NUTRIENTS AS CONTROLLING FACTORS OF PHYTOPLANKTON PRODUCTION IN THE BALSFJORD – NORTHERN NORWAY

by

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Abstract

Fisheries management research is mostly centered on providing the needed knowledge about the fish stock in order to influence fishermen's behavior at sea for stock sustainability. Management should also integrate knowledge acquired from primary producers (particularly phytoplankton) which form the foundations for fish production in implementing fishing controlling measures. Phytoplankton production therefore was studied in the Balsfjord from March to December in 2008. The study focused on nutrients as controlling factors. Water samples were collected at 5, 10 and 50 m from the Balsfjord from early March to early December. Nitrate, phosphate, silicate, Biogenic silica, chlorophyll *a* concentrations and phytoplankton abundance were analyzed throughout this sampling period. Seawater temperature and pH were also measured during sampling. The peak of the spring bloom occurred on 1st April at 5 and 10 m. Nitrate depletion and phosphate reduction occurred at 5, 10 and 50 m during summer and autumn while silicate showed major reduction during the spring bloom. Change in concentrations of silicate caused a shift in phytoplankton composition and abundance from diatoms to flagellates. The dominant phytoplankton genus and abundance was *Chaetoceros* during the spring bloom and flagellates after the bloom. Phytoplankton production in this fjord is controlled by nitrate.

Key words: Phytoplankton, nitrate, phosphate, silicate, Biogenic silica.

Acknowledgements

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1. Introduction

The ocean is a complex body of many chemical, physical and biological reactions. It plays a very important role in recycling the major nutrients such as nitrogen (N), phosphorus (P) and silicon (Si) which are very important in regulating primary production (Lalli and Parsons, 2001). The ocean's productivity depends largely on these nutrients. The measurement of the oceans productivity is represented as chlorophyll concentration on biological oceanography maps. Primary production is the basis of all trophic levels in any ecosystem. On land, the green plants are the primary producers while in the ocean it is the phytoplankton. The growth of the phytoplankton is controlled by chemical, biological and environmental factors. Spring bloom is a sudden and high bloom of phytoplankton production such as diatoms during the spring. It occurs in the temperature and sub-polar waters. The beginning of the spring bloom depends on the amount of the spores in the sediment from the previous spring bloom collapse or vegetative parts transported from the surrounding fjords (Eilertsen and Taasen, 1984). The termination of the blooms is normally associated with grazers, coagulation and/or sedimentation or lack of one of the many requirements such as nutrients (Kristiansen et al., 2001). N, P and Si play important role in regulating phytoplankton production due to their requirement in biological processes (Kirchman, 2000). Nutrients are most often depleted during the blooms. The knowledge of the phytoplankton in the ocean over a given period could be used also to determine the stability of the ecosystem (Hegseth et al., 1995). Apart from the upwelling and dissolution of nutrients from sediments, input from the atmosphere may be important nutrients source (Spokes and Jickells, 2005). Runoff waters containing dissolved nutrients mainly from agricultural and non-agricultural lands may be important nutrient sources in coastal waters (Hauxwell et al., 2008). Among all these factors, nutrients play a very important role in phytoplankton growth in the presence of all other variables (such as light, wind and temperature). The Balsfjord is among the well studied and important fjords in the Northern Norway for arctic research. The geological topography of the Balsfjord is an important factor for making it a productive fjord (Hegseth et al., 1995).

1.1. Nutrients

They are elements or compounds that play direct roles in the physiological, biological or chemical processes so that its absence could lead to malfunctioning, reduced growth or symptoms of depletion (Ingestad, 2006). Nutrients are classified as major if they are needed in large quantities for activities such as photosynthesis, for example N and P. Trace elements (minor nutrients) are required in small quantities like Co, Mn and vitamins. Large empirical data collected from various parts of the ocean have revealed that phytoplankton require C:N:P in the proportions 106:16:1 (Redfield, 1934; Tyrrell and Law, 1997). In freshwater systems P is considered to be the limiting nutrient, while in marine systems N is considered to be the limiting nutrient (Downing, 1997).

1.1.1. Nutrients absorption mechanisms

There are two main mechanisms by which nutrients are absorbed by cells (Atlas, 1984). These are diffusion and active transport. The properties of the cell membrane regulate which of the transport mechanisms take place.

1) Diffusion: takes place when nutrient particles move from region of higher concentrations to region of lower concentrations until there is equilibrium of particles between these two regions. During this process, the cell does not require energy to transport the nutrients across the cell membrane. The cell membrane restricts free movement of nutrients to and from the cell by using energy to maintain concentration gradients with its environment. This process also trigger osmosis (movement of water molecules from region of low solute concentration into region of higher solute concentration) due to the nutrient concentrations that exist between the cell and its environment. The occurrence of osmosis is regulated by the cell membrane.

2) Active transport: occurs when nutrients move across the cell membrane against a concentration gradient. It involves the use of energy. Membrane proteins are important as they may act as carriers of these nutrients. This process is most important in absorption of nutrients by cells. This is because the most important nutrients are generally available in low quantities in the cell's environment. Other long chain molecules are also absorbed

through this mechanism. Phytoplankton cell will absorb its nutrients in the water column through this process.

The uptake rate of nutrients is said to follow the Michaelis-Menten kinetics equation (Lehninger, 1975):

$$V = V_{max} [S] / K_m + [S] \qquad\qquad 1$$

V is velocity of uptake, V_{max} is maximum velocity, [S] is substrate concentration, K_m is Michaelis constant (substrate concentration) when $V = 1/2 \ V_{max}$

It was observed that the maximum absorption limits by phytoplankton cells follow similar pattern as described in equation 1 but these limit changes from species to species (Lalli and Parsons, 2001). In coastal and oceanic waters where nutrient concentrations, temperature and light are dynamic, the absorption rates are subject to change which will influence the K_m and V_{max}.

1.2. pH and nutrients availability

The chemical forms of nutrients change with change in pH of the medium in which they are found (Atkins and Beran, 1992). All organisms are controlled by some specific nutrients which are only available within a given pH range. All pH ranges are important based on the type of organism in question. N is mostly available as ammonium (NH_4^+) and nitrate (NO_3^-) and P as orthophosphates ($H_3PO_4, H_2PO_4^-, HPO_4^{2-}$ and PO_4^{3-}). All these forms of nutrients are pH dependent and a change in pH range can make them available or unavailable for the growth of phytoplankton. Nitrates are occluded by cations mainly calcium (Ca^{2+}) and magnesium (Mg^{2+}) ions at higher pH values. NH_4^+ is also occluded by negatively charged clay surface. In principle, acidification of the ocean is due to absorption of CO_2 by the ocean (as in equation 2 and 3). There is always a balance between HCO_3^-/ CO_3^{2-} that keeps the pH at an appropriate range.

$$CO_{2\,(g)} + H_2O_{\,(aq)} \longrightarrow HCO_3^-{}_{\,(aq)} + H^+{}_{\,(aq)} \qquad\qquad 2$$

$$2HCO_3^-{}_{\,(aq)} \longrightarrow CO_3^{2-}{}_{\,(aq)} + H_2O_{\,(aq)} + CO_{2\,(g)} \qquad\qquad 3$$
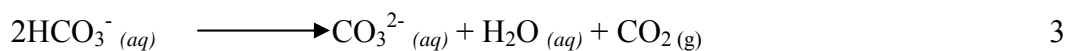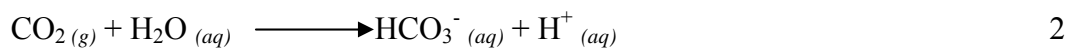
Phosphorus is less available at lower pH (< 6) where it forms complexes with hydrogen ions (H^+) and aluminium ions (Al^{3+}) and higher pH ($\geq$ 9) where it is occluded by Ca^{2+} and Mg^{2+}. At pH near 7 nitrate and phosphate are therefore mostly available for biological use. There will be high competition among all nitrate and phosphate users at this pH range. Microorganisms and biological processes are also pH dependent just as the nutrients (VanDemark and Batzing, 1987). The availability of specific nutrient does not warrant it's usage if the organism of interest (diatoms) cannot make use of it. There is always a balance between pH range on nutrients and microorganisms abundance (VanDemark and Batzing, 1987).

1.3. Biogeochemical cycling of nutrients

Deep water is nutrient rich. Upwelling of deep water is an important source of N, P and Si input into the euphotic zone. The other important source comes as a result of biogeochemical nutrient recycling which is discussed below.

Nitrogen (N): can be available for marine utilization from the deposit and decay of organic materials and conversion of atmospheric nitrogen (N_2) by N – fixing organisms into useful forms (Naqvi, 2006). Capone (2000) stated that low concentrations of nitrate (NO_3^-) can control productivity in the ocean surface layer. Apart from the ocean, nitrogen can also control the productivity of coastal upwelling areas (Kudela and Dugdale, 2000). It is well known that bacteria may compete with phytoplankton for N (Tanaka et al., 2007). Bacteria play an important role in breaking down of proteins into amino acids to ammonium and to nitrate. The process by which plant and animal materials are broken down into smaller units (monomers) by heterotrophic organisms is called mineralization. In the process of mineralization, microbial nutrients requirements are met first before the remaining nutrients are available for other users such as phytoplankton. The main forms are: NH_4^+ and NO_3^-. These are called dissolved inorganic nitrogen (DIN). According to Kirchman (2000) the similarity of heterotrophic bacteria and phytoplankton cells in carbon to nitrogen ratios (C:N) makes them to be competitive for nitrogen. A level of C:N is required by heterotrophic bacteria for growth, N is assimilated or regenerated to maintain a required ratio.

Nitrification is another process for N supply. Nitrification is an oxidation process whereby ammonium (NH_4^+) is converted into NO_3^- by cyanobacteria (Naqvi, 2006). This is only carried out by cyanobacteria with the enzyme nitrogenes. These set of bacteria are called nitrifiers and are limited by light. It is therefore assumed that nitrification mainly takes place in deep waters. Then mixing of the upper and the lower water layers makes NO_3^- available for phytoplankton utilization in the euphotic zone (Jonathan et al., 2002). Nitrification is aerobic reaction undertaken by *Azotobacter* and *Nitrosomonas*. Since temperature controls the activities of these nitrifiers, it therefore controls indirectly the availability of NO_3^- (Carpenter, 1983).

Phosphorus (P): is another important nutrient which heterotrophic bacteria may compete with phytoplankton for (Tanaka et al., 2007). According to Kirchman (2000), there are relatively more P in bacteria cell than phytoplankton cell due to the small cell nature of the former. P is available through microbial decay of plant and animal materials either from the marine or terrestrial origin. During summer and autumn, P is regenerated in the water column from the excretes of grazers.

Silicon (Si): is the about 25.7% of the earth's crust by weight, second most abundant element in the earth's crust (Heiserman, 1992). It is not naturally found in its free state but often in its oxide states called silica (SiO_2). It is transported into the oceans by runoff or wind in the form of particles (lithogenic silica, LSi) when it is physically, chemically or biologically weathered. It becomes useful only as silicate. Brzezinski et al. (1998) showed that absorption of Si follows immediately after cell division for the reconstruction of the cell wall and to complete its life cycle. Upwelling brings up the Si in the oceans sediments for utilization. The silicate is transformed into Biogenic silica (BSi) in the frustules (Kristiansen et al., 2001) and goes back into the geo-chemical cycle after death and sedimentation of diatoms (Treguer et al., 1995). Recycling of the Si is mainly carried out by dissolution of frustules (Kristiansen et al., 2001).

1.4. Primary production

Light reaching the polar waters is greatly reduced as the angle of incidence becomes large during winter due to the dark days (Lalli and Parsons, 1997). Also when it is moving from dense medium (air) into denser medium (water), its speed and intensity are greatly reduced and even further reduced as it travels even more deeper through the water column. This is

because light spreads and part of it is also absorbed by the water and particles. These properties make light an important factor in controlling primary production.

During winter, nutrients are supplied by deep mixing from lower layers (Rey, 2004). Temperature and salinity are homogeneously distributed by wind and winter cooling during this period. Nutrient concentrations generated for the next primary production season depend largely on the depth of this mixing. During spring and summer solarization becomes strong resulting in the warming the upper layer and low wind speed reduce vertical mixing resulting in high stratification during these periods. This divides the water into two main layers; upper warm layer and colder deep layer. There is high mixing (low stratification) during winter.

In this research primary production is confined on phytoplankton and follows equation 5.

$$6CO_{2\,(g)} + 6H_2O_{\,(l)} \xrightarrow[\text{Nutrients}]{\text{Light}} C_6H_{12}O_{6\,(s)} + 6O_{2\,(g)} \qquad\qquad 5$$
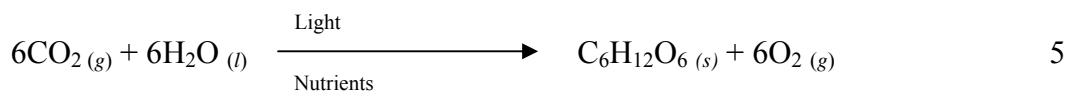
There is a high correlation between satellite views of chlorophyll concentration to fish landings all over the world (Brander, 2003). Areas of high chlorophyll concentration are tantamount to high phytoplankton production. Photosynthesis takes place mostly in the euphotic zone and other microorganisms that live far off this zone receive food through current transport.

1.5. Phytoplankton community

Phytoplankton is called 'the grass of the sea' (Rey, 2004). This is because of its importance in serving as the major primary producer. Diatoms are the most important constitutes of phytoplankton in terms of nutrients utilization and their preference by zooplankton and fish to other groups (Laane et al., 2005). They therefore establish an important link in the food chains as they are being fed upon by many microorganisms, zooplankton, fish larvae and grazing animals like mollusks (snails). In the Balsfjord, *Chaetoceros* are the most important representatives during the spring bloom and flagellates after the spring bloom (Lutter et al., 1989).

1.6. Microbial loop

The importance of microorganisms in nutrient cycling and energy transfer in the food web cannot be overlooked (Nybakken and Bertness, 2005). Microbial loop is important for nutrient regeneration. Microorganisms of considerable important players in the microbial loop are photosynthetic bacteria. It is estimated that the abundance of bacteria in the ocean is 10^{29} (Whitman et al., 1998). The abundance and diversity of bacteria in the ocean depicts their ability to make use of DOC by producing enzymes with high metabolic rates (Lawrence et al., 2007). These enzymes can breakdown complex organic materials such as lignin, cellulose and chitin into simple absorbable forms for bacteria and others in the microbial community. DOC gets into the marine and fresh waters from decay and dissolution of carbon in plants, animals and soils from terrestrial origin. DOC is also produced from photosynthesis. Runoff waters are the main carriers of DOC into these water bodies. Bacteria release nutrients when metabolizing DOC which benefit the whole food web. Feeding in principle is size dependant (larger organisms feed on the smaller ones). A simplified transfer of these energy could be as protista feed on bacteria, copepods could feed on protista and then larvae and small fishes could also feed on copepods. The transfer of energy from the protozoans to metazoans before subsequent transfer to the fish is also important but mostly neglected due to reduction of energy levels (Lawrence et al., 2007).

Primary production by nanoplankton accounted for 80 percent in the open ocean (Malone, 1980). Account of all microorganisms' contribution to photosynthesis is mostly impossible as some of them are too small to be trapped by the filters. The type, abundance and contributions of phytoplankton or nanoplankton to photosynthesis depend on the geographical location (coastal or open ocean), agents for nutrient availability (vertical circulation or upwelling) and seasonal variations (Nybakken and Bertness, 2005). During phytoplankton blooms the contribution of microplankton are very significant in northern Norwegian waters (Holdal and Kristiansen, 2008).

1.7. Nutrients, Eutrophication and the Environment

In recent times N and P concentrations and loads have increased between 10-20 fold due to anthropogenic activities in all water bodies mainly from fertilizers used on agricultural lands (Jickells, 1998). Eutrophication is nutrient enrichment in aquatic bodies which promote high primary production and changes in phytoplankton (algae) composition (Reid, 1977). It may reduce the level of oxygen concentration and many macro benthic organisms may decline (Rachor, 1980). A change in the primary production constituents affect all the other links in the food chain. In high productive shallow waters, piles of high levels of decayed and un-decayed organic materials become large. The cost of cleaning eutrophicated water is very expensive for example, in England and Wales where it costs between 105 and 160 million euros per year (Pretty et al., 2003). Eutrophication does not receive the much needed attention by the world and may be a more serious environmental problem than overfishing and global warming in some few decades to come if the current trend of environmental awareness only concentrate on curbing mass production of carbon dioxide evolution.

1.8. The scope of this study

This study focuses on the role of nutrients in controlling phytoplankton growth through the seasons. The main objectives of this study is to:

1. Evaluate the nutrients (N, P and Si) in the Balsfjord

2. Identify the various compositions of the phytoplankton in the fjord

3. Evaluate the controlling factors of primary production in the fjord.

I hypothesized that nutrients are the main controlling factors of primary production in the Balsfjord.

2. Materials and methods

2.1. Settings

Balsfjord is oriented south-southeast of Tromsø; Straumfjord and Kvalsund are the two inlets into this fjord (Eilertsen et al., 1981, Eilertsen and Taasen, 1984). Through Straumfjord, Balsfjord is linked to Malangen which is a fjord of about 30 km south of Tromsø. It is a cold-water fjord with maximum depth of 195 m, temperature which varies from 1 to 7^0C and salinity of 32.80 to 34.00 psu. The fjord is about 46 km long with a width of 5 km and 195 m above deep and a sill of 35 m deep. The fjord is not straight; the bending creates up-wellings and down-wellings which are the foundations of its productivity. 0-70 m form the upper layer and 70-180 m form the lower layer creating two different circulation patterns. The current is strongest in the upper and the bottom layers and is very weak at 70 m where the two layers change directions. The upper layer moves northward while the lower layer moves southwards. Figure 1 shows the Balsfjord and its surrounding fjords.
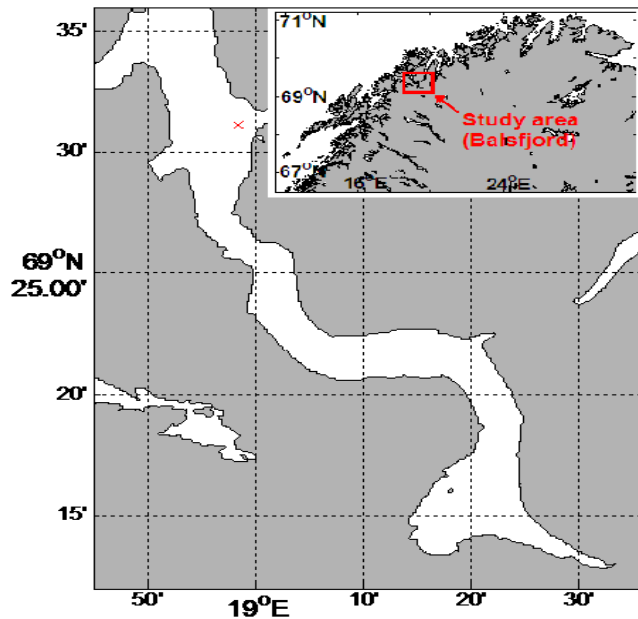
Figure 1: The map showing sampling position of the Balsfjord, Tromsø (Northern Norway). The cross is the position with coordinates N $069^0$31.271, E $018^0$58.841 where samples were collected.

2.2. Sampling

The sampling was carried out in the upper layer of the fjord with the research boat Hyas. The sampling depths were 5, 10 and 50 m. Waters were collected with Niskin water bottles and 5 liters from each depth were immediately transferred into acid-washed and ocean water rinsed 5 liter carboys. These were transported immediately to the laboratory for analysis. The YSI 30 Handheld Salinity Conductivity Temperature System was used to measure salinity and temperature at the depths of 2, 4, 6, 8, 10 and 14 m.

2.3. Laboratory analysis

All equipments used for analysis were acid washed and rinse at least 3 times with de-ionized distilled water.

2.3.1. Chlorophyll *a* determination

250 ml of sample was filtered through a 2.5 cm GF/F filter. This volume was reduced when the concentrations of chlorophyll *a* were becoming high. The filter was transferred into a test tube and 5 ml methanol was added as an extracting agent. The tubes were covered with parafilm and stored in the dark for 4 hours or left in the refrigerator overnight. The extract was then transferred into miniature test tube and read in a calibrated (Sigma chlorophyll *a*) Tuner fluorometer (Strickland and Parsons, 1972). This was then followed by addition of 2 drops of 10% HCl and the second reading was done. For each depth 3 replicates samples were measured. The values obtained from these two readings (before and after acidification) were used in the computation of the chlorophyll *a* content according to equation 6.

mg Chl *a* m^{-3} = 0.001938 x (R_b-R_a)/Volume   6

where R_b is reading before acidification and R_a is reading after acidification and volume in ml.

2.3.2. Biogenic silica (BSi)

Glassware is a product of silica therefore glassware must be avoided to reduce contamination. No forceps were used to handle glass fiber and no glassware was used in this analysis. A 750 ml of the sample was filtered through 47 mm polycarbonate filters with pore size 0.6 μm. Three replicates from each depth were filtered for analysis. The filters were transferred into cell culture wells and dried in an oven at 60^0C for 6 hours. The wells were cooled to room temperature and stored in small zip lock plastic bag for further analysis. BSi was measured by hydrolysis (Paasche, 1980) as described below.

Unfolded filters and tube were placed in a 50 ml polypropylene centrifuge and stopped to prevent loss of any Si particle. The contents in the centrifuge tubes were subjected to hydrolysis by adding 18 ml of 0.5% Na_2CO_3 (soda) solution and heated at 85^oC for 2 hrs. The tubes were allowed to cool and the filters were removed. A drop of methyl orange indicator was added and 0.5 N HCl was added from a burette to neutralize the soda to the turning point of methyl orange (pH 3–4) from red to pink. Distilled water was added to the content to make up to 25 ml. Equations 7 and 8 showed stepwise conversions from silica and subsequent products by each reagent into $Si(OH)_{4\,(aq)}$.

$$SiO_{2\,(s)} + Na_2CO_{3\,(aq)} \longrightarrow Na_2SiO_{3\,(aq)} + CO_{2\,(g)} \quad \text{(Hydrolysis step)} \qquad 7$$

$$Na_2SiO_{3\,(aq)} + 2HCl_{(aq)} + H_2O_{(aq)} \longrightarrow Si(OH)_{4\,(aq)} + 2NaCl_{(aq)} \quad \text{(Final)} \qquad 8$$
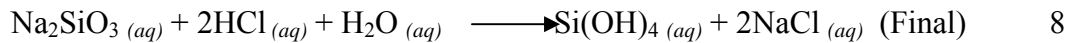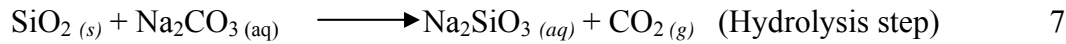
A 10 ml of a molybdate solution was added, the tubes were covered, mixed thoroughly and allowed to stand for 10 minutes. Reducing agent was immediately prepared from a mixture of methol-sulphite, oxalic acid and sulphuric acid. A volume of this was added to the content in the test tube up to the 50 ml mark. The tubes were allowed to stand for 2 – 6 hours before the concentration of Si $(OH)_4$ was determined by colorimetric method using 1 cm cells. The optical density for the standard OD_{ST} (5.00 mmol m^{-3}), blank (polycarbonate filter) OD_{BL} and synthetic seawater OD_{SSW} were measured first before the sample readings OD_{SA} were made. The concentrations of $Si(OH)_4$ were calculated by using equation 9. Further conversions were done to obtain the level of BSi in the ocean at the time of sampling based on the volume of sample water filtered.

$$\text{mmol m}^{-3} = (5.00/(OD_{ST} - OD_{SSW})) \times (OD_{SA} - OD_{BL}) \qquad 9$$

BSi concentrations measured were in samples collected at 5 m depths at selected dates based on chlorophyll *a* concentrations and phytoplankton identification and abundance examination.

2.3.3. pH determination

Electronic pH meter (744 pH meter) was used in determining the pH values on the days the samples were collected and throughout the sampling period. It was first calibrated with pH standards at 4.0, 7.0 and 9.0. A 20 ml water sample was taken at each depth 5, 10 and 50 m and allowed to adjust to the room temperature before pH reading was made.

2.3.4. Nutrients

100 ml of the sample was transferred into acid washed plastic bottle. Gloves were used in handling the plastic bottles. The bottles were put in a zip-lock plastic bag and frozen. The samples were used later for further analysis using a nutrient analyzer (O. I. Analytical, Texas USA). Nitrate was read as $NO_3^- + NO_2^-$, silicate as $Si(OH)_4$ and phosphate as orthophosphate.

The nutrient analyzer works under the same principles used in the chemistry laboratory for colorimetric determination of nitrate, phosphate and silicate according to Stockwell (1996). It measures nutrients of very minute concentrations. It works well when carefully operated. The major components are: the sampler, processor and monitor.

2.3.4.1. Nutrient analyzer operation mechanisms

The frozen samples were allowed to thaw and adjust to room temperature and mixed well by shaking. The test tubes were rinsed with the water sample three times and filled almost to the brim with sample. The filled test tubes were arranged in racks under the sampler according to a sample table.

The analyzer was calibrated with reference water from Ocean Scientific International Limited (Marine nutrients standards kit 2001) before water samples were measured. Artificial seawater was used as blank.

Sampler section: consists of a pistol containing a suction needle for taking fixed volumes of seawater from the test tubes. After each suction, artificial seawater flows through the needle to wash it of any of the previous water sample before the next sample.

Processor section: has in-let tube which receives the sample from the needle suction. This is then distributed into different tube channels where reagent mixtures are added and mixed in a reaction chamber. The out-let flow of the sample is delayed by mixing coils to ensure complete color development. Wash water (artificial seawater) and sample are separated by air or helium (He) bubbles to avoid dilution. Air is replayed by He in the nitrate line because air interferes with the nitrate measurements. As the developed color mixture gets into the detector, the air and helium bubbles are removed in a debubler before the color mixture enters the detector.

Monitor: displays the readings made from the detector and converts the readings to concentrations. It also allows any part of the graph to be viewed in detail. The detection limits for each of these nutrients can also be determined (see section 2.4).

Nitrate to phosphate ratios were calculated from concentrations of nitrate and phosphate obtained at 5 m for the time series plot. The same reason as stated under BSi method.

2.3.5. Phytoplankton

100 ml sample was transferred into a glass bottle and conserved with neutralized formaldehyde (2 ml of formaldehyde in 100 ml of seawater). The bottles were stored in a dark room. The samples were examined under a light microscope and genus identification was done according to Throndsen et al., (2007).

2ml of the preserved water samples was transferred into cell culture chamber by a clean-sterile pipette and covered with the lid. It was allowed to stand for at least 2 hours or overnight to allow all cells in the water sample to settle and to adjust to room temperature. A calibrated light microscope was used for identification and counting of the cells under 20x and 40x magnification respectively. Focusing on the dominating genera, chlorophyll *a* concentrations were used as a guide for which samples to select. Identification and counting were done at the 5 m depth before spring bloom, spring bloom and after spring bloom. The number of strips observed and counted was influenced by the number of cells seen in each

strip. For instant, one strip was enough in estimating the dominating genera in the spring bloom because 100 and more cells were identified and counted. In the other seasons, the whole cell chamber was counted because of low numbers of cell per each strip.

2.4. Statistical methods

Sample sizes were influenced by the four seasons: spring (March – April), summer (May – July), autumn (August – October) and winter (November – February). Samples were collected every week during the spring up to the mid of summer. Weekly collection during March was important to monitor the spring bloom peak and collapsed stage due to it's dynamic nature. After the collapse of the spring bloom samples were collected every two weeks.

Standard deviation (std), coefficient of determination (r^2) and coefficient of variation (CV) were used to validate the observed values. Most of CV in Table 2 were < 10%. Simple scatter diagrams and graphs were used to analyze relationships between the variables. MATLAB was used to draw Balsfjord and locate the position of sample collection. Surfer software was used for contour plots.

Table 1: Detection limits for the Automated nutrient analyzer.

Nutreint	Detection limit (mmol m^{-3})
NO_3^-/NO_2^-	0.15
PO_4^{3-}	0.02
$Si(OH)_4$	0.02

Detection limits for the nutrient analyzer are given in Table 1. They were calculated as 3 x standard deviation from 7 measurements.

Table 2: Average CV% of nutrients, BSi and chlorophyll *a* at 5, 10 and 50 m.

Nutrient	5 m	10 m	50 m
Nitrate	6	5	4
Phosphate	9	8	7
Silicate	4	3	4
BSi	10	nd	nd
Chl *a*	9	7	16

nd = not determined

3. Results

3.1. Seawater temperature

Very low temperatures of 2.3 – 4.3 ^{O}C were recorded during spring (Appendix 9). In Figure 2, during summer the highest temperature variations ranged from 5.0 – 9.7 ^{O}C. Temperature variations were very high in the upper layers (2 – 10 m) during this period. During autumn temperatures were constant throughout the entire profile. Temperatures during winter ranged from 5.5 – 6.5 ^{O}C.
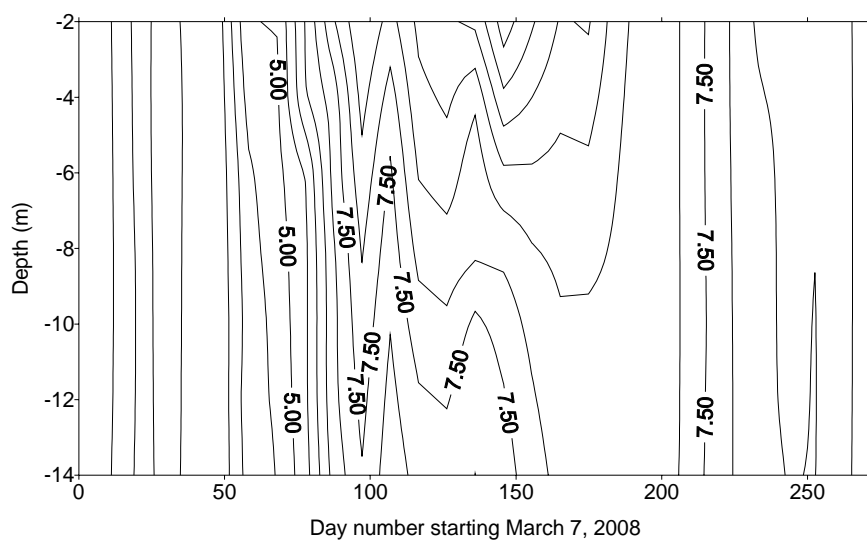
Figure 2: Temperature throughout the sampling period. The contour plot is based on measurements at 2, 4, 6, 8, 10, 12 and 14 m.

Salinity and density results were biased due to the limitation of the YSI 30 Handheld Salinity Conductivity Temperature System used. These results have therefore not been included in this presentation.

3.2. Nutrients

Table 3 shows a summary of the nutrients measured on some specific days for samples collected in 2008. The table shows events before (February), during (March) and after (May) the spring bloom.

Table 3: Nutrient concentrations (mmolm^{-3}) on some specific sampling dates at 5, 10 and 50 m.

Dates in 2008	Nitrate			Phosphate			Silicate		
	5	10	50	5	10	50	5	10	50
7 Mar	6.16	6.86	7.78	0.58	0.66	0.66	5.62	6.15	6.35
12 Mar	7.90	7.97	7.76	0.65	0.65	0.68	6.78	6.90	6.46
28 Mar	2.46	3.99	8.00	0.34	0.44	0.57	3.50	3.95	5.87
1 Apr	3.91	4.25	6.72	0.41	0.43	0.58	5.79	5.95	6.61
11 Apr	3.85	3.82	3.80	0.43	0.44	0.42	3.54	3.46	3.31
13 Apr	2.38	2.70	2.50	0.36	0.33	0.32	2.73	2.73	2.72
23 Apr	1.16	1.13	3.08	0.30	0.30	0.41	3.25	3.05	3.19
28 Apr	2.80	0.03	0.15	0.44	0.23	0.15	3.27	2.89	2.81
5 May	0.56	1.01	2.13	0.10	0.16	0.32	3.04	3.04	3.38
26 May	0.74	1.17	2.52	0.14	0.18	0.36	5.32	5.02	5.31
3 Jun	0.15*	0.15*	2.97	0.07	0.09	0.41	5.32	4.58	5.14
21 Jul	1.95	2.69	4.65	0.19	0.25	0.43	4.62	5.20	5.92

*Detection limit.

3.2.1. Nitrate

Nitrate was depleted during summer with some values <0.15 mmol m^{-3} (detection limit) at 5 m and was replenished in November with an average value of 4.25 mmol m^{-3} as in (Table 3 and Appendix 4). Depletion trend was similar at 10 m but was not that pronounced at 50 m (Figures 3 and 4).
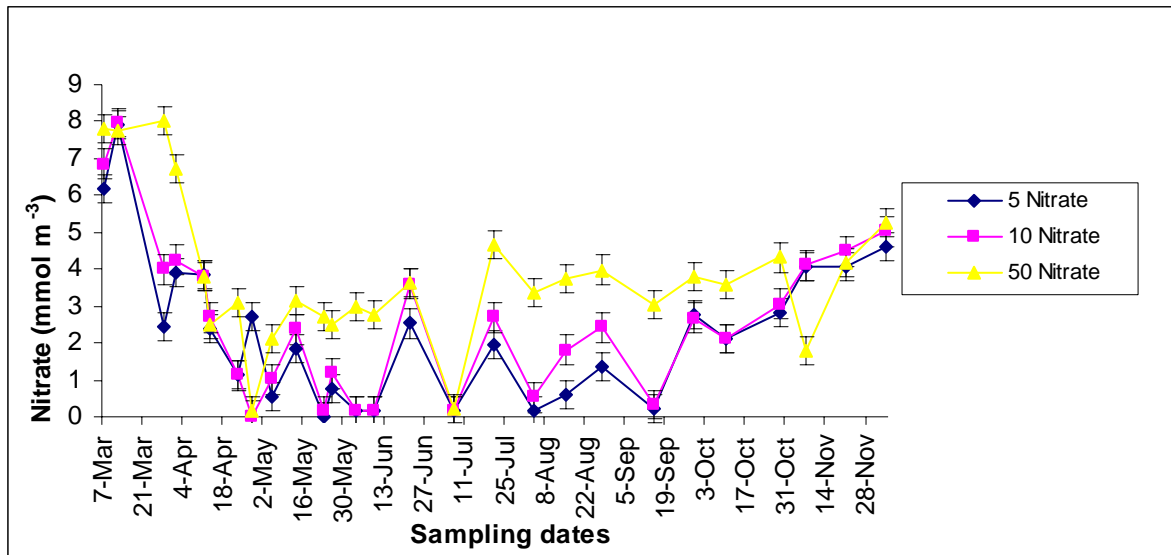
Figure 3: Nitrate concentration (average $\pm$ std in mmol m^{-3}) in the Balsfjord measured at 5, 10 and 50 m. A low concentration on November 7 has been excluded from the discussion.
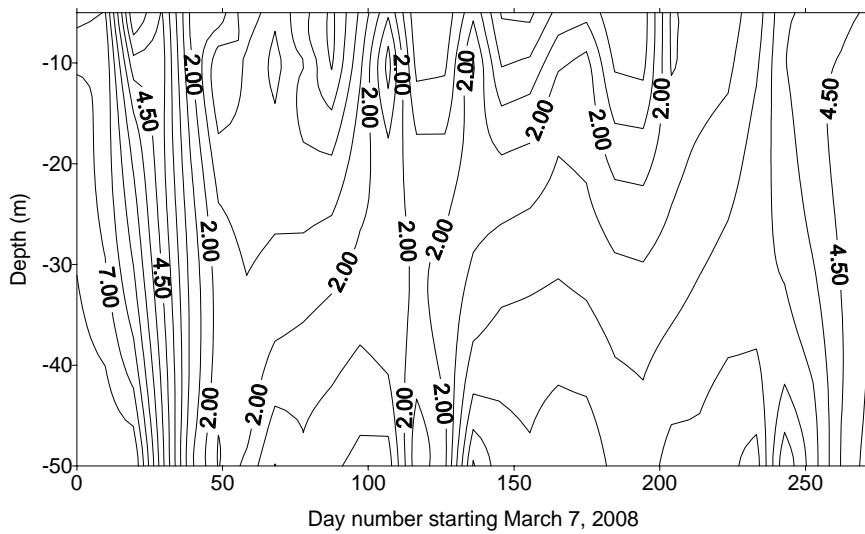
Figure 4: Contour plot of the nitrate concentrations at 5, 10 and 50 m.

3.2.2. Phosphate

Phosphate was gradually reduced from the beginning of the spring and the reduction became intense as spring bloom set-in in June (Table 3). Phosphate was highly reduced at 5 and 10 m during summer and autumn as compared to concentrations at 50 m. Figure 5 and 6 showed the depletion trends.
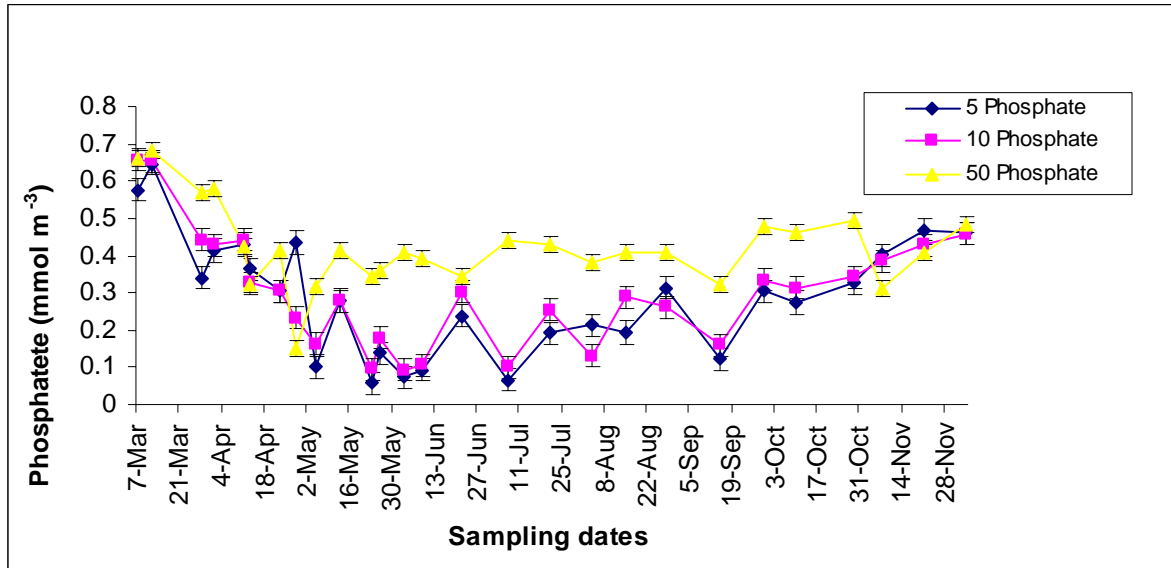
Figure 5: Phosphate concentration (average $\pm$ std in mmol m^{-3}) in the Balsfjord measured at 5, 10 and 50 m. A low concentration on November 7 was not included in the discussion.
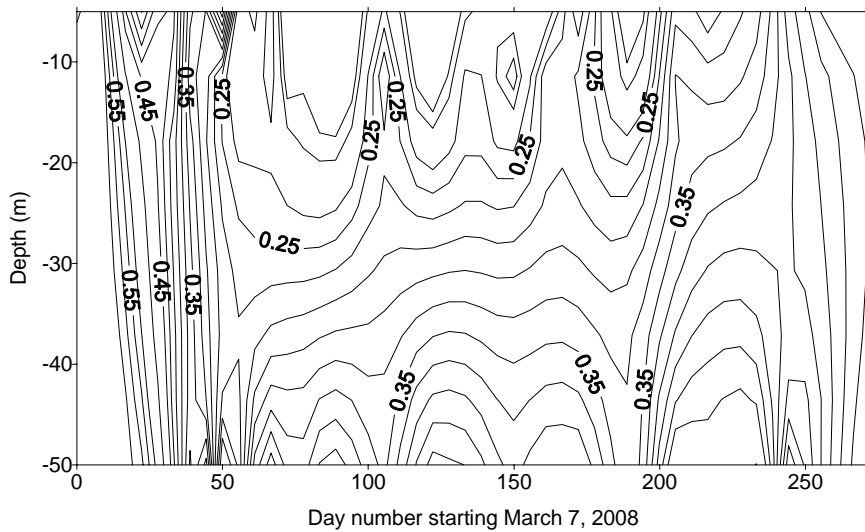
Figure 6: Contour plot of the phosphate concentrations at 5, 10 and 50 m.

3.2.3. Silicate

Major reduction of silicate occurred during the spring bloom at all depths (Table 3). Reduction was gradual and replenishment was very fast. The average concentrations in all the seasons and depths were almost the same (4.9 mmol m^{-3} for 5 and 10 m and 5.1 mmol m^{-3} for

50 m). Figure 7 and 8 showed minor depletion during mid-summer to mid-autumn mainly at 5 and 10 m. All depths showed higher replenishment during winter.
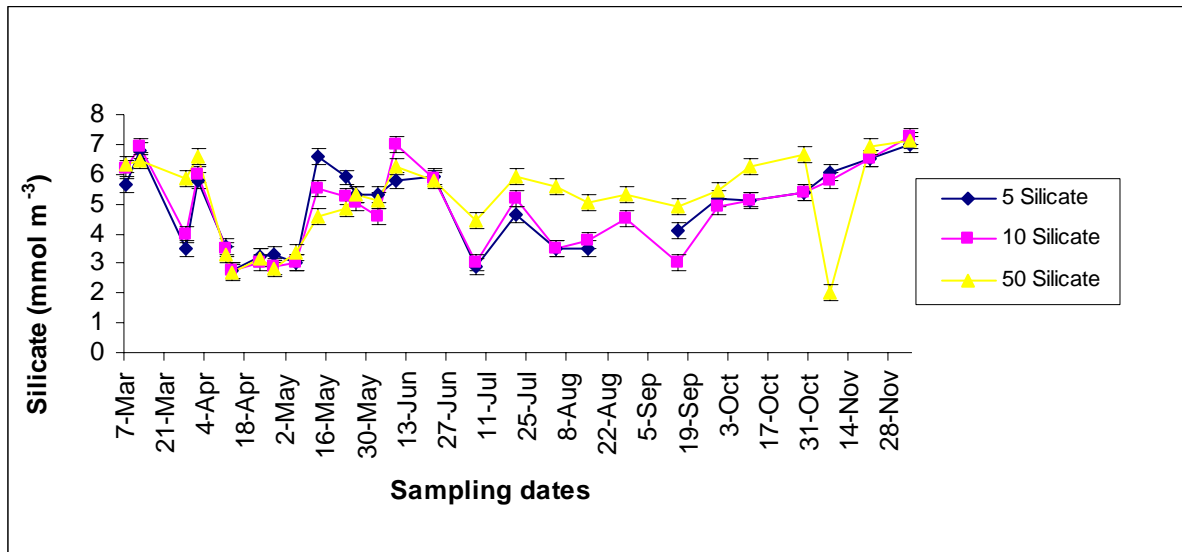
Figure 7: Silicate concentration (average $\pm$ std in mmol m^{-3}) in the Balsfjord measured at 5, 10 and 50 m. A low concentration on November 7 was excluded from the discussion.
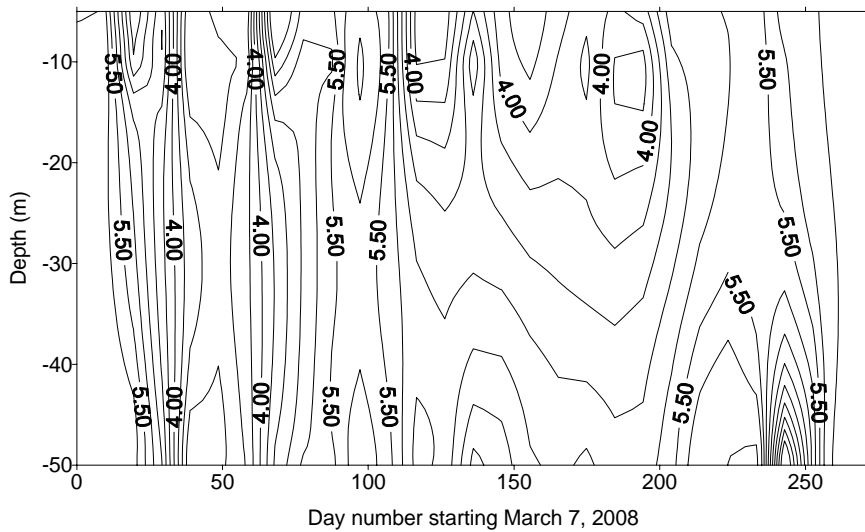
Figure 8: Contour plot of the silicate concentrations at 5, 10 and 50 m.

3.3. Nutrient ratios

Trend lines from scatter plots of nitrate versus phosphate at 5, 10 and 50 m showed slopes in the range 12–15 (Figure 9a, b and c). All depths showed positive *x* intercepts indicating the

availability of phosphate when nitrate was depleted. The plots were statistically significant with *F significance* <0.0000 (see Appendix 11-14).

Seasonal development of the nitrate: phosphate ratio at 5 m depth is given in Figure 10. The ratio was higher during the winter and spring (8-10) than during summer and autumn (5). The plot for 5 m was shown as a case study for similar trends were seen at 10 and 50 m.
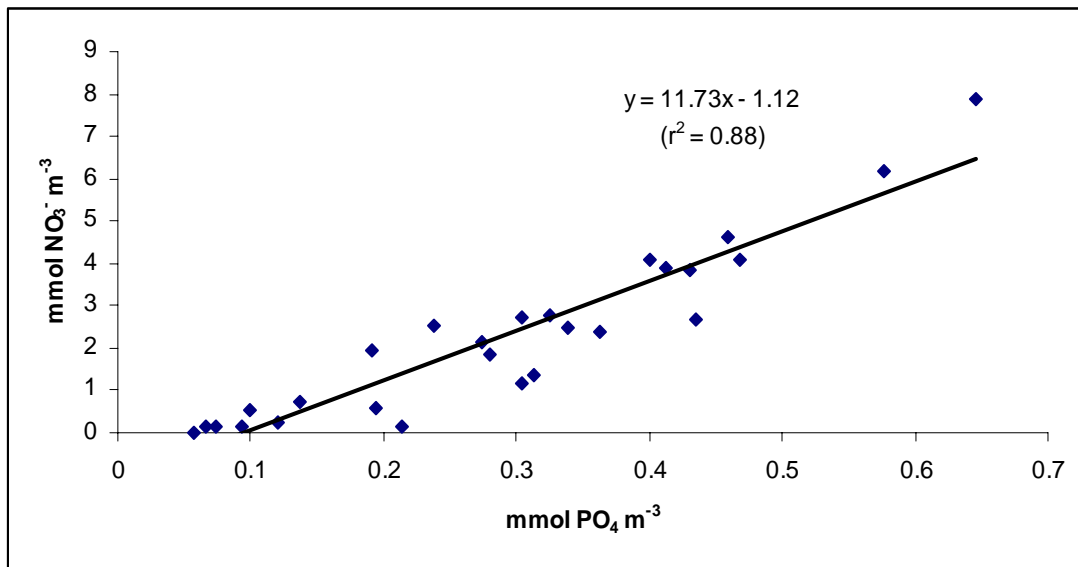
Figure 9a: Nitrate verses phosphate plot at 5 m for all seasons in 2008.
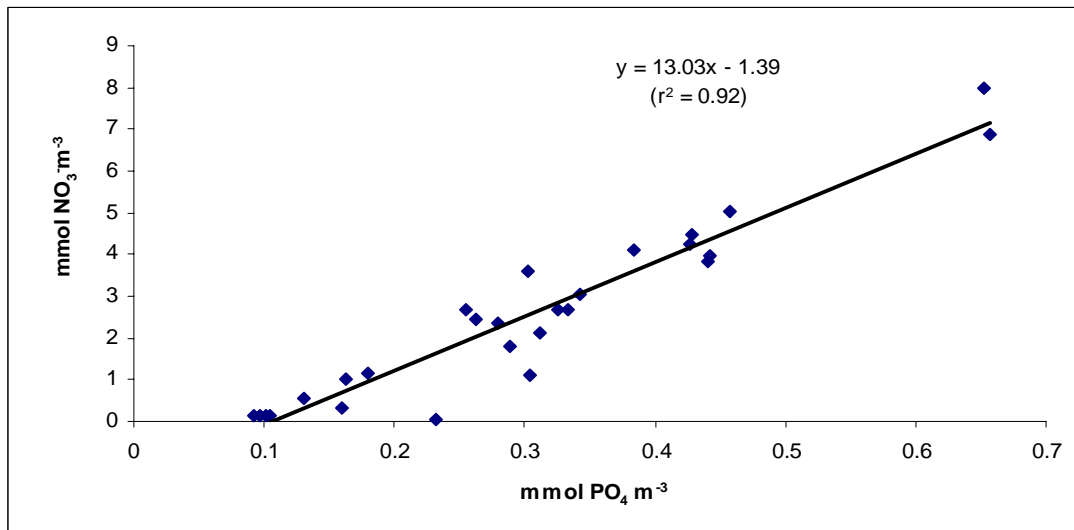
Figure 9b: Nitrate verses phosphate plot at 10 m for all seasons in 2008.
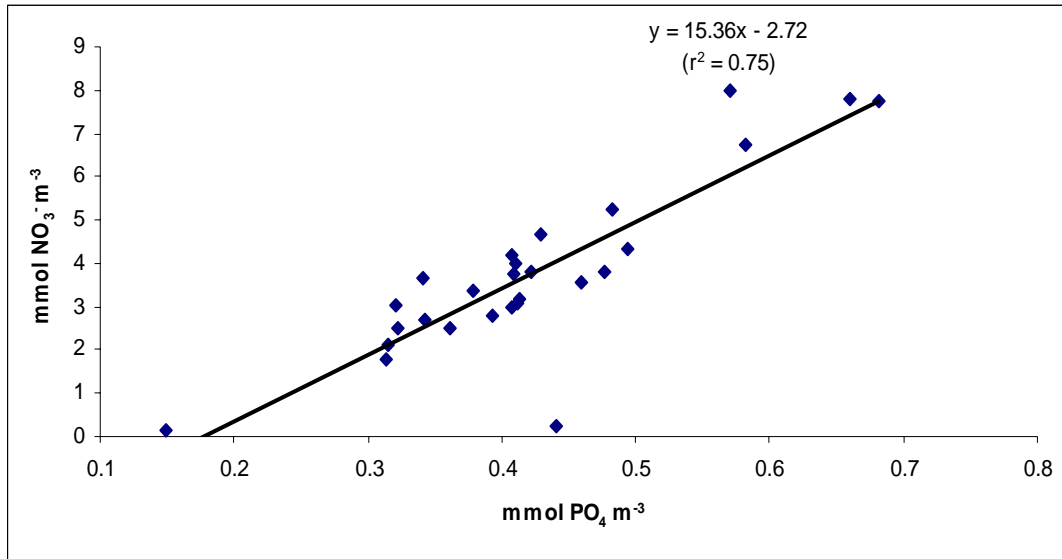
Figure 9c: Nitrate verses phosphate plot at 50 m for all seasons in 2008.
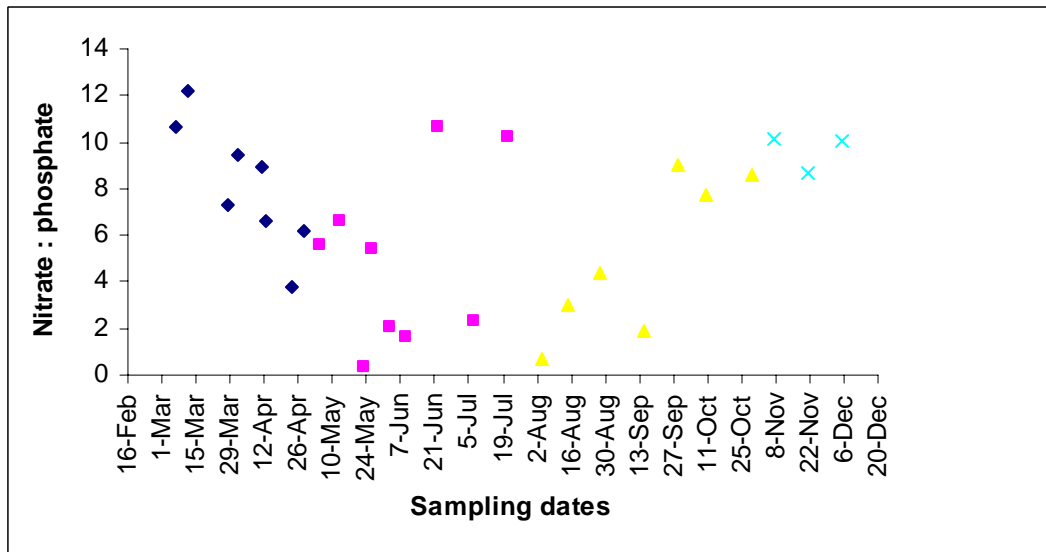
Figure 10: Nitrate to phosphate ratio at 5 m start in March 7, 2008 (diamond = spring, square = summer, triangle = autumn, cross = winter).

Silicate to nitrate ratios trend as seen in Table 4 showed nitrate were highly depleted as none of the ratio values were <1. The highest depletion occurred during the spring bloom (1.3) and nutrients rebuilding occurred afterwards. Figure 11 showed a plot of silicate and nitrate

concentrations with 4.1 mmol m^{-3} of silicate when nitrate was completely depleted. The regression line is significant at F = 0.0117 (see Appendice 15).

Table 4: Silicate to nitrate ratios (mol: mol) in the different seasons at 5, 10 and 50 m.

Season	5 m	10 m	50 m
Spring	1	14	3
Summer	42	16	4
Autumn	8	4	2
Winter	2	1	2
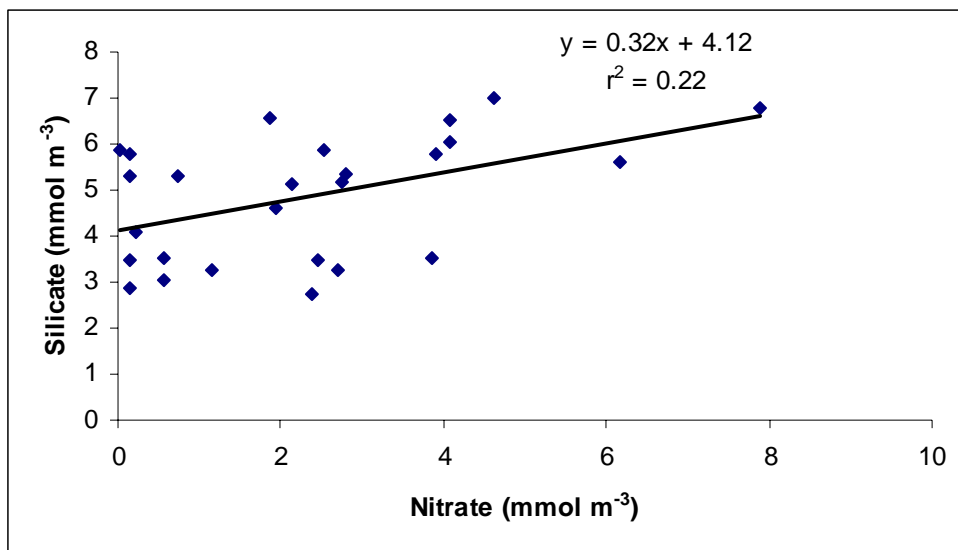
Figure 11: Silicate and nitrate concentrations plot at 5 m.

3.4. pH

pH values ranged from 7.2 – 8.0 at 5 m, 7.6 – 8.0 at 10 m and 7.7 – 8.1 at 50 m (Appendix 8). There are similar ranges for all the depths but a wider pH range at the 5 m than at 10 and 50 m.

3.5. Chlorophyll *a* concentrations

Figure 12 and 13 showed peaks at all depths and seasons. The average chlorophyll *a* concentration was 2.0 mg m^{-3} during spring at 5 m (Appendix 2). The highest concentrations were 3.9 and 5.7 mg m^{-3} during the spring bloom on April at 5 and 10 m respectively (Table 5). After these peaks concentrations declined sharply and steadily (Figures 12 and 13). The lowest average chlorophyll *a* concentrations at these depths occurred during winter. The highest peaks during summer were 3.2 and 4.7 mg m^{-3} at 5 and 10 m respectively. The highest peak of chlorophyll *a* concentration at 50 m was 3.5 mg m^{-3} observed during early summer and lowest was 0.1 mg m^{-3} during early spring and late winter (Table 5).
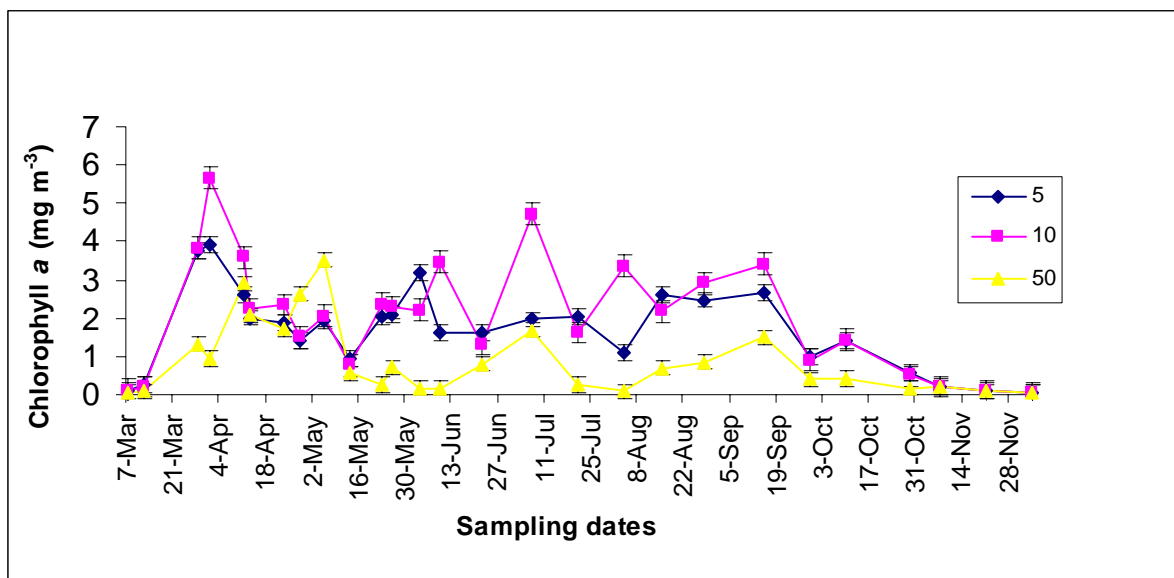
Figure 12: Chlorophyll *a* concentration (average $\pm$ std in mmol m^{-3}) in the Balsfjord measured at 5, 10 and 50 m.
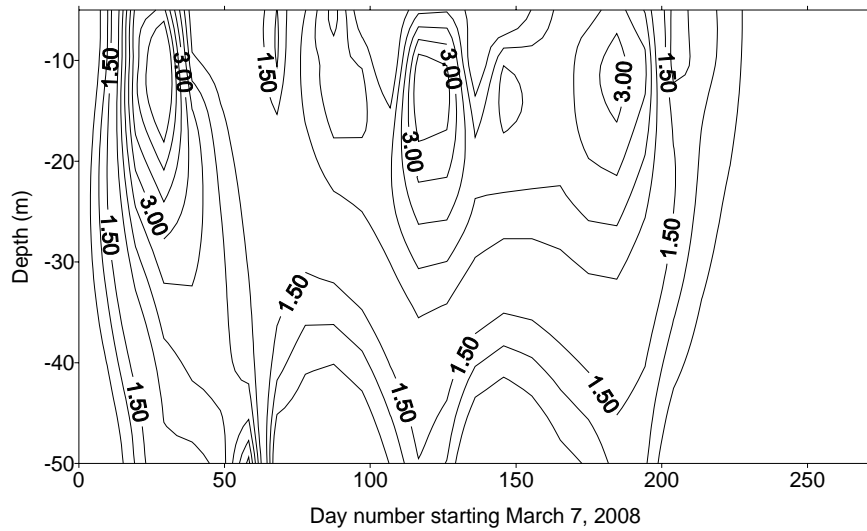
Figure 13: Contour plot of the chlorophyll *a* concentrations at 5, 10 and 50 m.

3.6. Trends of chlorophyll *a* and nitrate concentrations

Figure 14 show the chlorophyll *a* and nitrate depleting trends. Similar trends were seen at all depths but only values from 5 m are presented in this figure (see BSi method). Chlorophyll *a* concentrations were very low early during spring when nitrate concentrations were high. Nitrate depletion was observed when chlorophyll *a* concentrations were high during the spring bloom, summer and autumn. When chlorophyll *a* concentrations became low again during winter nitrate concentrations recovered and high values of nitrates were observed once again.
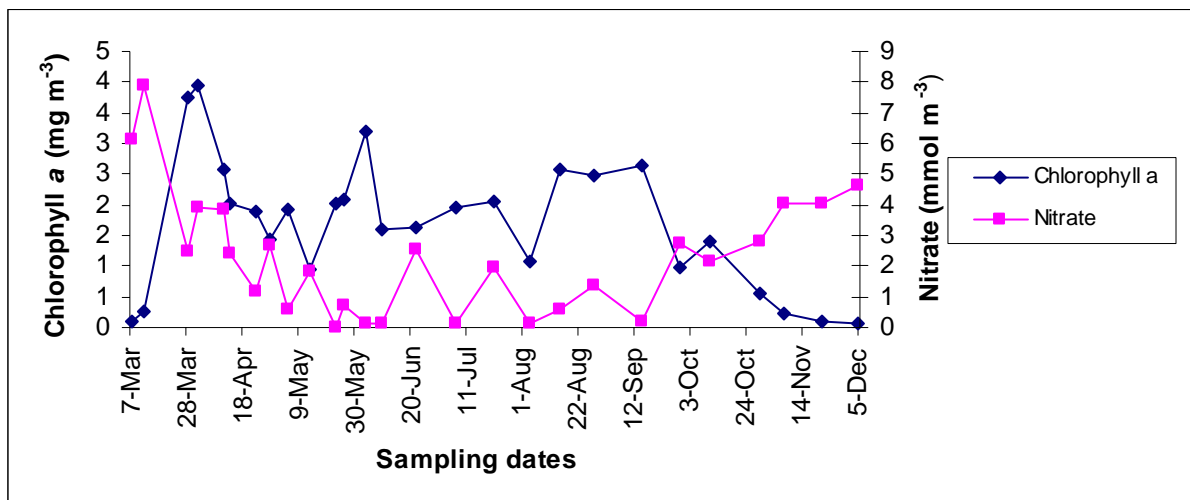
Figure 14: Nitrate depletion and chlorophyll *a* production trends at 5 m.

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3.7. Biogenic silica (BSi) concentration

Selected peaks from the chlorophyll *a* values were used as a guide for BSi analysis. These peaks were before, during and after the spring bloom. The BSi concentrations increased steadily as primary production rose until the highest BSi concentration was observed in April. After April BSi concentration declined and remained low with no abrupt change. The BSi concentration ranged from 0.2–4.3 mmol m^{-3} (see Figure 15a and Table 5). During spring BSi concentrations ranged from 0.2–4.3 mmol m^{-3} and during summer 0.3–0.9 mmol m^{-3}.
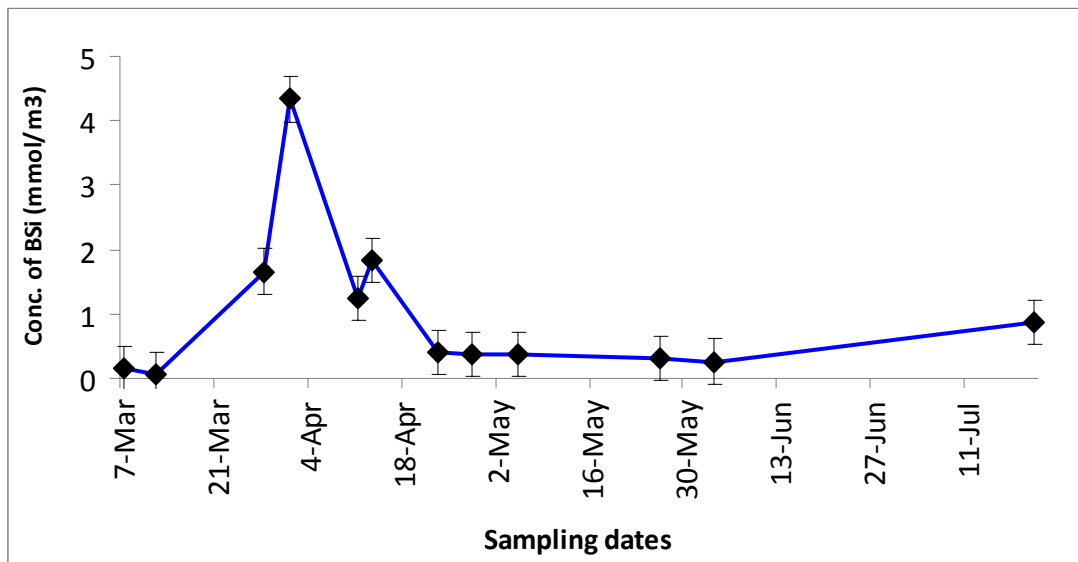
Figure 15a: Biogenic silica concentrations at 5 m depth on selected dates.

There is almost an inverse relationship between silicate and BSi as in Figure 15b. Generally there was higher concentration of silicate during the early stages of spring and summer when the use of silicate was minimal. A corresponding low concentrations of BSi were recorded. Relatively the highest BSi concentration was on April 1 which resulted in high reduction in silicate concentration (Table 5). The lowest BSi (0.07 mmol m^{-3}) was observed on March 12 which also recorded the highest silicate concentration (6.78 mmol m^{-3}).
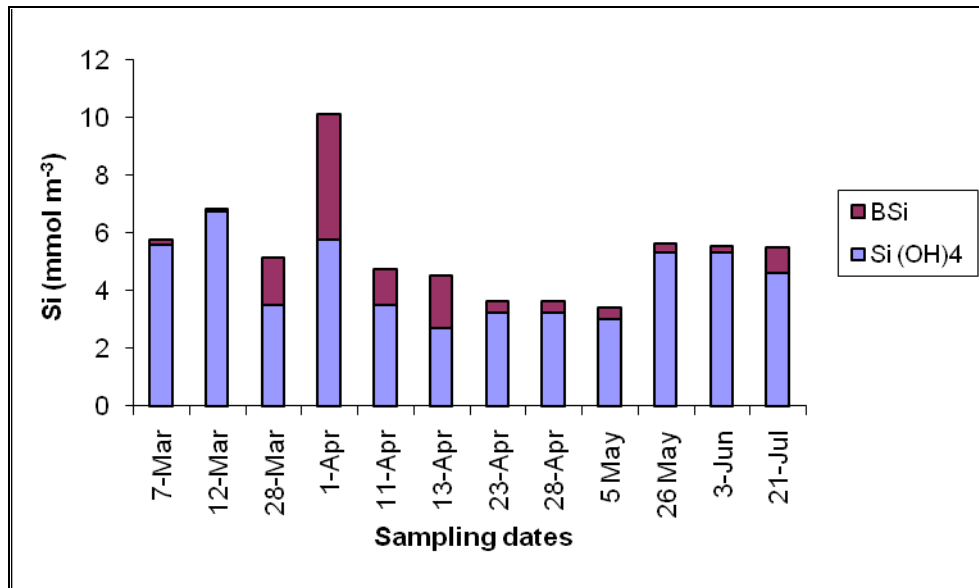
Figure 15b: The concentration between silicate and BSi during before, during and after the spring bloom at 5 m.

3.8. Phytoplankton genera composition

Phytoplankton composition observed from March to July was dominated by *Chaetoceros*, *Fragilariopsis*, *Phaeocystis*, unidentified flagellates and unidentified diatoms (see Table 5). Early in the spring (March), unidentified diatoms dominated with cell abundance of 120 cells mL^{-1}. As spring bloom occurred in April, *Chaetoceros* became dominant with 1122 cells mL^{-1} on April 1 and declined afterwards on April 13 with 52 cells mL^{-1}. After the collapse of the diatom community, *Fragilariopsis* then became more dominant than any other genera in those periods with 175 and 285 cells mL^{-1} on April 23 and 28 respectively. It was succeeded by *Phaeocystis* with 55 cells mL^{-1} on May 5. Unidentified flagellates dominated after May. All flagellates observed were less than half the size of the diatom (*Chaetoceros*).

Table 5: Chlorophyll *a* concentrations measured at 5, 10 and 50 m and BSi, dominant genera identified and cell abundance measured at 5 m on some specific sampling dates.

Dates in 2008	Chl *a* (mg m^{-3})			BSi (mmol m^{-3})	Dominant genera identified	Cell abundance (x 1000/L)
	5	10	50	5	5	5
7 Mar	0.10	0.11	0.05	0.15	Unidentified diatoms	10
12 Mar	0.25	0.21	0.08	0.07	Unidentified diatoms	120
28 Mar	3.76	3.82	1.33	1.66	Unidentified diatoms	75
1 Apr	3.93	5.65	0.94	4.34	*Chaetoceros*	1122
11 Apr	2.59	3.60	2.91	1.24	*Chaetoceros*	375
13 Apr	2.01	2.23	2.08	1.83	*Chaetoceros*	52
23 Apr	1.90	2.35	1.70	0.41	*Fragilariopsis*	175
28 Apr	1.43	1.49	2.62	0.37	*Fragilariopsis*	285
5 May	1.94	2.38	3.52	0.38	*Phaeocystis*	55
26 May	2.09	2.28	0.72	0.31	Flagellates (autotrophic and heterotrophic)	64
3 Jun	3.19	2.20	0.17	0.26	Flagellates (autotrophic and heterotrophic)	72
21 Jul	2.04	1.62	0.26	0.88	Flagellates (autotrophic and heterotrophic)	62

4. Limitation of this study

The sources of the nutrients and the amount they contribute could give information of the major nutrient supply into this fjord. Hydrology of the Balsfjord was not included in this study which would have provided why there is nutrient reflux and possibility of predicting the trend of nutrient availability with time. Other nutrient competitors like bacteria were not experimentally sampled and counted.

Chlorophyll *a* was used as a measure of phytoplankton production represented total production (photosynthesis). This was because essential step such as energy required for respiration (for example diatom) was not experimentally determined in this study.

5. Discussions

5.1. Temperature and turbulences control on phytoplankton

In general phytoplankton growth increase by increasing temperature (Eppley, 1972; Elliot et al., 2006). In the Balsfjord low water temperature apparently led to high phytoplankton species diversity and *Chaetoceros* abundance during the spring due to high nutrient availability (Table 5) and solarization (Hegseth et al., 1995). Other factors such as low stratification of the water masses and light might play a very important role (Huisman and Sommeijer, 2002). Temperature values were similar to those observed by Hegseth et al., (1995). During spring it was observed from the temperature contour plot that water profile became calm (Figure 2). During summer, autumn and winter temperatures were quite high but those values did not result in high growth of phytoplankton due to nutrient depletion which is discussed below. Temperature is important in regulating phytoplankton growth but data collected was not large enough to prove this. Specific nutrients like nitrate and silicate are the possible controlling factors of the spring bloom development and will be further discussed below.

The strength of turbulence and stability of the water column are important in regulating phytoplankton production (Ghosal et al., 2000, Kirchman, 2000). These were not also considered during sampling as time for this research was limited but were discussed due to their importance in phytoplankton production. Turbulence can act as an agent for nutrients supply for primary production. The strength of turbulence is important as too low turbulence will not bring up nutrients in sediments of the sea floor. Likewise too high turbulence could result in too high mixing in the euphotic zone. Therefore intermediary turbulence is required for primary production. Temperature contour plot showed mixing after the spring bloom (Figure 2). Apart from change in temperatures, the spring bloom collapse could also be as a result of high cell densities and high mixing in the water column (Eilertsen and Taasen, 1984). Also aggregation and sedimentation of diatoms are capable of causing the collapse (Tiselius and Kuylenstierna,1996). Furthermore grazing by copepods during the summer on phytoplankton (diatoms) could have also collapsed the bloom (Nybakken and Bertness, 2005). This was because copepod was found in the water sample for phytoplankton species

identification under the light microscope examination. This was treated as a flyer since it was the only one identified in June.

5.2. Nutrients control on phytoplankton

Phytoplankton requires nutrients for growth, most important are phosphate, nitrate and silicate (Brown et al., 1995). Primary production was highest during the spring but nutrients seemed to be less depleted during this period due to high nutrients availability from the last winter season. In particular there is always surplus of phosphate in the marine waters which are important in the next production. Nitrate depletion occurred during summer, phosphate and silicate reduction occurred during summer and spring respectively. Phosphate reduction was very prominent at 5 and 10 m than at 50 m (Figure 5). These were regions where active photosynthesis takes place and nutrients demand would be high (VanDemark and Batzing, 1987). 5 and 10 m received a lot of sunlight which encouraged nutrients depletion through photosynthesis. In the periods when low concentrations of these nutrients were observed there were corresponding high chlorophyll *a* and abundance of phytoplankton (diatom) composition (Table 5). Nitrate was highly depleted at these depths because of its importance in most biological activities (Figures 3 and 4). Nitrate must control phytoplankton production. Depletion of nitrate was very intense from late spring into summer to autumn at 5 and 10 m than the same depths for phosphate due to its utilization in production (Figures 3 and 4). There must be constant supply of phosphate or its demand for phytoplankton and bacteria activities must be lower than nitrate (Kirchman, 2000). It is known that phosphate is regenerated in the water column but nitrogen is regenerated in the form of ammonia instead of nitrate (Kirchman, 2000). Also heterotrophic bacteria have higher cellular phosphate than phytoplankton therefore competition for it may be low. These reasons make nitrate supply limited by supply of nitrate rich water only and therefore prone to easy depletion when demand for it is more than its supply. At 50 m depth nitrate and phosphate values were low but nitrate depletion was more intense than phosphate at this depth. Silicate reduction was generally slow at all depths throughout the sampling periods as was also observed by Holdal and Kristiansen (2008). Intense reduction occurred during spring bloom because of more cell division leading to high diatom abundance (Tables 3 and 5). Similar reduction was observed during spring bloom by Kristiansen et al., (2000). Minor reduction also occurred in autumn at

5 and 10 m when cell abundance were low. Restoration of silicate concentrations after spring bloom was rapid as cell abundance was low and a shift of phytoplankton composition from diatoms to flagellates. In most cases reduction was faster at 5 and 10 m and restoration was faster at 50 m (Figure 7). This was as a result of the supply of nutrients by upwellings from sea floor playing important role in nutrient availability in the water column (Rey, 2004). There are also supply of silicate, nitrate and phosphate from in-flow of water from surrounding rivers into the fjord (Eilertsen and Taasen, 1984). According to Chester (2003) silicate is generally never depleted in marine waters due to constant dissolution of shells throughout the water column. The results show that silicate concentrations were intensely reduced (for example at 5 m, 21%) during the spring bloom when diatom production was at its peak and probably due to the short period of the bloom (Tables 3 and 5). Silicate is important for diatom abundance and at low concentrations flagellates increase while diatoms decline. The available silicate and BSi trend gave important relationship throughout the production seasons. The highest BSi value was observed when diatom abundance was highest on 1st April. On this date about 50% of Si expressed in BSi was obtained. The remaining days had lower BSi/silicate fractions in accordance to variations in phytoplankton composition (Table 5). In general there was an inverse relationship between BSi and silicate as in Figure 15b. There was also high concentrations of silicate than actually utilized by the diatoms since silicate was never depleted. There was no autumn bloom in 2008 which could have utilized more of the silicate available.

Primary production was highest during the spring but nutrients seemed to be less depleted or reduced during this period due to the high nutrients availability from the last winter season (Figures 3, 5 and 7). Nitrate and phosphate built up again after summer and autumn when their demands were low. The restoration of silicate begun immediately after the spring bloom since only diatoms utilize it. Higher nutrient concentrations were observed at 50 m as minimal primary production occurred because of low light intensity. Phytoplankton cell size distributions are important in pelagic food web (Malone, 1980). This is because smaller cells are more efficient in nutrient assimilation than larger cells and most often dominate after the peak of the bloom (Holdal and Kristiansen, 2008). Phytoplankton genera changed from diatoms *Chaetoceros* to less abundance flagellates which could survive in low nutrient concentrations after the spring bloom. The change in phytoplankton composition from *Chaetoceros* to flagellates was as a result of silicate reduction. The cell abundance per liter

confirmed this trend (Table 5). Eilertsen et al., (1981) also observed that the main phytoplankton communities were *Chaetoceros* as among the main genera in Balsfjord and the abundance were also similar to what were observed during this research. Cell specialization in nutrient utilization could also be the reason for the change in genera composition.

5.3. pH

pH is important factor which regulates nutrients chemical composition and spectrum of biological activities (VanDemark and Batzing, 1987). The pH values observed represented typical seawater values also observed by others like Hegseth et al., (1995). Most biological reactions occur within these pH ranges 7.2-8.0 (Appendix 8) as was observed by VanDemark and Batzing, (1987). This exposes the nutrients required by phytoplankton to competition mostly from bacteria. Large amounts of phytoplankton and bacteria also accounted for the rapid reduction of phosphates and depletion of nitrates during the peak seasons of production (spring and summer). At these pH values, cations such as Al^{3+}, Ca^{2+} and Mg^{2+} would be precipitated and nutrients especially phosphates would be in mobile states. The wider range of pH observed at 5 m could give a large range spectrum of biological reactions for more microbial activities than at 10 and 50 m (VanDemark and Batzing, 1987).

5.4. Nutrient ratios

Nutrients were highly depleted or reduced during the active seasons of phytoplankton production and this resulted in low nutrient availability in the water column (Figure 9a, b and c). Nitrate was depleted during the active production period while phosphate was reduced; therefore the collapse of the bloom was probably a result of nitrate deficiency. Tyrrell and Law (1997) also observed the same trend in the global ocean studies. The positive *x*-intercepts of at 5, 10 and 50 m respectively (Figure 9a, b and c) were indications of the availability of phosphate to support production when nitrates were totally depleted. An equation for these depths could be summarized as $[NO_3^-] = (11\text{-}15)\ [PO_4^{3-}]$. The main observation made from these graphs was that the slopes were more tilted to the *x – axis* (phosphate axis) than to the *y – axis* (nitrate axis). Also 1 mmolm^{-3} of phosphate to 11-15 mmol m^{-3} of nitrate were required for biological activities. These two observations indicated more demand and utilization of

nitrate than phosphate. Earlier research by Officer and Rhyther (1980) suggested the importance of silicate to nitrate ratios to marine life. Silicate to nitrate ratios observed in this research were above 1:1 which were similar observations made by Turner et al. (1998). They stated that when the ratio falls below 1:1, there would be a change in the trophic levels from diatoms to higher feeders. This would also reduce the diatom abundance. Since all the silicate to nitrate ratios were above 1:1 ratio, there would be higher energy efficiency and diatoms formed the dominate genera in this fjord. The results of silicate and nitrate ratios also confirm that nitrate was the main controlling factor.

5.5. Chlorophyll *a* and phytoplankton production

In Figure 12 chlorophyll *a* concentrations observed at different periods corresponded to phytoplankton productions as BSi and cell abundance (Table 5) and are in accordance with values observed by Wassmann et al., (2000). Phytoplankton composition varied a lot throughout the seasons as nutrients did. Chlorophyll *a* was highest during spring and lowest during winter at 5 and 10 m. Chlorophyll *a* was highest in early summer and least during winter at 50 m. Low light and high mixing of the water column were responsible for the lowest production during winter at 5, 10 and 50 m. Chlorophyll *a* concentration trends changed from season to season due to the dynamic nature of oceanic conditions. This also resulted in change in phytoplankton composition (Table 5). Microscopic identification and abundance revealed that high chlorophyll *a* peaks have high diversity of phytoplankton genera and abundance. For example April 1st at 5 m had the highest phytoplankton abundance and genera.

5.6. Phytoplankton and Fisheries management

The basis of fisheries management begins with the knowledge of phytoplankton on which the fish depends. The composition of phytoplankton is dynamic and prone to change in response to its environmental conditions such as climate change and pollution (Hays et al., 2005). A basic sign to that effect is an increase in smaller cells dominating the water ecosystem such as flagellates which were a minority in previous times (Turner et al., 1998). This change could increase the number of trophic levels, reduce energy efficiency, reduce fish production and

change the flow of energy to other predators. Hydrological conditions do not only result in nutrient reflux but can also change the composition of phytoplankton composition (Hays et al., 2005). In Table 4, *Chaetoceros* dominated the genera of phytoplankton community during spring and flagellates became dominate after the collapse of the bloom. Flagellates only formed 8% while *Chaetoceros* formed 63% of the phytoplankton community in these two seasons (spring and summer). This high cell numbers of *Chaetoceros* indicated that there was enough food to support many forms of primary consumers to support high fish production. There would therefore be high energy efficiency within the ecological community of Balsfjord. Any shift in phytoplankton composition in the long term can change the spawning grounds, feeding and migration pattern of many primary and secondary consumers. In the process of photosynthesis, phytoplankton performs other valuable ecological activities such as biogeochemical recycling of nutrients, carbon and pollutants as different biochemical transformations take place.

6. Conclusion

The study evaluated N, P, Si, identified the dominating compositions of phytoplankton and evaluated these controlling factors on primary production in the Balsfjord. It has been demonstrated from this study that phytoplankton production is governed by several environmental factors which are inter-dependent. It is therefore difficult to single out factors like light, turbulence, temperature and nutrients as the only controller of primary production. Temperature was low especially during the spring than in the remaining seasons which facilitated changed in phytoplankton composition. Nutrient concentrations showed depletion during the spring bloom and least during winter. Nitrate was more depleted than phosphate than silicate during the entire seasons. Microscopic examination also showed a shift in phytoplankton species as nutrients were depleted or reduced. The nitrate to phosphate ratios at 5, 10 and 50 m revealed a strong correlation between these nutrients in facilitating phytoplankton production with r^2 of 0.9, 0.9 and 0.8 respectively. Nitrate was the major controlling factor of phytoplankton production in the Balsfjord. Also silicate to nitrate ratios also revealed nitrate as the controlling factor. Nutrients therefore remain important factors for phytoplankton production in the Balsfjord. Balsfjord is therefore an ecologically healthy fjord which can support the growth of most species.

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8. Appendices

Appendix 1

Table 5: Chlorophyll *a* concentrations from March-December 2008 at 5, 10 and 50 m.

Dates	5m Mean±std	10 m Mean±std	50 m Mean±std
7 Mar	0.10±0.00	0.11±0.00	0.05±0.00
12 Mar	0.25±0.01	0.21±0.00	0.08±0.00
28 Mar	3.76±0.44	3.82±0.59	1.33±0.04
1 Apr	3.93±0.64	5.65±0.21	0.94±0.07
11 Apr	2.59±0.30	3.60±0.53	2.91±0.14
13 Apr	2.01±0.05	2.23±0.24	2.08±0.06
23 Apr	1.90±0.27	2.35±0.05	1.70±0.17
28 Apr	1.43±0.36	1.49±0.23	2.62±0.12
5 May	1.94±0.34	2.38±0.22	3.52±0.16
13 May	0.93±0.14	0.76±0.02	0.55±0.04
23 May	2.03±0.07	2.36±0.02	0.26±0.01
26 May	2.09±0.08	2.28±0.19	0.72±0.04
3 Jun	3.19±0.10	2.20±0.11	0.17±0.02
9 Jun	1.61±0.09	3.47±0.06	0.17±0.02
22 Jun	1.64±0.03	1.33±0.05	0.80±0.02
7 Jul	1.96±0.03	4.71±0.20	1.68±0.18
21 Jul	2.04±0.07	1.62±0.01	0.26±0.02
4 Aug	1.09±0.05	3.35±0.12	0.10±0.00
15 Aug	2.59±0.19	2.18±0.12	0.69±0.04
28 Aug	2.48±0.16	2.90±0.13	0.85±0.05
15 Sep	2.64±0.36	3.42±0.14	1.49±0.18
29 Sep	0.99±0.04	0.90±0.02	0.40±0.02
10 Oct	1.40±0.13	1.42±0.09	0.42±0.02
29 Oct	0.55±0.06	0.52±0.03	0.16±0.01
7 Nov	0.22±0.03	0.21±0.03	0.19±0.04
21 Nov	0.09±0.01	0.09±0.00	0.08±0.00
5 Dec	0.05±0.01	0.04±0.01	0.05±0.01

Appendix 2

Averages of Chl *a* concentrations in the different seasons at 5, 10 and 50 m depths.

Season	5 m	10 m	50 m
Spring	2.00	2.43	1.46
Summer	1.94	2.35	0.90
Autumn	1.68	2.10	0.59
Winter	0.12	0.11	0.11

Appendix 3

Means of BSi concentrations from March to December 2008 at 5 m.

Dates in 2008	mean±std
7 Mar	0.15±0.00
12 Mar	0.07±0.01
28 Mar	1.66±0.08
1 Apr	4.34±0.16
11 Apr	1.24±0.02
13 Apr	1.83±0.19
23 Apr	0.41±0.09
28 Apr	0.37±0.08
5 May	0.38±0.01
26 May	0.31±0.04
3 Jun	0.26±0.04
21 Jul	0.88±0.10

Appendix 4

Concentrations of nitrate, phosphate and silicate (average ± std) at 5 m in the Balsfjord in 2008.

Dates in 2008	Nitrate average (mmolm^{-3})± std	Phosphate average (mmolm^{-3})± std	Silicate average (mmolm^{-3})± std
7 Mar	6.16±0.34	0.58±0.03	5.62±0.21
12 Mar	7.90±0.47	0.65±0.05	6.78±0.08
28 Mar	2.46±0.15	0.34±0.02	3.50±0.09
1 Apr	3.91±0.03	0.41±0.03	5.79±0.07
11 Apr	3.85±0.34	0.43±0.01	3.54±0.02
13 Apr	2.38±0.01	0.36±0.03	2.73±0.02
23 Apr	1.16±0.08	0.30±0.02	3.25±0.13
28 Apr	2.70±0.14	0.44±0.03	3.27±0.12
5 May	0.56±0.09	0.10±0.01	3.04±0.06
13 May	1.86±0.19	0.28±0.04	6.59±0.28
23 May	0.02±0.01	0.06±0.01	5.88±0.34
26 May	0.74±0.05	0.14±0.01	5.32±0.16
3 Jun	0.15*	0.07±0.01	5.32±0.02
9 Jun	0.15*	0.09±0.00	5.80±0.11
22 Jun	2.52±0.18	0.24±0.02	5.89±0.55
7 Jul	0.15*	0.07±0.02	2.88±0.14
21 Jul	1.95±0.06	0.19±0.01	4.62±0.36
4 Aug	0.15*	0.21±0.05	3.50±0.69
15 Aug	0.58±0.02	0.19±0.03	3.51±0.42
28 Aug	1.36±0.08	0.31±0.01	na
15 Sep	0.23±0.01	0.12±0.01	4.08±0.24
29 Sep	2.74±0.09	0.30±0.04	5.18±0.40
10 Oct	2.13±0.10	0.27±0.01	5.14±0.08
29 Oct	2.80±0.27	0.33±0.03	5.36±0.26
7 Nov	4.08±0.17	0.40±0.03	6.06±0.11
21 Nov	4.07±0.12	0.47±0.02	6.53±0.10
5 Dec	4.61±0.27	0.46±0.04	7.01±0.12

*Detection limit; na = not available

Appendix 5

Concentrations of nitrate, phosphate and silicate (average ± std) at 10 m in the Balsfjord in 2008.

Dates in 2008	Nitrate average (mmolm^{-3})± std	Phosphate average (mmolm^{-3})± std	Silicate average (mmolm^{-3})± std
7 Mar	6.86±0.22	0.66±0.04	6.15±0.09
12 Mar	7.97±0.24	0.65±0.02	6.90±0.02
28 Mar	3.99±0.08	0.44±0.03	3.95±0.04
1 Apr	4.25±0.28	0.43±0.03	5.95±0.00
11 Apr	3.82±0.41	0.44±0.02	3.46±0.05
13 Apr	2.70±0.15	0.33±0.01	2.73±0.11
23 Apr	1.13±0.05	0.30±0.02	3.05±0.06
28 Apr	0.03±0.00	0.23±0.06	2.89±0.05
5 May	1.01±0.06	0.16±0.01	3.04±0.10
13 May	2.38±0.11	0.28±0.01	5.54±0.48
23 May	0.15	0.10±0.01	5.21±0.09
26 May	1.17±0.08	0.18±0.02	5.02±0.16
3 Jun	0.15*	0.09±0.00	4.58±0.13
9 Jun	0.15*	0.11±0.01	7.01±0.33
22 Jun	3.60±0.15	0.30±0.03	5.82±0.52
7 Jul	0.15*	0.10±0.00	3.01±0.20
21 Jul	2.69±0.15	0.25±0.02	5.20±0.41
4 Aug	0.54±0.04	0.13±0.03	3.49±0.41
15 Aug	1.80±0.05	0.29±0.05	3.79±0.11
28 Aug	2.43±0.12	0.26±0.06	4.49±0.60
15 Sep	0.33±0.02	0.16±0.02	3.05±0.04
29 Sep	2.68±0.12	0.33±0.02	4.90±0.02
10 Oct	2.11±0.07	0.31±0.01	5.08±0.31
29 Oct	3.06±0.18	0.34±0.01	5.39±0.24
7 Nov	4.11±0.35	0.38±0.05	5.81±0.03
21 Nov	4.48±0.28	0.43±0.04	6.53±0.09
5 Dec	5.02±0.14	0.46±0.01	7.27±0.13

*Detection limit

Appendix 6

Concentrations of nitrate, phosphate and silicate (average ± std) at 50 m in the Balsfjord in 2008.

Dates in 2008	Nitrate average (mmolm^{-3})± std	Phosphate average (mmolm^{-3})± std	Silicate average (mmolm^{-3})± std
7 Mar	7.78±0.06	0.66±0.02	6.35±0.11
12 Mar	7.76±0.12	0.68±0.04	6.46±0.17
28 Mar	8.00±0.63	0.57±0.06	5.87±0.08
1 Apr	6.72±0.07	0.58±0.01	6.61±0.02
11 Apr	3.80±0.08	0.42±0.02	3.31±0.12
13 Apr	2.50±0.09	0.32±0.01	2.72±0.09
23 Apr	3.08±0.13	0.41±0.01	3.19±0.06
28 Apr	0.15*	0.15±0.01	2.81±0.10
5 May	2.13±0.10	0.32±0.01	3.38±0.25
13 May	3.16±0.11	0.41±0.04	4.57±0.07
23 May	2.71±0.12	0.34±0.01	4.84±0.04
26 May	2.52±0.02	0.36±0.02	5.31±0.09
3 Jun	2.97±0.23	0.41±0.01	5.14±0.14
9 Jun	2.79±0.08	0.39±0.03	6.26±0.11
22 Jun	3.64±0.23	0.34±0.02	5.77±0.33
7 Jul	0.22±0.02	0.44±0.06	4.43±0.17
21 Jul	4.65±0.18	0.43±0.02	5.92±0.11
4 Aug	3.38±0.23	0.38±0.05	5.58±0.05
15 Aug	3.74±0.18	0.41±0.01	5.02±0.06
28 Aug	3.98±0.26	0.41±0.04	5.32±0.33
15 Sep	3.02±0.25	0.32±0.03	4.94±0.88
29 Sep	3.79±0.08	0.48±0.02	5.43±0.23
10 Oct	3.58±0.29	0.46±0.06	6.28±0.32
29 Oct	4.31±0.10	0.49±0.07	6.63±0.04
7 Nov	1.79±0.02	0.31±0.00	1.99±0.07
21 Nov	4.20±0.08	0.41±0.02	6.94±0.56
5 Dec	5.25±0.35	0.48±0.05	7.11±0.06

*Detection limit

Appendix 7

Averages nutrient concentrations (mmol m^{-3}) at 5, 10 50 m in the different seasons.

	Nitrates			Phosphates			Silicates		
Season	5	10	50	5	10	50	5	10	50
Spring	3.82	3.84	4.97	0.44	0.43	0.47	4.31	4.39	4.66
Summer	0.90	1.27	2.75	0.14	0.17	0.38	5.04	4.94	5.07
Autumn	1.43	1.85	3.69	0.25	0.26	0.42	4.46	4.31	5.60
Winter	4.25	4.54	3.74	0.44	0.42	0.40	6.53	6.53	5.35

Appendix 8

The pH values from March to December in 2008 at 5, 10 and 50 m.

Dates in 2008	5 m	10 m	50 m
7 Mar	7.2	7.6	7.7
12 Mar	8.0	7.9	8.0
28 Mar	7.7	8.0	8.0
1 Apr	8.0	8.0	8.0
11 Apr	7.8	7.9	7.9
13 Apr	7.8	7.9	7.9
23 Apr	7.7	7.8	7.8
28 Apr	7.8	7.9	7.8
5 May	7.9	8.0	8.0
13 May	7.9	7.9	8.0
23 May	7.9	8.0	8.0
26 May	7.8	7.9	8.0
3 Jun	7.9	8.0	7.9
9 Jun	7.9	8.1	8.1
22 Jun	7.5	7.7	7.7
7 Jul	7.9	8.0	7.9
21 Jul	7.7	8.0	8.0
4 Aug	7.7	7.9	7.9
15 Aug	7.5	7.8	7.9
28 Aug	7.9	8.1	8.0
15 Sep	8.0	8.0	7.8
29 Sep	8.0	7.9	8.0
10 Oct	7.9	8.0	8.0
29 Oct	7.7	7.8	7.9
7 Nov	8.0	8.0	8.0
21 Nov	7.5	7.9	7.9
5 Dec	7.6	7.9	7.9

Appendix 9

The temperature readings from March to December in 2008 at 2, 4, 6, 8, 10, 12 and 14 m.

Dates in 2008	2 m	4 m	6 m	8 m	10 m	12 m	14 m
7 Mar	4.2	4.2	4.2	4.2	4.2	4.2	4.2
12 Mar	4.3	4.3	4.3	4.3	4.3	4.3	4.3
28 Mar	3.2	3.2	3.2	3.3	3.3	3.3	3.3
1 Apr	2.3	2.5	2.6	2.6	2.6	2.6	2.6
11 Apr	3.1	3.1	3.1	3.2	3.1	3.1	3.1
13 Apr	3.2	3.1	3.2	3.2	3.2	3.2	3.2
23 Apr	3.3	3.2	3.2	3.1	3.1	3.1	3.1
28 Apr	3.5	3.5	3.4	3.4	3.4	3.3	3.3
5 May	5.0	4.7	4.4	4.3	4.2	4.3	4.2
13 May	4.3	4.5	4.6	4.5	4.4	4.3	4.3
23 May	6.9	5.9	5.7	5.4	5.4	5.3	5.1
26 May	6.5	6.5	5.5	5.4	5.4	5.4	5.3
3 Jun	7.7	6.4	7.0	6.5	6.5	6.6	6.3
9 Jun	9.5	9.1	8.0	8.0	7.9	7.9	7.8
22 Jun	8.4	7.6	7.3	7.2	7.0	6.8	6.7
7 Jul	9.5	9.4	8.9	8.7	7.9	7.3	7.3
21 Jul	9.7	8.4	8.1	8.3	7.2	7.1	7.0
4 Aug	11.8	10.2	8.5	7.8	7.6	7.5	7.4
15 Aug	9.5	8.9	8.8	8.3	8.3	8.3	8.1
28 Aug	9.8	9.2	8.9	8.7	8.3	8.3	8.3
15 Sep	8.2	8.2	8.2	8.2	8.2	8.2	8.2
29 Sep	8.1	8.1	8.1	8.1	8.1	8.1	8.1
10 Oct	7.4	7.4	7.4	7.4	7.5	7.4	7.4
29 Oct	6.2	6.6	6.6	6.6	6.6	6.6	6.6
7 Nov	5.9	6.4	6.4	6.4	6.4	6.4	6.5
21 Nov	6.5	6.5	6.5	6.5	6.5	6.5	6.5
5 Dec	5.5	5.5	5.5	5.5	5.5	5.5	5.5

Appendix 10

Nitrate verses phosphate ratios (mol: mol) at 5 m.

Dates in 2008	N:P
Spring	8
Summer	5
Autumn	5
Winter	10

Appendix 11

Table of statistical summary

Regression Statistics	5 m	10 m	50 m
Multiple R	0.9360	0.7547	0.8646
R^2	0.8761	0.5696	0.7475
Adjusted R^2	0.8711	0.5524	0.7374
Standard Error	0.7127	1.3254	1.0152
Observations	27	27	27

Appendix 12

Table of ANOVA of nitrate verses phosphate at 5 m

	df	SS	MS	F	Significance F
Regression	1	89.7875	89.7875	176.7692	0.0000
Residual	25	12.6984	0.5079		

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	-1.1214	0.2898	-3.8701	0.0007	-1.7182	-0.5246
Slope	11.7251	0.8819	13.2955	0.0000	9.9088	13.5413

Appendix 13

Table of ANOVA of nitrate verses phosphate at 10 m

	df	SS	MS	F	Significance F
Regression	1	58.1256	58.1256	33.0881	0.0000
Residual	25	43.9173	1.7567		

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	0.8245	0.5711	1.4438	0.1612	-0.3516	2.0007
Slope	9.7366	1.6927	5.7522	0.0000	6.2505	13.2227

Appendix 14

Table of ANOVA of nitrate verses phosphate at 50 m

	df	SS	MS	F	Significance F
Regression	1	76.2768	76.2768	74.0090	0.0000
Residual	25	25.7661	1.0306		

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	-2.7175	0.7783	-3.4916	0.0018	-4.3204	-1.1146
Slope	15.3576	1.7852	8.6029	0.0000	11.6810	19.0342

Appendix 15

ANOVA table for silicate and nitrate concentrations at 5 m.

Sources of error	df	SS	MS	F	Significance F
Regression	1	11.1581	11.1581	7.3904	0.0117
Residual	25	37.7454	1.5098		