

Composition and distribution of phytoplankton around the Galapagos Archipelago

By

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[Running Header: Galapagos phytoplankton distribution]

Non-Technical Summary

The Galapagos Islands marine ecosystem has regionally high phytoplankton growth and biomass concentrations that are uncharacteristic of the surrounding waters of the Eastern Equatorial Pacific. Even with these high concentrations of phytoplankton, their abundance still remains highly variable throughout the islands. To better quantify this variability, phytoplankton species composition and size distributions were determined at seven stations around the Galapagos Archipelago, three west (area of expected high upwelling of nutrients and iron) and four east of Isabela Island (area of expected low upwelling and low iron). Samples were collected from the *R/V Thomas G Thompson* and put into size groupings using filters of different pore size to concentrate the cells, extract their chlorophyll, and measure their abundance through the amounts of chlorophyll. They were also visually identified via microscopic analyses. Stations west of Isabela Island not only had higher total chlorophyll concentrations than at stations east of the island, but also had highest amounts of chlorophyll at the surface, dominated by phytoplankton larger than 20 μ m. In contrast, the stations east of Isabela had the highest levels of chlorophyll at about 20-30m and were dominated by phytoplankton less than 2 μ m in size throughout most of the water column. Total chlorophyll concentrations and primary production at each station were comparable, which implied that grazing was not significantly different between stations and that it was not the factor that created the differences in chlorophyll distributions between stations. Iron incubation experiments by other students suggested that some stations may not have had enough iron to support the needs of the largest size fraction of phytoplankton, but the data could not conclusively show that iron limitation was the determinant of chlorophyll size distributions.

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Abstract

The Galapagos Islands marine ecosystem has regionally high primary production and chlorophyll concentrations that are uncharacteristic of the surrounding high-nitrate low-chlorophyll waters of the Eastern Equatorial Pacific. Even with these high concentrations of phytoplankton, their abundance still remains highly variable throughout the islands. To better quantify this variability, phytoplankton community composition and distribution were determined at seven stations around the Galapagos Archipelago, three west and four east of Isabela Island. Samples were collected with a CTD and net tow from the *R/V Thomas G Thompson* and analyzed via size fractionated chlorophyll and microscopic analyses. It was found that stations west of Isabela Island not only had higher total chlorophyll concentrations than stations east of Isabela, but also had chlorophyll maxima at the surface dominated by phytoplankton larger than 20 μ m. The stations east of Isabela had sub-surface chlorophyll maxima that coincided with the bottom of the mixed layer and a strong dominance of phytoplankton less than 2 μ m in size throughout most of the water column. Total chlorophyll concentrations and primary production at each station were comparable, which implied that grazing was not significantly different between stations and that it was not the controlling factor of the differences in chlorophyll distributions between stations. Iron incubation experiments by other students suggested that some stations may not have had enough iron to support the needs of the largest size fraction of phytoplankton, but the data could not conclusively show that iron limitation was the determinant of chlorophyll size distributions.

Introduction

The Galapagos Islands are a volcanic archipelago that rises from the sea floor at the equator about 600 miles west of Ecuador, South America. They are home to a productive marine community that is both biologically diverse and highly productive, reflecting the variability of the environment. This diverse environment includes contributions from three different major current systems (the Equatorial Undercurrent from the west, Humboldt Current from the south, and the Panama Current from the northeast) and the effects of both an open ocean and coastal regime (Jimenez 1981).

One of the most distinguishing factors of the Galapagos marine ecosystem is its regionally high primary production and chlorophyll concentrations. In comparison to the high-nitrate low-chlorophyll (HNLC) areas characterizing the eastern Equatorial Pacific at large (Landry et al. 2000), the archipelago supports rich plumes of phytoplankton and corresponding high chlorophyll concentrations of about 0.529mg/m^3 throughout the year, which in turn support more growth in the upper trophic levels within the food web (Torres-Zambrano and Tapia 2000). High chlorophyll concentrations are not spatially uniform throughout the islands, however. In satellite images, chlorophyll concentrations are typically observed to be in high concentrations on the western side of Isabela Island and in much lower concentrations on the eastern side of the island (Figure 1) (Feldman 1986; Palacios 2002; Palacios 2004).

A factor contributing to the size and spatial distribution of phytoplankton in the Galapagos is the upwelling of the Equatorial Undercurrent (EUC). The EUC's main upwelling site is usually on the western side of Isabela where the highest concentrations of chlorophyll are observed by satellite (Jimenez 1981; Feldman 1986). Macro- and micronutrients and cool water are brought to the surface by the current as it runs into Isabela on its eastward track (Jimenez

1981). On the eastern side of Isabela, warmer waters with less nutrients dominate at the surface (Jimenez 1981).

For the area around and within the Galapagos, high concentrations of iron in the water are thought to support phytoplankton growth (Richardson et al. 2004). In the Galapagos, the upwelling of the EUC and the island mass effect are hypothesized to be main sources of this iron input (Landry et al. 1997; Palacios 2002). The island mass effect theory proposes that the iron comes primarily from the island itself, whether as Aeolian dust, water runoff, or by interaction with the island platform. Due to generally westward, wind-driven advection of the water and topographically-induced upwelling on the west side of Isabela, there is expected to be less iron input on the eastern side of Isabela compared to the western side.

Differences in iron input directly and indirectly affect phytoplankton growth rate, distribution, and composition. Iron can hinder the growth of both large and small-sized phytoplankton, but more severely limits the larger sizes. This occurs because larger phytoplankton have a smaller surface area per unit volume ratio than smaller cells and are thus less efficient at the uptake of nutrients, especially nutrients at low concentration, like iron. Supporting this, in iron-limited waters south of the Galapagos and in other HNLC regions, the less than 2 μ m phytoplankton make up the largest fraction of the phytoplankton community (Landry et al. 2000a). When iron is added, as was done in the mesoscale iron enrichment studies in the Equatorial Pacific known as IronEx I and II, only greater than 10 μ m phytoplankton bloom while the smaller cells remain at the same constant abundance, even though both have increased growth rates (Cavender-Bares et al. 1999; Landry et al. 2000a). This observation may be explained by the second controlling factor of the phytoplankton, grazers. The grazers of smaller phytoplankton are comprised mostly of microzooplankton (<500 μ m), which typically have

growth rates that are equal to or greater than those of their phytoplankton prey (Landry et al. 2000b). For this reason, in iron-enrichment experiments the microzooplankton can increase in numbers just as quickly as the phytoplankton and control their population numbers. Mesozooplankton (>500 μm), on the other hand, usually graze phytoplankton that are greater than 10 μm ; they tend to have a much slower growth rate than their prey (Bollens and Landry 2000; Landry et al. 2000b). Larger-celled phytoplankton relieved from iron limitation thus bloom until the mesozooplankton catch up and again control the population. It follows, therefore, that large cells tend to dominate water that has been recently iron-enriched while small cells dominate the community in iron-limited water (Cavender-Bares et al. 1999; Landry et al. 2000a).

In this experiment, the size distribution and community composition of phytoplankton in the Galapagos were measured in order to relate the phytoplankton community to nutrient availability, zooplankton community composition, primary production, phytoplankton growth rate, and herbivory, all determined in other student projects. Samples were analyzed via size fractionated chlorophyll and visual, microscopic analysis. The measured phytoplankton distributions were compared between expected high (west of Isabela Island) and low (east of Isabela Island) chlorophyll areas around the Galapagos and then related to other physical and biological data for each area. It was hypothesized that, if the size distribution of phytoplankton was shifted to larger size fractions on the west side of Isabela Island than on the east side, then the size distribution probably reflected similar controls to those found in the IronEx experiments, namely, interactions between iron limitation and grazing already described. If not, then this could be due to a difference of the long-term availability of iron around the islands, perhaps supporting large phytoplankton and large standing stocks of their grazers, compared to the short-term effects seen in iron-enrichment experiments. When combined with the other projects on the

mesozooplankton community structure, microzooplankton grazing rates, phytoplankton growth rates, and nutrient concentrations, this project will contribute to an overall assessment of the regional food web.

Methods

In order to determine phytoplankton community composition and distribution, CTD casts and net tows were taken at seven different locations in the Galapagos Archipelago (Table 1; Fig. 1) on the *R/V Thomas G. Thompson* from 20 June to 28 June 2006. At each station, five samples were taken at different depths that corresponded to the surface, chlorophyll maximum, depth of no chlorophyll (monitored via the CTD fluorometer), and two additional depths chosen to improve resolution of the upper water column. Water was collected with Niskin bottles attached to the CTD rosette. The net tow was taken with a 25 μ m mesh hand-held net deployed at the surface.

Size-fractionated chlorophyll was used to estimate the size-distribution of phytoplankton community. The size fractionation was performed for each depth at each site in duplicate. Niskin samples were passed sequentially through filters with pore sizes of 20 μ m, 2 μ m (at BIO-1, BIO-2, BIO-3, and BIO-6) or 3 μ m (at BIO-4, BIO-5, and XO-1), and 0.7 μ m (GF/F) thus establishing fractionation groups of >20 μ m, 2 or 3 -20 μ m and <2 or 3 μ m. This allowed for a separation of groups into broad size distinctions. Volumes used depended on the estimated concentration of phytoplankton at the station (estimated from the fluorometry) and ranged from 250 ml for high chlorophyll stations to 500 ml at the lower concentration stations. After filtrations, the chlorophyll on each filter was extracted into 10 ml of acetone, sonicated, and stored in a dark incubator. Samples were then centrifuged and fluorescence was read initially

(F_o) and again after acidification (F_a), following the techniques of Newton and Van Voorhis (2002).

Microscopy and visual identification were used to distinguish between phytoplankton assemblages at most sites. Microscopy was performed on the net-tow samples from BIO-1, BIO-3, BIO-4, and BIO-6. Triplicates of 1ml from each sample were put onto a slide and examined at 100x magnification. Phytoplankton were identified to the genus level using the aid of identification guides (Tomas et al. 1993; Horner 2002) and the local Ecuadorian phytoplankton expert on board, M.E. Tapia.

Results

The CTD measured the highest fluorescence values for chlorophyll maxima to be at BIO-1, BIO-3, and XO-1. Vertical profiles were similar among the stations west of Isabela (BIO-1, BIO-2, BIO-3) with chlorophyll maxima at the surface, and among stations east of Isabela (BIO-4, BIO-5, BIO-6, XO-1) with sub-surface chlorophyll maxima. Mixed layers (as determined from CTD density profiles) were similar at the stations west of Isabela with a 5-10m mixed layer and at stations east of Isabela, with the base of the layer ranging from 20-30m (Fig. 2). The chlorophyll maximum at each station was found at or very close to the bottom of these mixed layers. Surface temperatures for western stations ranged from 20-22°C and for eastern stations ranged from 25-26°C. Salinity showed a similar station grouping, also, with 35 PSU at depth at all stations and between 34.6-34.8 PSU at the surface in the western stations and 33.6-34.2 PSU at the surface in the eastern stations.

As expected, the highest chlorophyll measurements within the water column were found at two of the stations on the west side of Isabela Island, BIO-1 and BIO-3 with 1.87µg L⁻¹ and

1.44 $\mu\text{g L}^{-1}$ respectively. The lowest chlorophyll values were measured east of Isabela Island at BIO-4 and BIO-6 (chlorophyll maxima of 0.30 $\mu\text{g L}^{-1}$ and 0.24 $\mu\text{g L}^{-1}$ respectively) (Fig. 3).

Within the seven stations, common total chlorophyll profiles can be compiled into two groups: stations with surface chlorophyll maxima and stations with sub-surface chlorophyll maxima. The former were all found west of Isabela, while the latter were all found east of Isabela (Fig. 3). Overall BIO-1, BIO-2, BIO-3, and XO-1 had the highest concentrations of chlorophyll at the chlorophyll maximum with values ranging from 0.79-1.86 $\mu\text{g L}^{-1}$ while values from the other stations ranged from 0.23-0.57 $\mu\text{g L}^{-1}$. The eastern stations had low chlorophyll values at the surface that ranged from 0.13-0.34 $\mu\text{g L}^{-1}$ (Fig. 3).

All western stations were dominated by phytoplankton $>20\mu\text{m}$ in size at the surface/chlorophyll maximum, which represented 55-80% of the total chlorophyll. On the eastern side, however, the smaller phytoplankton dominated at the surface. At BIO-4, BIO-5, and XO-1 <2 or $3\mu\text{m}$ phytoplankton comprised of 58-62% of the total (Figs. 4-6). At BIO-6, however, 2-20 μm phytoplankton dominated at the surface. At the chlorophyll maximum for BIO-4, BIO-5, and BIO-6, less than 2 or $3\mu\text{m}$ phytoplankton also dominated with 55-67% of the total. XO-1 demonstrated characteristics similar to that of the western stations with a dominance of greater than 20 μm phytoplankton (49%) at the chlorophyll maximum (Fig. 4; Fig. 5; Fig. 7). At the deepest chlorophyll readings, all stations had total chlorophyll values that were 0.2 $\mu\text{g L}^{-1}$ or less, with BIO-2 having the highest concentration. The western stations had deepest measurements dominated by 2-20 μm phytoplankton (35-50%) and the eastern stations by less than 2 μm phytoplankton (60-67%) (Fig. 8).

Stations also differed in genre of large phytoplankton observed microscopically. Samples showed that most of the phytoplankton larger than 25 μm were diatoms. Of the samples, BIO-6

had the most diverse phytoplankton assemblage that was sampled and observed under the microscope, followed by BIO-4, BIO-1, and BIO-3 (Table 2). *Pseudo-nitzschia / Nitzschia* and *Citoserous* were the most abundant genera at this station, with *Cylindrotheca*, *Rhizosolenia*, *Grommatophora*, *Plantonielia*, and *Coscinodiscus* also being very abundant. BIO-3 had the same dominant species as BIO-6 with *Pseudo-nitzschia / Nitzschia* and *Citoserous/Bacterionella*. BIO-1 was mainly only dominated by *Pseudo-nitzschia / Nitzschia* and BIO-4 was dominated only by *Radiolarian* and *Coscinodiscus* (Table 2). The samples from BIO-6 and BIO-4 were observed within one day of being sampled and the BIO-1 and BIO-3 samples were observed 3-4 days after being taken. This means that sample compositions may have been changed in the later observed samples due to cell death or consumption.

Discussion

The size distributions of phytoplankton around the Galapagos were very close to what was expected. The highest chlorophyll values came from areas that known to have an upwelling of nutrients while also having a hypothesized source of iron from the island. The stimuli for this and all other observations, though, can only be deduced from the analysis of other contributing factors such as nutrients, indicators of primary production, iron enrichment, and their grazers, zooplankton.

First, there is a direct relationship between the mixed layer and the chlorophyll maximum. When a shallow mixed layer is present, the chlorophyll maximum is at the surface (Fig. 2). When there is a deeper mixed layer, the chlorophyll maximum appears just about its base. This may be because the bottom of the mixed layer is where the phytoplankton can get their nutrients. Within the mixed layer, nutrients are depleted because they have been used by

phytoplankton. The bottom of the mixed layer has a gradient where nutrients can diffuse up from high nutrient water that is held below. By staying at the bottom of the mixed layer, the phytoplankton can find the greatest source of nutrients as they diffuse upwards. So this is the area where they live in order to survive.

A hypothesis as to why there is much more chlorophyll on the west side than the east and a much smaller percentage of the greater than 20 μ m phytoplankton is because the larger sized phytoplankton will not be able to uptake low concentrations of nutrients as efficiently as the smaller sized cells. So the large difference in only greater than 20 μ m phytoplankton growth would create the difference in total chlorophyll, as shown in Figs. 5 and 6.

In relation to the nutrient data, there seems to be macronutrients were not limiting at all stations and, if limiting, were doing so in with several nutrients. Nitrate is less than necessary for Redfield Ratio of 1:16 P:N at BIO-1, BIO-3 and BIO-6 (Fig. 9 from Dickson 2006). These stations exhibit ratios of less than 2 at the surface, which shows limitation of nitrate. They also show similar limitations, at the same stations, of silicate. P:Si ratios are below the Redfield Ratio of 2.4 at ratios that are less than 1.5 in the surface waters. This shows that the higher chlorophyll areas are complexly limited by macronutrients, but the areas with low growth have more than enough macronutrients. So something else must be limiting to cause this large difference in chlorophyll biomass between western and eastern stations (Fig. 9 from Dickson 2006).

Another hypothesis as to why the phytoplankton distributions were different that was proven wrong was the idea that primary production was actually occurring in equal amounts at all stations, there were just more predators. Primary production roughly coincided with the results from chlorophyll analyses (Fig. 10 from Gilmore 2006)). Primary production rates were

highest at the surfaces of the western stations, ranging from 9.12-49.1 $\mu\text{mol L}^{-1} \text{d}^{-1}$, and lower there at depth (range of 3.2-4.5 $\mu\text{mol L}^{-1} \text{d}^{-1}$). The eastern stations showed higher primary production at their chlorophyll maxima (which were subsurface), with BIO-4 having a still very low amount of production of 4.8 $\mu\text{mol L}^{-1} \text{d}^{-1}$ (similar to the low chlorophyll values) and BIO-6 having a high primary production rate of 28.9 $\mu\text{mol L}^{-1} \text{d}^{-1}$ that corresponded the larger amount of chlorophyll found at the chlorophyll maximum. There was a small variation in this comparison with BIO-1 having more chlorophyll than BIO-3 and less primary productivity, but between the two sides of Isabela, this observation held true. This shows that, though there was most likely grazing at every station, there were no significant differences in production versus grazing between the western and eastern sides that would result in the large difference in chlorophyll distributions (Gilmore 2006).

The hypothesis that iron was the limiting factor on the eastern side of Isabela was the leading idea in this project. After the iron enrichment experiments on both Leg 1 and Leg 2, the iron impacts at each station seemed to be inconclusive. In one project, it was found that after several days of incubation of a sample taken near BIO-2, the greater than 20 μm phytoplankton did positively respond to the iron addition by increasing approximately 4 $\mu\text{g L}^{-1}$ more than in the control incubation (Fig. 11). No other size group at the station had a significant difference in their iron addition and control incubations. The sample that was taken from a higher chlorophyll area had no significant changes that were observed. This station, however, does not correspond to any of the BIO stations, which makes it incomparable in interpreting the changes within the BIO stations. The data from BIO-2 does show that the greater than 20 μm phytoplankton are limited, which could suggest that either all stations west of Isabela are limited by iron, or that only BIO-2 is iron limited and that this is the reason why the lowest chlorophyll values west of

Isabela were found at this station. The latter idea of the two is more likely because the chlorophyll at BIO-1 and BIO-3 is much higher, suggesting that they are more complexly limited than a single limitation of iron (Litchendorf 2006).

In the second iron enrichment incubations performed by Wendy Guo during Leg 2, it was found that greater than 20µm phytoplankton were limited by iron at both BIO-2 and BIO-4. Significant increases in their growth and grazing rates were found after one-day incubations. All other incubations with smaller cells and at other stations, were found to have no significant trends and were inconclusive. What this suggests is that the largest phytoplankton at BIO-2 and BIO-4 were limited by iron. From the lack of other significant finding at the other stations, it may be that a one-day incubation is not enough to really see the full extent of the effect of iron limitation on phytoplankton and that there may possibly be more limitation on one than the other. A lag time of growth that was longer than one day may have been the reason why most incubations were inconclusive and why changes were not observed. Though the data that BIO-2 and BIO-4 did find a significant increase in growth and grazing rates, there is a lack of data to compare it to. Also, there is no data to compare these stations to the stations of highest chlorophyll biomass (BIO-1 and BIO-3), which could yield a better understanding of the iron processes that create the large differences in chlorophyll. For these reasons, the iron enrichment incubations did not provide the proof necessary to confidently show that chlorophyll size distributions were linked to iron limitation, but suggest that it is a contributing factor (Guo 2006).

Conclusion

Overall, it was found that there was a significant difference in the phytoplankton size distributions throughout the Galapagos Islands. Chlorophyll maxima were found to coincide with the bottom of the mixed layers, which may suggest that phytoplankton experience nutrient limitation at the surface waters and, thus, move to the lower depths of the mixed layer where nutrients diffuse upward from the deep. Greater than 20 μ m phytoplankton dominated at the surface/chlorophyll maximum at stations west of Isabela, and less than 2 μ m phytoplankton were dominant at the surface stations east of Isabela. Less than 2 μ m phytoplankton were also seen to be dominant at the chlorophyll maxima at all of the eastern stations except for XO-1, where greater than 20 μ m phytoplankton were dominant. Some of these size distributions were shown not to be as a result of nutrient limitation because the lowest levels of nutrients only occur where large amounts of production have occurred and consumed all of them. Distributions of phytoplankton closely coincided with primary production levels showing that large differences in predations between stations were not creating the large differences in chlorophyll biomass between stations; the amount of production itself seems to have accounted for most of the difference.

Iron incubations did not provide enough significant data to confidently determine whether iron was or was not limiting in the east versus west stations, but suggested it was a contributing factor. BIO-2 and BIO-4 did suggest an iron limitation on phytoplankton larger than 20 μ m in size, but inconclusive data for the other sizes in this station and all others provided no basis for comparison, and were thus, inconclusive in determining if iron limitation was affecting phytoplankton at stations east of Isabela more than the those on the west side. As a result of the compilation of the other projects on nutrient, primary production, iron enrichment,

and zooplankton distributions, the actual cause of the phytoplankton distributions throughout the Galapagos is suggested to be as a result of iron limitations, but cannot be confidently determined.

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Tables

Table 1. Stations, dates and times, locations, and sample depth for each site.

Station	Date	Time	Latitude	Longitude	Depth (m)
BIO-1	21 January 2006	23:22	S 00 36.9963	W 091 41.9812	131.6
					71.2
					21.5
					11.9
					1.5
BIO-2	23 January 2006	8:02	S 00 36.9759	W 091 18.9998	100.7
					51.7
					21.7
					11.8
					1.4
BIO-3	22 January 2006	19:33	S 00 13.6160	W 091 36.3927	132.8
					82.7
					43.9
					13.5
					1.4
BIO-4	25 January 2006	8:49	S 00 00.9827	W 091.07.9866	101.7
					71.5
					47
					22.1
					1.3
BIO-5	24 January 2006	13:08	S 00 32.0035	W 090 46.9851	101.7
					51.2
					31.7
					16.2
					1
BIO-6	21 January 2006	7:04	S 00 55.0189	W 089 59.9560	67.9
					37.6
					23.4
					12.8
					0
XO-1	27 January 2006	7:11	S 02 00.0050	W 088 59.9860	101.7
					60.7
					21.8
					1.5

Table 2. Genre of phytoplankton at each station, sampled from a net tow for 25µm phytoplankton. Genre are ordered from most to least abundant with **Bolded** names being the most prevalent.

BIO-1	BIO-3	BIO-4	BIO-6
<i>Psuedo-nitzschia / Nitzschia</i>	<i>Citoserous / Bacterionella</i>	<i>Radiolarian</i>	<i>Psuedo-nitzschia / Nitzschia</i>
<i>Citoserous / Bacterionella</i>	<i>Psuedo-nitzschia / Nitzschia</i>	<i>Coscinodiscus</i>	<i>Citoserous</i>
<i>Thalassiosira</i>	<i>Coscinodiscus</i>	<i>Planctonella</i>	<i>Cylindrotheca</i>
<i>Grommatophora</i>	<i>Grommatophora</i>	<i>Psuedo-nitzschia / Nitzschia</i>	<i>Rhizosolenia</i>
<i>Coscinodiscus</i>	<i>Planctonella</i>	<i>Rhizosolenia</i>	<i>Grommatophora</i>
<i>Rhizosolenia</i>		<i>Corethron</i>	<i>Planctonella</i>
<i>Corethron</i>		<i>Asteromphalus</i>	<i>Coscinodiscus</i>
		<i>Thalassiosira</i>	<i>Thalassiosira</i>
		<i>Citoserous</i>	<i>Naviculae</i>
		<i>Grommatophora</i>	<i>Radiolarian</i>
			<i>Asterianopsis</i>
			<i>Bacteriastrum</i>
			<i>Asteromphalus</i>

Figure Legend

Figure 1 – Satellite ocean color image showing the distribution of phytoplankton pigments around the Galapagos Islands acquired on 11 June 1981 (Feldman 1986). Locations sampled during this cruise are also indicated as BIO 1-6 with 7 being XO-1.

Figure 2 – CTD fluorescence ($\mu\text{g L}^{-1}$) and density (kg/m^3) showing the chlorophyll maximum in comparison to the mixed layer depth for (A) BIO-3 representing stations west of Isabela and (B) BIO-5 representing stations east of Isabela.

Figure 3 – Total chlorophyll ($\mu\text{g L}^{-1}$) per depth at stations (A) west (BIO-1, 2, 3) and (B) east (BIO-4, 5, 6, XO-1) of Isabela. Error bars are one standard deviation for two measurements.

Figure 4 – Amounts of size fractionated chlorophyll ($<2\mu\text{m}$, $2\text{-}20\mu\text{m}$, $>20\mu\text{m}$ filters) per depth (A) BIO-1, (B) BIO-2, and (C) BIO-3. Error bars represent one standard deviation for two measurements.

Figure 5 – Amounts of size fractionated chlorophyll ($<2\mu\text{m}$, $2\text{-}20\mu\text{m}$, $>20\mu\text{m}$ filters) per depth (A) BIO-4, (B) BIO-5, (C) BIO-6, and (D) XO-1. Error bars represent one standard deviation for two measurements.

Note: BIO-4, BIO-5, and XO-1 use $3\mu\text{m}$ filters instead of $2\mu\text{m}$ filters.

Figure 6 – For surface depths (A) amounts of chlorophyll per size fractionation ($\mu\text{g L}^{-1}$) per station (error bars are one standard deviation) and (B) percents of each size fraction per station. Station 7 is XO-1.

Figure 7 – For the chlorophyll maximum (A) amounts of chlorophyll per size fractionation ($\mu\text{g L}^{-1}$) per stations (error bars are one standard deviation for two measurements) (BIO-1-3 have same data points used in Fig. 6) and (B) percents of each size fraction per station. Station 7 is XO-1.

Figure 8 – Percents of each size fraction per station at greatest depth for each station. Station 7 is XO-1.

Figure 9 – Concentrations of macronutrients at (A) surface, (B) chlorophyll maximum, and (C) deepest measurement. Data points for BIO-1-3 are the same between (A) and (B) (Dickson 2006).

Figure 10 – Average primary production ($\mu\text{mol L}^{-1} \text{d}^{-1}$) at the surface and 20m at each station (Gilmore 2006).

Figure 11 – Increase in chlorophyll concentrations ($\text{Chl}_f - \text{Chl}_o$) over 72h incubations with and without iron additions at BIO-2. Error bars are one standard deviation (Litchendorf 2006).

Figures

Fig. 1

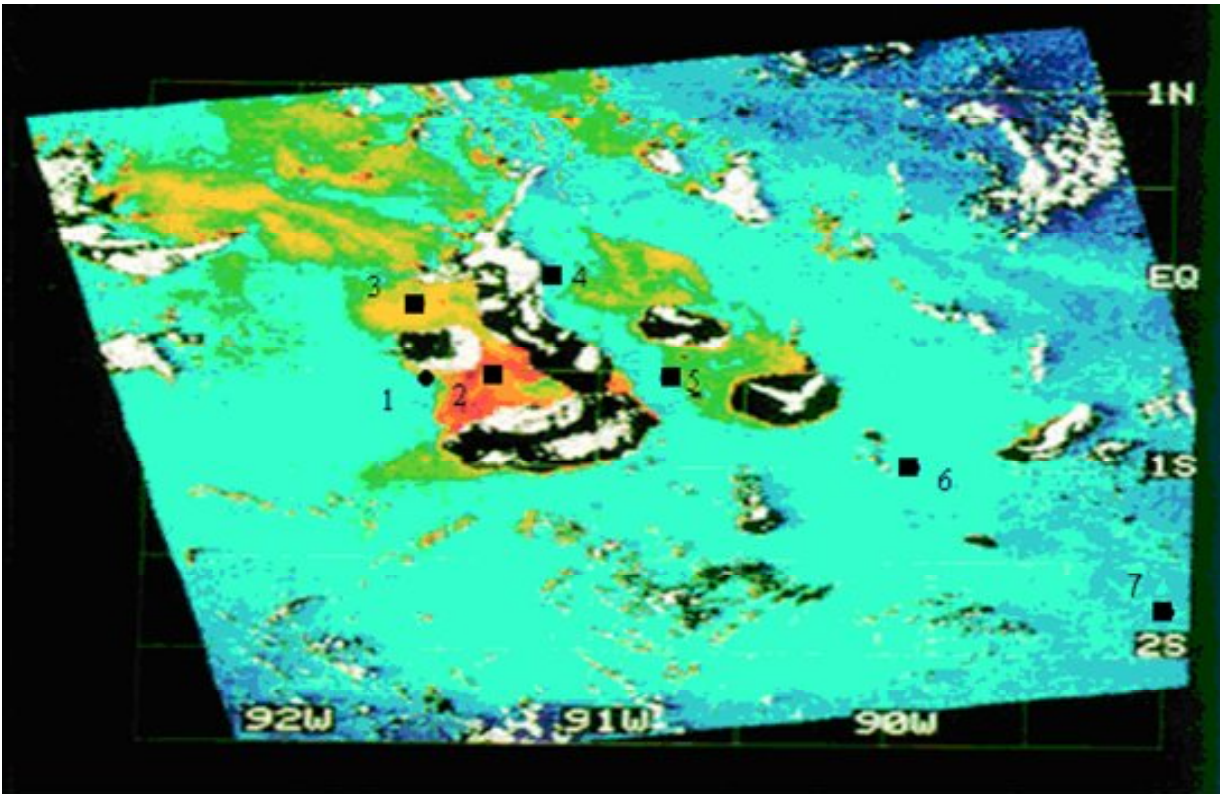


Fig. 2

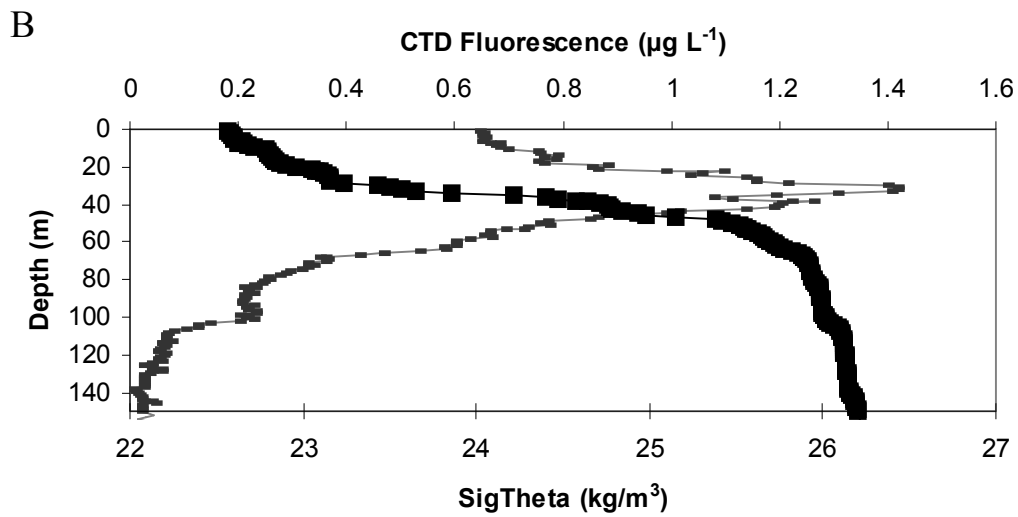
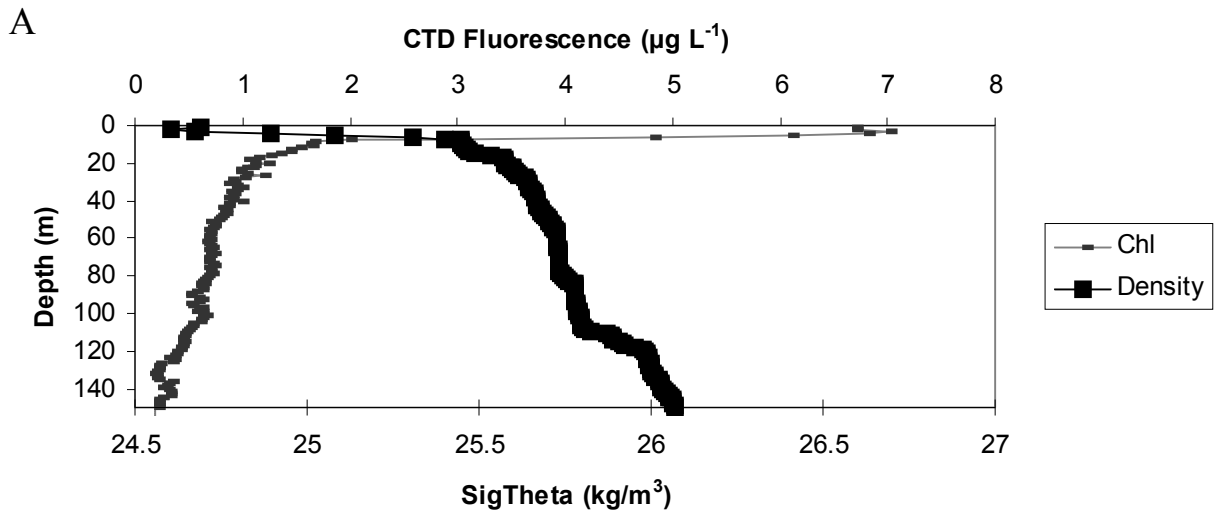


Fig. 3

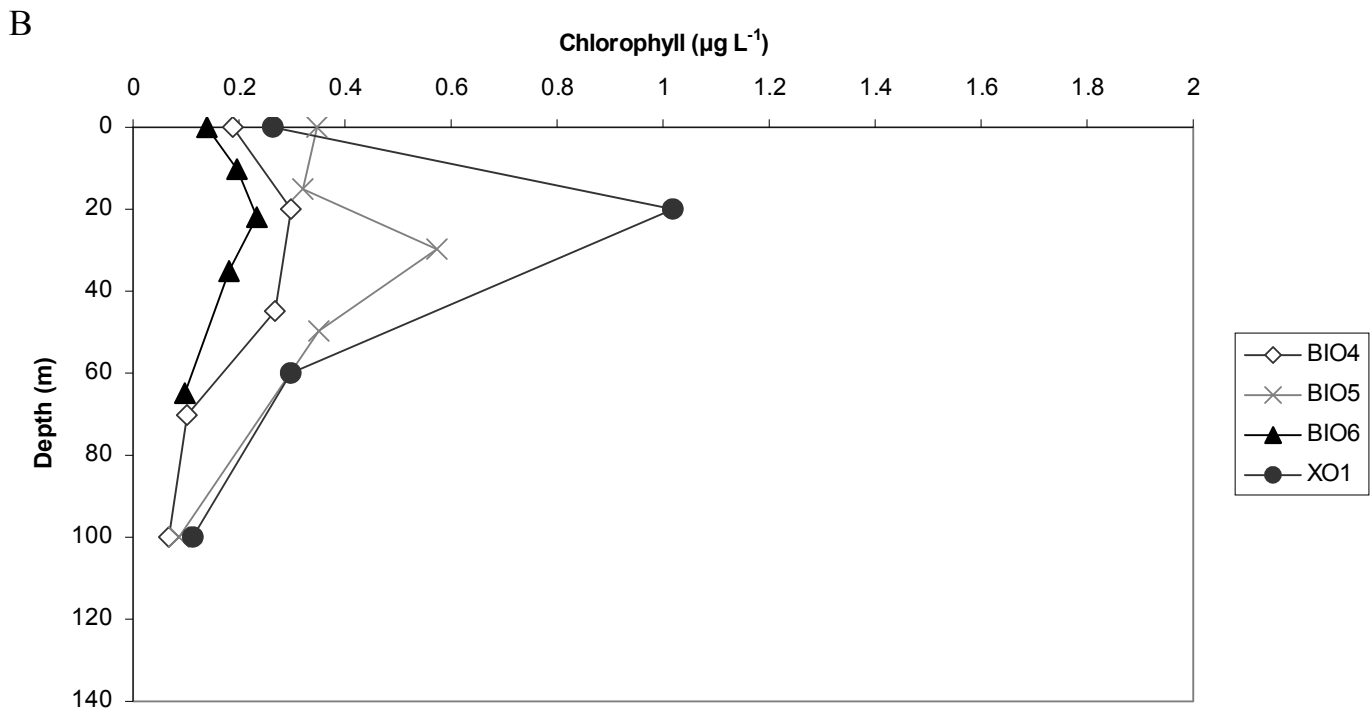
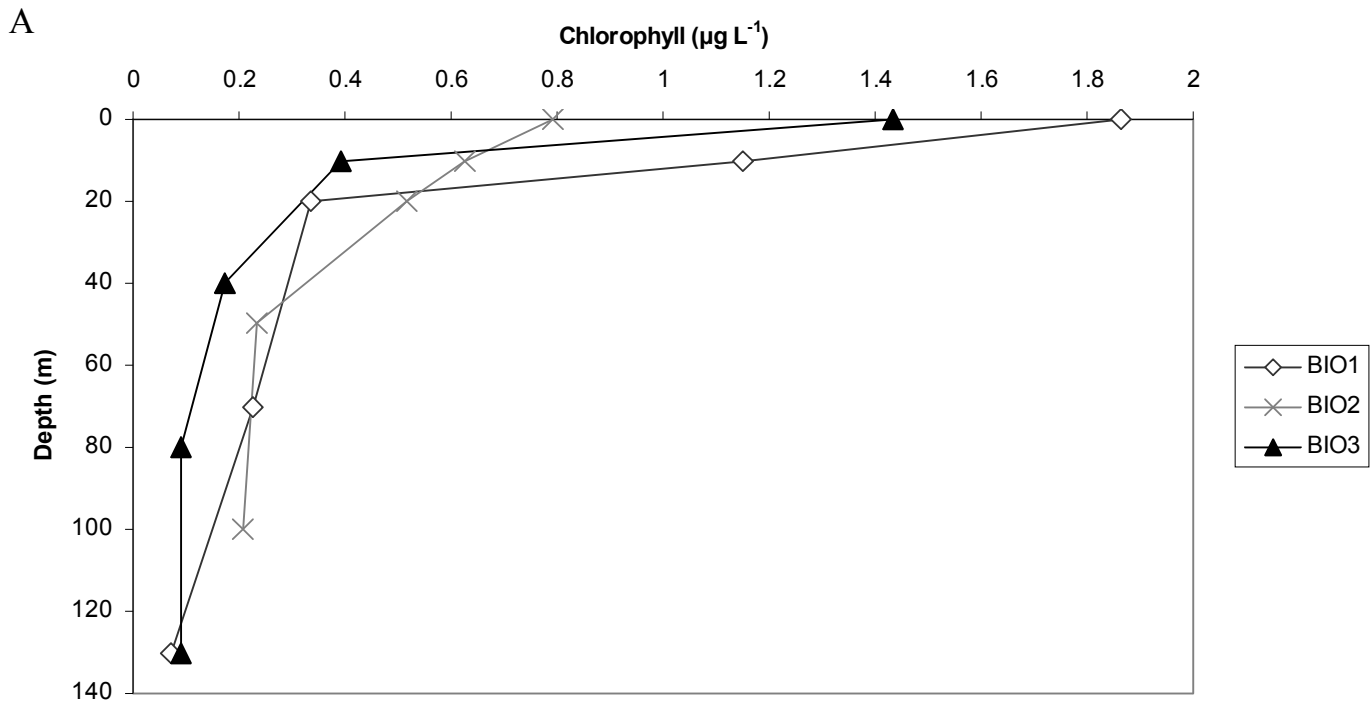


Fig. 4

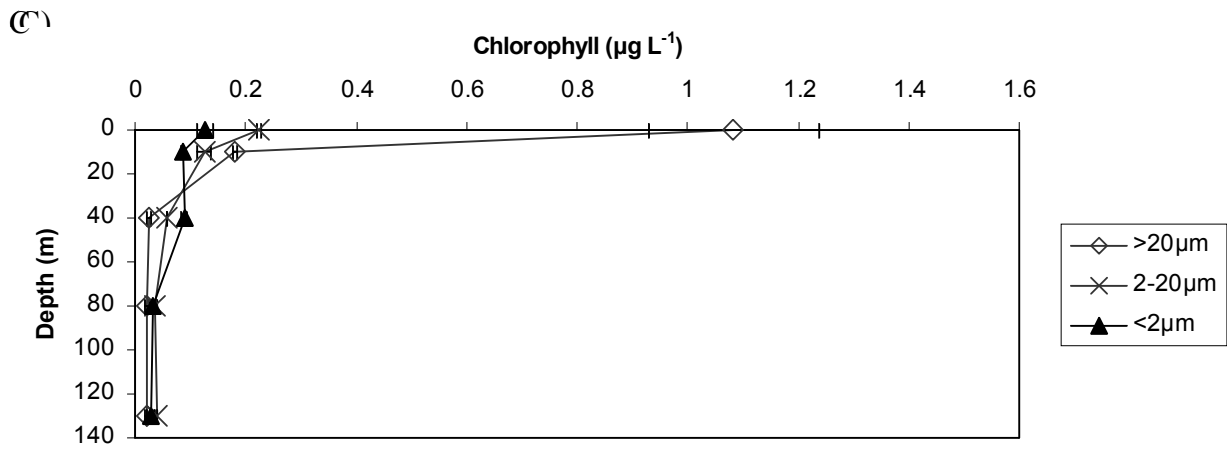
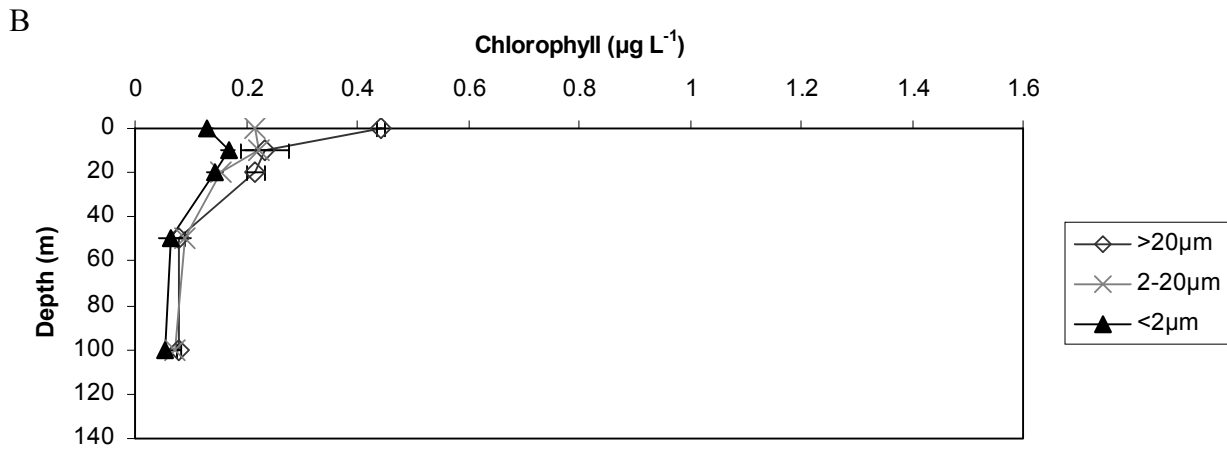
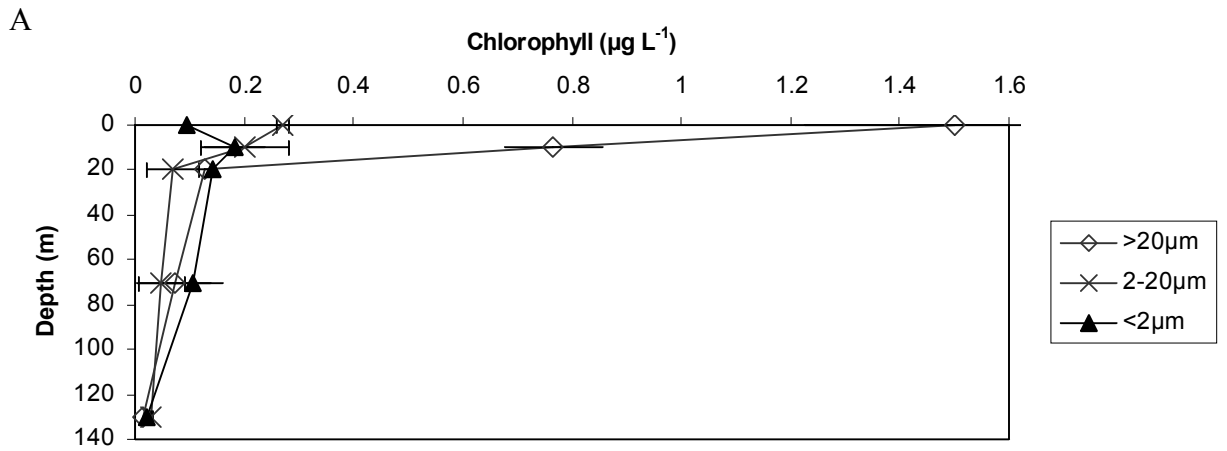


Fig. 5

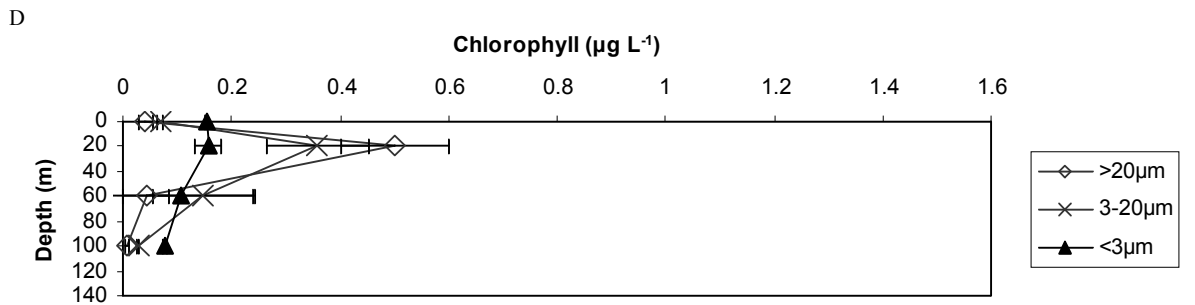
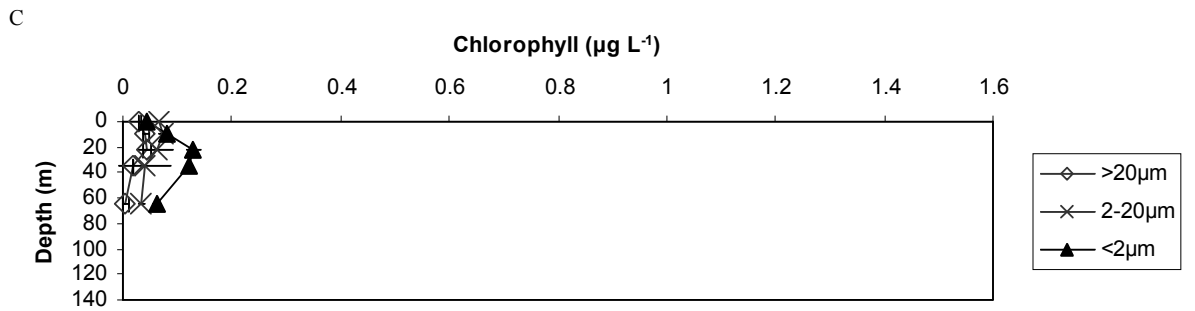
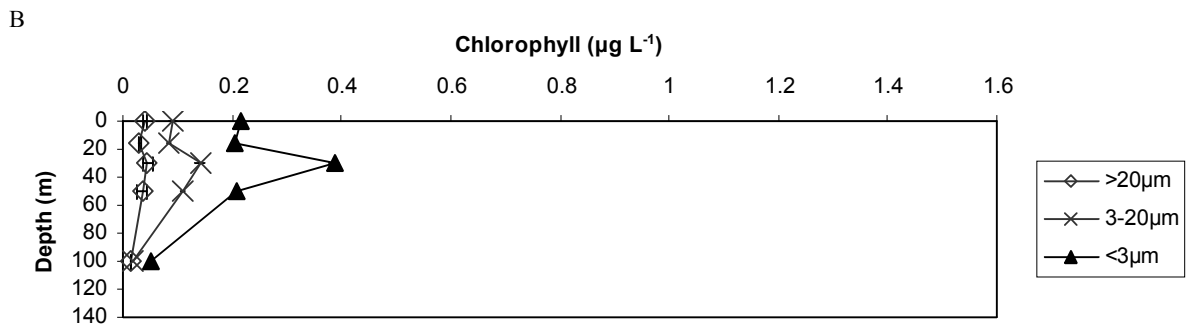
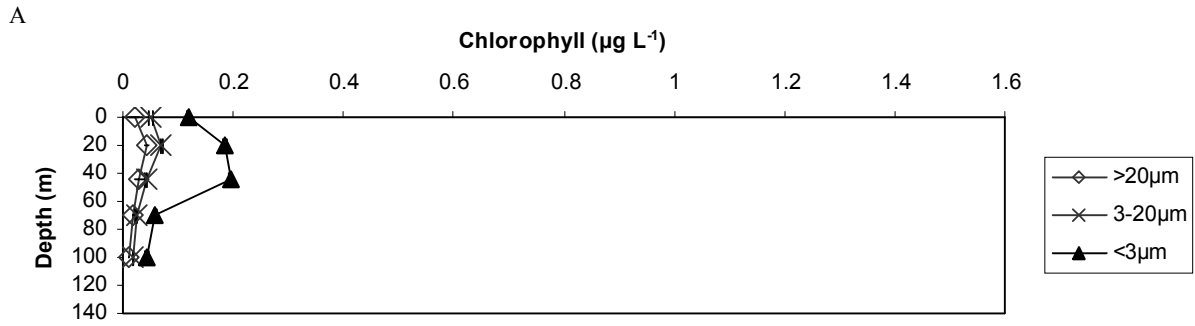


Fig. 6

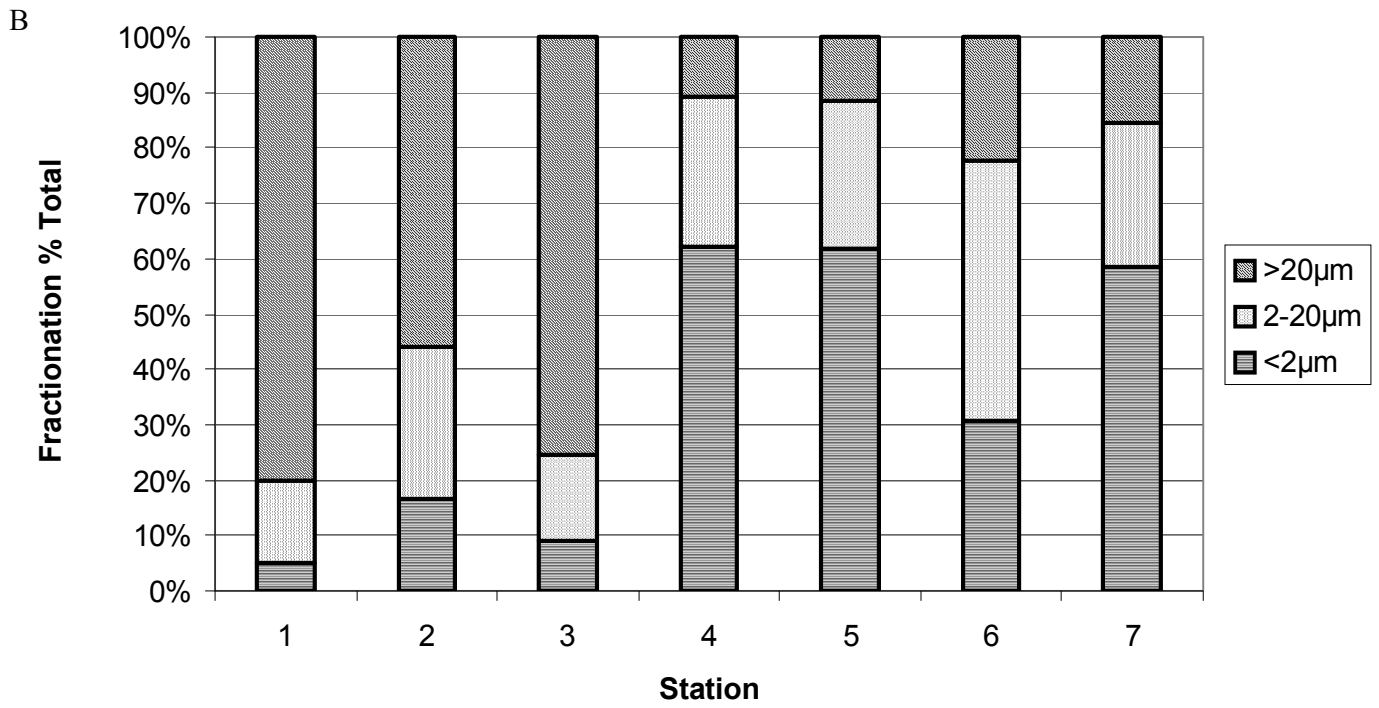
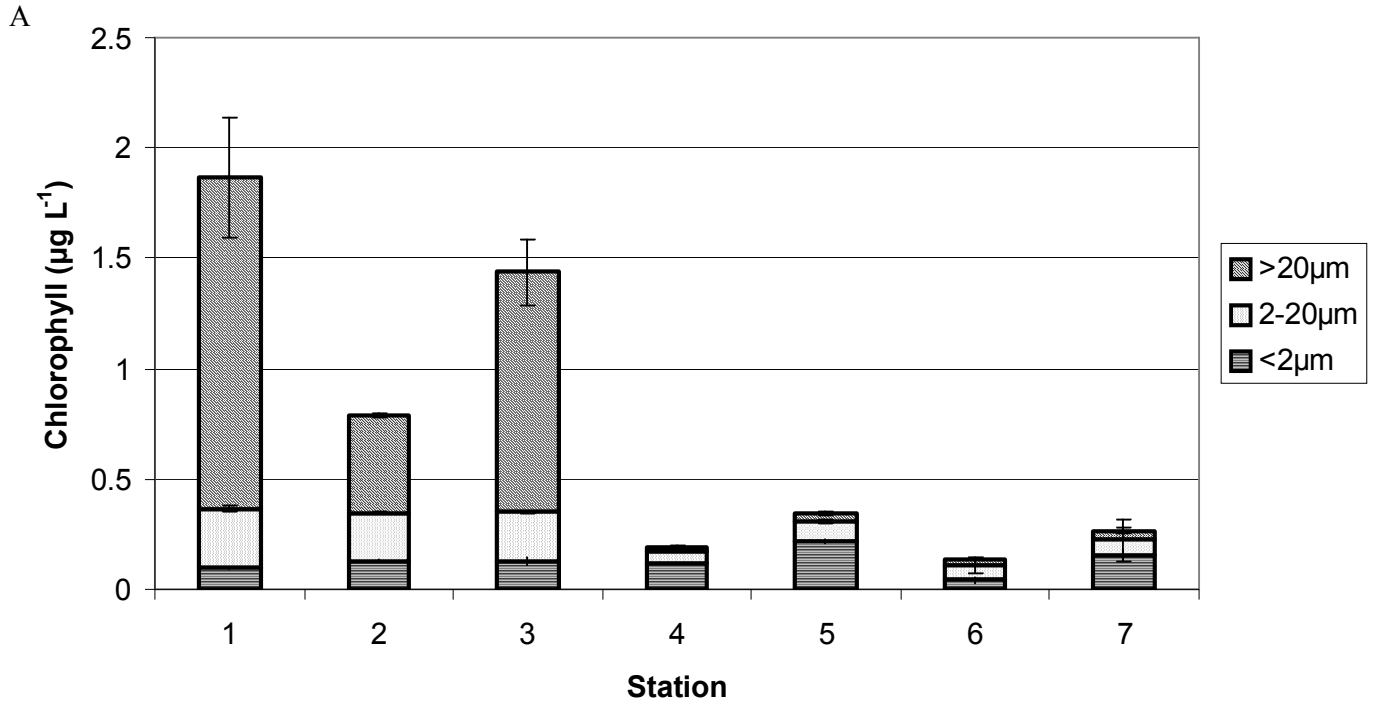
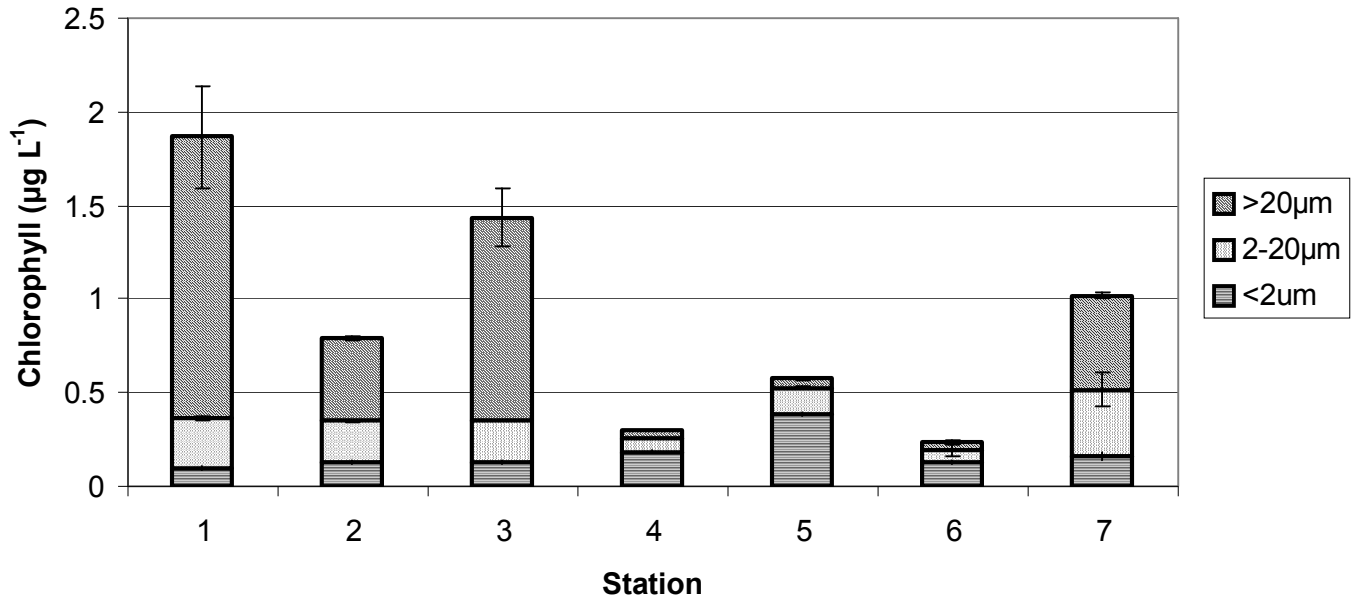


Fig. 7

A



B

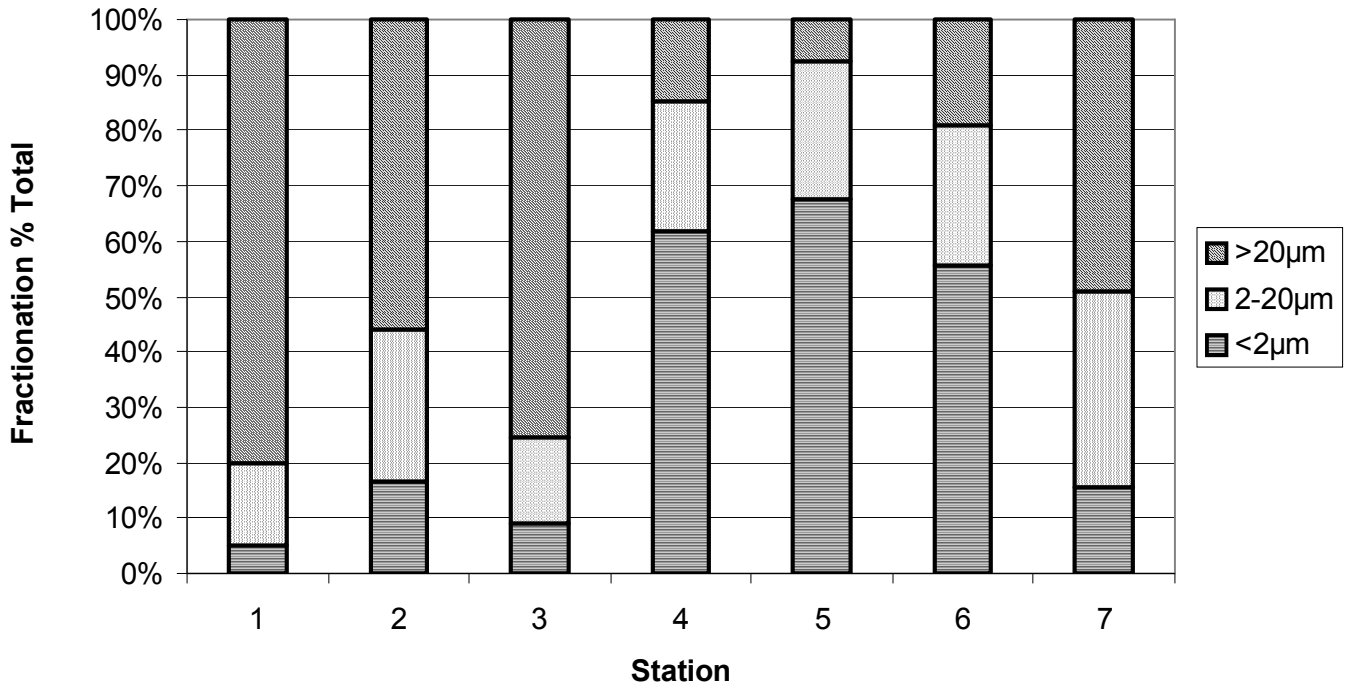


Fig. 8

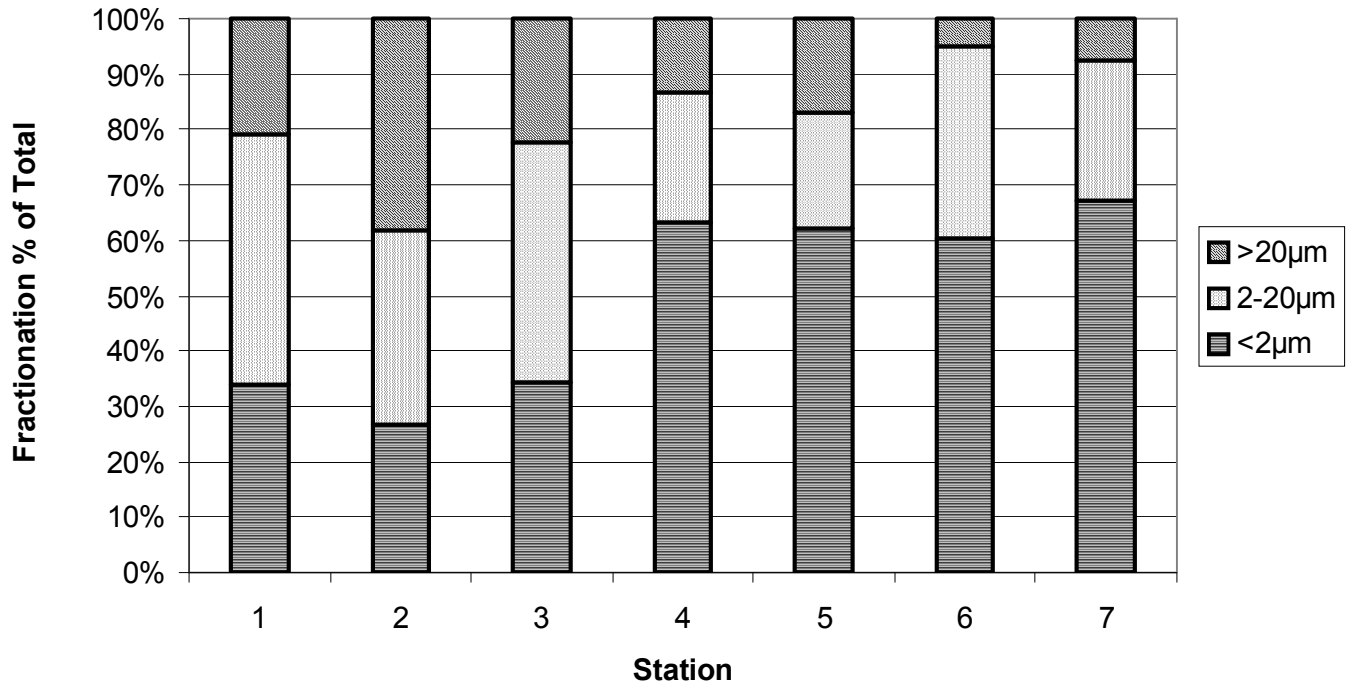


Fig. 9

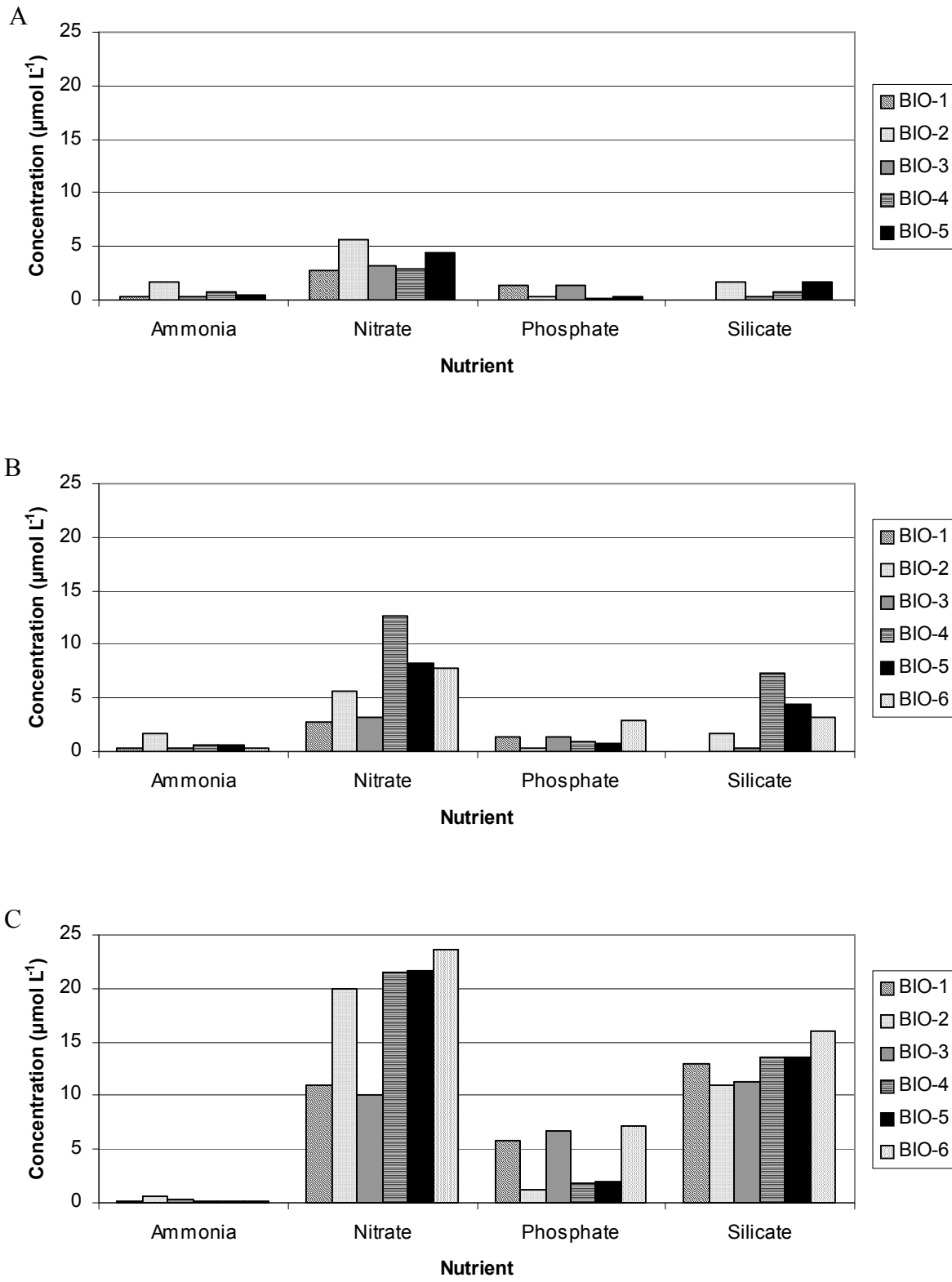


Fig. 10

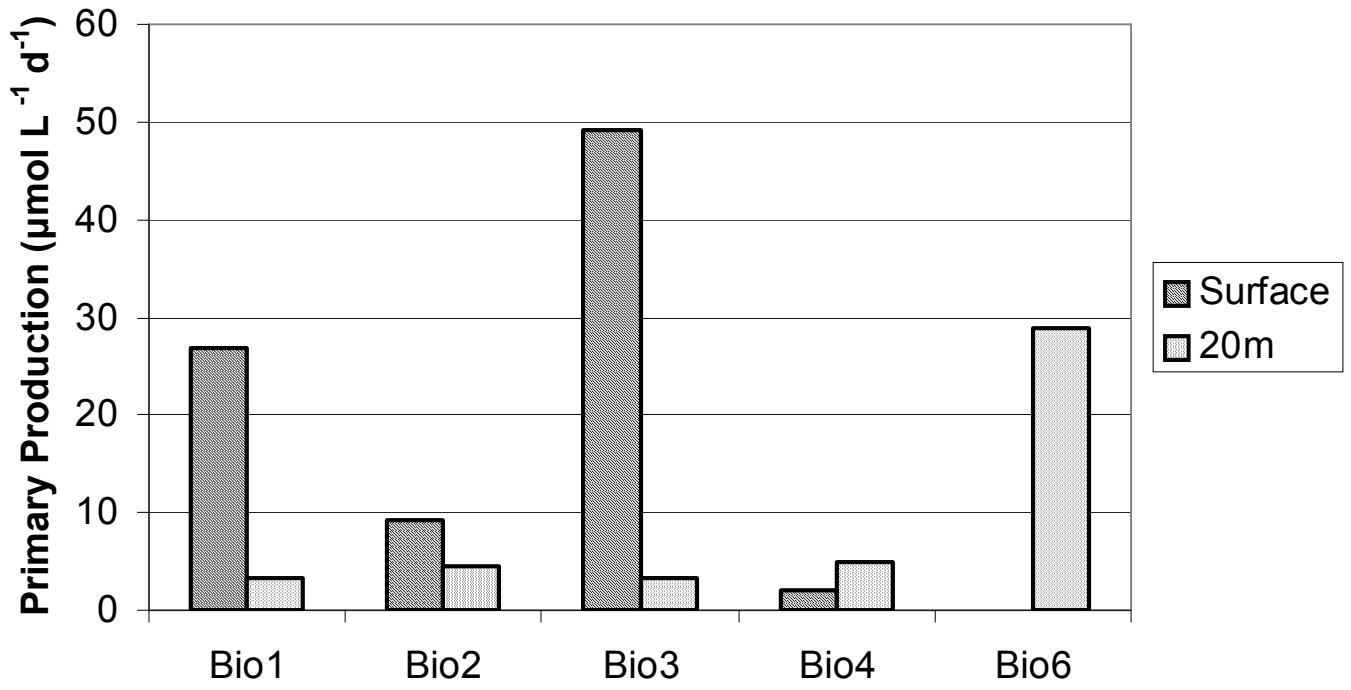


Fig. 11

