Primary Production around the Galapagos Islands and the effects of cloud cover and differing light regimes

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Running title: Primary production and cloud cover of the Galapagos Islands

Non-Technical Summary

This paper highlights my study on the effects of cloud cover on the primary production around the Galapagos Islands in the Equatorial Pacific Ocean. Primary production is the photosynthesis done by marine phytoplankton, who serve as the base of the marine food web. Considerable emphasis has been placed on understanding the controls of primary production with much of the focus falling on possible iron limitation. Iron is a land-derived nutrient needed by phytoplankton to photosynthesize. Many large-scale iron fertilization experiments have been conducted near the Galapagos region and have found that iron does indeed limit phytoplankton growth. Another factor that has received less attention but is also regionally relevant is the effects of differing light intensities on the phytoplankton growth. To examine this, I measured primary production at eight stations around the Galapagos Islands as a function of light intensity and cloud cover, as measured by shipboard sensors, monitored by satellite images, and manipulated experimentally. To determine production, oxygen analyses were done on time-zero and 24-hour incubated water samples, since photosynthesis results in oxygen production. Samples were incubated with different levels of screening to control light levels. Results showed that changing light conditions had little effect on oxygen production in these experiments; therefore it can be concluded that changing light regimes caused by cloud cover in the region of the Galapagos Islands may not have an important effect on primary production.

Acknowledgements

I would first like to thank the University of Washington's Oceanography department for providing this amazing opportunity to go and study such a great place as the Galapagos Islands. I am also very thankful to the captain and crew of R/V Thomas G Thompson for their hospitality and a great cruise and my Ocean 444 teaching team, especially Llyd Wells, for all of their time, effort, patience and unparalleled knowledge. Another thanks to my fellow classmates for supplying pertinent data for my study. Finally, thanks to my grandmother who has blessed me with such life-giving love and support.

Abstract

The spatial distribution and effect of light intensity on primary production around the Galapagos Islands were studied in late January 2006 using measurements of dissolved oxygen concentration, surface photosynthetically active radiation (PAR) and satellite imagery. Measured primary production values in incubations of differing light intensities were found to be statistically indistinguishable; measurements of daylight PAR also did not correlate with primary production values. Primary production values averaged across treatments displayed much spatial variability. On the west side of Isabela Island, surface waters produced the highest values of production (~ 35 μmol C $L^{-1}d^{-1}$) with nearly undetectable values produced from sub-surface waters. In contrast, on the east side of Isabela Island sub-surface waters produced the highest values (~ 20 μmol C $L^{-1}d^{-1}$) with lowest values (~ 7 μmol C $L^{-1}d^{-1}$) produced from surface waters. The vertical distribution of chlorophyll *a* in the water column showed a similar pattern, with the maximum at the surface to the west and below the surface to the east. Chlorophyll *a* size fractionations, measured by collaborating scientists, showed a dominance of larger size fractions (mostly diatoms) on the west side and a dominance of small size fractions on the east side. Thus, differences in primary production from the east side of Isabela Island versus the west side of Isabela Island may be due to phytoplankton community composition rather than differing light intensities.

Introduction

There is much debate about the factors that limit phytoplankton growth in the equatorial Pacific Ocean, much of which is a high-nitrate, low-chlorophyll (HNLC) region. To address the issue, mesoscale iron enrichment experiments in the open ocean, such as IronEx I and IronEx II, have tested the idea that iron is limiting phytoplankton growth in this region. The IronEx I findings of a doubling in phytoplankton biomass, a tripling in chlorophyll concentration and a quadrupling in primary production due to iron enrichment (Martin el al. 1994) strongly suggest that iron is a limiting factor in the production of the equatorial Pacific Ocean. This is also suggested by even more dramatic increases in carbon biomass, chlorophyll concentration and phytoplankton abundance in IronEx II (Landry et al. 2000). With respect to the Eastern Equatorial Pacific, anomalously high chlorophyll conditions are found downstream to the west of the Galapagos Islands, an observation that may be explained in the context of the IronEx studies by natural enrichment of the area by island-derived iron (Martin et al. 1994).

Another factor thought to have contributed to the muted phytoplankton response to IronEx I, compared to IronEx II, was subduction of the seeded water– a circumstance that in some ways parallels reduced light levels during heavy cloud cover, since primary production depends on light intensity (Macedo et al. 1998). Although photosynthesis occurs over a range from nearly full sunlight at the sea surface to nearly complete darkness at the bottom of the photic zone, higher light regimes typically favor enhanced rates of photosynthesis, except at extreme light intensities that result in photoinhibition (Harris and Lott 1973). The relationship between photosynthesis and irradiance is thus fundamental to understanding phytoplankton ecology. Along with other factors (such as turbulence, tides, and suspended solids), clouds

diminish light intensity in the water column. Clouds alone can account for 14-17% of the total annual variation in irradiance, with surface irradiances of 20-40% less on cloudy days in the summer than on cloudless days (Anthony et al. 2004).

Only a few measurements of primary production are yet published for the Galapagos Islands region. Houvenaghel (1978) linked the variability of his primary production measurements (using the same methods as used for my study) only to the availability of nutrients associated with different circulation regimes, without considering cloud cover.

Contrary to expectations for an equatorial locale, Galapagos weather is relatively temperate due to cold upwelled waters surrounding the islands. This region has two main seasons: the warm and wet season from January to June and the cool and dry season from July to December. During the cool and dry season, warm tropical air passing over cool water results in extensive evaporation leading to dense cloud cover. Analysis of 28 randomly chosen processed satellite images (http://oceancolor.gsfc.nasa.gov) spanning 7 months from 13 May 2005 to 18 Nov 2005 (Fig. 1 and Table 1; details of data analysis are described in the Methods section) reveal that the Galapagos region on average has high cloud cover, though distribution is not uniform around the islands (the area west and north of Isabela commonly being less cloud influenced, for example; Table 1). The work described in this study occurred in late January 2006 during the transition period from the cool and dry season to the warm and wet season, when clouds tend to predominate.

The purpose of this study was to examine the relative contribution of clouds to the variation in irradiance and consequent primary production in the Galapagos Islands region. Variations of production with irradiance were studied using artificially manipulated light regimes and compared to daily levels of photosynthetically active radiation measured shipboard.

Additionally, true color satellite images were analyzed to consider the extent and distribution of cloud cover and pigment concentration. Excluding possible photoinhibition, I expected higher amounts of primary production to result from higher light intensities and lower amounts of primary production to result from lower light intensities. My data also provide general information on the spatial distribution of primary production around the Galapagos Islands during the 8-day sampling period.

Methods

Sample collection— Sampling was conducted from R/V Thomas G. Thompson from 20-28 January 2006. Water samples were collected from four stations on the western side of Isabela Island and four stations on the eastern side of Isabela Island (Table 2, Fig.2). Bio stations samples were collected at or near the surface and at the chlorophyll maximum (or at 20-40 m if the chlorophyll maximum was at the surface), as measured by the fluorometer on the conductivity temperature depth (CTD) rosette, whereas Bc stations were only measured at one depth. Specifically, two stations in Elizabeth Bay (Bio 2 and Bc 1) on the western side of Isabela Island were chosen because a plume of chlorophyll rich water typically exists there (Martin et al. 1994), while two stations on the eastern side of Isabela Island were selected due to the low concentrations of chlorophyll commonly found there (Feldman 1986). Other stations were chosen to coordinate with fellow student projects. Water was collected in six Niskin bottles, 3 at the surface and 3 at the chlorophyll maximum (or at 20-40 m if the chlorophyll maximum was at the surface), using a CTD rosette.

Once shipboard, primary production was determined from oxygen production measured using the classic Winkler method (Carpenter 1965) over 24 hour incubation periods. Water was carefully transferred from the Niskins into 24 separate 120 ml glass bottles using plastic tubing connected to the Niskin to prevent oxygen contamination. Before filling, each bottle was rinsed 3 times with ambient seawater to prevent any other contaminations. Six bottles (3 from each depth) were immediately injected with 1 ml of manganese chloride and 1 ml of sodium hydroxide-sodium iodide, to fix the oxygen in the bottle, shaken to promote thorough mixing, and placed in dark storage to be analyzed at a later time. The remaining 18 bottles, 9 from one depth and 9 from the other, were labeled, sealed with a glass stopper and ordinary electrical tape and placed into the shipboard incubators. Light levels were manipulated using ordinary screen door screening, which decreases the intensity of irradiance by 50% per layer, as measured in the lab. Bottles incubated at 100% light intensity were placed in one incubator with no screening. Bottles incubated at 50% light intensity were placed in another incubator, which had been wrapped with one layer of screening. Bottles incubated at 25% light intensities were placed in bags made of one layer of screening and also incubated in the screened incubator. The 2 incubators used were covered plexiglass tanks filled with continuously flowing surface seawater.

The 18 oxygen bottles were incubated for 24 hours. After incubation, each bottle was opened and fixed and measurements of dissolved oxygen were made as in Carpenter (1965). Once all measurements had been made, values from the unincubated bottles ($O_{2\ initial}$) were subtracted from the values obtained from the incubated bottles ($O_{2\ final}$), which gave total values of oxygen production. In theory, the change in O_2 concentration is proportional to the quantity of organic carbon fixed by the phytoplankton (106 moles of C are fixed into organic matter per

155 moles of O_2 gas released). Thus, changes in O_2 concentrations were converted to primary production using the methods of J. Murray (2006, personal communication).

Cloud Cover and light intensity— Processed true color satellite images were downloaded from http://oceancolor.gsfc.nasa.gov for the period of 20-28 January 2006 to correlate with shipboard experiments. These images, as well as the 2005 images already discussed, were captured by the SeaWiFS satellite and qualitatively analyzed as follows: each image was partitioned into 9 square degree grids (Fig. 2). Each individual grid was rated and assigned a value between 1 and 4, where 1 was < 10% cloud cover, 2 was > 10% but < 50%, 3 was > 50% but >90%, and 4 was >90%. Average assigned values were then calculated for each daily image as well as for each individual grid (Table 1).

Light intensity values were also measured by the onboard Biospherical Instruments QSP-200 Photosynthetically Active Radiation (PAR) sensor and the Alden 7070-A short wave radiation sensor and recorded once every 5 seconds on R/V Thomas G. Thompson's DAS/IMET system. These intensities were then averaged for daylight hours of each incubation period.

Results

Primary production values were measured at eight stations around the Galapagos Islands. At five of those stations (Bio 1-4, and Bio 6) primary production was measured in experimentally manipulated light regimes at the surface and the chlorophyll maximum (or at 20-40 m if the chlorophyll maximum was at the surface). The range of production of the 50% light intensity bottles was the largest of the three treatments. Values ranged from

-1.4 μmol C L^{-1} d^{-1} in sub-surface bottles indicating net respiration, to ~50 μmol C L^{-1} d^{-1} in surface bottles, both from Bio 3 (Fig. 3). Different screening treatments had no pronounced effect on measured primary production, except for surface water at Bio 1, where production was noticeable higher at 50 and 100% PAR than 25% (Fig. 3A). Since production values were not noticeably different among light-level treatments, they were averaged across all treatments (including, for consistency, Bio 1).

In surface waters, these averaged values were variable, ranging from as low as ~2 μmol C L^{-1} d^{-1} (at Bio 4) to as high as ~50 μmol C L^{-1} d^{-1} (at Bio 3; Fig. 4), with values much higher on the west side of Isabela Island (range: 10 – 50 μmol C L^{-1} d^{-1}) than the east side (range: undetectable – 10 μmol C L^{-1} d^{-1}) . On average, surface waters also had more production than those at depth, where primary production ranged from nearly undetectable (at Bio 3) to 30 μmol C L^{-1} d^{-1} (at Bio 6; Fig. 4). Subsurface primary production tended to be higher east of Isabela Island than west. Production values from samples collected at the chlorophyll maximum (regardless of depth) averaged more production (~30 μmol C $L^{-1}d^{-1}$) than non-chlorophyll maximum samples (~5 μmol C L^{-1} d^{-1}; Fig. 4).

Measured chlorophyll *a* concentrations (Snow 2006) showed larger values in surface waters on the western side of Isabela Island (range: 0.75 – 1.75 μg L^{-1}) than on the east side of Isabela Island (range: 0.2 – 0.3 μg L^{-1}; Fig. 5). Correspondingly, the chlorophyll maximums of western Isabela Island stations were at the surface, in contrast to subsurface chlorophyll maximums on the eastern side. Nutrient analysis showed concentrations of silicate (at chlorophyll maximums) ranging from ~ 4 – 7 μmol L^{-1} at stations with sub-surface maximums and nearly depleted at stations with surface maximums (Fig. 6) (Dickson 2006). Surface waters

to the west of Isabela Island also showed a dominance of > 20 μm phytoplankton, whereas, the eastern side of Isabela Island was dominated by smaller phytoplankton cells (< 2 μm) (Snow 2006).

Cloud cover analysis of daily satellite images, downloaded for the experimental period, showed larger temporal than spatial variability. The weekly average of cloud cover was calculated at a value of 2.5 with a low value of 1.7 on 27 Jan 2006 and a high value of 3.8 on 22 Jan 2006 (Table 3). On a spatial scale, values ranged from 2.0 in grid 1C, which is the southwestern section of each image, to 3.0 in grid 1B, which is the western section of each image (Table 3).

Averaged PAR values ranged from ~500 μE m^{-2} s^{-1} for the incubation daylight hours of station Bio 1 experiments to ~1010 μE m^{-2} s^{-1} for the incubation daylight hours of stations Bio 2 and Bc 5 experiments (Table 2). Maximum daylight PAR values were also measured and were found to slightly range from 2180 to 2355 μE m^{-2} s^{-1} (Table 2). No direct correlation was found between averaged PAR values and primary production or between maximum PAR values and primary production (Fig. 7).

Discussion

The results of this study indicate that differing light regimes had little effect on the primary production of the region during this sampling period. Supporting this, no correlation was observed between primary production and averaged daylight values or primary production and maximum daylight values (Fig.7) (Note: averaged values of daylight PAR will be integrated during future analysis to provide more definitive values). Although the results of this study were

not expected, much variability was found between the primary production of different locations rather than between different treatments.

Iron fertilization of Eastern Equatorial Pacific Ocean waters near the Galapagos Islands, in IronEx II, resulted in a dramatic phytoplankton bloom with primary production values increasing from ~1.25 – 2.08 μmol C L^{-1} d^{-1} in ambient waters to ~12.5 – 17.0 μmol C L^{-1} d^{-1} in fertilized patch waters (Landry et al. 2000). Landry et al.'s measured values fall within the range of values measured in this study, but are much smaller than Houvenaghel's (1978) reported values of 33 to 103 μmol C L^{-1} d^{-1} in Bahia Academia. This kind of response is indicative of the phytoplankton's inability to fully utilize high levels of macronutrients because of iron limitation. For the reasons already described it was expected that diminished light levels would yield reduced amounts of primary production. Yet this was observed only at one station (Bio 1; Fig.3A) arguing that other factors were more important to determining primary production in these experiments. At Bio 1, significantly lower primary production was measured only at the 25% light-level treatment (Fig. 3A).

As mentioned above, significant differences in primary production were measured from station to station and between the surface and 20 m. The most noticeable difference was the west/east divide, with higher amounts of surface production on the western side of Isabela Island compared to that of the eastern side and generally higher amounts of sub-surface production on the eastern side compared to that of the western side (Fig. 4). Considering little to no effects from differing light intensities, these noticeably different production values must be attributed to some other factors.

Measurements of macronutrient concentrations, chlorophyll *a* concentrations and size fractionations, and growth and grazing rates of iron-enriched phytoplankton communities, were

all collected by collaborating scientists on this cruise. The measured distribution of total chlorophyll *a* does appear to reflect the east/west divide observed in the primary production data, especially in surface waters (Fig. 5). Size fractionation experiments further suggest that western surface waters were dominated by phytoplankton > 20 μm, which were mostly diatoms (Snow 2006). In contrast, smaller phytoplankton dominated at all depths on the east side of Isabela Island. These conditions are indicative of the conditions found in IronEx II. Waters outside the iron-fertilized patch, where primary production was found to be low (~1.25 – 2.08 μmol C L^{-1} d^{-1}), were dominated by phytoplankton < 2 μm, whereas waters inside the patch, where increased levels of primary production were measured (~12.5 – 17.0 μmol C L^{-1} d^{-1}), were dominated by larger phytoplankton (>18 μm; Landry et al. 2000).

The results of nutrient analysis done on chlorophyll maximum waters indicate higher nutrient concentrations on the eastern side of Isabela Island than on the western side. The most striking difference is the nearly depleted concentrations of silicate on the western side compared to measurable amounts on the eastern side (Fig. 6) (Dickson 2006). This may be a direct result of the observed larger-sized diatom community uptaking most of the silicate to build their shells. This is significant because it may suggest that iron is not limiting growth on the western side of Isabela Island, but maybe on the eastern side of Isabela Island.

Iron enrichment growth and grazing experiments detected significant growth and microzooplankton grazing only in large size fractions (> 20 μm) when enriched with iron (Guo 2006). This was measured in samples colleted from sub-surface waters at stations Bio 2, on the western side of Isabela Island, and Bio 4 on the eastern side of Isabela Island. More

statistical analysis is needed on these measurements to truly see what exact effects iron fertilization had on the biological community.

Conclusions

No significant differences in primary production were found in differing light intensity treatments and daylight PAR levels had no corresponding affects on primary production incubations. Spatial variability was found around the Galapagos Islands with higher amounts of production in surface waters to the west of Isabela Island and higher amounts of production in sub-surface waters to the east of Isabela Island. This variability coincided with the spatial variability of chlorophyll *a* concentrations. These findings suggest that differing light intensities minimally affect the variability of primary production around the Galapagos Islands and, that other factors such as differences in phytoplankton community structure, due to iron limitations, may dictate the spatial variability of primary production.

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Table 1. Cloud Cover Analysis

Values 1-4 equivelent to: 1<10% cloud cover, 2>10% cloud cover <50%, 3>50% cloud cover <90%, 4>90% cloud cover

	Grid									Daily	Monthly
Date	1A	2A	3A	1B	2B	3B	1C	2C	3C	Ave.	Ave.
13-May-05	2	1	1	3	2	1	3	2	1	1.8	
25-May-05	2	1	2	3	3	2	3	3	2	2.3	
26-May-05	2	3	3	2	3	4	2	4	3	2.9	
28-May-05	1	1	1	1	1	2	2	2	2	1.4	2.1
6-Jun-05	2	3	3	3	3	3	3	3	3	2.9	
13-Jun-05	3	2	1	2	2	2	4	4	4	2.7	
15-Jun-05	2	2	2	1	2	3	2	1	3	2.0	
23-Jun-05	2	3	4	2	2	3	2	4	4	2.9	2.6
3-Jul-05	3	4	2	3	4	4	4	4	4	3.6	
10-Jul-05	3	3	4	1	2	4	3	3	4	3.0	
17-Jul-05	3	3	4	4	3	2	4	4	4	3.4	
23-Jul-05	2	3	4	1	2	3	2	2	3	2.4	3.1
1-Aug-05	3	3	3	3	3	4	4	4	4	3.4	
9-Aug-05	2	2	4	1	2	3	3	4	4	2.8	
19-Aug-05	1	1	1	1	1	1	2	2	2	1.3	
23-Aug-05	4	4	4	4	4	4	4	4	4	4.0	2.9
1-Sep-05	2	4	4	4	4	4	3	3	3	3.4	
8-Sep-05	4	3	4	3	3	3	4	3	3	3.3	
13-Sep-05	2	3	4	2	3	4	4	4	4	3.3	
27-Sep-05	3	4	4	2	3	4	4	4	4	3.6	3.4
4-Oct-05	3	3	4	1	2	4	4	4	4	3.2	
9-Oct-05	3	4	4	2	3	4	1	3	3	3.0	
18-Oct-05	3	3	3	2	3	4	3	4	4	3.2	
23-Oct-05	1	1	4	1	2	3	4	4	4	2.7	3.0
1-Nov-05	1	1	3	1	2	3	2	2	4	2.1	
6-Nov-05	2	2	3	1	2	3	3	3	3	2.4	
11-Nov-05	4	2	3	3	2	3	2	3	4	2.9	
18-Nov-05	3	2	3	1	2	3	3	3	4	2.7	2.5
Average	2.4	2.5	3.1	2.1	2.5	3.1	3	3.2	3.4	2.8	

Table 2. Locations of Sample Collection

Station	Date	Ave. Photosynthetically Active Radiation per Incubation ($\mu E\ m^{-2}s^{-1}$)	Max. Photosynthetically Active Radiation per Incubation ($\mu E\ m^{-2}s^{-1}$)	Latitude (S)	Longitude (W)
Bio 1	21-Jan-2006	553	2180	00° 36.99	91° 41.90
Bio 2	23-Jan-2006	1014	2183	00° 36.97	91° 19.00
Bio 3	22-Jan-2006	872	2323	00° 13.63	91° 36.40
Bio 4	25-Jan-2006	686	2355	00° 01.02	91° 08.00
Bio 6	21-Jan-2006	972	2180	00° 55.02	89° 59.95
BC 1	22-Jan-2006	872	2323	00° 33.34	91° 22.39
BC 2	25-Jan-2006	686	2355	00° 21.41	90° 48.75
BC 5	23-Jan-2006	1014	2183	00° 09.82	91° 03.84

Table 3. Cloud Cover Analysis

Values 1-4 equivalent to: 1<10% cloud cover, 2>10% cloud cover <50%, 3>50% cloud cover <90%, 4>90% cloud cover

Date	1A	2A	3A	1B	Grid 2B	3B	1C	2C	3C	Daily Ave.	Week Ave.
20-Jan-06	2	2	1	3	3	1	1	3	2	2.0	
21-Jan-06	4	4	4	3	3	4	1	4	4	3.4	
22-Jan-06	3	3	4	4	4	4	4	4	4	3.8	
23-Jan-06	1	1	2	2	1	1	2	3	3	1.8	
24-Jan-06	1	2	3	2	2	3	1	2	3	2.1	
25-Jan-06	1	3	4	4	4	4	4	4	3	3.4	
26-Jan-06	3	1	1	3	2	2	2	2	3	2.1	
27-Jan-06	3	2	2	3	1	1	1	1	1	1.7	2.5
Average	2.3	2.3	2.6	3.0	2.5	2.5	2.0	2.9	2.9	2.5	

Figure Legends

Fig. 1. Two examples of satellite images used for cloud cover analysis (A) 11 November 2005 and (B) 18 November 2005. Insert in panel B labels each individual 1º x 1º grid for each image used in Table 1 analysis.

Fig. 2. Locations of sample collection.

Fig. 3. Primary production values of samples collected from (A) surface and (B) sub-surface at Bio stations only. Bars represent standard error. Note: no surface data collected from Bio 6.

Fig. 4. Averaged primary production of sample stations. Station location relative to Isabela Island noted below station ID. Note: values for Bio stations are averaged from the averages for each treatment where as values for Bc stations are averaged from individual bottles values. Standard error for Bio stations calculated from averages of treatments. Also note: no data collected for Bc 1, sub-surface; Bio 6, surface; Bc 2, surface; and Bc 5, sub-surface.

Fig. 5. Averaged chlorophyll concentrations of sample locations. Station location relative to Isabela Island noted below station ID. Note: no data collected from Bc stations.

Fig. 6. Nutrient concentrations of samples collected from chlorophyll maximum at Bio stations only. Bio 1, Bio 2, and Bio 3 collected at the surface. Bio 4 and Bio 6 collected at 20 m.

Fig. 7. (A) Averaged production versus averaged daylight PAR and (B) averaged production versus maximum daylight PAR.

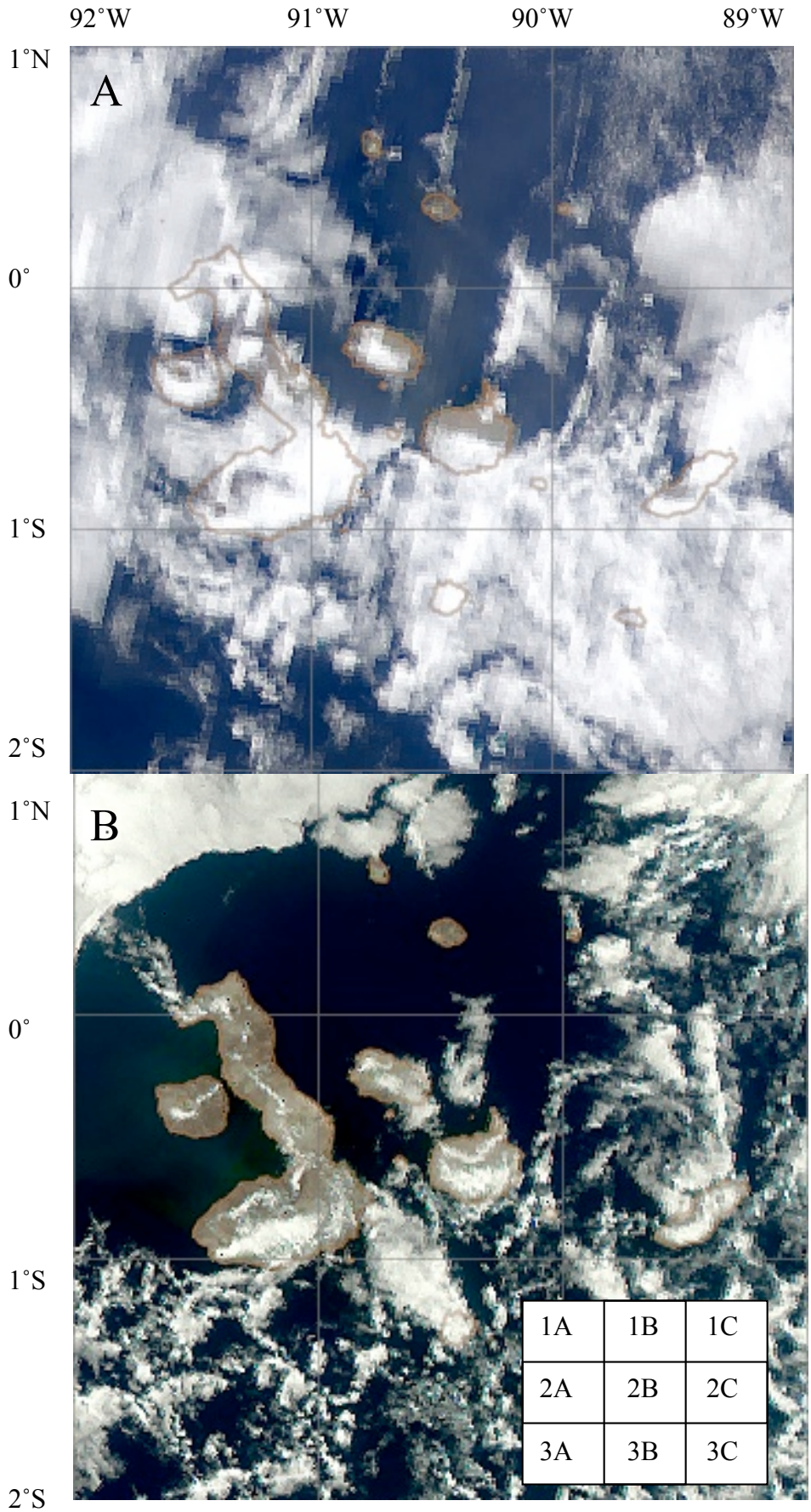
92˚W
91˚W
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Fig. 2

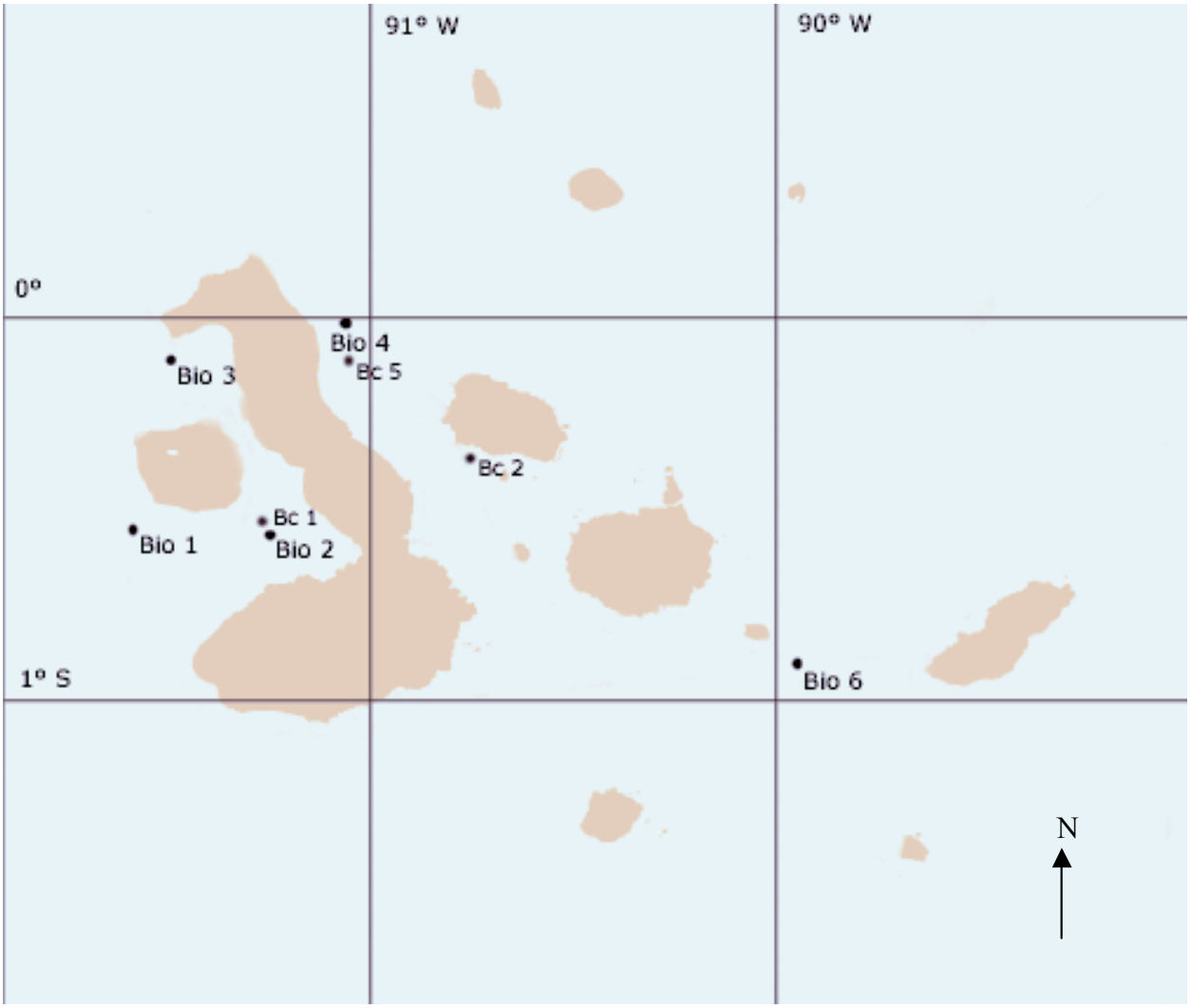
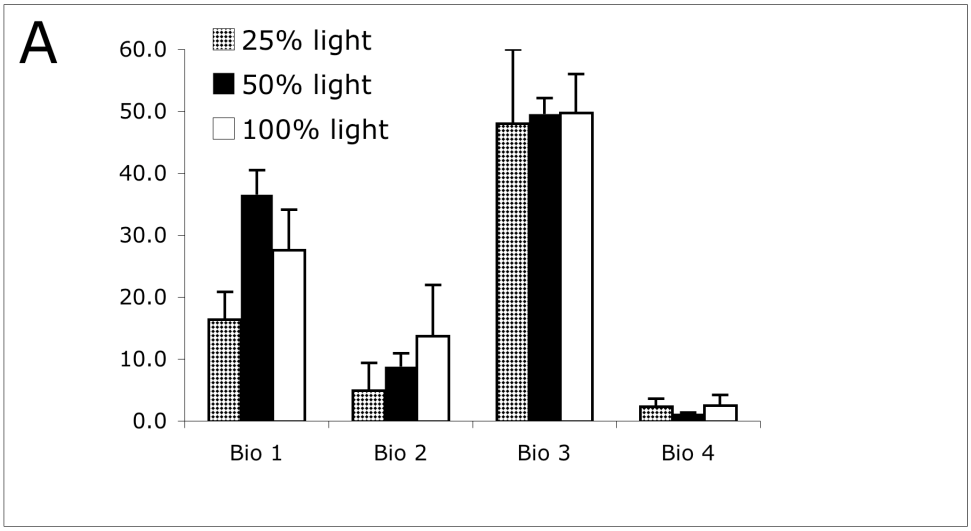


Fig. 3


A
25% light
50% light
100% light
60.0
50.0
40.0
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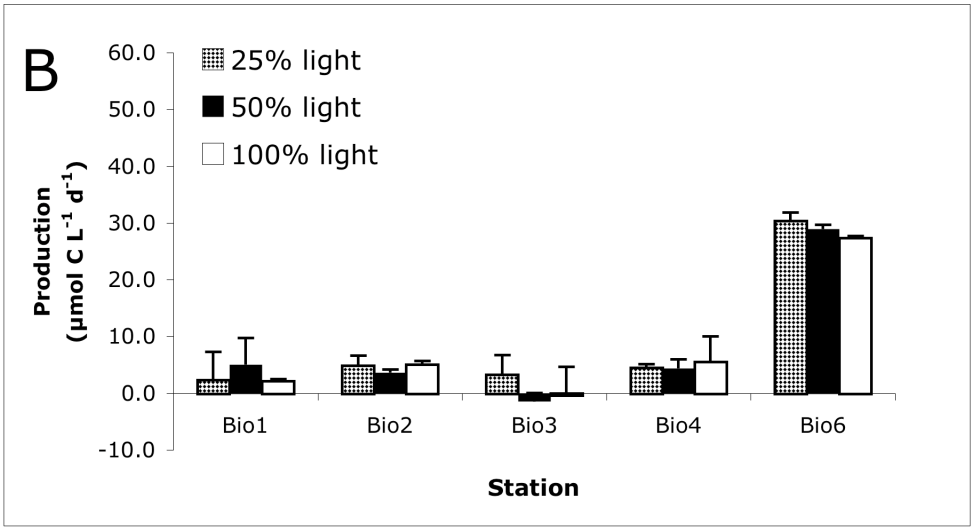
Bio 1
Bio 2
Bio 3
Bio 4


B
25% light
50% light
100% light
Production
(µmol C L-1 d-1)
60.0
50.0
40.0
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20.0
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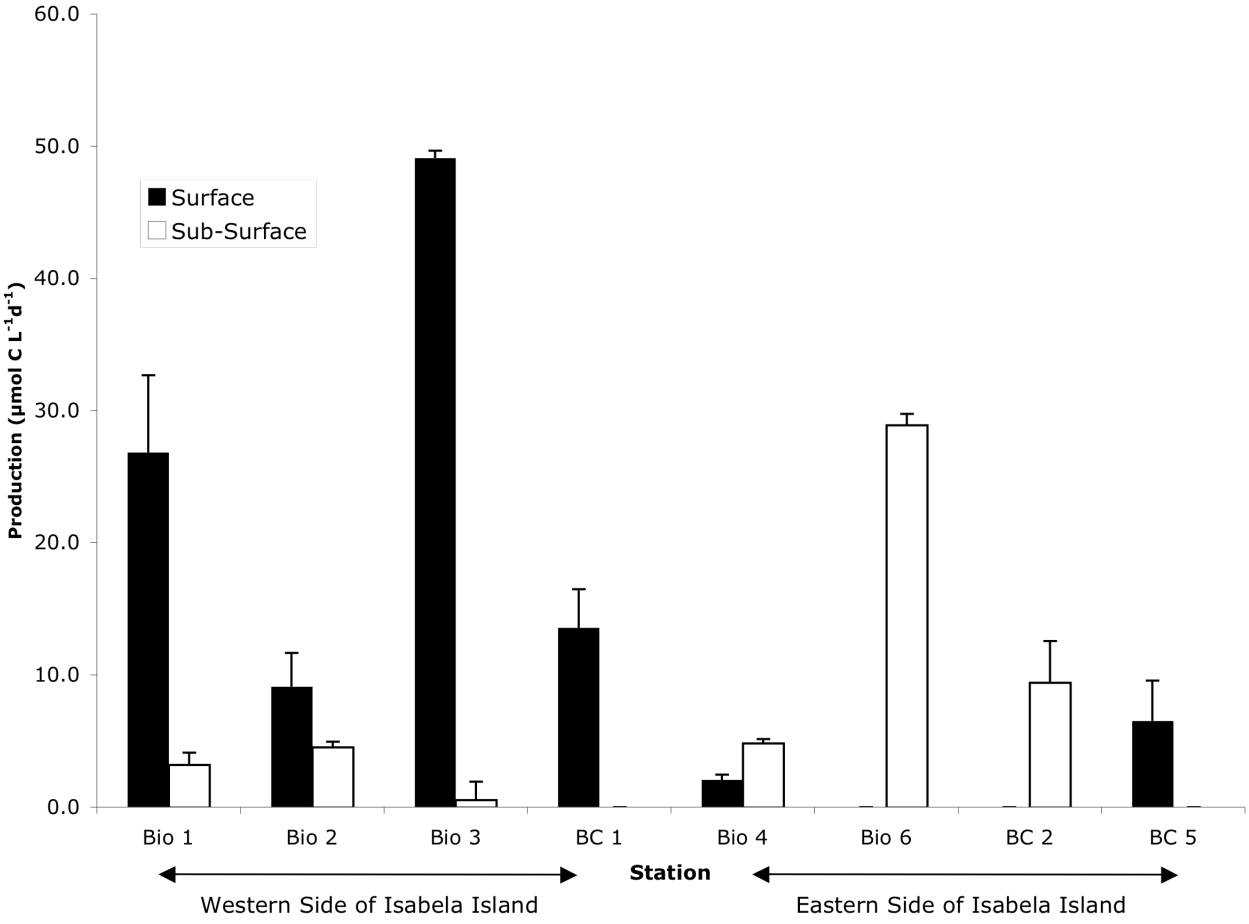
Bio1
Bio2
Bio3
Bio4
Bio6
Station

Fig. 4


60.0
50.0
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Production (µmol C L-1d-1)
Surface
Sub-Surface
Bio 1
Bio 2
Bio 3
BC 1
Bio 4
Bio 6
BC 2
BC 5
Station
Western Side of Isabela Island
Eastern Side of Isabela Island

Fig. 5

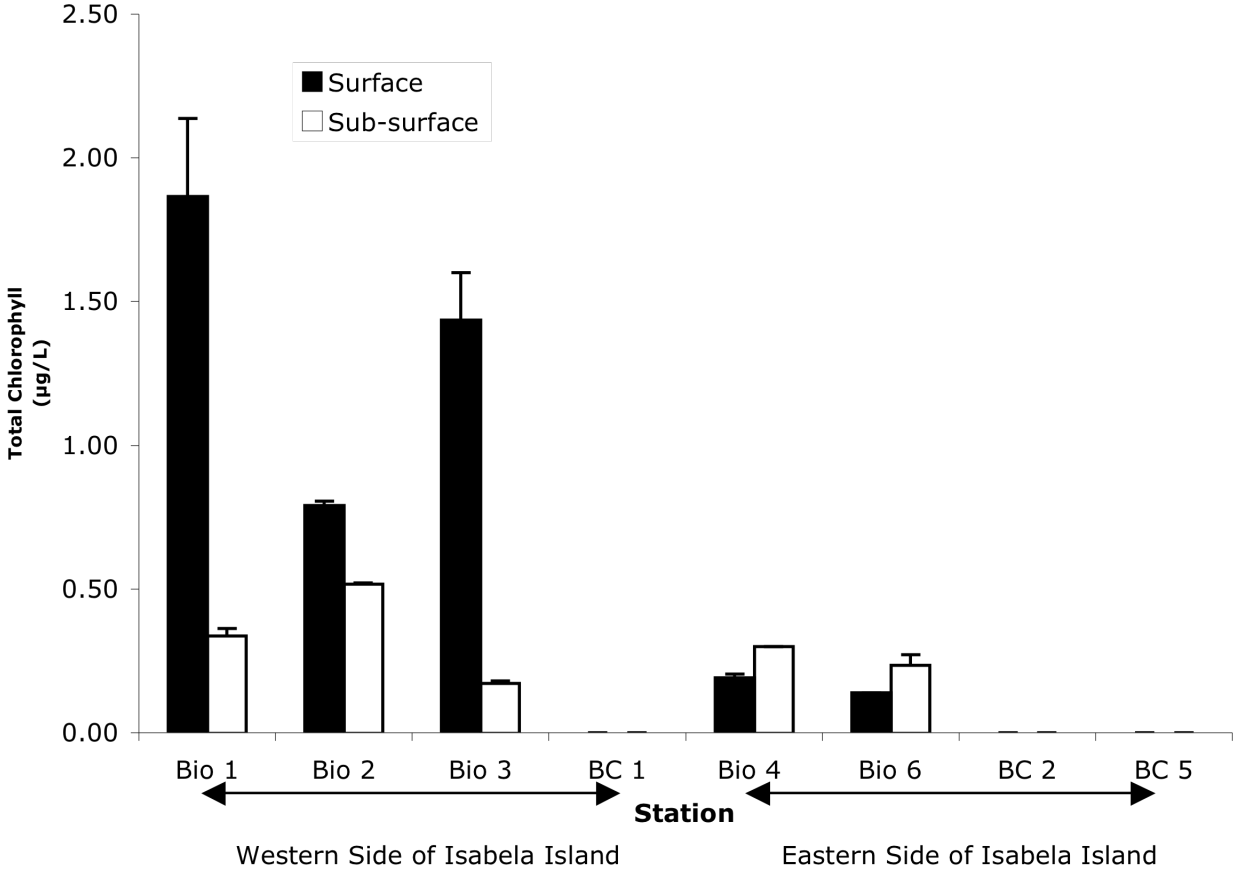

2.50
2.00
1.50
1.00
0.50
0.00
Total Chlorophyll (µg/L)
Surface
Sub-surface
Bio 1
Bio 2
Bio 3
BC 1
Bio 4
Bio 6
BC 2
BC 5
Station
Western Side of Isabela Island
Eastern Side of Isabela Island

Fig. 6

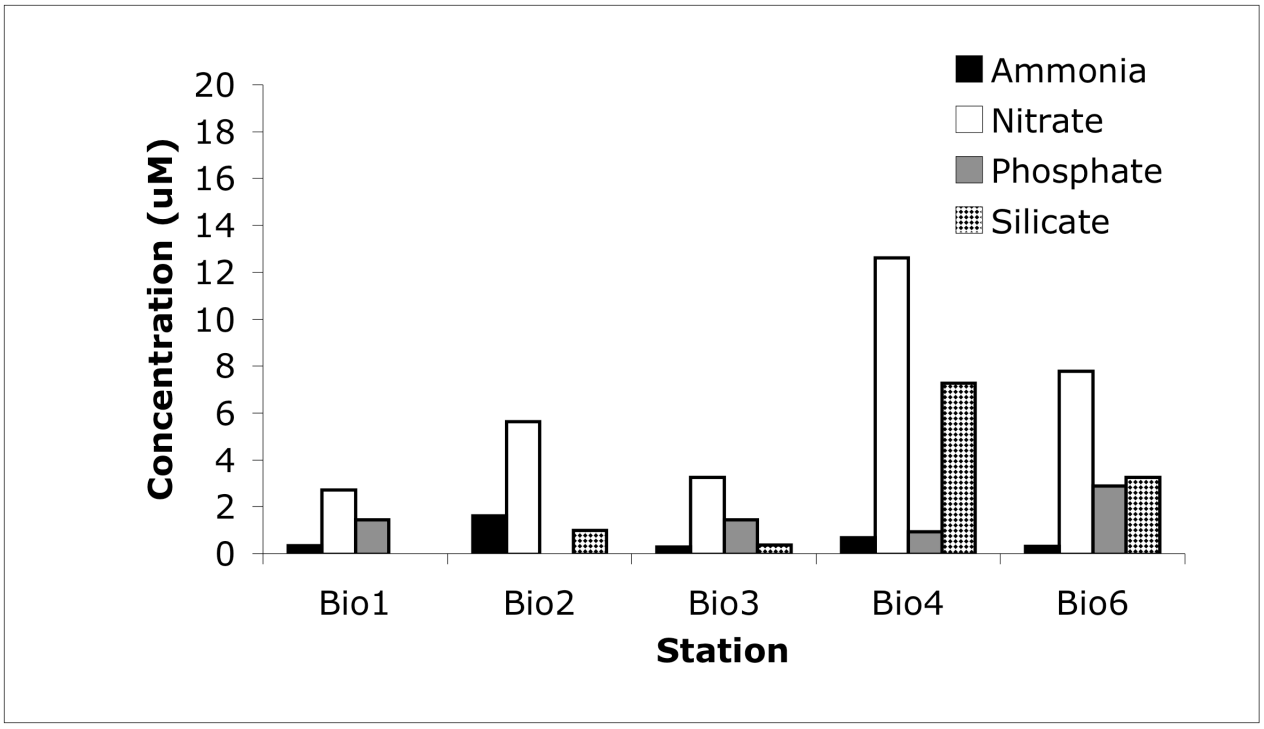
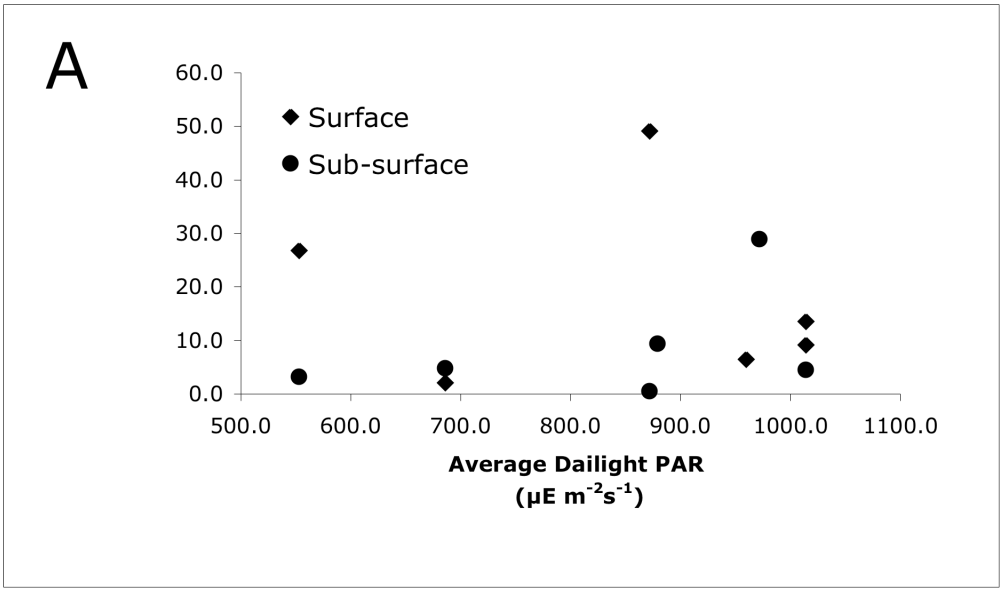
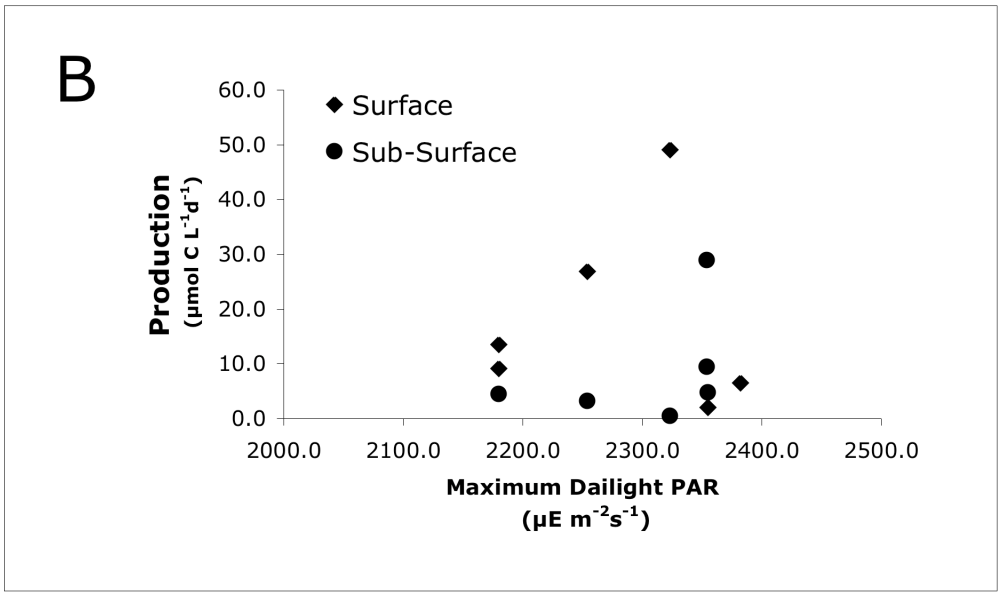

Ammonia
Nitrate
Phosphate
Silicate
Concentration (uM)
20
18
16
14
12
10
8
6
4
2
0
Bio1
Bio2
Bio3
Bio4
Bio6
Station

Fig. 7


A
60.0
50.0
40.0
30.0
20.0
10.0
0.0
Surface
Sub-surface
500.0
600.0
700.0
800.0
900.0
1000.0
1100.0
Average Dailight PAR
(µE m-2s-1)


B
60.0
50.0
40.0
30.0
20.0
10.0
0.0
Surface
Sub-Surface
Production
(µmol C L-1d-1)
2000.0
2100.0
2200.0
2300.0
2400.0
2500.0
Maximum Dailight PAR
(µE m-2s-1)