turbidity	pH	NOx	NH₄	PO₄
0	2	Treatment	0.01ns	0.00ns	0.3ns	0.01ns	0.05ns
	6	Residual	0.03	0.00	0.19	0.01	0.04
30 mins	2	Treatment	299.29***	2.52***	23.09ns	4.54***	14.51ns
			IM>C,CM	**C>CM>IM**		**IM>CM>C**	
	6	Residual	4.19	0.04	14.39	0.05	7.85
3 hrs	2	Treatment	117.87***	3.62***	0.55ns	4.93***	0.96***
			IM>C,CM	**C>CM>IM**		**IM>CM>C**	**IM>CM>C**
	6	Residual	4.85	0.06	0.14	0.05	0.01
1 day	2	Treatment	25.77*	1.86*	0.30ns	3.63***	0.68***
			IM>C,CM	**CM,C>IM**		**C,IM>CM**	**IM>CM>C**
	6	Residual	0.75	0.06	0.15	0.14	0.00
2 days	2	Treatment	22.47***	2.34***	1.11ns	5.51***	0.72***
			IM>CM>C	**CM,C>IM**		**IM>C,CM**	**IM>CM>C**
	6	Residual	0.31	0.03	0.17	0.01	0.01
3 days	2	Treatment	12.20***	1.75***	0.42ns	4.99***	0.59***
			IM>CM>C	**CM>C>IM**		**IM>C,CM**	**IM>CM>C**
	6	Residual	0.37	0.02	0.22	0.01	0.01
4 days	2	Treatment	12.20**	107**	0.42ns	4.83***	1.21***
			IM>C,CM	**CM>C>IM**		**IM>C,CM**	**IM>CM>C**
	6	Residual	0.52	0.03	0.43	0.01	0.01
5 days	2	Treatment	15.57**	0.70**	0.03ns	4.12***	1.11***
			IM,CM>C	**CM>C>IM**		**IM>C,CM**	**IM>CM>C**
	6	Residual	0.81	0.05	0.12	0.01	0.01

treatments (IM>CM>C), at all times observed, except at 30 min post disturbance (Table 1).

Available data for silicate (SiO_2) is limited to initial conditions and 2 and 5 days after sediment disturbance (Figure 3d). Silicate levels at control sites were ~ 550 µg/L prior to and following the gyttja mixing event. Silicate levels rose markedly over the 5 day period in both the control mesocosms and the impact mesocosms, with the IMs and CMs exhibiting ~ 2000 µg/L and 1300 µg/L, respectively, on Day 5 (Figure 3f).

3.2 Cell abundance and diversity
Total cell abundance in surface waters (0-0.5 m) at the start of the experiment was 20,000-30,000 cells/mL and remained in this range until Day 2, when the IMs showed a significant increase in cell number (Figure 4a, Table 2). By Day 4, cell abundance in the IMs peaked and exceeded 55,000 cells/mL while, other treatments exhibited mean maxima of <30,000 cells/mL and no net growth in cell abundance. One-way ANOVA, followed by post hoc LSD tests,

indicated significantly higher cell densities in IMs (IM>CM=C) on Days 2, 3, 4 and 5 (Table 2).

Temporal trends in abundance of Cyanophyceae were similar to that shown for total cell abundance, as cyanophytes were the dominant cell types present (numerically >65%) and were the taxa that exhibited the strongest growth response following gyttja disturbance (Figure 4b). As with total cells, one-way ANOVA of Cyanophyceae abundance demonstrated significant differences among treatments at Days 2-5 (IM>CM=C, Table 2).

Although abundance of Bacillariophyceae was below 150 cells/mL at the commencement of the experiment and in all CMs and Control samples throughout the experiment, numbers in the IMs just 3 hours after the disturbance of gyttja were >1000 cell/mL (Figure 4c). The number of microalgal taxa increased dramatically shortly after disturbance, with most new taxa being of benthic origin, e.g. *Achnanthes*, *Achnanthidium*, *Amphora*, *Cocconeis*, *Craticula*, *Cymbella*, *Fragilaria* and *Melosira*. After 24 hours, the abundance of
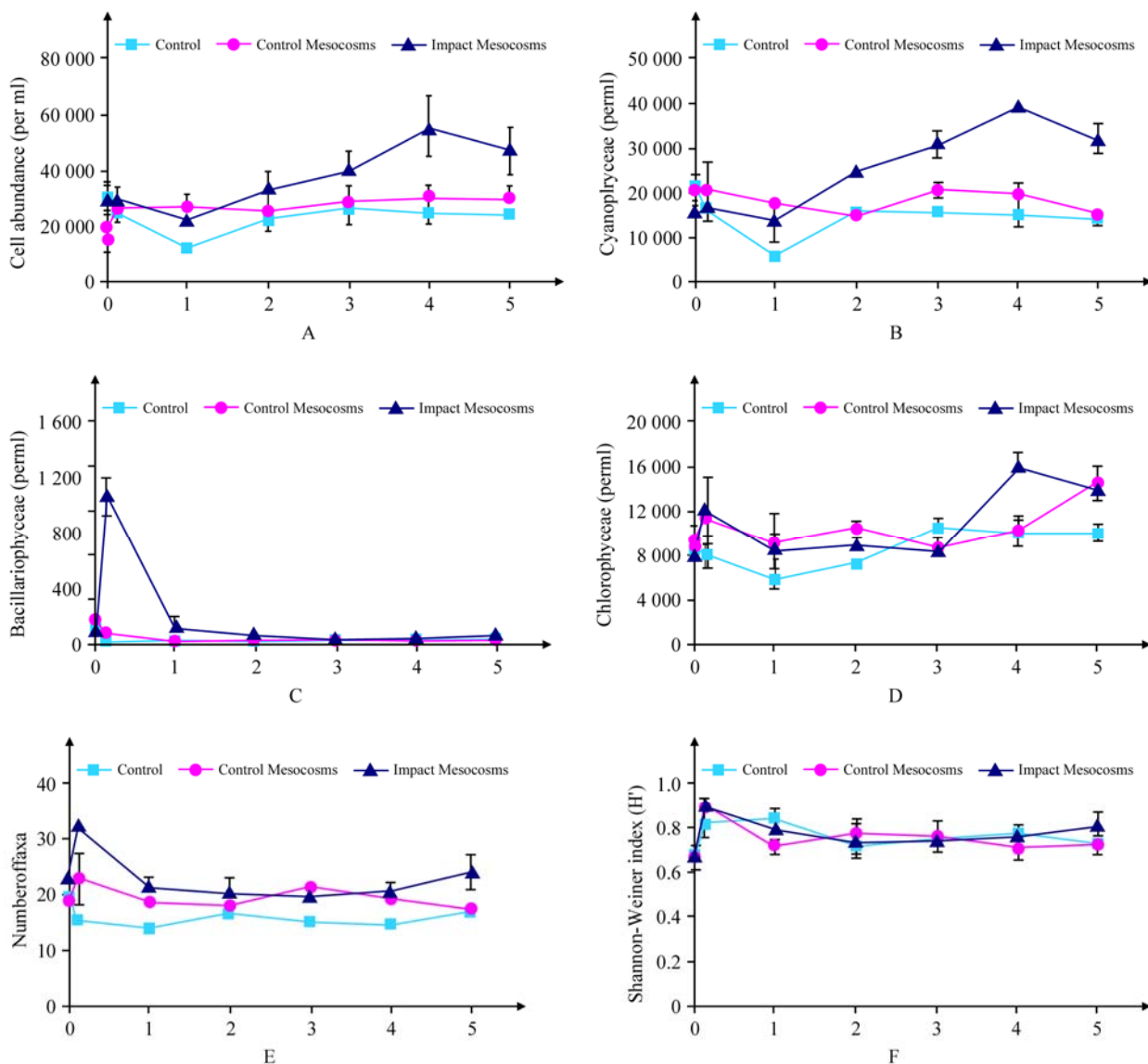
Figure 4 Abundance of A: all cells, B: Cyanophyceae, C: Bacillariophyceae and D: Chlorophyceae, and E: number of taxa observed and F: Shannon-Wiener Index (H') (mean ±SE, n=3). In some cases, the error bars are too small to be visible

diatoms was reduced to <200 cells/mL and dropped further to pre-mixing densities for the remainder of the experiment. The abundance of Bacillariophyceae differed significantly between mesocosm treatments but only for a short period following disturbance (30 min and 1 day), with IMs exhibiting greater diatom abundance than the control treatments.

There was little apparent difference in abundance of Chlorophyceae between control and impact mesocosms up to Day 4, when Chlorophyceae cell numbers increased by a factor of 2 in the IMs. The dominant taxa of Chlorophyceae in the IMs 4 days following sediment disturbance was *Gloeocystis,* which contributed

18% of total cell abundance. The result of one-way ANOVAs showed that abundance of Chlorophyceae was significantly different at 30 min, 4 and 5 days after sediment disturbance, with IMs having a greater abundance of Chlorophyceae than control treatments at Day 4 (Table 2). Chlorophyceae in CMs also showed a significant increase in abundance, but not until Day 5 (Figure 4 d).

There were 110 microalgal taxa identified in the 120 samples collected during the mesocosm study. Of these, Chlorophyceae and Bacillariophyceae were represented by 55 and 35 taxa, respectively. The remaining taxa fell with the following Classes:

Table 2 Mean squares and their significance values derived from ANOVA of total cell abundance, the abundances of Cyanophyceae, Bacillariophyceae and Chlorophyceae (Log$_{10}$(n+1) transformed), taxonomic richness and Shannon-Wiener index, among treatments, at each sampling time. * = $p<0.05$; ** = $p<0.01$; *** = $p<0.001$. Bolded LSD results are shown where treatments are significantly different

Time interval	df	Sources of variation	Total cell	Cyanophyceae	Bacillariophyceae	Chlorophyceaea	Taxonomic richness	Shannon-Weiner Index
0	2	Treatment	0.003ns	0.011ns	0.033ns	0.002ns	1.00ns	0.01ns
	6	Residual	0.006	0.009	0.075	0.009	18.00	0.001
30 mins	2	Treatment	0.012ns	0.205***	4.104***	0.204*	58.11**	0.010ns
				C,CM>IM	**IM>CM>C**	**C,CM>IM**	**IM>CM>C**	
	6	Residual	0.104	0.005	0.124	0.032	15.0	0.006
3 hrs	2	Treatment	0.007ns	0.002ns	6.904***	0.021ns	218.11***	0.003*
					IM>CM>C		**IM>CM,C**	**IM,CM>C**
	6	Residual	0.42	0.038	0.038	0.066	23.33	0.002
1 day	2	Treatment	0.099ns	0.190ns	3.166*	0.027ns	41.33**	0.003*
					CM>IM,C		**IM,CM>C**	**IM,CM>C**
	6	Residual	0.053	0.057	0.203	0.061	3.56	0.000
2 days	2	Treatment	0.024**	0.044**	1.288ns	0.019ns	10.33ns	0.002ns
			IM>CM,C	**IM>CM,C**				
	6	Residual	0.002	0.002	0.482	0.007	9.22	0.006
3 days	2	Treatment	0.025*	0.065**	0.644ns	0.007ns	32.33**	0.004ns
			IM,CM>C	**IM>CM,C**			**IM,CM>C**	
	6	Residual	0.003	0.005	0.443	0.007	2.22	0.005
4 days	2	Treatment	0.107***	0.153**	0.254ns	0.047*	30.00**	0.001ns
			IM>CM,C	**IM>CM,C**		**IM,CM>C**	**IM>CM>C**	
	6	Residual	0.003	0.008	0.866	0.009	2.58	0.002
5 days	2	Treatment	0.063***	0.117**	1.138ns	0.024*	49.00*	0.001ns
			IM>CM>C	**IM>CM,C**		**IM,CM>C**	**IM>CM,C**	
	6	Residual	0.002	0.006	0.604	0.004	9.67	0.001

Cyanophyceae, Dinophyceae, Cryptophyceae, Chrysophyceae and Euglenophyceae.

The highest mean taxonomic richness (32 genera) was observed in samples from IMs 2 hrs following sediment disturbance (Figure 4e). This was largely due to the temporary appearance of benthic diatoms as a result of gyttja injection into overlying water. One-way ANOVAs detected significant differences in taxonomic richness on most of the sampling occasions, with the LSD tests confirming that IMs were significant greater in taxonomic richness than control treatments. Although the number of taxa observed was often higher in the IMs than the control treatments, the Shannon-Wiener Index indicated a significant difference only in samples collected 2 hours following gyttja mixing (Table 2, Figure 4e).

3.3 Phytoplankton assemblages
Dominant taxa within treatments at each sampling time are shown in Table 3 and include cyanophytes (largely *Coelasphaerium* and *Merismopedia*) and green microalgae (mostly *Gloeocystis* and *Coelastrum*). Cyanophytes were numerically dominant in all treatment groups, during the entire experiment.

Patterns in phytoplankton assemblages are depicted in the series of nMDS plots in Figure 5. They show stress levels below 0.10 and thus are reasonable representations of the relationships between assemblages in different treatments for each time sampled. On all sampling occasions after IM gyttja disturbance, the treatments yielded significantly different phytoplankton assemblages ($p<0.05$). The impact of mixing was clearly evident 30 min after mixing; at this time, samples included suspended benthic diatoms. SIMPER results for samples collected 30 min and 2 hours after mixing show that the taxa contributing most to the differences between control sites and IMs were the diatom genera *Nitzschia, Navicula, Melosira, Pinnularia* and *Cocconeis* (Table 4), all of which are known to include benthic species. The ordination plots of phytoplankton assemblages on Days 2-5 showed

Table 3 The three most numerous taxa (mean %) in each treatment (N=3), at each sampling time

Time	Control		Control Mesocosm		Impacted Mesocosm	
Before mixing (0)	Gloeocystis	18%	Merismopedia	24%	Merismopedia	38%
	Coelasphaerium	15%	Gloeocapsa	22%	Gloeocystis	19%
	Chroococcus	15%	Gloeocystis	14%	Coelasphaerium	15%
30 mins	Merismopedia	32%	Coelasphaerium	39%	Merismopedia	37%
	Gloeocystis	26%	Merismopedia	23%	Coelasphaerium	30%
	Coelasphaerium	16%	Gloeocystis	17%	Gloeocystis	12%
3 hrs	Coelasphaerium	29%	Merismopedia	30%	Coelastrum	22%
	Merismopedia	27%	Gloeocystis	13%	Merismopedia	19%
	Gloeocystis	14%	Coelastrum	11%	Coelasphaerium	16%
1 Day	Coelastrum	17%	Merismopedia	40%	Gloeocystis	26%
	Merismopedia	16%	Gloeocystis	30%	Merismopedia	25%
	Gloeocystis	12%	Aphanocapsa	9%	Coelasphaerium	19%
2 Days	Merismopedia	28%	Coelasphaerium	31%	Coelasphaerium	44%
	Coelasphaerium	25%	Merismopedia	23%	Merismopedia	19%
	Gloeocystis	16%	Palmellopsis	13%	Gloeocystis	9%
3 Days	Coelasphaerium	31%	Merismopedia	36%	Coelasphaerium	43%
	Merismopedia	20%	Coelasphaerium	27%	Gloeocystis	23%
	Gloeocystis	17%	Gloeocystis	14%	Aphanocapsa	12%
4 Days	Coelasphaerium	25%	Coelasphaerium	34%	Coelasphaerium	31%
	Merismopedia	16%	Merismopedia	33%	Gloeocystis	18%
	Tetraspora	5%	Coelastrum	8%	Merismopedia	17%
5 Days	Merismopedia	31%	Gloeocystis	32%	Coelasphaerium	26%
	Gloeocystis	28%	Coelasphaerium	24%	Merismopedia	20%
	Coelasphaerium	18%	Coelastrum	8%	Gloeocystis	15%

Table 4 ANOSIM pairwise tests and Similarity of Percentage (SIMPER) results for phytoplankton assemblages at each sampling time.
Bolded genera are more numerous in 1ˢᵗ treatment of listed pairs

	ANOSIM Pairwise Test			SIMPER Results
Pair	Global R	Sig. Level (%)	Diss. (%)	Taxa most responsible to dissimilarity
Before (0)	Before (0)	Before (0)	Before (0)	Before (0)
C vs CM	-0.333	100	24.93	Merismopedia 20%, Aphanocapsa 14% and Artosphira 9%
C vs IM	0.185	30	33.34	Merismopedia 12%, Palmellopsis 12%, Arthospira 10%
CM vs IM	0.074	40	34.93	Merismopedia 12%, Palmellopsis 11%, Arthospira 9%
30 minutes				
C vs CM	0.333	10	21.05	Coelasphaerium 26%, Aphanocapsa 14%, Merismopedia 14%
C vs IM	0.815	10	28.96	Coelasphaerium 21%, Merismopedia 15%, Gloeocystis 12%
CM vs IM	0.889	10	24.32	Coelasphaerium 18%, Merismopedia 16%, Gloeocystis 11%
3 hours				
C vs CM	0.222	30	23.69	Gloeothece 12%, Tetraspora 11%, Palmellopsis 9%
C vs IM	0.926	10	28.31	Coelastrum 10%, Coelasphaerium 9%, Palmellopsis 6%
CM vs IM	0.556	10	30.55	Gloeothece 8%, Coelastrum 6%, Tetraspora 6 %
1 day	1 day	1 day	1 day	1 day
C vs CM	0.407	10	53.43	Merismopedia 28%, Coelasphaerium 25%, Gloeocystis 15%
C vs IM	0.185	30	51.61	Merismopedia 28%, Coelasphaerium 22%, Gloeocystis 14%
CM vs IM	0.074	40	33.67	Merismopedia 22%, Coelasphaerium 20%, Gloeocystis 17%
2 days				
C vs CM	0.556	10	22.65	Coelasphaerium 21%, Palmellopsis 20%, Aphanocapsa 12%
C vs IM	0.519	20	24.93	Merismopedia 34%, Coelasphaerium 16%, Aphanocapsa 15%
CM vs IM	0.741	10	29.47	Merismopedia 31%, Aphanocapsa 18%, Coelasphaerium 15%
3 days	3 days	3 days	3 days	3 days
C vs CM	0.333	20	20.3	Coelastrum 10%, Palmellopsis 9%, Merismopedia 8 %
C vs IM	1	10	25.4	Coelastrum 14%, Merismopedia 11%, Tetraspora 9%
CM vs IM	0.556	10	18.5	Tetraspora 12%, Aphanocapsa 10%, Coelastrum 8%
4 days				
C vs CM	0.333	20	18.88	Tetraspora 14%, Palmellopsis 11%, Anabaena 7%
C vs IM	1	10	23.29	Palmellopsis 14%, Merismopedia 10%, Coelastrum 10%
CM vs IM	1	10	20.58	Palmellopsis 16%, Merismopedia 9 %, Coelastrum 12%
5 days				
C vs CM	0.259	20	19.28	Coelastrum 18%, Palmella 6%, Aphanocapsa 6%
C vs IM	1	10	21.58	Merismopedia 13%, Gloeocystis 11%, Coelasphaerium 7%
CM vs IM	1	10	24.48	Coelastrum 15%, Merismopedia 15%, Coelasphaerium 6%

that the points for each treatment formed relatively tight groups that were discrete from each other. This

corresponds to the period when the growth response of cyanophytes was most apparent (Figure 5b).
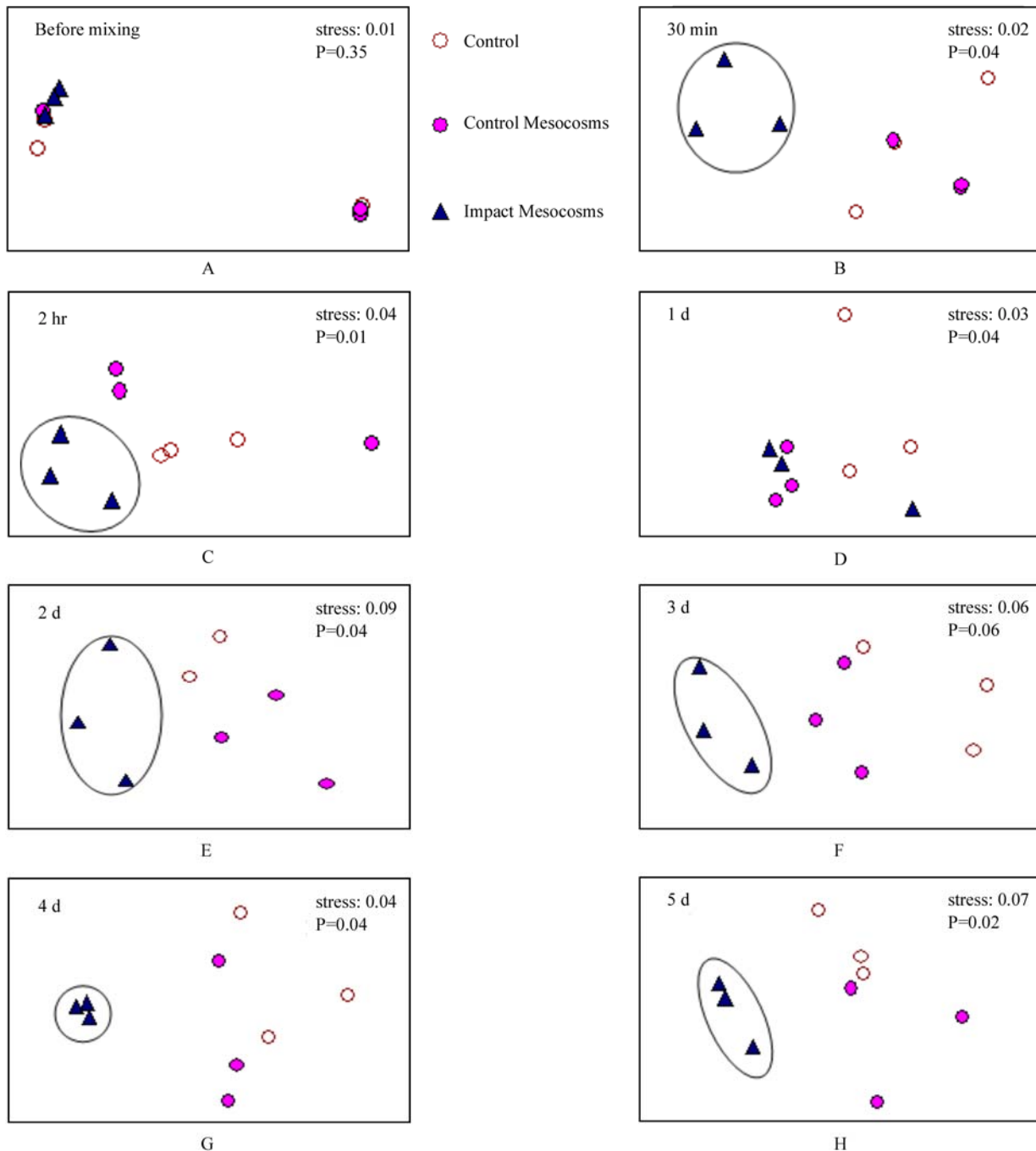

Figure 5 nMDS ordination plots of phytoplankton assemblages for the three treatments at each time sampled: A: before disturbance, B: 30 minutes after disturbance, C: 3 hours after disturbance, D: 1 day, E: 2 days, F: 3 days, G: 4 days and H: 5 days after disturbance

A one-way ANOSIM indicated an overall difference between treatments when all times were pooled (Global R = 0.414, P = 0.001). Due to the limited the number of samples representing each treatment at each sampling time (N=3), it was not possible to detect significant differences using pairwise ANOSIM

tests (Table 4). Thus, the magnitude of the R-statistic value is used as a guideline for ascertaining the extent of the differences between treatments at the different times. In this case, Global R values exceeding 0.8 are considered to represent a strong difference between pairs (30 min, 3 hr, 4 days and 5 days) and Global R

values of 0.5-0.8 to represent a moderate difference.

4 Discussion

4.1 Effects of sediment disturbance on water quality and nutrients

Disturbance of the gyttja layer resulted in the introduction of hydrous organic sediments and associated dead and living microalgae into overlying water within mesocosms. Physically disturbing the gyttja not only increased turbidity but also affected other water quality variables (e.g. minor decreases in pH and dissolved oxygen). pH decreased to about 6.5 but recovered gradually to normal levels within 5 days. Under severely reduced pH conditions, the availability of nitrogen and phosphorus can be affected (Wetzel, 1975; Fisher et al., 1992; Bartram and Balance, 1996). pH plays a role in mobilizing phosphorus from the sediment into the water column (Fisher and Wood, 2004).

The disturbance of gyttja introduced significant levels of NH_4^+ (~2000 µg/L) into overlying water, while NO_x levels, although slightly elevated, remained low (<6 µg/L). This was due to the highly organic nature of gyttja sediments. Bacterial utilization of oxygen creates anoxic, reducing conditions which hampers coupled nitrification-denitrification processes and results in NH_4^+ as the primary breakdown product of organic matter decomposition (Bronmark and Hansson, 1998; Scheffer, 2001).

Elevated SiO_3^- concentrations also followed sediment disturbance and continued to rise during the course of the 5 day experiment. The latter effect may be due to suspension of diatoms and subsequent degradation to silicate. Release of dissolved silicate from undisturbed sediments is largely dependent on remineralization of bio-silicates from dead diatom cells (Srithongouthai et al., 2003).

Sediments play an important role in phosphorus (P) cycling in aquatic systems (Bostrom et al., 1988; Berdalet et al., 1996; Caetano et al., 1997; Scheffer, 2001). Sediments can act as both sinks and sources of P (Bostrom et al., 1988; Clavero et al., 2000). In Myall Lake, gyttja and overlying charophytes (*Chara* and *Nitella*) serve primarily as sinks for P (Shilla et al., 2006; Siong et al., 2006). Phosphates within the gyttja of Myall Lake are highly bound and not readily available to phytoplankton in overlying waters (Siong

et al., 2006). Gyttja disturbance introduced only very small amounts of orthophosphate (PO_4^{-3}) into the water column, with concentrations of ~6 µg/L (oligotrophic level) appearing within 30 minutes of the mixing event. These levels dropped to ~2 µg/L within 24 hr. Data from two years of monitoring in Myall Lake show that TP levels are naturally low, and that P is the most limiting macronutrient for phytoplankton growth in the Myall Lakes (DIPNR, 2004).

4.2 Effects of gyttja disturbance on phytoplankton

Light availability, a major factor driving phytoplankton growth (Yentsch, 1980; Eilers and Peters, 1988; Gaevskii et al., 2000), decreased shortly after sediment disturbance due to an immediate increase in turbidity (>20 NTU), which remained at levels of 5-10 NTU on Days 1-5. Although significantly higher than other treatments, it is unlikely that phytoplankton growth was inhibited by these turbidity levels as they are low relative to turbidity levels in most coastal waters (Kendrick et al., 1998).

Typically, algal growth is either controlled or limited by ambient light conditions or by the supply of critical nutrients (e.g. nitrogen, silicate, phosphate) (Huisman et al., 1999; Wild-Allen et al., 2002). Growth in phytoplankton cell numbers, in response to increases in NH_4, was apparent 2 days following the mixing event, with peak cell abundance observed on Day 4. This is in line with other studies, which show that phytoplankton growth response to elevated dissolved nutrient concentration occurs within a few days (Chang and Rossmann, 1988; Schelske et al., 1995).

Although both Cyanophyceae and Chlorophyceae were present at cell numbers >8000/mL at the start of the experiment, cyanophytes showed the greatest growth response following sediment disturbance. Cyanophytes appear to be more competitive for available nutrients when orthophosphate levels are low.

Cyanophytes associated with the gyttja in Myall Lake are mostly Chroococcales and Nostocales, with a high abundance of *Aphanothece* and *Aphanocapsa* (Dasey et al. 2005). Potentially toxic benthic cyanobacteria (*Microcystis flos-aquae*) were also found in the surface gyttja layer but these large colonies quickly sank out of the water column when suspended.

It was expected that sediment disturbance would introduce benthic algae (diatoms and benthic

Cyanophyceae) into the water column following the mixing event. Diatoms that appeared in the impact mesocosm with 30 min of gyttja mixing were *Amphora, Craticula, Fallacia, Fragilaria* and *Melosira*, the only one of these to remain in the water column throughout the 5 days of observation. Most, if not all of these taxa, were benthic microalgae (Potapova and Charles, 2003). With the exception of *Melosira*, their presence in the water column was short-lived (<1 day), presumably due to cell sinking. Large cells (≥ 100 μm) tend to fall rapidly out of the water column and require water motion or turbulence to remain suspended (Kiorboe, 1993). Low orthophosphate levels and a lack of vertical mixing may explain why there was no stimulation of diatom growth in the water column, despite high concentrations of both dissolved nitrogen and silicate in the impacted mesocosm (N:Si ratios >1).

Phytoplankton are known to respond to sediment disturbance with changes in biomass, assemblage structure and taxonomic diversity (Jacobsen and Simonsen, 1993; Floder and Sommer, 1999; Hillebrand and Sommer, 2000a; Floder and Burns, 2004). This study found that diversity of phytoplankton was higher in disturbed mesocosms than in surrounding water. This was not unexpected given that intermediate levels of disturbance generally lead to elevated species diversity (Connell, 1978). With the temporary influx of benthic algae and the growth of primarily cyanophytes, the assemblage structure of phytoplankton changed markedly over the 5-day study period. Similar changes in phytoplankton assemblage structure, following nutrient increases, have been observed by other researchers (Vanni, 1987; Chang and Rossmann, 1988; Burford and Pearson, 1998; Vuorio et al., 2005).

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