The response of water quality and phytoplankton communities in the Northern Lagoon of the Coorong and Murray Mouth to barrage releases from the Lower Lakes, November 2010 – May 2011

Kane T. Aldridge and Justin D. Brookes

Final report prepared for the Department of Environment and Natural Resources and Department for Water, the Government of South Australia

June 2011

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Executive summary

From September 2001 to 2008 the Murray-Darling Basin experienced the second driest seven-year period in its recorded history. The resulting low flows severely impacted the Coorong ecosystem with little freshwater entering the Coorong. This led lead to elevated salinity levels, which reduced habitat availability for biota. The concomitant low inputs of nutrients appeared to limit phytoplankton abundance, diversity and productivity. However, in 2010 the Murray-Darling Basin experienced its wettest year on record, with high rainfall continuing into 2011. This provided the opportunity to release significant water from the Lower Lakes to the Coorong.

It was hypothesised that these inflows would provide many ecological benefits, including increased habitat availability (decreased salinity and stratification) and increased food availability (increased autochthonous productivity and allochthonous material) for various aquatic organisms. These hypotheses were investigated by monitoring physico-chemical conditions, nutrient concentrations and the phytoplankton community between November

2010 and May 2011 at 11 sites in the Northern Coorong, Murray Mouth and Southern Ocean.

The inflows reduced salinity levels considerably in the North Lagoon of the Coorong, Murray Mouth and even the Southern Ocean near shore environment. Electrical conductivities in the study region prior to the inflow were approximately 54000 µS/cm. Electrical conductivities measured in the Coorong between Goolwa and Tauwitchere Barrages during the study fell from approximately 2500 µS/cm to <500 µS/cm. Average electrical conductivity at the Southern Ocean site for the study period was 7692.6 µS/cm, well below that of seawater (approximately 54000 µS/cm), demonstrating the sheer volume of water moving through the Murray Mouth. Salinity levels at Mark Point were also reduced considerably on occasions (less than 5000 µS/cm on 13/12/2010 and 27/04/2011), demonstrating that freshwater inflows from the barrages have the capacity to influence salinities in the Coorong south-east of Mark Point.

Salinity stratification was observed at a number of sites at the beginning of the study, which resulted from the flow of less dense freshwater over the denser saline water. The density difference prevented complete mixing of the two water bodies with anoxic conditions observed in the hypolimnion, which would have restricted habitat for flora and fauna. However, continued high flows broke down the salinity stratification and dissolved oxygen concentrations increased. Dissolved oxygen levels initially decreased at most sites, most likely reflecting increased microbial respiration associated with the flow event, either in the Coorong or upstream. A gradual fall in pH during the study was most likely associated with inputs from the Lower Lakes, where lower pH water was observed during the high flow event. Turbidity initially increased and then decreased during the study period and this too was associated with changes in the Lower Lakes, as expected during a high flow event.

The inflows appeared to increase total nutrient concentrations and changed the nutrient forms, with decreased proportion of the total nitrogen present as ammonia and oxidised nitrogen and an increase in proportion of phosphorus as filterable reactive phosphorus. The high ammonia concentrations at the beginning of the study period may have been due to release from previously dry sediments or the decomposition of organic material in the Coorong or further upstream. The decreased ammonia was most likely due to uptake by phytoplankton as biomass (chlorophyll) increased. However, chlorophyll concentrations fell towards the end of the study period but organic nitrogen concentrations did not, suggesting an incorporation of the nitrogen into bacterial or zooplankton biomass.

Changes in nutrient concentrations resulting from altered inputs and internal cycling were clearly associated with changes in the phytoplankton community. As a result of the River Murray inflows there was an increase in the abundance, diversity and productivity of phytoplankton within the Northern Lagoon of the Coorong. At the beginning of the study period the phytoplankton community was dominated by Chlorophyta. As flows continued, the phytoplankton community became dominated by Cyanobacteria, which was considered to be the movement of phytoplankton from the Lower Lakes. However, numbers of Cyanobacteria fell and numbers of Chlorophyta and Bacillariophyta continued to increase throughout the study period. Bacillariophyta are considered to be an important food source for Goolwa Cockles. Their increase in abundance and diversity was associated with the increasing silica concentrations that were observed.

The large inflows to the Coorong from the Lower Lakes between October 2010 and January 2011 caused rapid changes within the Northern Lagoon of the Coorong, Murray Mouth and the near-shore environment. While there may have been short-term negative impacts on the distribution and abundances of marine and sensitive estuarine organisms, there are also many immediate benefits of reduced salinities, particularly for freshwater organisms and diadromous fish. The reduced salinity and increased dissolved oxygen levels in the hypolimnion, due to the breakdown of stratification, would increase habitat availability for many organisms. In addition, the large inflow event clearly resulted in increased loads of nutrients from the basin, which increased the abundance, diversity and productivity of the phytoplankton community. The import of nutrients into the region is likely to result in elevated primary productivity for some time. Assuming that this primary productivity occurs in forms that are available to higher organisms, these benefits will cascade through the food-web, resulting in increased secondary productivity.

Introduction

The Coorong is an estuarine-hypersaline coastal lagoon that contains high biodiversity and is ecologically important for South Australia and the Murray-Darling Basin, Australia's largest drainage basin (1063000 km^2) and is internationally important. Together with the Lower Lakes, the Coorong was declared a *Wetland of International Importance* in 1985 under the Ramsar Convention. This status is recognition of the abundant and diverse ecological communities within the region, which result from high habitat diversity created largely by the salinity gradient and morphology that supports large expanses of mudflats. The region is an important refuge for a number of threatened freshwater fish species, an important feeding habitat for waterbirds and an important source of water and resources to the near shore environment (Cook *et al.* 2008). It also supports a substantial fishery, provides recreational pursuits and has a high cultural and aesthetic value.

While small volumes of water are provided to the South Lagoon of the Coorong (≈7 GL/year) from the Upper South East Drainage (USED) scheme, the majority of its inflows are received from Lake Alexandrina, which is separated from the Coorong by five barrages constructed in the late 1930s (Figure 1). The River Murray carries the largest and most constant flow of water to the Lower Lakes. The Darling River also contributes significant flow, although this is more variable and carries high loads of fine particles, resulting in extremely high turbidity. Although several local streams discharge into the Lower River Murray and Lake Alexandrina, their overall contribution to total annual flow are small relative to River Murray inputs, but become important during periods of low River Murray inputs (Anon 2007).

Inflows from Lake Alexandrina to the Coorong are controlled by opening gates in the barrages. However, extraction of water upstream for irrigation and human use has severely reduced the amount of water passing into and through the Lower Lakes. Consumptive water use within the Murray-Darling Basin has reduced average stream-flow through the Murray Mouth from 12233 GL/yr to 4733 GL/yr (CSIRO 2008). From September 2001 to 2008 the Murray-Darling Basin experienced severe rainfall deficiencies, the second driest seven-year period in its recorded history (MDBC 2008). This combined with the over-allocation of water within the Murray-Darling Basin resulted in no inflows to the Coorong in 2007-2009, following on from below average inflows from 1993 to 2007 (MDBA, unpublished). This has severely impacted upon the Coorong ecosystem due to elevated salinity (Brookes *et al.* 2009). While phytoplankton communities have received little attention in the Coorong, there was evidence to suggest that during the drought the phytoplankton community had low diversity, abundance and productivity (Seuront and Leterme 2010). This was most likely associated with low nutrient availability due to low inflows from the River Murray (Haese *et al.* 2009; Nayar and Loo 2009). The extremely low inflows to the Lower Lakes have also resulted in a gradual but unprecedented water level drawdown. From August 2006 to August 2009, water levels fell in the Lower Lakes from average levels of 0.75 m AHD to -0.75 m AHD, resulting in the intrusion of saline water into the lakes (Aldridge *et al*. 2009) and the formation of acid sulfate soils due to the exposure of large areas of previously inundated sediments (Fitzpatrick *et al.* 2008).

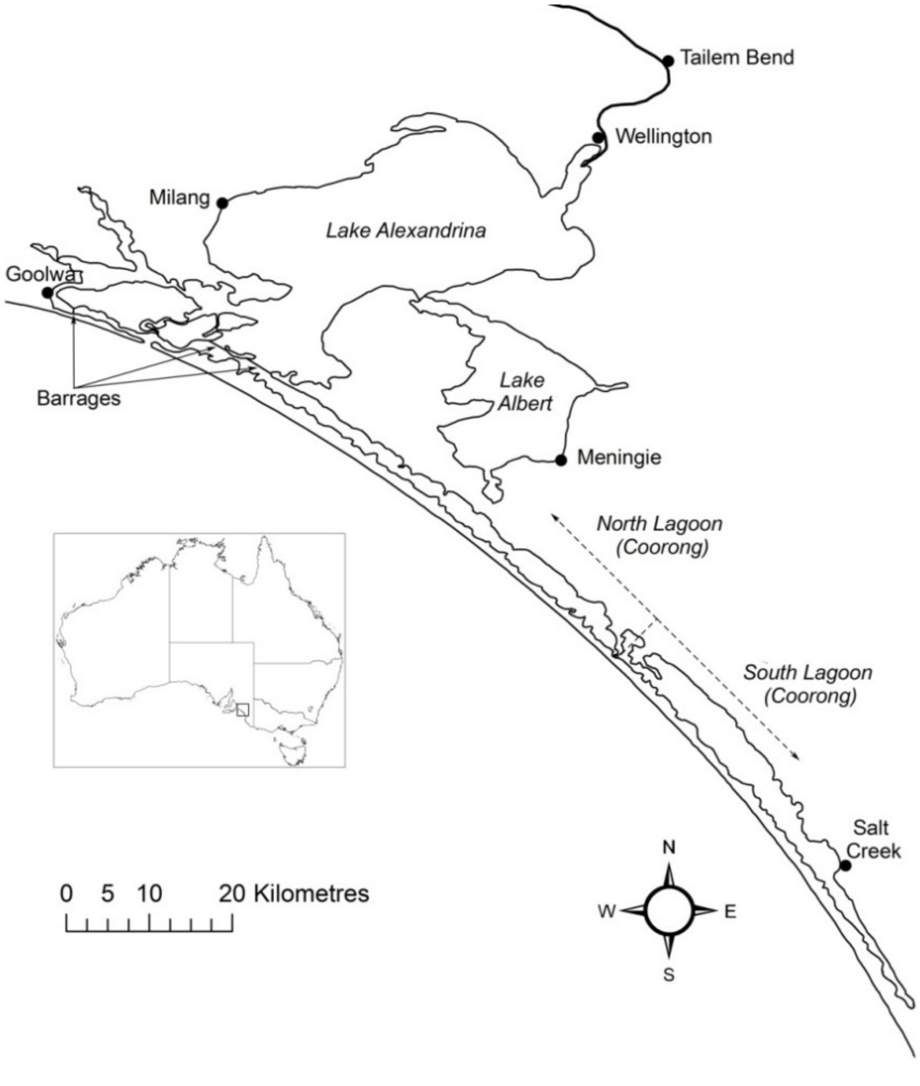

Figure 1. Map of the Lower River Murray, Lake Alexandrina, Lake Albert and the Coorong.

However, 2010 saw the Murray-Darling Basin experience its wettest year on record (Bureau of Meteorology, unpublished), with high rainfall in the catchment continuing into 2011. This has resulted in high inflows to the Murray-Darling Basin, providing the opportunity to release significant water from the Lower Lakes to the Coorong. While it was initially anticipated that releases from the barrages would total approximately 100-200 GL between late 2010 and early 2011, continued rainfall across the basin has meant that releases have been far greater, with target discharges of between 10-126 GL/day from October 2010 to May 2011 (SA Water, unpublished).

The high inflows to the Murray-Darling Basin are likely to have brought in large quantities of nutrients from the landscape, stimulating primary and secondary productivity. In particular, the reinundation of large areas of exposed sediments within wetlands, including the Lower Lakes, is likely to have resulted in large nutrient inputs into the Coorong (Aldridge *et al.* 2009). However, the presence of large areas of acid sulfate soils (Fitzpatrick *et al.* 2008) means there was also potential for acidification of the water column upon reinundation of dried sediments (Simpson *et al.* 2010), with acidic water passing into the Coorong.

It was hypothesised that the inflows would provide many benefits to the ecosystem of the North Lagoon of the Coorong and Murray Mouth, including:

- Increased habitat availability for aquatic organisms, resulting from:
    - Decreased salinity
    - Decreased levels of hypolimnetic hypoxia/anoxia caused by salinity stratification
- Increased food availability for aquatic organisms, resulting from:
    - Increased importation of nutrients and autochthonous (See Appendix 1) productivity
    - Increased importation of phytoplankton, with high abundances of diatoms and green algae which are preferred food sources for first order consumers, including Goolwa Cockles (*Donax deltoides*) and zooplankton

Due to the greater than expected volumes of water that were released over the barrages, these include additional hypotheses to those provided by the Department of Environment and Natural Resources and Department for Water in the original proposal request.

Methods

From 1/11/10 to 25/05/11, 11 sites in the region of the North Lagoon of the Coorong were visited at approximately fortnightly intervals (Figure 2 and Appendix 2). One site was within the Murray Mouth (C5) and one site in the surf zone of the Southern Ocean, approximately 1 km north-east of the Murray Mouth (C4). In order to increase the temporal coverage, the final two trips were conducted approximately 6 and 4 weeks after the previous trip, respectively.

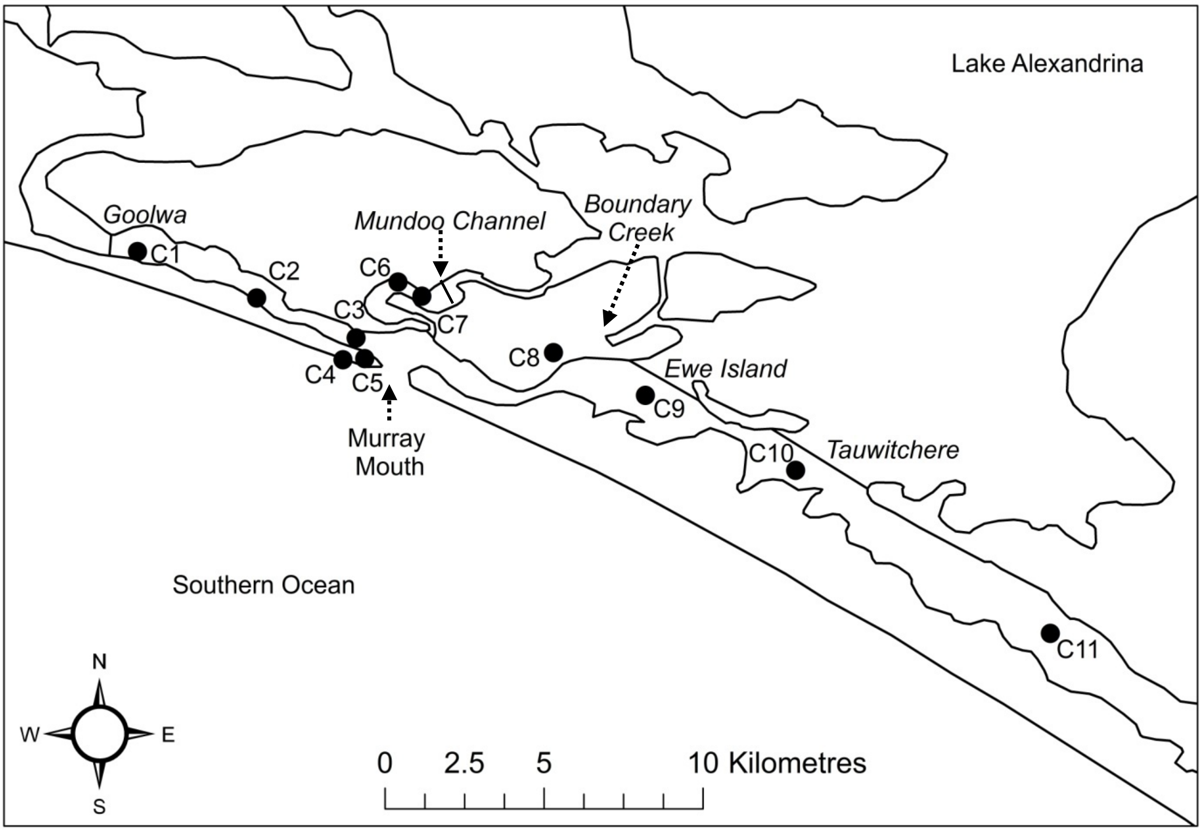

Figure 2. Map of sampling locations in the North Lagoon of the Coorong and Murray Mouth region. C1 – Goolwa Barrage Downstream; C2 – Half Way; C3 – Sugar's Beach; C4 – Southern Ocean; C5 – Murray Mouth; C6 – Hunter's Creek; C7 – Mundoo Channel; C8 – Boundary Creek; C9 – Ewe Island; C10 – Tauwitchere; C11 – Mark Point. Barrages are labelled in italics.

Physico-chemical depth profiles

At each site on every trip, a calibrated Hydrolab DS-5X (Hach) multi-probe was lowered through the water column and measurements were made at approximately 0.25 m intervals for water temperature, specific electrical conductivity, dissolved oxygen (concentration and saturation), pH, turbidity and chlorophyll *a* upon equilibration. Chlorophyll *a* measurements made with the Hydrolab DS-5X were corrected for laboratory measurements of collected integrated water samples, analysed using methods described below.

Nutrients and phytoplankton

At approximately four-weekly intervals from 1/11/10 to 28/02/11 integrated water samples were also collected from each of the 11 sites. To increase the temporal coverage, the final trip for collection of nutrient and phytoplankton samples was conducted on 24/05/11, approximately 8 weeks after the previous collection.

Integrated water-column samples were collected using a polyvinyl chloride tube with an internal diameter of 5.4 cm. Tubing was lowered through the water column to ~0.15 m above the sediment surface, sealed on top and water was retrieved into a plastic container. For each site this was repeated 3 times and composite samples were collected.

Approximately 1 L of unfiltered water was collected and 100 mL of was immediately filtered through a Millex® AP 20 GF prefilter and a Millex ® 0.45µm PES Membrane filter for dissolved nutrient analysis. Filters were not pre-rinsed as they were found not to leach detectable levels of nutrients; however, the first 5 mL of filtered sample was not dispensed into the sample bottle. All samples were immediately stored in the dark below 3°C until analysis.

Unfiltered water samples were analysed for total phosphorus (TP), total Kjeldahl nitrogen (TKN), chlorophyll *a* and phytoplankton identification and abundance. Analyses for nutrient concentrations and phytoplankton identification and abundance were conducted following standard methods by the Australian Water Quality Centre, a NATA (National Association of Testing Authorities) accredited laboratory. Chlorophyll *a* was measured following Golterman *et al.* (1978). This involved concentrating suspended particulate material onto Whatman

International GF-C filters, extracting chlorophyllin 99.8% methanol and measuring absorbance at 750 and 665 nm using a Hitachi U-2000 spectrophotometer (Hitachi Ltd., Tokyo, Japan), with a path length of 10 mm. Filtered samples were analysed for ammonia (NH_4-N), oxidised nitrogen (NO_x-N), filterable reactive phosphorus (FRP) and filterable reactive silica (FRSi). Total nitrogen (TN) was calculated as the sum of TKN and NO_x-N. Total organic nitrogen (TON) was calculated as the difference between TKN and NH_4-N. Non FRP phosphorus (which includes particulate phosphorus and non-reactive unfilterable phosphorus) was calculated as the difference between TP and FRP.

Statistical analyses

Multivariate statistical analyses were conducted to determine changes in phytoplankton community composition during the barrage releases and identify the primary drivers of changes in the phytoplankton community. Ordinations were carried out using PC-Ord with a main matrix containing cell numbers of each genera at each site for each sampling trip and this was overlain with a second matrix containing the same data-set as well as NH_4-N, NO_x-N, TON, FRP, Non FRP, FRSi, electrical conductivity, temperature, pH, dissolved oxygen, dissolved oxygen saturation and turbidity. A successful three-dimensional NMS ordination (Sorensen) was conducted on individual phytoplankton genera, with a stress level of 10.4.

Results

Temporal and spatial variation in physico-chemical conditions

Physico-chemical conditions varied considerably in the region during the study period. As expected, average water temperatures increased from late spring to the end of summer and then fell through to the end of autumn (Table 1). Specific electrical conductivity increased between the beginning and end of November 2011, but then fell rapidly until the beginning of January 2011 before a more gradual decrease to 27/04/2011 (Figure 3). Between 27/04/2011 and 25/05/2011 there was a rapid increase in electrical conductivity owing to higher tides during autumn and strong on-shore winds in the days preceding 25/05/2011.

Table 1. Average physico-chemical conditions for the North Lagoon of the Coorong and Murray Mouth, November 2010-May 2011. Variation is reported as standard deviation.

Date	Water temperature (°C)	pH	Dissolved oxygen (mg/L)	Dissolved oxygen (% saturation)	Turbidity (NTU)
1/11/10	16.10 ± 0.99	8.58 ± 0.17	10.38 ± 0.53	106.6 ± 4.6	31.8 ± 15.1
15/11/10	19.11 ± 0.53	8.90 ± 0.36	8.99 ± 1.20	98.1 ± 12.5	32.5 ± 9.3
27/11/10	20.64 ± 0.61	8.53 ± 0.22	7.44 ± 0.56	84.1 ± 6.3	55.4± 29.7
13/12/10	19.35 ± 0.52	8.29 ± 0.10	8.67 ± 0.60	95.6 ± 5.8	90.7 ± 41.9
5/01/11	21.36 ± 0.77	8.15 ± 0.11	8.67 ± 0.44	98.8 ± 4.0	216.8 ± 68.4
16/01/11	23.59 ± 0.49	8.14 ± 0.20	7.79 ± 1.09	92.6 ± 12.4	182.7 ± 63.4
31/01/2011	25.75 ± 0.93	8.07 ± 0.18	7.83 ± 0.79	96.9 ± 10.4	156.7 ± 48.5
15/02/2011	21.05 ± 0.83	8.06 ± 0.08	8.52 ± 0.55	97.5 ± 6.3	149.1 ± 59.4
28/02/2011	21.36 ± 0.37	8.06 ± 0.12	8.61 ± 0.63	97.6 ± 6.9	131.9 ± 43.7
16/03/2011	19.53 ± 0.50	8.06 ± 0.15	8.96 ± 0.65	98.1 ± 7.0	89.8 ± 43.7
27/04/2011	17.86 ± 0.47	8.12 ± 0.12	9.68 ± 0.68	102.4 ± 7.4	57.6 ± 19.6
25/05/2011	12.84 ± 0.22	7.92 ± 0.06	9.60 ± 0.38	96.3 ± 3.4	19.5 ± 8.4

Between 1/11/10 and 13/12/10, electrical conductivity at C2 was considerably higher than that at upstream (C1) and downstream (C3) sites, which was associated high electrical conductivity in the hypolimnion of C2 during this time (Figure 4). No salinity stratification was observed at C1. The salinity stratification at C2 was not present after January 2011 and even though salinity increased on 25/05//2011 salinity stratification was still absent. Salinity stratification was also present at C11, where electrical conductivity was highly variable (3913.1 to 34628.8 µS/cm; Figure 3). However, the extent of stratification was clearly lower at the end of the study period than the beginning. While salinity stratification was also evident at C10, the extent of stratification decreased through the study period with no stratification present after 16/01/11, except on 25/05/2011 (Figure 3 and Figure 4). However, this was associated with the large input of marine water due to high tides and strong on-shore winds in days preceding 25/05/2011. At this time the electrical conductivity at C11 was similar to that of sites located close to the barrages, suggesting enhanced mixing of water within the Northern Lagoon coinciding with the elevated water levels.

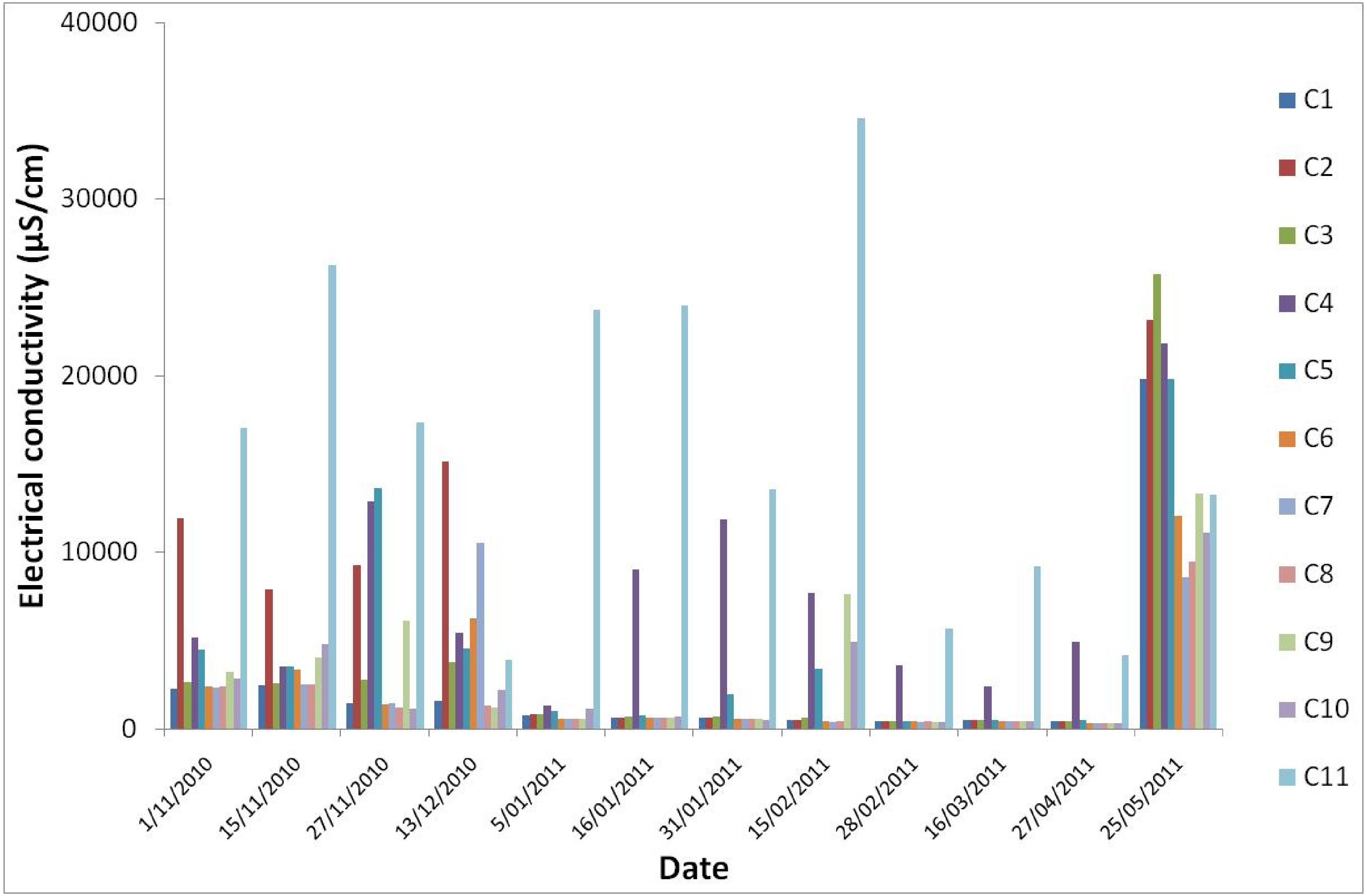

Figure 3. Changes in electrical conductivity in the North Lagoon of the Coorong and Murray Mouth, November 2010-May 2011.

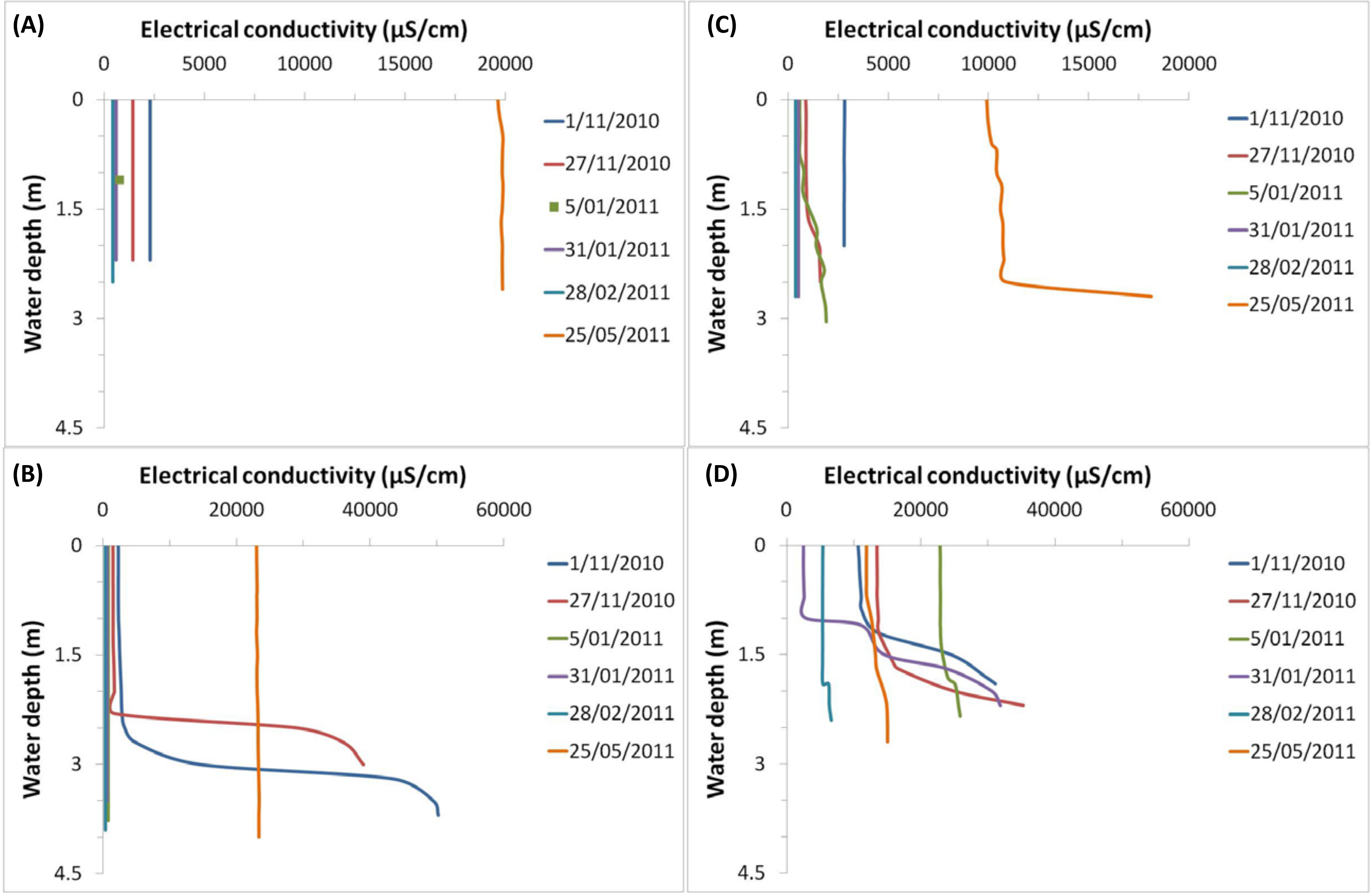

Figure 4. Changes in vertical profiles of electrical conductivity at selected sites in the North Lagoon of the Coorong and Murray Mouth, November 2010-May 2011. Shown are C1 (A), C2 (B), C10 (C) and C11 (D). Note differences in scale of x-axes.

Dissolved oxygen fell between 1/11/10 and 27/11/10 at all sites, increased to 05/01/11 before falling slightly on 16/01/2010 (Table 1, Figure 5). Following this there was a gradual increase to the end of the study period. Changes in dissolved oxygen were particularly evident at C6. Both C2 and C11, which experienced salinity stratification, displayed the lowest dissolved oxygen levels at the beginning of the study period. This was associated with depletion of oxygen in the hypolimnion in these waters (Figure 6) due to salinity stratification. However, at C2 oxygen levels in the hypolimnion increased as salinity stratification was broken down and mixing facilitated gas exchange with the atmosphere. At C11, the level of dissolved oxygen depletion in the hypolimnion was strongly related to salinity stratification with anoxic conditions experienced in the hypolimnion when salinity stratification was strongest. The level of oxygen depletion decreased from January 2011 onwards and was particularly low on 25/05/2011.

In all sites, except C6, the pH increased slightly between 1/11/10 and 15/11/10 and then gradually fell to the end of the study period (Table 1, Figure 7). In contrast at C6, pH was closely associated with changes in dissolved oxygen, lowest on 15/11/2010 and highest in January 2011. Turbidity increased between 1/11/2010 and 05/01/2011 before falling to 25/05/2011 (Table 1). This was the case at all sites except C11, where turbidity remained low (Figure 8). Turbidity generally decreased with increasing distance from the barrages.

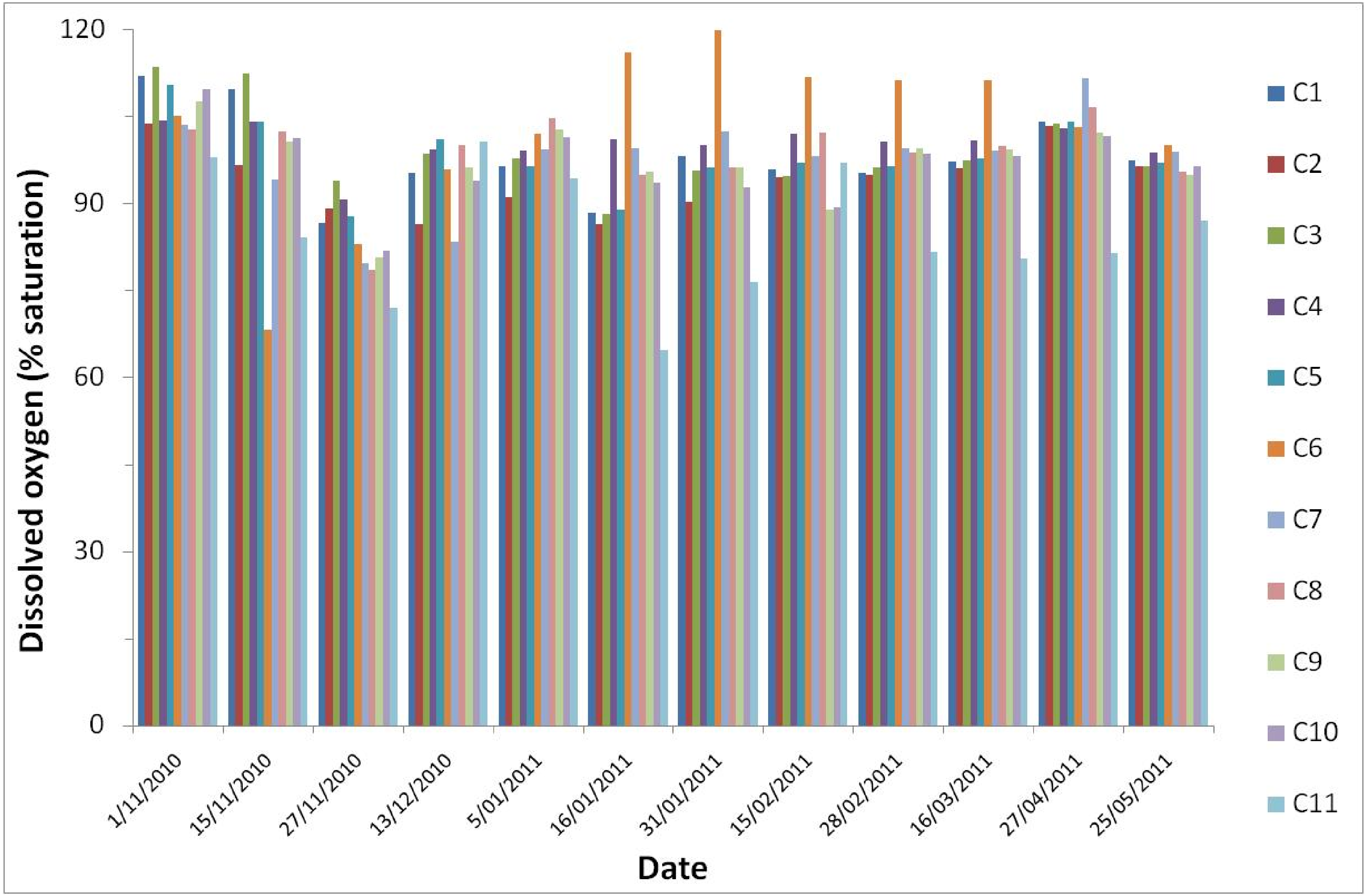

Figure 5. Changes in dissolved oxygen saturation in the North Lagoon of the Coorong and Murray Mouth, November 2010-May 2011.

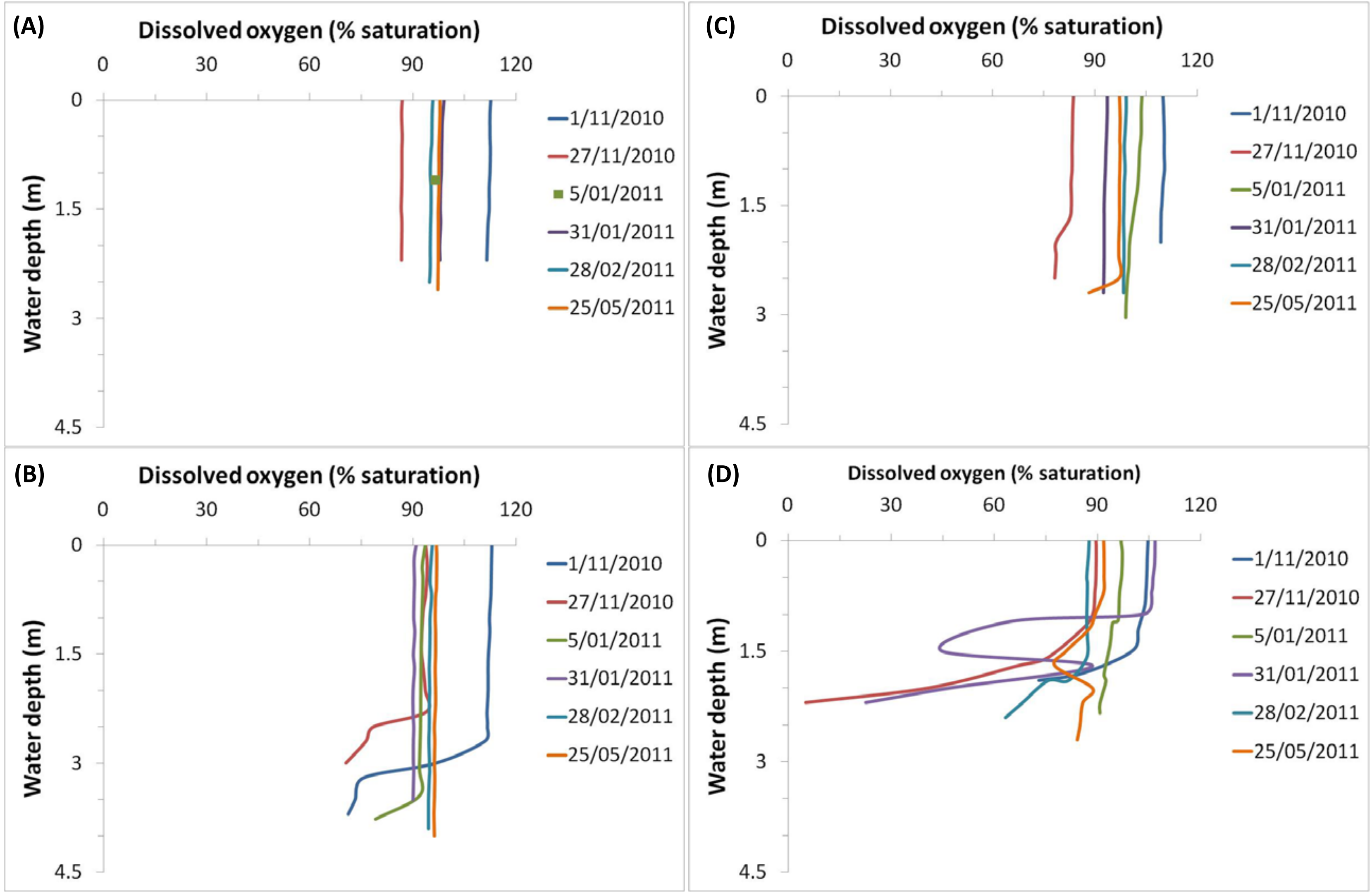

Figure 6. Changes in vertical profiles of dissolved oxygen saturation at selected sites in the North Lagoon of the Coorong and Murray Mouth, November 2010-May 2011. Shown are C1 (A), C2 (B), C10 (C) and C11 (D).

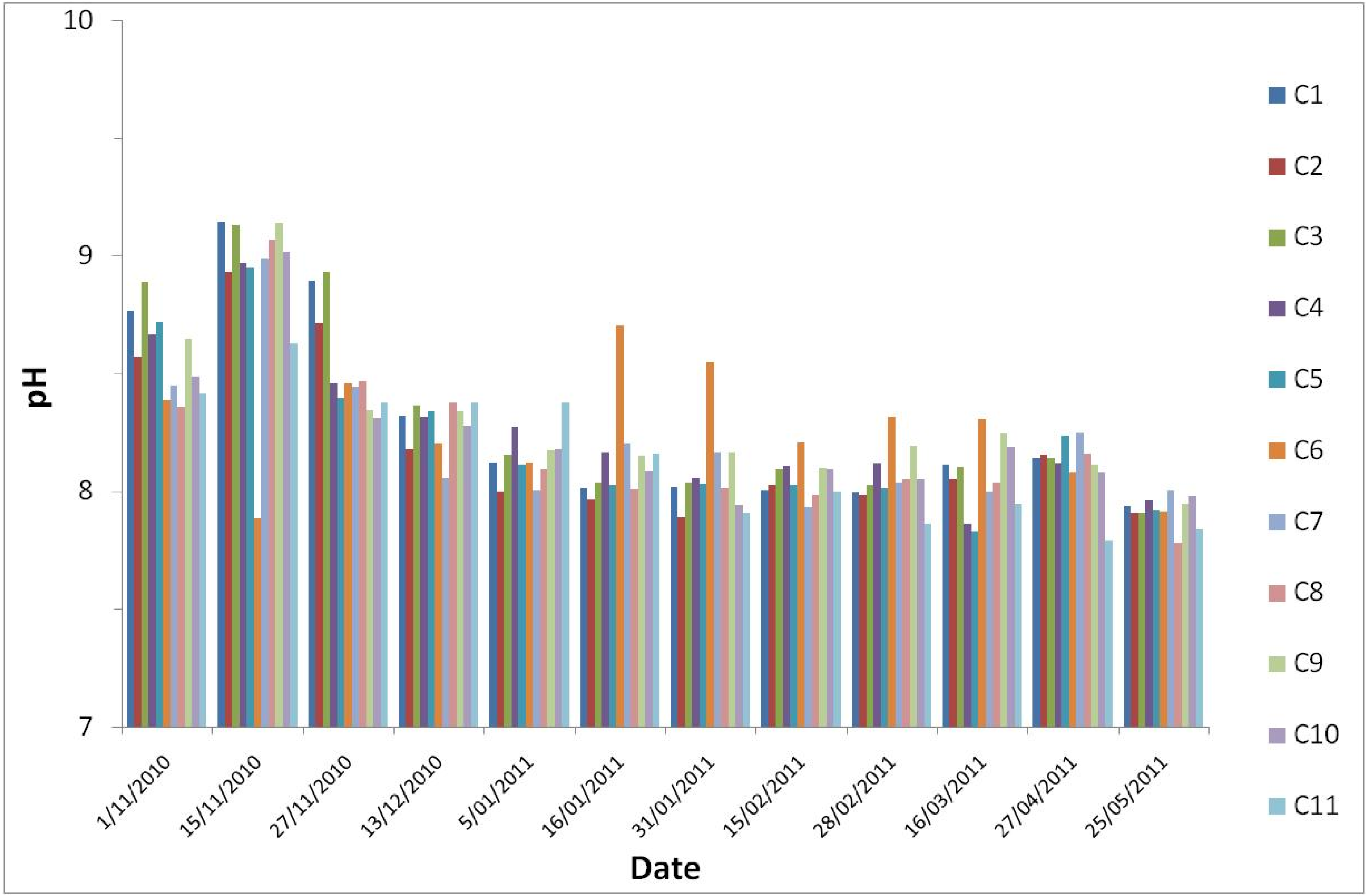

Figure 7. Changes in pH in the North Lagoon of the Coorong and Murray Mouth, November 2010-May 2011.

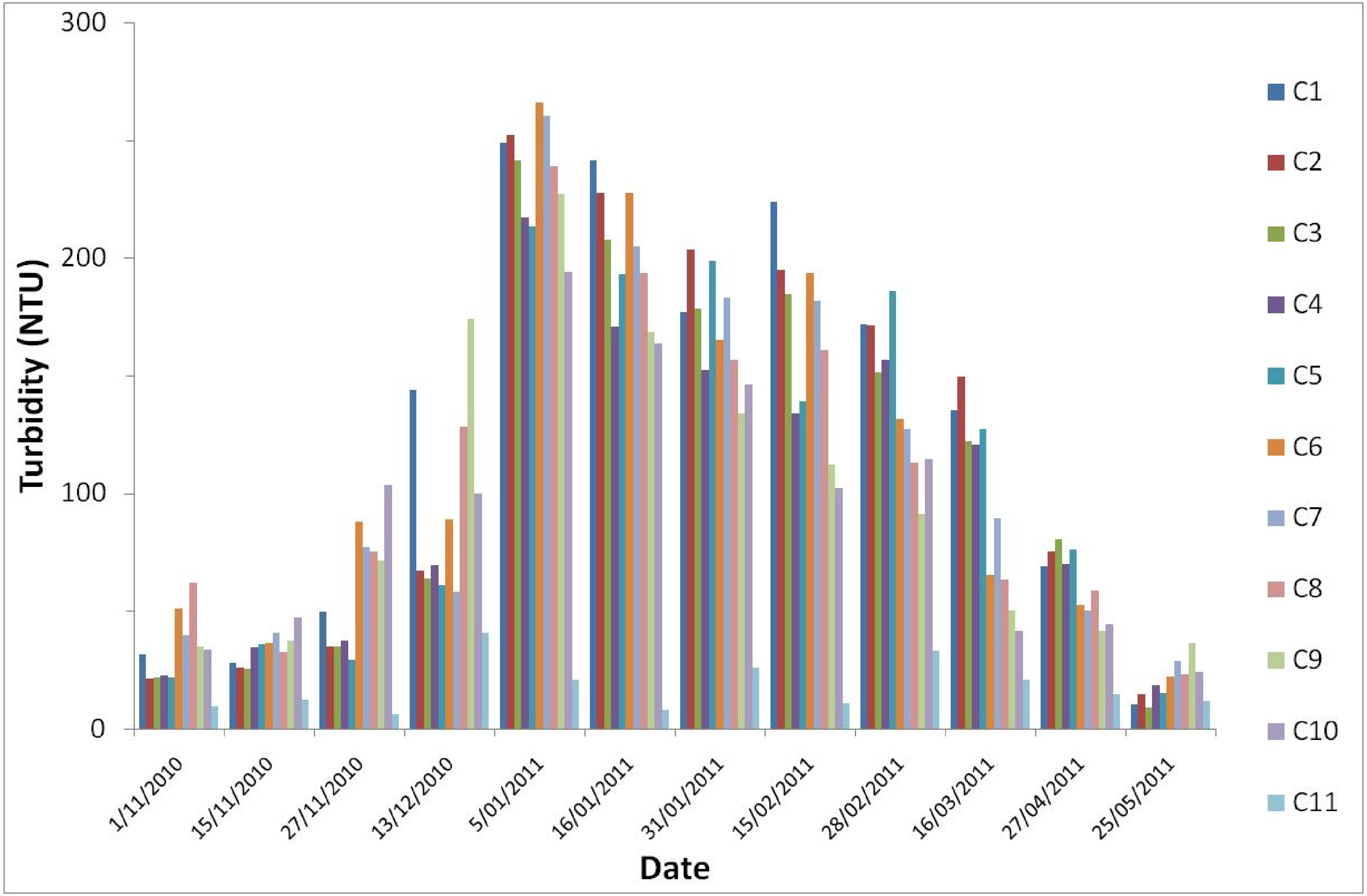

Figure 8. Changes in turbidity in the North Lagoon of the Coorong and Murray Mouth, November 2010-May 2011.

Nutrients

Nitrogen consisted of predominately TON, although there were high concentrations of NH_4-N and NO_x-N at the beginning of the study period (Figure 9). Average concentrations of NH_4-N and NO_x-N on 01/11/2010 were 0.133 ± 0.048 and 0.118 ± 0.034 mg/L, respectively. There were only small temporal differences in TN concentrations, with concentrations peaking in January-February 2011. The most evident change in nitrogen concentrations during the study period was the composition with decreasing concentrations of NH_4-N and NO_x-N and increasing concentrations of TON. On 27/04/2011 concentrations of NH_4-N were just above detection limits (0.007 ± 0.003 mg/L), while concentrations of NO_x-N were below detection limits (i.e. < 0.003 mg/L).

TP consisted of predominately non-FRP, however the proportion of TP that was in the form of FRP increased during the study period (Figure 10). On 01/11/2010 concentrations of FRP were at or below detection limits of 0.003 mg/L at all sites, whereas on 27/04/2011 average concentrations were 0.029 ± 0.005 mg/L. There was a general increase in TP between 1/11/2010 (average concentration of 0.133 ± 0.043 mg/L) and 28/02/2011 (0.229 ± 0.047 mg/L), with concentrations falling again to 27/04/2011 (0.155 ± 0.025 mg/L). Concentrations of TP were generally lower at C11. FRSi concentrations increased at all sites during the study period, peaking on 28/02/2011 (Figure 11). Concentrations were generally lowest at sites furthest from the barrages, including C4 but particularly C11, with concentrations below detection levels on 1/11/10 and 5/01/11.

TN to TP ratios were always above Redfield ratios (Figure 12) suggesting that phosphorus was in lower supply than nitrogen relative to nutritional requirements of aquatic organisms. This was particularly evident at C11 due to low phosphorus concentrations. TN to FRSi ratios were highly variable above and below 1 (Figure 12), which is considered the approximate growth requirement for diatoms (Turner 2002). Differences in the TN to FRSi ratio reflected the increasing FRSi concentrations during the study period. Average TN to FRSi ratios increased from 2.3 at the beginning to 0.5 at the end of the study period. The TN to FRSi ratios were particularly high (>5) on 1/11/2010 and 15/01/2011, but from 31/01/2011 until 27/04/2011 the ratios were below 1. The TN to FRSi ratios at C5 and C4 were 2.7 on 1/11/2011, but generally less than one thereafter.

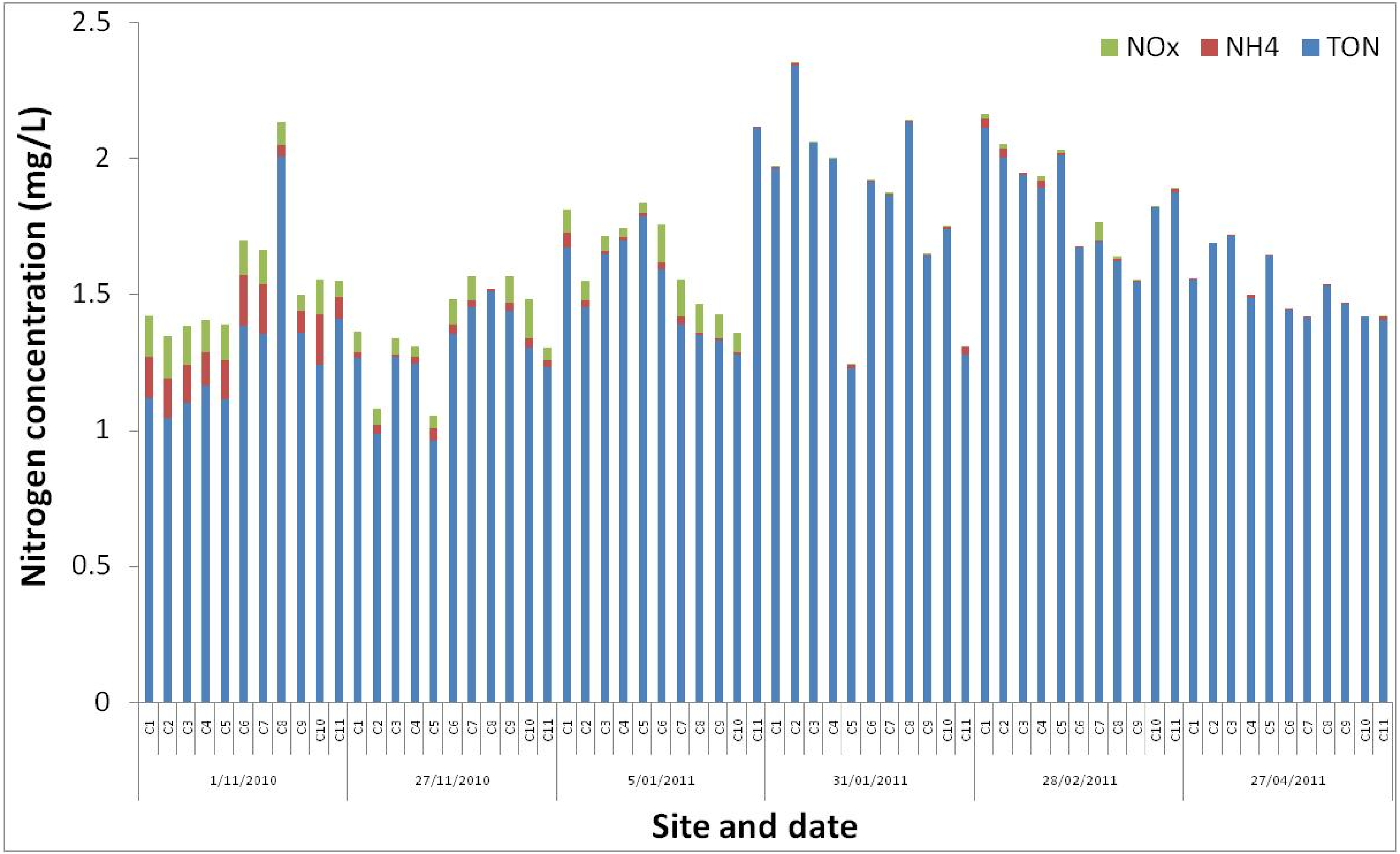

Figure 9. Changes in concentrations of different forms of nitrogen in the North Lagoon of the Coorong and Murray Mouth, November 2010-May 2011. NOx is oxidised nitrogen; NH4 is ammonia and TON is total organic nitrogen. The sum of NOx, NH4 and TON is total nitrogen.

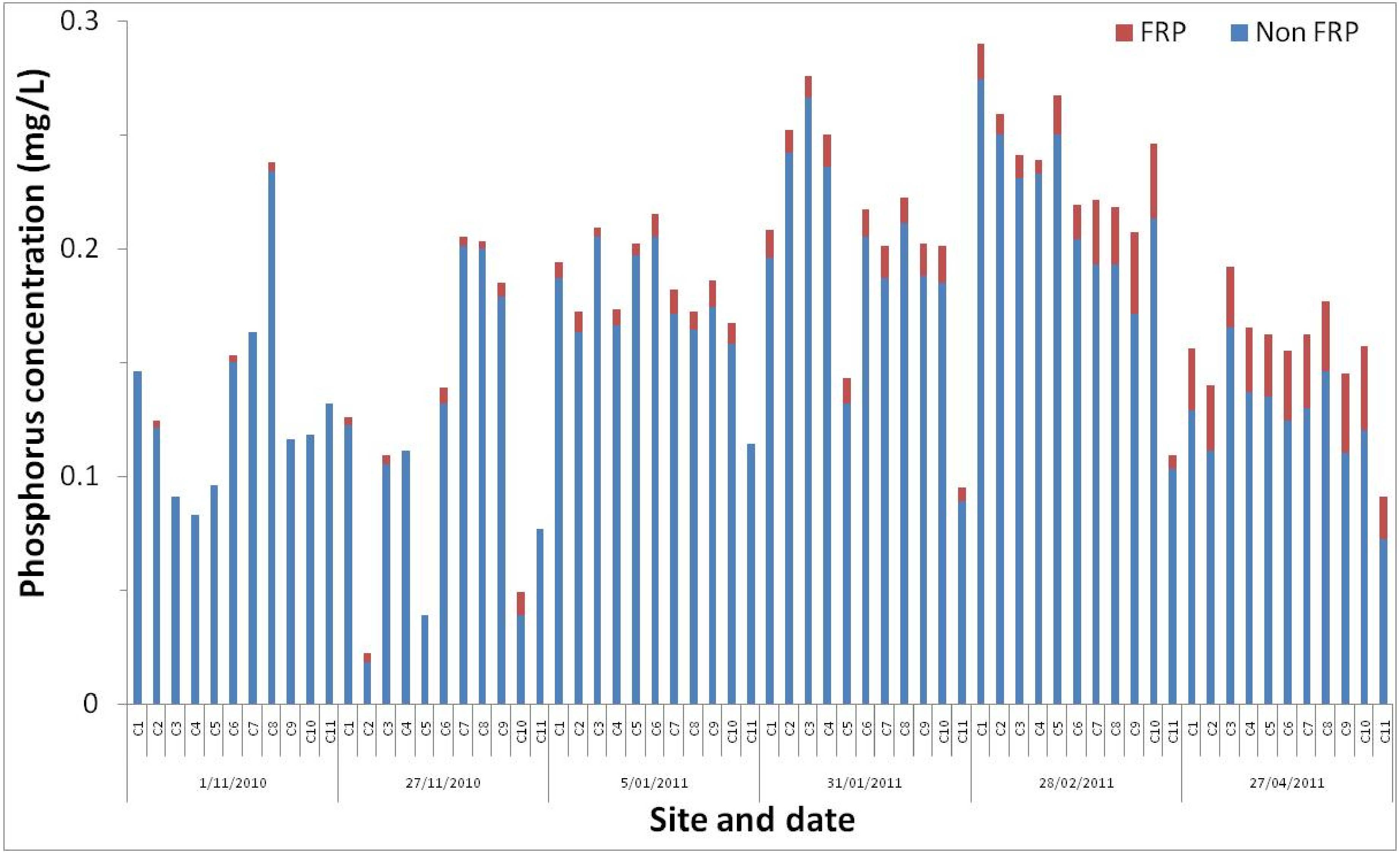

Figure 10. Changes in concentrations of different forms of phosphorus in the North Lagoon of the Coorong and Murray Mouth, November 2010-May 2011. FRP is filterable reactive phosphorus and non FRP is total phosphorus minus FRP.

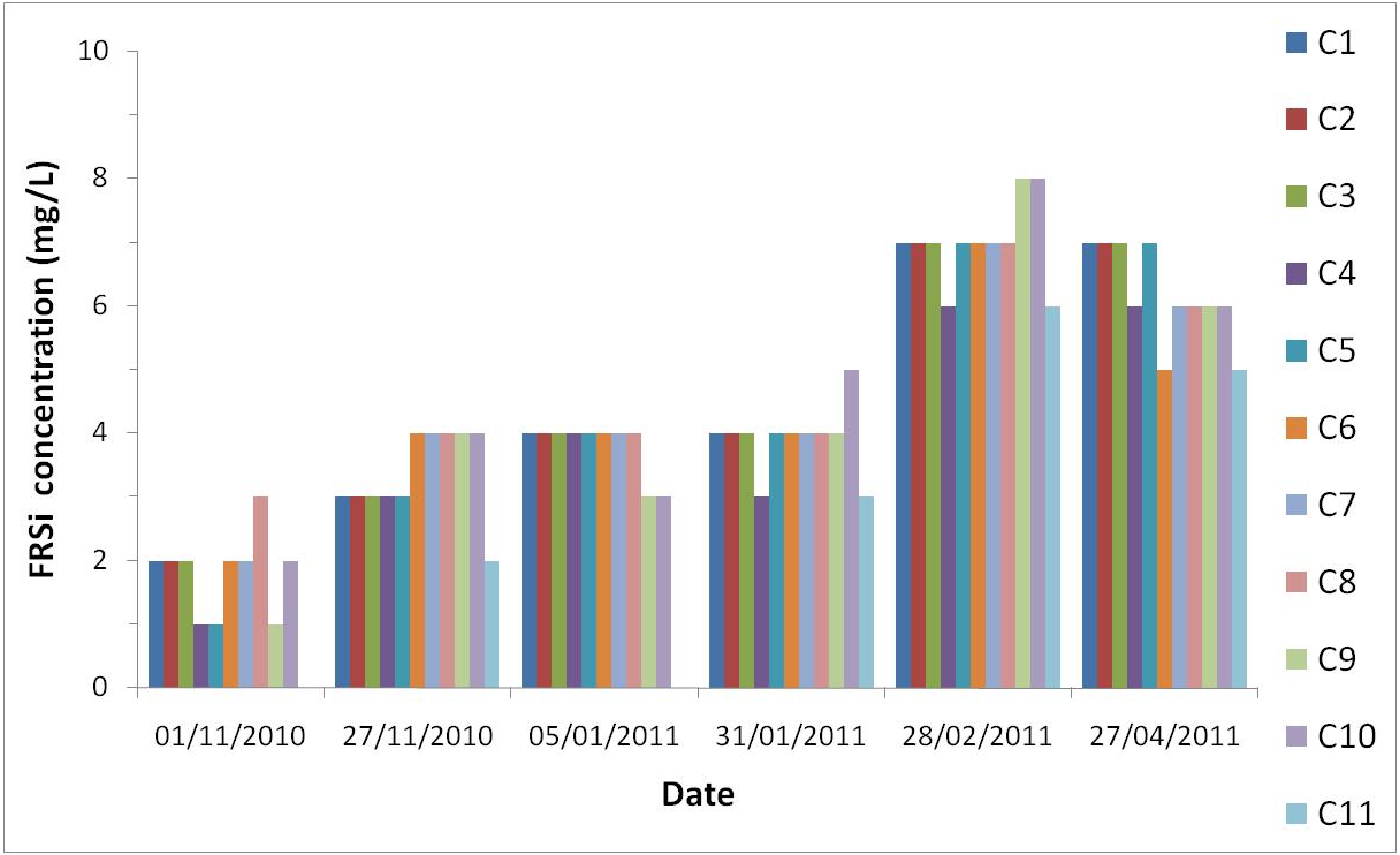

Figure 11. Changes in filterable reactive silica (FRSi) concentrations in the North Lagoon of the Coorong and Murray Mouth, November 2010-May 2011. Concentrations were below detection at C11 on 01/11/2010 and 05/01/2011.

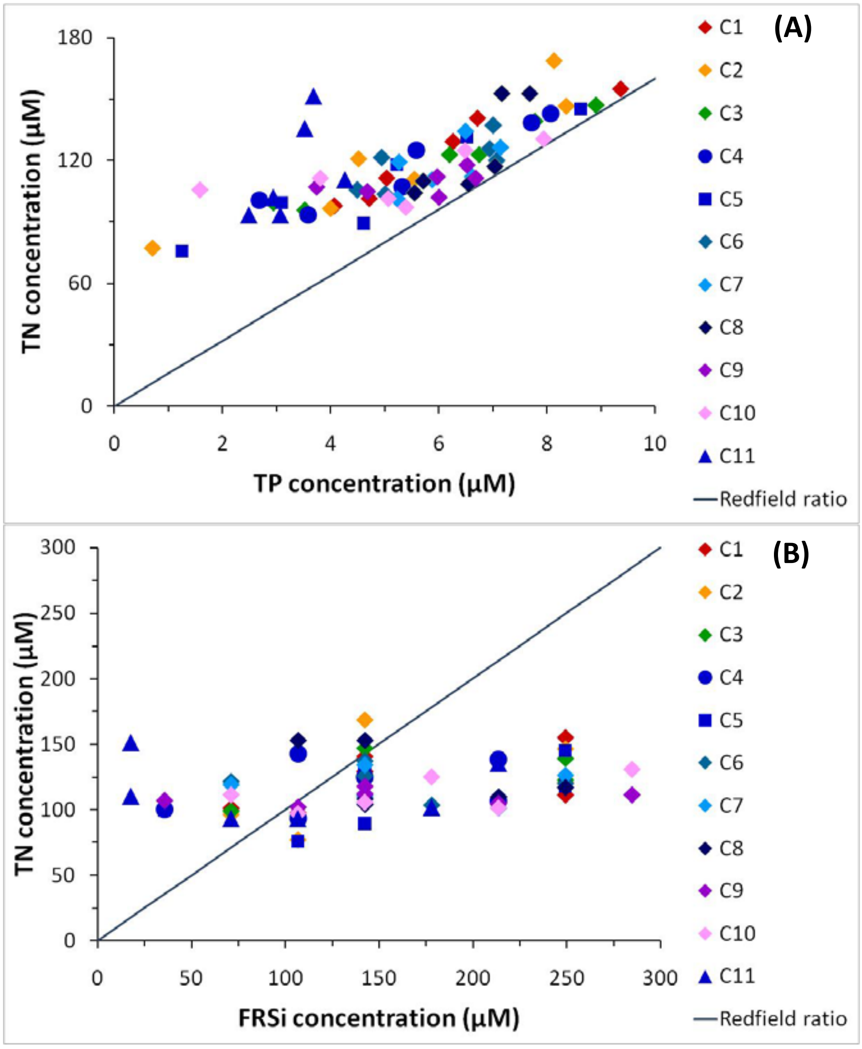

Figure 12. Nutrient ratios in the North Lagoon of the Coorong and Murray Mouth, November 2010-May 2011. In (A) the line represents the Redfield ratio. In (B) the line represents the silica to nitrogen ratio of approximate 1, which is required for diatoms growth (Turner 2002). TN is total nitrogen, TP is total phosphorus, FRSi is filterable reactive silica.

Phytoplankton

Changes in the phytoplankton community through the study period were strongly associated with changes in nutrient concentrations (Figure 13). There was a transition over time from a community associated with high NH$_4$-N and NO$_x$-N and low FRP and FRSi concentrations to a community associated with low NH$_4$-N and NO$_x$-N and high FRP and FRSi concentrations (Figure 14). Indicator species for this change included *Cryptomonas* (Cryptophyta) on 1/11/2010, *Aphanocapsa* (Cyanobacteria) on 27/11/2010, *Staurosira* (Bacillariophyta) and *Tetraspora* (Chlorophyta) on 31/01/2011 and 28/02/2011 and *Planktolyngbya* (Cyanobacteria) on 27/04/2011. There were no consistent differences in the phytoplankton community between sites. This was also the case for chlorophyll *a* concentrations, which displayed considerable spatial variation but few consistent differences between sites, although concentrations were generally lowest at C11 (Figure 14). At all sites except C11 and C4, chlorophyll *a* concentrations increased considerably between 1/11/10 and 28/02/11 before decreasing slightly to 25/05/2011. On 25/05/2011 concentrations were high at C4 and C11 relative to other sites.

On 1/11/10 the phytoplankton abundance (cells/mL) was dominated by Chlorophyta (green algae) at all sites with some Cyanobacteria (blue-green algae) and Bacillariophyta (diatoms) (Figure 15). There were similar numbers of Chlorophyta on 27/11/10, but the number of Cyanobacteria increased rapidly at all sites owing to the appearance of *Coelosphaerium*, which was not present thereafter. The number of Cyanobacteria at all sites fell from 27/11/10 to 28/02/11 before increasing again on 27/04/2011. There were fewer Bacillariophyta on 27/11/10 except at C11. Average number of Bacillariophyta across the region continued to increase during the study period with an average abundance of 1200 cells/mL on 01/11/2011 and 7200 cells/mL on 27/04/2011. In comparison, numbers of Chlorophyta peaked on 31/01/2011 and fell to 20/04/2011. While Euglenozoa, Dinoflagellata, Streptophyta and Cryptophyta phytoplankton were present they contributed little to the overall phytoplankton abundance.

The diversity of phytoplankton genera was highly variable during the study period (Figure 16). There was an average 13 genera across the study period and each site, but the number of genera ranged from 20 at C10 on 05/01/2011 to 8 at C3 on 31/01/2011. Indeed, the number of genera were lowest on 31/01/2011 at most sites. At sites C1-C4 and C7, C9 and C10 diversity increased from 01/11/2011 to 05/01/2011 due to increasing numbers of Bacillariophyta and Streptophyta genera. This was followed by a decrease to 31/01/2011 and a subsequent increase to completion of the study period. In comparison, the number of genera decreased during the study period at C5, C6 and C8 due to decreasing numbers of Chlorophyta and Streptophyta. At C11 the number of genera decreased between 1/11/2010 and 28/02/2011, but then increased to 27/02/2011. Overall, the numbers of genera of Cyanobacteria peaked on 27/11/2011 but were higher on completion of the study than the beginning; Chlorophyta peaked on 5/01/2011 and were lower on completion of the study than the beginning; and Bacillariophyta peaked on completion of the study.

Overall, Cyanobacteria, and to a lesser extent Chlorophyta, were not most abundant phytoplankton. However, Cyanobacteria were dominated by fewer genera than Chlorophyta. While the abundance of Cyanobacteria and Chlorophyta appeared to be decreasing towards the end of the study period, there was an increasing abundance of Bacillariophyta. This was concurrent with an increasing diversity of Bacillariophyta during the study period.

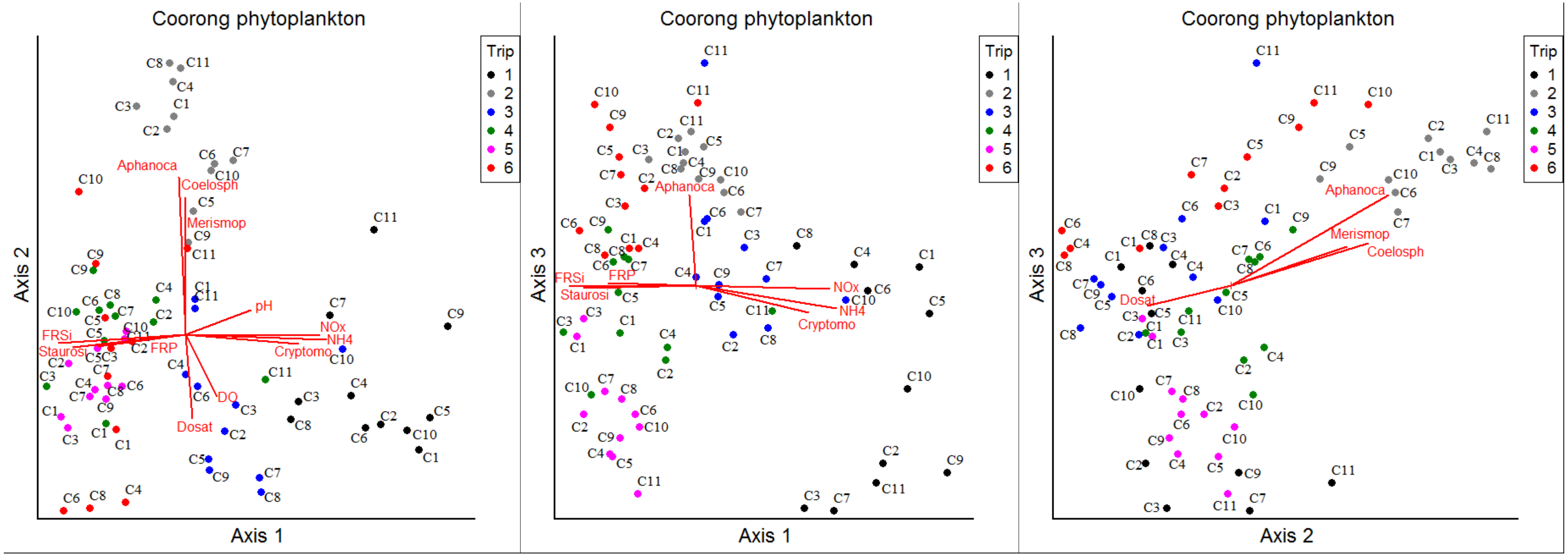

Figure 13. NMS Ordination (Sorensen) of changes in Coorong phytoplankton community November 2010-May 2011. Circles represent phytoplankton communities at a particular site (labelled as site ID) and sampling trip (see legend, labelled sequentially). Vectors show major drivers of change in the phytoplankton community and indicator genera of changes. Drivers include FRSi (r^2 = 0.54), FRP (r^2 = 0.49), NH_4 (r^2 = 0.48), NO_X (r^2 = 0.45), pH (r^2 = 0.37), DOsat (r^2 = 0.33) and DO (r^2 = 0.30). Indicator genera include Aphaoca (*Aphanocapsa*, r^2 = 0.75), Staurosi (*Staurosira,* r^2 = 0.51), Coelsoph (*Coelosphaerium,* r^2 = 0.50), Merismop (*Merismopedia,* r^2 = 0.43) and Cryptomo (*Cryptomonas,* r^2 = 0.42).

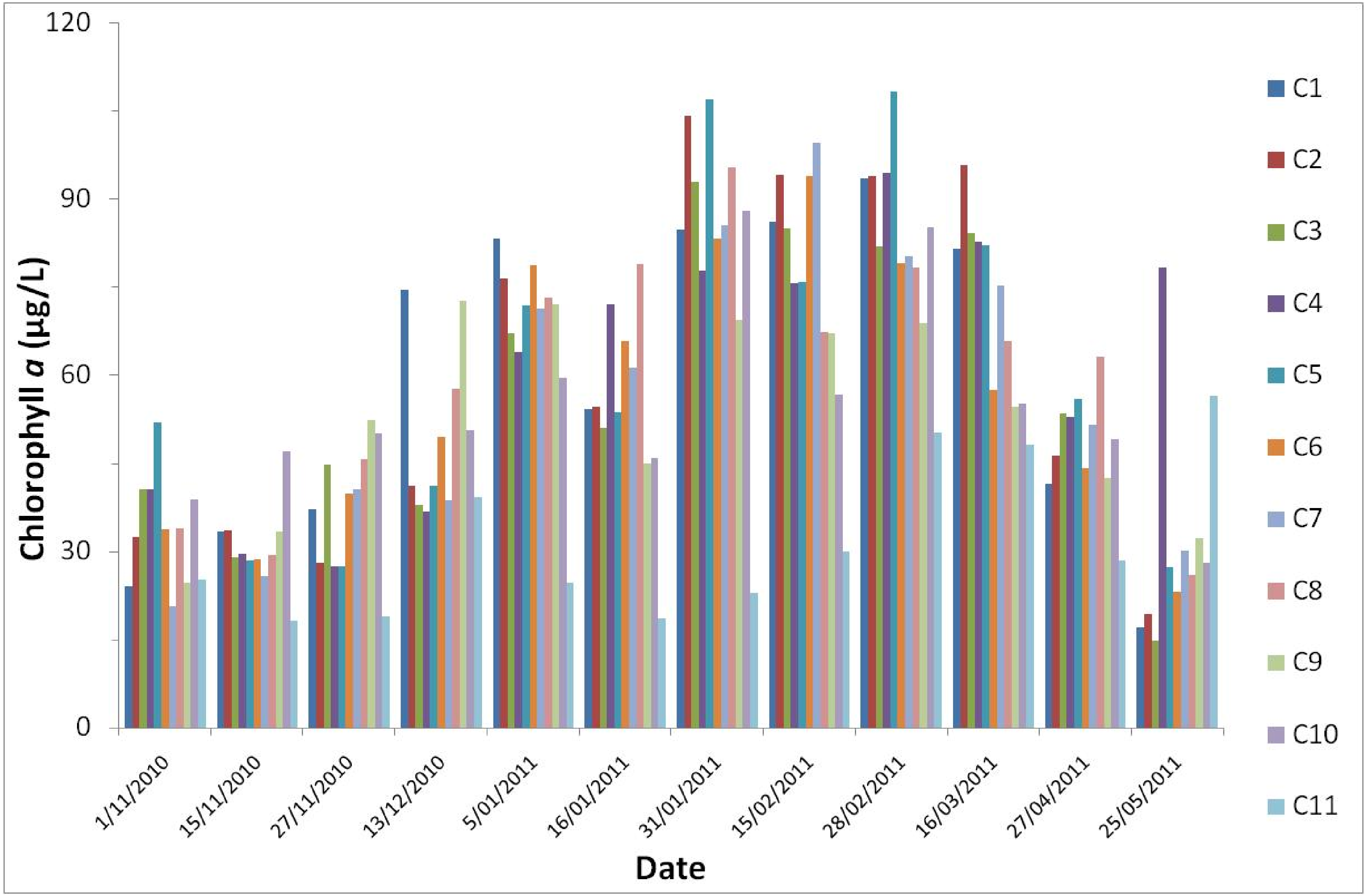

Figure 14. Changes in chlorophyll *a* concentrations in the North Lagoon of the Coorong and Murray Mouth, November 2010-May 2011.

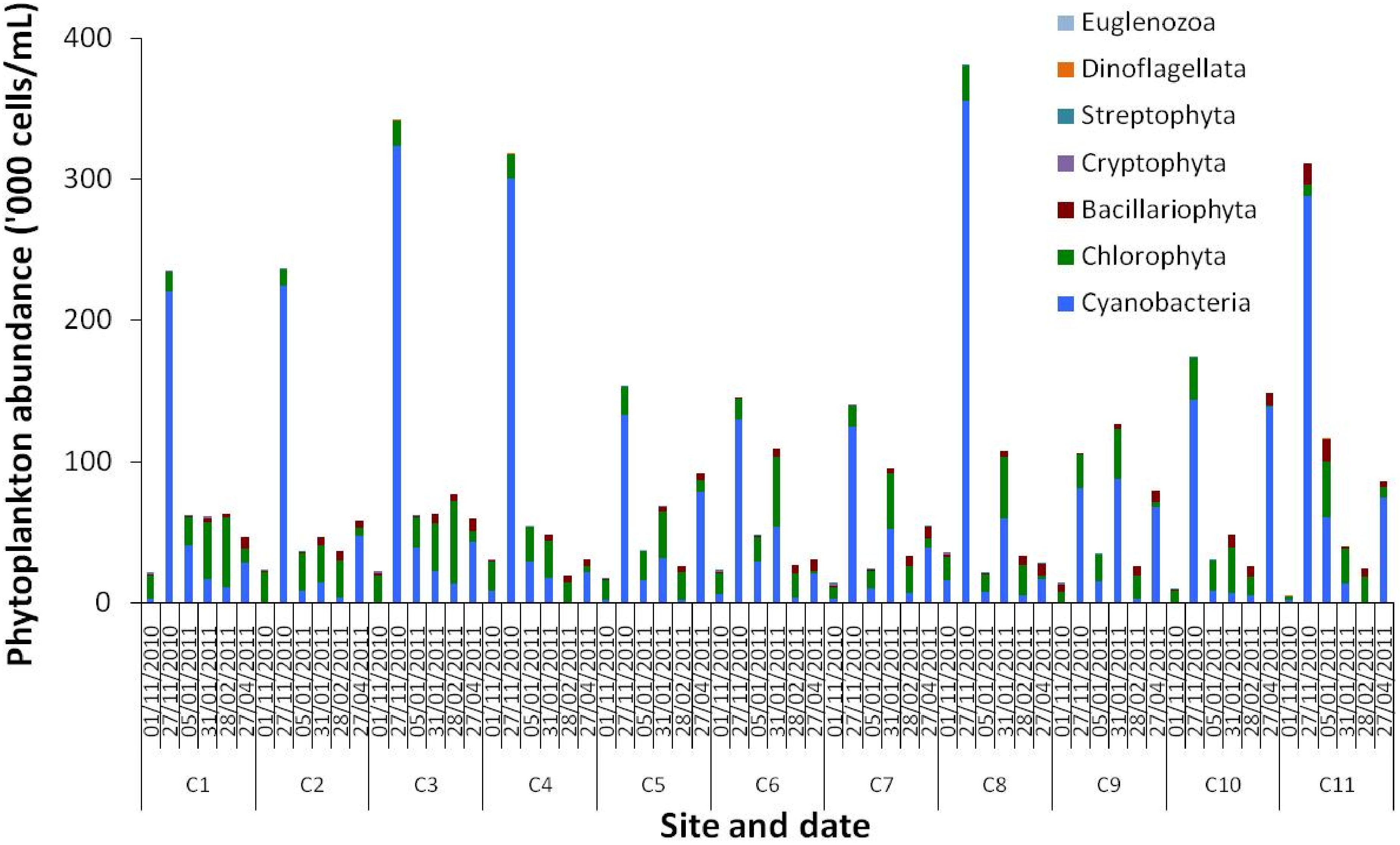

Figure 15. Changes in abundance of phytoplankton groups in the North Lagoon of the Coorong and Murray Mouth, November 2010-May 2011.

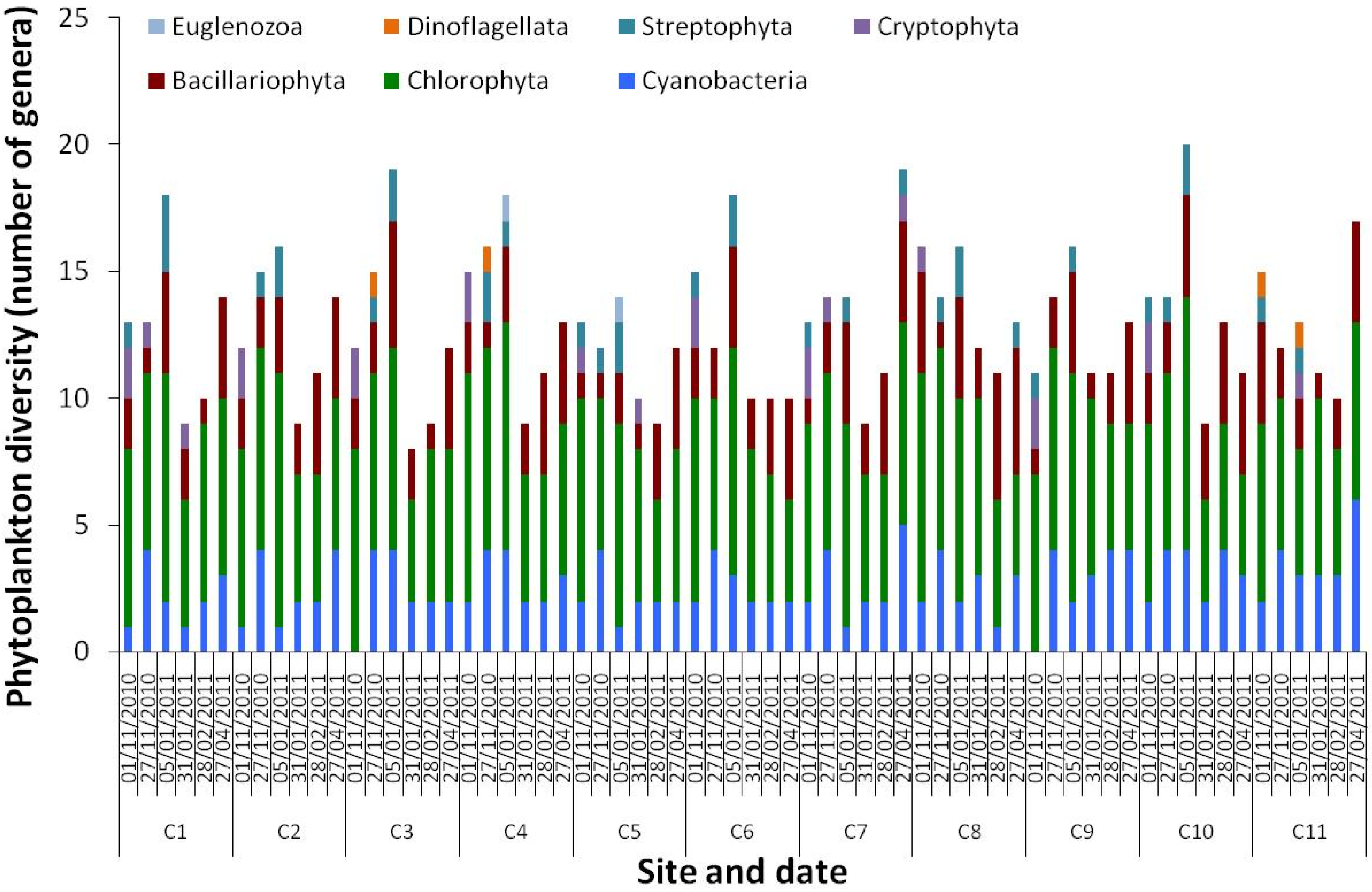

Figure 16. Changes in diversity of phytoplankton groups in the North Lagoon of the Coorong and Murray Mouth, November 2010-May 2011.

Discussion

The greater than anticipated flows have significantly reduced salinity in the North Lagoon of the Coorong, Murray Mouth and even the Southern Ocean near shore environment. Electrical conductivities measured during this study fell from approximately 2500 µS/cm or greater on 1/11/2010 to <500 µS/cm on 27/04/2011 at all sites other than C4 and C11. However, the beginning of the inflow event was not captured during the study and changes in electrical conductivity were greater than those captured within this study. A comparison of data collected between August 2008 and September 2009 by Aldridge (unpublished data) shows that average electrical conductivity of surface water at C2 was 54158.6 µS/cm, whereas during this study the average was 2945.4 µS/cm (Table 2). Due to the magnitude of the inflows there was little variation in electrical conductivity between Tauwitchere and Goolwa Barrages. The large increase in electrical conductivity on 25/05/2011 was associated with high autumn tides and strong on-shore winds in the days preceding. These rapid changes reflect the dynamic nature of the Coorong, which was absent during the drought conditions.

Table 2. Average surface physico-chemical conditions at C2 pre- and post-barrage releases. Pre barrage release measurements were taken every four weeks from August 2008 to September 2009 by Aldridge (unpublished data). Variation is reported as standard deviation.

Parameter	Pre-barrage release	Post-barrage release
Electrical conductivity (µS/cm)	54158.6 ± 7481.8	2945.4 ± 6371.7
Water temperature (°C)	16.70 ± 5.58	20.24 ± 3.40
pH	8.35 ± 0.49	8.28 ± 0.44
Dissolved oxygen (mg/L)	7.99 ± 1.85	8.86 ± 1.09
Turbidity (NTU)	22.2 ± 26.8	119.8 ± 85.7

The electrical conductivity at C4 was highly variable also reflecting the dynamic nature of the Southern Ocean, with daily tide and wind conditions influencing measurements. However, salinity levels were always well below that of seawater demonstrating the sheer volume of water moving through the Murray Mouth. Similarly, there was large variation in electrical conductivity at C11, which most likely reflects the influence of water levels (controlled by tides and inflows) and wind. The results show that freshwater inflows from the barrages have the capacity to influence salinities South-East of C11 with electrical conductivities less than 5000 µS/cm observed on 13/12/10 and 28/02/2011-27/04/2011. The salinity stratification observed at C11 reflects the movement of less dense freshwater over the top of more dense saline water. The density difference prevented complete mixing of the two water bodies with anoxic conditions observed in the hypolimnion. The low oxygen conditions would restrict habitat for flora and fauna and promote nutrient release from sediments. However, the continued inflows disrupted the salinity stratification at C2 and C11, increasing hypolimnetic oxygen concentrations.

Dissolved oxygen concentrations fell initially at most sites, perhaps reflecting inputs of dissolved organic carbon and increased microbial respiration during the flow event. This may have been due to the breakdown of organic material within the Coorong due to the rapid change in salinity. The fall in dissolved oxygen was most apparent at C6 and was associated with a decrease in pH and what appeared to be water with high dissolved organic carbon concentrations. These observations suggest that the lower dissolved oxygen concentrations are the result of inputs of low dissolved oxygen water into the Coorong associated with the inundation of previously dry sediments and dead organic matter. The dissolved organic carbon would increase bacterial respiration and decrease the dissolved oxygen concentrations and pH. During the preceding drought Hunter's Creek had become disconnected from the Lower Lakes and Coorong due to the low water levels and a blocking bank at the Hunter's Creek fishway (Alec Rolston, personal communication). This would have resulted in the drying of sediments and the accumulation of organic matter, promoting deoxygenation upon reconnection. After the initial decrease, average dissolved oxygen concentrations increased again towards the end of the study period, due largely to the breakdown of oxygen depletion associated with salinity stratification. Similarly, the observed fall in pH and increase in turbidity most likely reflects inputs from the Lower Lakes where lower pH and higher turbidity have been observed during the inflow event (DFW, unpublished data) than in recent drought years.

During the inflow event there was an apparent decrease in NH_4 and NO_X concentrations and an increase in FRP, FRSi and TON concentrations. While, NO_X concentrations appeared to be higher than those during the preceding drought period, NH_4 concentrations were comparable (Table 3). A likely explanation is that during the preceding drought, salinity stratification and oxygen depletion prevented nitrification (formation of NO_X), thus promoting the accumulation of NH_4 due to organic matter decomposition with the sediment. Upon re-inundation of previously dry sediments and soils throughout the basin, inorganic nitrogen would have been released resulting in an initial increase in both NH_4 and NO_X concentrations in the Coorong. The subsequent decrease in NH_4 and NO_X concentrations is most likely due to uptake and incorporation into phytoplankton biomass, which is supported by the increasing chlorophyll and TON concentrations. However, towards the end of the study period chlorophyll concentrations fell, but TON did not suggesting that there was incorporation of the nitrogen into the biomass of bacteria or zooplankton. Alternatively, the continued low concentrations of NH_4 and NO_X could have resulted from tightly coupled nitrification-denitrification due to the well oxygenated conditions within the Coorong.

Table 3. Nutrient concentrations and phytoplankton abundance pre- and post-barrage releases. Pre barrage release measurements were taken in March 2009 by Seuront and Leterme (2010), except chlorophyll *a* which collected every four weeks from August 2008 to September 2009 by Aldridge (unpublished data) for C2. Post-barrage releases for chlorophyll *a* is the average concentration at C2 during the study period.

Parameter	Pre-barrage release	Post-barrage release
NH_4-N (mg/L)	≈0.05	0.034
NO_X-N (mg/L)	≈0.005	0.046
FRP (mg/L)	≈0.03	0.012
FRSi (mg/L)	≈0.03	4.3
Chlorophyll *a*	5.8 ± 2.8	53.3 ± 32.5
Cyanobacteria (cells/mL)	0	55640
Chlorophyta (cells/mL)	0	19897
Bacillariophyta (cells/mL)	513-872	3792
Cryptophyta (cells/mL)	0	214
Streptophyta (cells/mL)	0	33
Dinoflagellata (cells/mL)	154-487	2
Euglenozoa (cells/mL)	0	1

Although Redfield ratios suggest that phosphorus is more likely to be limiting than nitrogen, the increased FRP concentrations suggest that phosphorus is not limiting phytoplankton productivity. Indeed, the increasing FRP and decreasing NH_4 and NO_X concentrations may suggest movement towards nitrogen being more limiting than phosphorus as the inflow event continued. At the beginning of the study period it was evident that silica would have been more limiting to Bacillariophyta than nitrogen. However, the incoming flows rapidly increased FRSi concentrations with nitrogen becoming more limiting than silica.

Changes in nutrient concentrations resulting from altered inputs and internal cycling were clearly associated with changes in the phytoplankton community. At the beginning of the study period the phytoplankton community was dominated by Chlorophyta. This community appears to be different to one observed in the region by Seuront and Leterme (Seuront and Leterme 2010) in 2009, which was dominated by Bacillariophyta and Dinoflagellata (Table 3). In December 2007, the phytoplankton community in the Coorong near the Murray Mouth were limited to three genera: a Chlorococcales (believed to be *Nannochloris*, Chlorophyta), *Chaetoceros* (Bacillariophyta) and *Cryptomonas* (Cryptophyta) (Rod Oliver, CSIRO, unpublished). It is evident that as a result of the River Murray inflows there has been an increase in both the abundance and diversity of phytoplankton within the Northern Lagoon of the Coorong. The low diversity and abundance observed during the preceding drought was presumably associated with low nutrient availability (Seuront and Leterme 2010). Indeed, Nayar and Loo (Nayar and Loo 2009) suggested that low phytoplankton productivity was due to nutrient limitation associated with salinity stratification.

As flows continued during this study, the phytoplankton community initially became dominated by Cyanobacteria, which is considered to be the movement of phytoplankton from the Lower Lakes. However, numbers of Cyanobacteria fell and Chlorophyta abundance increased. Bacillariophyta abundance continued to increase throughout the study period. It is envisaged that the phytoplankton community will continue to change with time with an apparent availability of nutrients. Indeed, increasing FRSi concentrations will be more favourable for growth of Bacillariophyta, which are considered to be an important food source for Goolwa Cockles (Seuront and Leterme 2010).

Conclusion

The large inflows to the Coorong from the Lower Lakes between October 2010 and January 2011 clearly caused rapid changes within the Northern Lagoon of the Coorong, Murray Mouth and the near-shore environment (Southern Ocean). Most evident was the rapid and large decrease in salinity levels. Since the studied region contained much of the diversity of the Coorong during the drought (Brookes *et al.* 2009), the rapid changes in salinity may have had short-term negative impacts on the distribution and abundances of marine and sensitive estuarine organisms, particularly less mobile organisms. However, these impacts must be considered at a regional scale with the estuary and marine conditions now present within the Southern Ocean and saline-hypersaline conditions present within the Coorong south-east of the study area. There are also likely to be many immediate benefits of reduced salinity, particularly for freshwater organisms and diadromous fish. Furthermore, the observed increase in dissolved oxygen concentration in the hypolimnion resulting from the breakdown of stratification would increase habitat availability for many organisms.

Although the long-term benefits are less clear at this stage, there is evidence to suggest that they will occur. The large inflow event clearly resulted in increased loads of nutrients from the basin, which increased the abundance, diversity and productivity of the phytoplankton community. The import of nutrients to the Coorong, Murray Mouth and Southern Ocean from the Lower Lakes is likely to result in elevated primary productivity for some time. Assuming that this primary productivity occurs in forms that are available to higher organisms, these benefits will cascade through the food-web, resulting in increased secondary productivity.

Recommendations

- Ecological monitoring
    - Observe longer term response to the inflows, including the response to subsequent inflow events – it is anticipated that changes will be different due to different starting conditions.
    - Application of monitoring framework that is able to capture the onset of unforseen events such as larger than expected floods.

    - Use a long-term monitoring framework to build an understanding of how water quality and phytoplankton communities respond to different flow events and determine habitat preferences of particularly phytoplankton species or groups.
- Research
    - Investigation into the influence of inflows on salinity levels along the entire length of Coorong, including the rate of mixing of freshwater and saline water. This would enable validation of the hydrodynamic model that has been used extensively in prediction of future Coorong habitat (Webster 2007).
    - Research to understand interactions between higher and lower trophic organisms so that monitoring data can be assessed against clear targets.
- Management
    - Where possible for large barrage releases, more gradual initial releases from the barrages to prevent rapid changes to habitat for susceptible organisms.
    - Consideration of barrage release mechanisms to enhance mixing of fresh and saline water south-east of Tauwitchere Barrage.

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Appendix 1: Glossary

Term	Significance for aquatic ecosystems
Allochthonous	Organic material produced externally and imported into a water body
Autochthonous	Organic material produced within a water body
Ammonia (NH_4)	A form of nitrogen that is considered readily available to aquatic organisms in that it requires the lowest amount of energy for incorporation in biomass. Much of the NH_4 arises as the primary end-product of the decomposition of organic matter.
Denitrification	A bacterially mediated process of reducing oxidised nitrogen in anaerobic environments, with the concomitant oxidation of organic matter. It leads to the release of nitrogen gas, which may be released back into the atmosphere.
Dissolved organic carbon (DOC)	A broad classification for dissolved organic molecules of varied origin and composition that is a food/energy source supporting the growth of microorganisms. In general, organic carbon compounds are a result of decomposition of organic matter.
Filterable reactive phosphorus (FRP)	Forms of phosphorus that are considered to be readily available to aquatic organisms. Filterable is in place of dissolved because it is more technically correct as FRP is reactive phosphorus that is able to pass through 0.45 µm (or in some cases 0.22 µm) filters.
Filterable reactive silica (FRSi)	Forms of silica that are considered to be readily available to aquatic organisms. Filterable is in place of dissolved because it is more technically correct as FRSi is reactive silica that is able to pass through 0.45 µm (or in some cases 0.22 µm) filters. It is particularly important for diatoms, which incorporate silica into their cell walls.
Hypolimnion	The bottom layer of a stratified water column layer. It is more dense than the epilimnion (surface water), preventing mixing of the two layers. The density difference is caused by difference in temperature or salinity.
Oxidised nitrogen (NO_x)	The sum of nitrite (NO_2) and nitrate (NO_3), important forms of nitrogen. NO_2 is an intermediate in the nitrogen cycle that is either rapidly oxidised to NO_3 (nitrification) or reduced to nitrogen gas (denitrification). NO_3 is an important source of nitrogen to aquatic organisms, which must be reduced to NH_4 before it can be assimilated.
Redfield ratio	The molecular ratio of carbon, nitrogen and phosphorus in phytoplankton (106:16:1) that is used to assess nutrient availability of aquatic ecosystems. Observed, diversions from the redfield ratio are used to indicate the possibility of nutrient limitation.

Stratification	The formation of distinct vertical layers of water of different densities in a water body. The density differences may be due to differences in temperature or salinity. Stratification prevents the mixing of the different layers.
Total Kjeldahl nitrogen (TKN)	The sum of organic nitrogen and NH_4

Appendix 2: Site coordinates. Geodatic data used was WGS 84.

Site reference	Site description	Longitude (°E)	Latitude (°S)
C1	Goolwa Barrage Downstream	138.81737	35.52718
C2	Half Way	138.85110	35.54021
C3	Sugar’s Beach	138.87921	35.55139
C4	Southern Ocean	138.87552	35.55749
C5	Murray Mouth	138.88164	35.55720
C6	Hunter’s Creek	138.89107	35.53571
C7	Mundoo Channel	138.89784	35.53969
C8	Boundary Creek	138.93509	35.55551
C9	Ewe Island	138.96111	35.56748
C10	Tauwitchere	139.00363	35.58852
C11	Mark Point	139.07573	35.63423