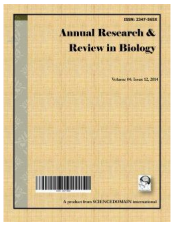

Annual Research & Review in Biology

24(1): 1-17, 2018; Article no.ARRB.38457
ISSN: 2347-565X, NLM ID: 101632869

Population Dynamics of Diatoms in a Spring-Neap Tidal Cycle in an Estuarine Creek of the Bonny River System

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Authors' contributions

This work was carried out in collaboration between both authors. Author JO designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Author COP managed the analyses of the study and managed the literature searches. Both authors read and approved the final manuscript.

Article Information

DOI: 10.9734/ARRB/2018/38457
Editor(s):
(1) Eugene A. Silow, Institute of Biology, Chair of invertebrate Zoology and Aquatic Ecology Sukhe-Baator str., 5, Irkutsk, Russia.
(2) George Perry, Dean and Professor of Biology, University of Texas at San Antonio, USA.
Reviewers:
(1) Ben Willis, USA.
(2) G. M. Narasimha Rao, Andhra University, India
(3) Carlos Eduardo de Mattos Bicudo, Instituto de Botânica, Brazil.
Complete Peer review History: http://www.sciencedomain.org/review-history/23148

Original Research Article

Received 17th October 2017
Accepted 31st January 2018
Published 12th February 2018

ABSTRACT

The present study focused on the aspects of diatom population changes through the spring-neap-spring tidal phases along the Elechi creek - an estuary of the Bonny River. Water samples at high and low tide were collected during a cycle of spring-neap-spring cycle between September and November 2015. Diatoms were counted at different magnifications of x250 and x400. Counting was in 100 fields of view along several transects. Total diatoms were calculated as a relationship between the area of grid (mm^2), number of grids counted and area of counting chamber (1000 mm^2). Diatoms density ranged from 1678 cells L^{-1} (high tide) to 3731 cells L^{-1} (low tide) with a mean value of 8.87 ± 6.64 cells L^{-1}. During the lunar phases diatoms abundance ranged from 431 ± 0.2 cells L^{-1} (last quarter) to 396 ± 0.2 cells L^{-1} (new moon), to 430 ± 0.3 cells L^{-1} (full moon), to 421 ± 0.2 cells L^{-1} (first quarter). The result revealed evidence of changes in diatom abundance and variability. At low tide, the abundance and variability of diatom was higher than the observation at

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high tide. There was also a significant difference between mean counts of the diatoms during various moon phases; but there was no significant difference in the abundance between spring and neap tide. These findings are crucial for ecological inference during environmental assessment surveys. A consideration of these factors is suggested as necessary to avoid poor estimates that can drastically alter impact assessment conclusions.

Keywords: Diatom; high tide; low tide; spring tide; neap tide.

1. INTRODUCTION

Estuarine systems are key environments in the transfer of nutrients from river drainage basins to adjacent coastal areas. These systems are among the World's most productive [1], serving as nursery grounds for a diversity of commercially important species of mollusks, crustaceans and fish [2]. In these environments, phytoplankton communities in particular diatoms, and to a lesser extent, Dinoflagellates and Chlorophytes [3] consume dissolved nutrients to produce organic matter which is transferred to higher levels of the aquatic food webs [4]. According to Valiela [5], understanding the composition and dynamics of these communities provides insights into their spatial and temporal variation, as well as distribution patterns related to eutrophication and pollution. The distribution, abundance and diversity reflect the physicochemical conditions of aquatic ecosystem in general and its nutrient state in particular [6].

Phytoplankton dominated by diatoms are microscopic single celled algae drifting at the mercy of water current [6]. They constitute the primary producers of aquatic ecosystems. They are restricted to the photic zone where there is enough light for photosynthesis. In tidal environments, the phytoplankton community has to cope with continual changes in water level, current strength and direction. In these estuaries, tidal flushing constitutes a relevant phytoplankton driving force. Tidal flushing induces substantial horizontal and vertical mixing of the water column, as well as upstream and downstream displacement of water masses along the main longitudinal estuarine axis. The extent and degree of tidal flushing is regulated within the cycles of spring and neap tides which are also correlated with the phases of the moon. Variations in phytoplankton composition and abundance have been correlated with spring and neap tide alterations, to tidal cycles and moon phases [7-14].

In the Niger Delta and in Nigeria, several workers have investigated the composition and numerical abundance of phytoplankton in estuarine bodies [15-25]. In one study in the upper Bonny River, Davies and Ugwumba [26] provided information on species composition, abundance, distribution and seasonality in relation to a range of physical and chemical features and tidal. In many of these were no indications of the tidal phases from which phytoplankton samples were collected. From these studies immense information are available. However because of the importance of phytoplankton in environmental monitoring, understanding the drivers of phytoplankton variability is essential due to the unpredictability of phytoplankton abundances imposed by known tidal forcing functions [10,13,27,28,29]. To examine the phenomenon of tidal forces the paper evaluates the abundance and composition of the Bacillariophyceae (diatoms) within a complete cycle of spring-neap-spring tide at Elechi creek, an estuary of the Bonny River, Nigeria. The Bacillariophyceae was chosen because they are dominant by 40-68% over other phytoplankton in most of the studies in the Niger Delta [21,22,23,24].

2. METHOD OF DATA COLLECTION

The survey was conducted for three months between September and November 2015 with the sampling regime designed with the tide table to coincide with the daily heights of the low or high tide. A total of one hundred and ninety-two thousand (192,000) litres of water was collected throughout the study. During field periods water was collected 20-30 cm below the surface with a 2 L sampling water bottle closed by messenger. The water samples were filtered through a 25 µm plankton net at the eagle Island station (6^0.58' 22.74"E; 4^0 47' 37.46"N) on Elechi creek. The samples were decanted into a preservative bottle of 300 ml where 15 ml of formalin was added to preserve the plankton immediately before taking it to the laboratory for further study. The collection was hand-mixed and a 250 ml subsample removed. The subsample was treated with 5 ml of lugol solution. Lugol solution both preserves the samples and stains the organisms facilitating later laboratory work. Preserved samples were placed on ice, returned to the laboratory and stored in the dark. The laboratory procedure involved concentrating the 250 ml subsample to 15 ml by allowing the sample to settle. From the concentrated sample 1 ml subsamples were pipetted individually to a Sedgewick-Rafter counting chamber using Stempel pipettes. Three replicates of the subsamples were analysed. Taxonomic identifications were made to identify the centric and pennate diatoms [20,22,30,31,32]. Microscopic counts were made of slides for each station at an intermediate magnification of x250 for medium and large centric and pennate diatoms and at high magnification of x400 for small centric and pennate diatoms. Counting was in 100 fields of view along several diagonal transects. Microscopy was with a Brunnel digital microscope (DN-117M). The abundance of the diatoms were recorded and used to compute the number of cells per litre. Total diatoms were calculated as a relationship between the area of grid (mm^2), number of grids counted and area of counting chamber (1000 mm^2). Data were analysed by the aid of JMP4 software in form of graphs, mean, quartile, standard deviation and coefficient of variance, while overlay plots were used to show comparison.

3. RESULTS

Figs. 1 and 2 show the abundance of diatom at low and high tides respectively during several

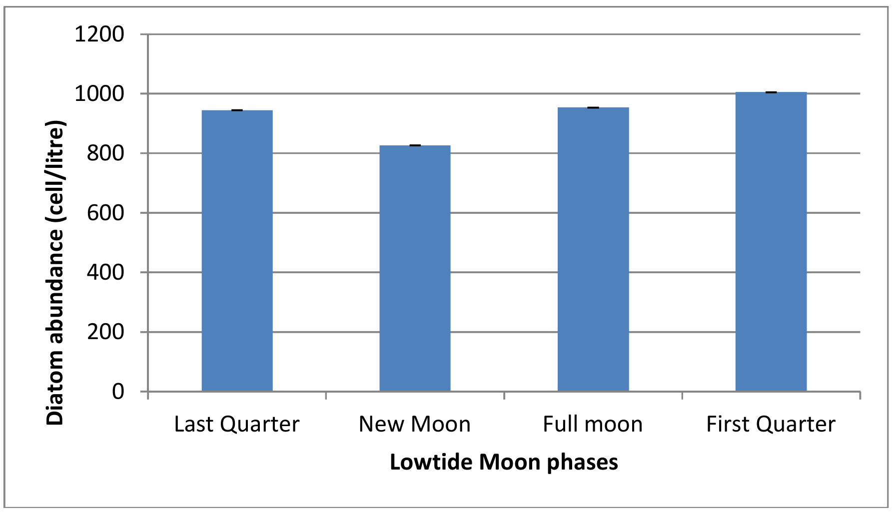


Fig. 1. Low tide diatom abundance during several moon phases

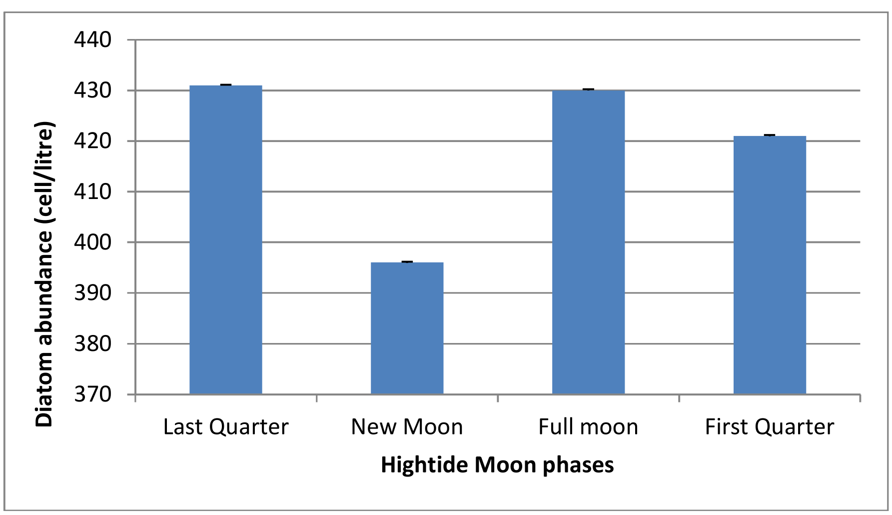


Fig. 2. High tide diatom abundance during several moon phases

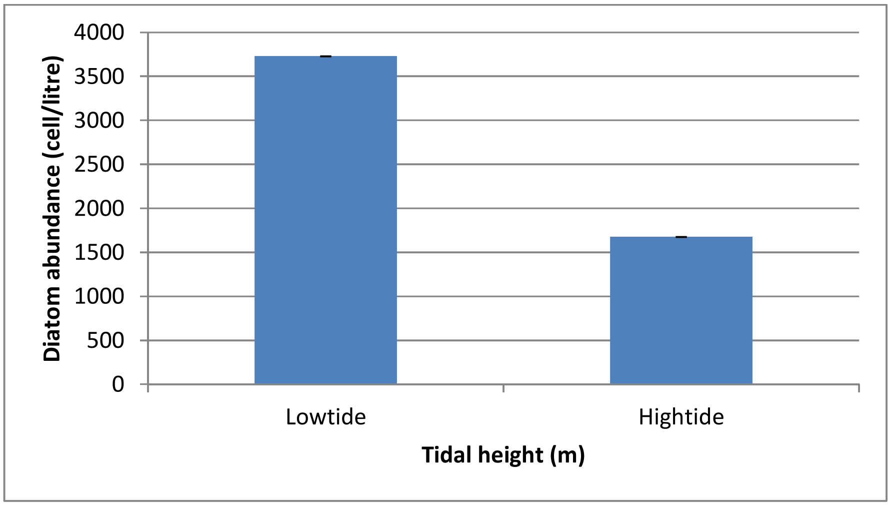
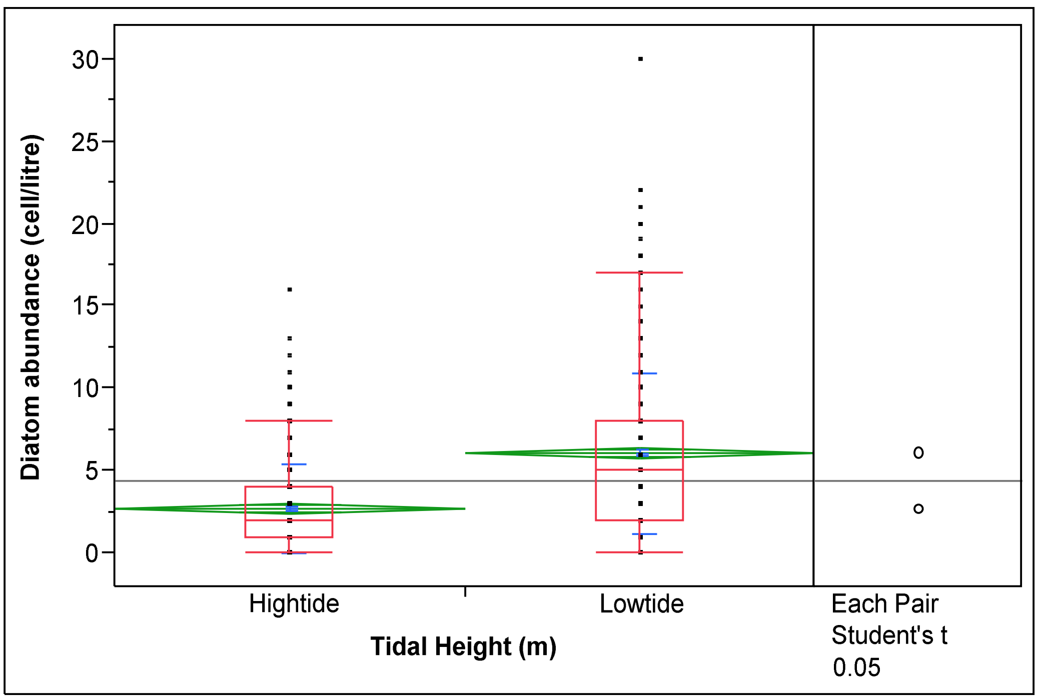


Fig. 3. Diatom abundance during high and low tide



Means Comparisons

Connecting Letters Report

Level			Mean
Lowtide	A		6.1163934
Hightide		B	2.7508197

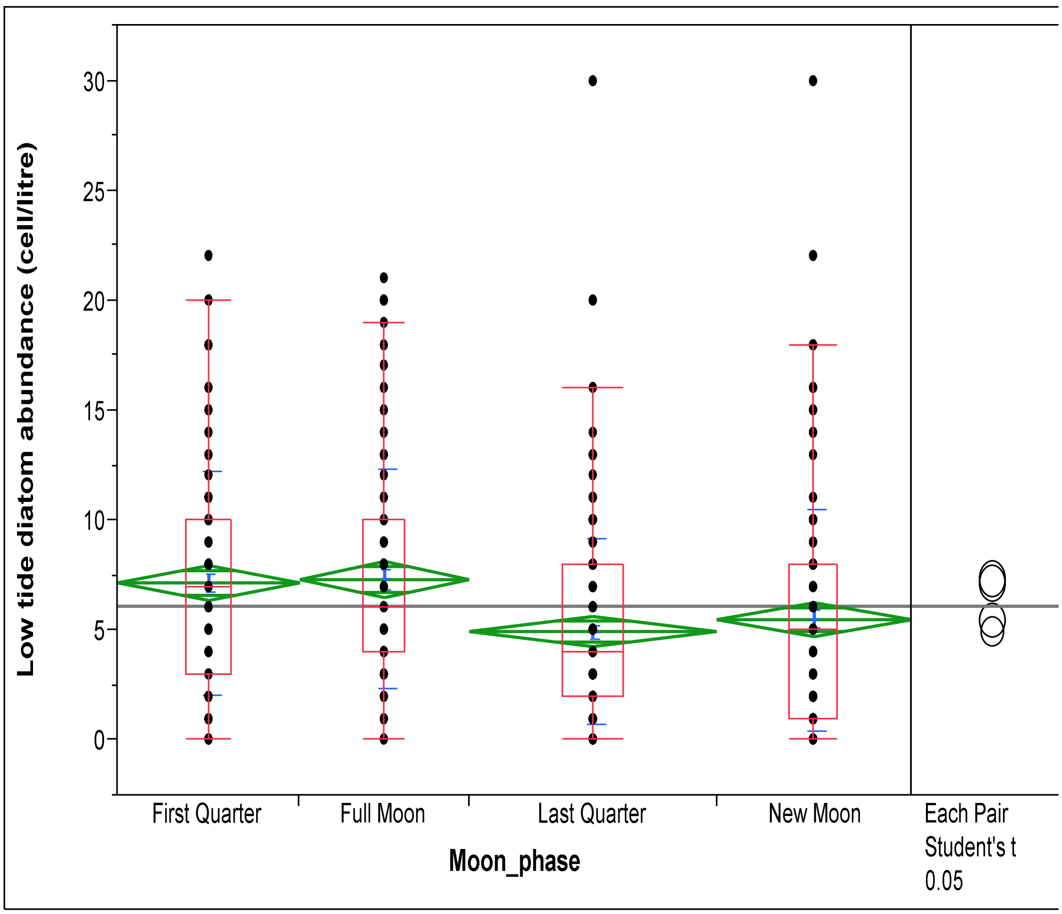
Levels not connected by same letter are significantly different.

Fig. 4. Student's t analysis of diatom abundance by tidal height

moon phases. Fig. 1 (low tide) shows in decreasing order that first quarter had the highest number of diatoms (1005 ± 0.4), followed by the full moon (954 ± 0.4), last quarter (945 ± 0.3) and new moon (827±0.4). In Fig. 2 (high tide), diatom were more abundant during last quarter (431±0.2), followed in decreasing order by full moon (430±0.3), first quarter (421±0.2) and new moon (396 ± 0.2).

Fig. 3 shows abundance of diatoms at low and high tides in the study area. From highest to lowest, 3731 ± 0.2 diatoms were counted for low tide and 1678 ± 0.1 diatoms were counted at high tide.

Fig. 4 shows student's t analysis of diatom abundance by tidal height. The abundance of diatoms at high and low tide had mean diamonds



Means Comparisons

Connecting Letters Report

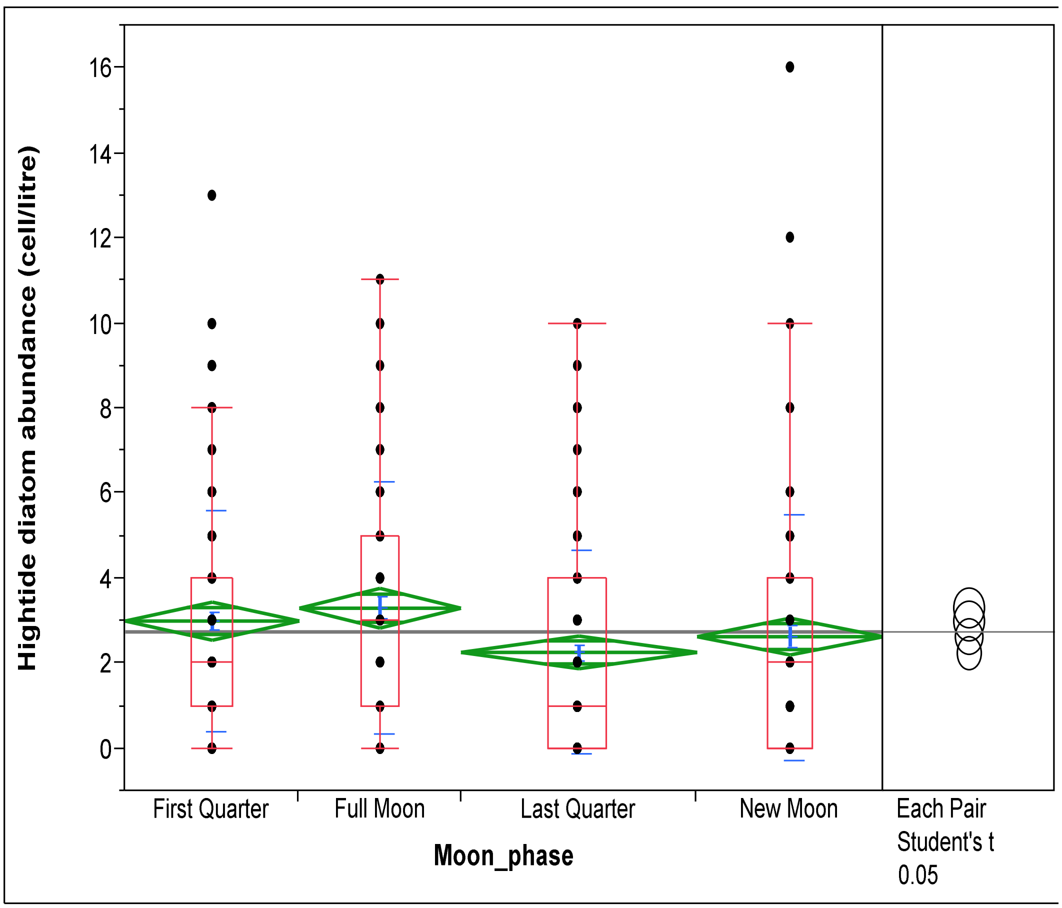
Level			Mean
Full Moon	A		7.3384615
First Quarter	A		7.1785714
New Moon		B	5.5133333
Last Quarter		B	4.9736842

Levels not connected by same letter are significantly different.

Fig. 5. One way analysis of low tide diatom abundance by moon phase

that were below and above the grand mean respectively. The different positions of the mean diamonds show significant differences (p > 0.05) in the abundance of diatoms at high and low tide; the t-test connecting letters further shows that the pair of mean is significantly different. The box plots were not symmetrical and there were equal number of outliers for low and high tide values.

Fig. 5 shows the one way analysis of low tide diatom abundance by moon phase. The mean diamonds of the first quarter and full moon were above the grand mean, the last quarter was below the grand mean, while the new moon touched the grand mean slightly. The box plots were not equal and had few outliers. The different positions of the mean diamonds show significant differences in the abundance of diatoms at various moon phases during the study, and this is further confirmed by the connecting letter report.



Means Comparisons

Connecting Letters Report

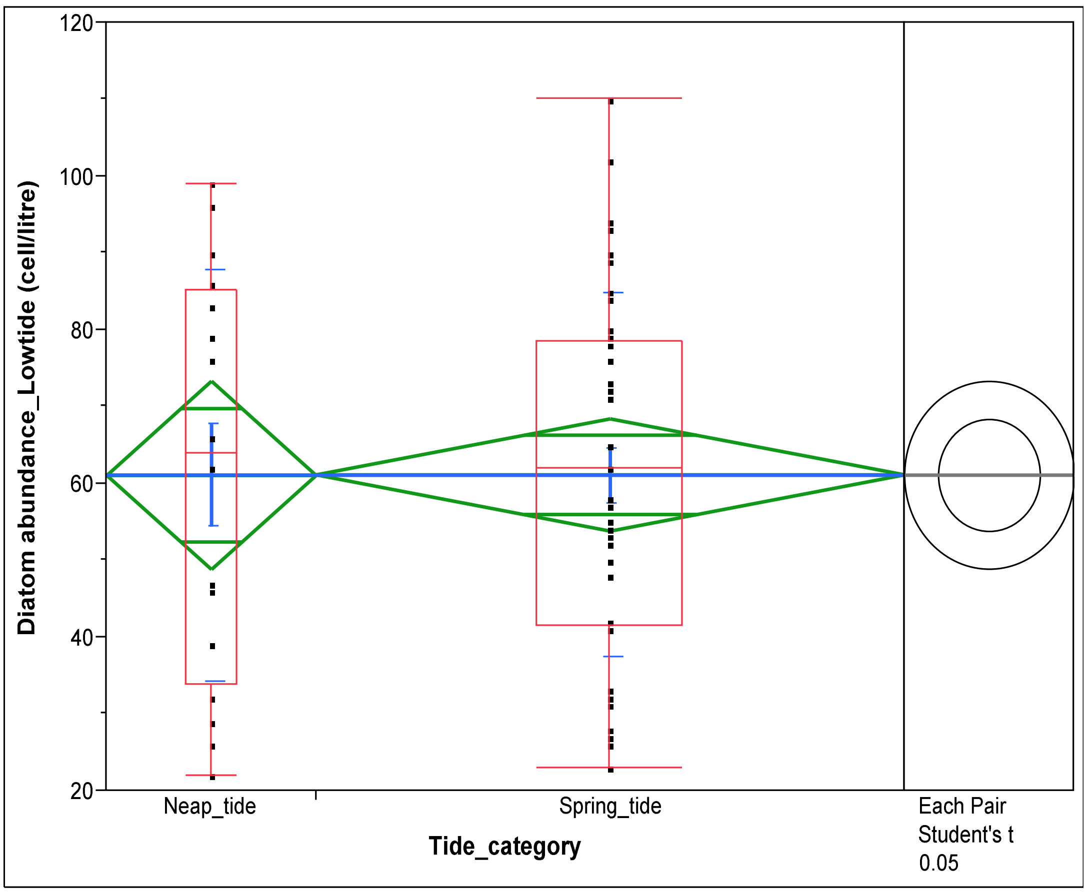
Level				Mean
Full Moon	A			3.3076923
First Quarter	A	B		3.0071429
New Moon		B	C	2.6400000
Last Quarter			C	2.2684211

Levels not connected by same letter are significantly different.

Fig. 6. One way analysis of high tide diatom abundance by moon phase

Fig. 6 shows the one way analysis of high tide diatom abundance by moon phase. Moon phases in the first quarter and new moon had their mean diamonds overlapping the grand mean, while moon phase's full moon and last quarter had their mean diamonds above and below grand mean respectively. Varying positions of the mean diamond indicate significant differences ($p > 0.05$) in the diatom abundance during the moon phases. The box plots were unequal and there were few outliers during the first quarter and the new moon.

Fig. 7 shows the student's t analysis of diatom abundance by tide category. The mean diamond of the neap and spring tide intersect the grand mean at similar intervals, while the values on the box plot were evenly distributed with no outliers. Similar positions of the mean diamond indicate no significant differences ($p > 0.05$) in the diatom



Connecting Letters Report

Level		Mean
Spring_tide	A	61.177778
Neap_tide	A	61.125000

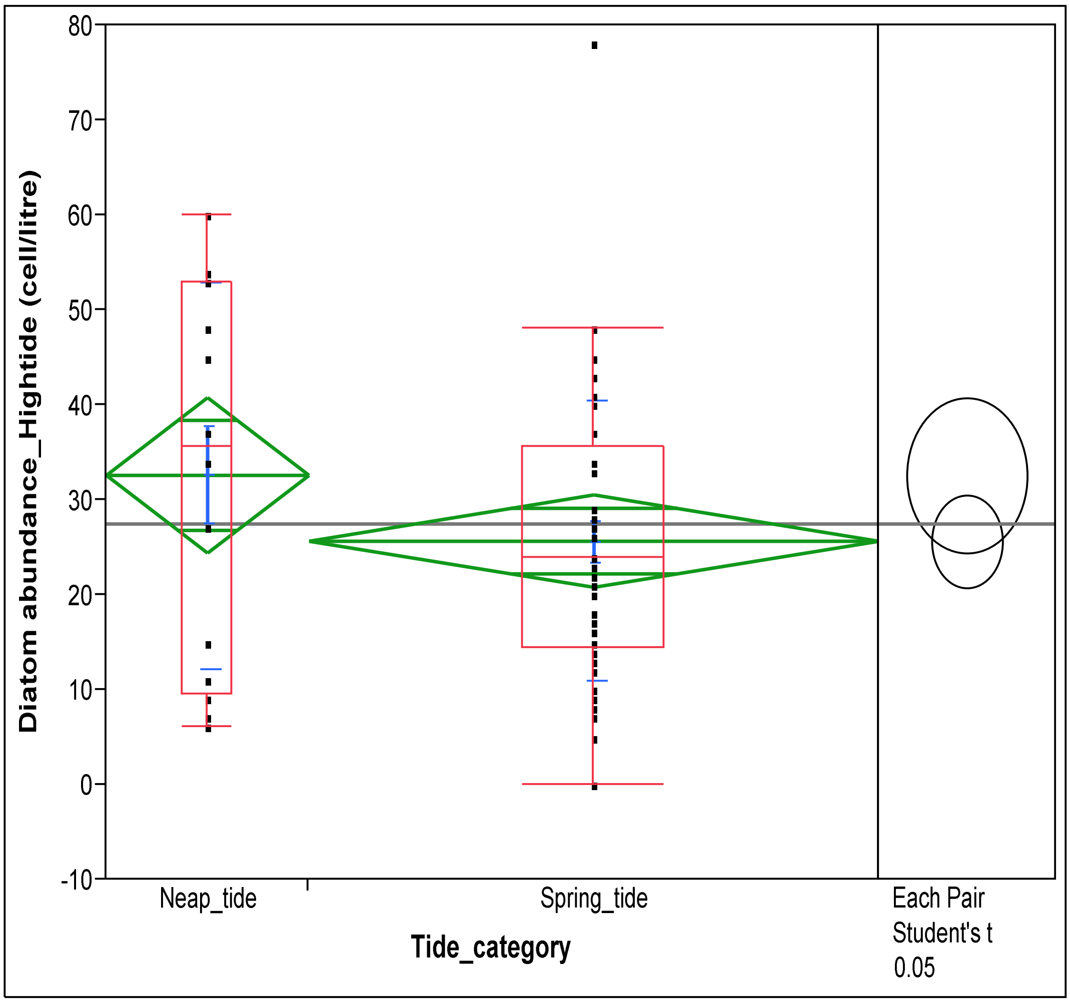
Levels not connected by same letter are significantly different

Fig. 7. Student's t analysis of low tide abundance by tide category

abundance during neap and spring tide. This claim is further justified by the connecting letter report.

Fig. 8 shows the student's t analysis of high tide diatom abundance by tide category. The mean diamonds of the neap and spring tide intersect the grand mean at various levels, indicating evidence of no significant difference in the abundance of diatom. Furthermore, the connecting letter report indicates that the pair of means for the neap and spring tide were not significantly different at 95% confidence interval.

Fig. 9 shows the relationship between diatom abundance and neap low tidal height. The scatterplot matrix and the least squared regression line show an inverse relationship



Connecting Letters Report

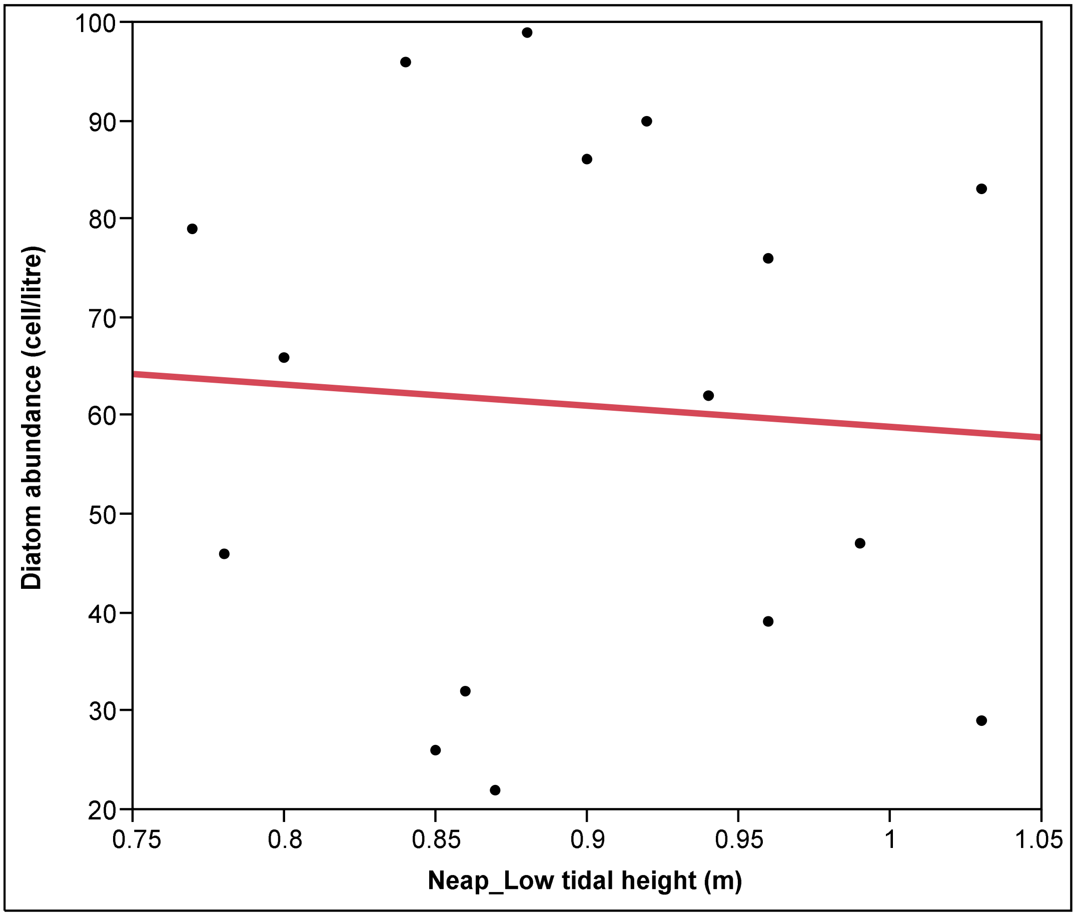
Level		Mean
Neap_tide	A	32.625000
Spring_tide	A	25.688889

Levels not connected by same letter are significantly different

Fig. 8. Student's t analysis of high tide abundance by tide category

between both parameters. This implies that a change in the tidal height during spring tide resulted in an inverse response by the abundance variable. The result further produced a slope of 21.5, an intercept of 80.4 and an R^2 value of 0.004. The R^2 value of 0.004 implies that 0.4% of the variability in the diatom abundance is explained by the neap low tidal height.

Fig. 10 shows the relationship between diatom abundance and spring low tidal height. The scatterplot matrix and the least squared regression line show an inverse relationship between both parameters. This means that an increase in the height of tide resulted in a decrease in the abundance of diatom during the spring tide sampling period. More so, the R^2



Linear Fit

Diatom abundance = 80.42984 - 21.479655*Neap_Low tidal height

Summary of Fit

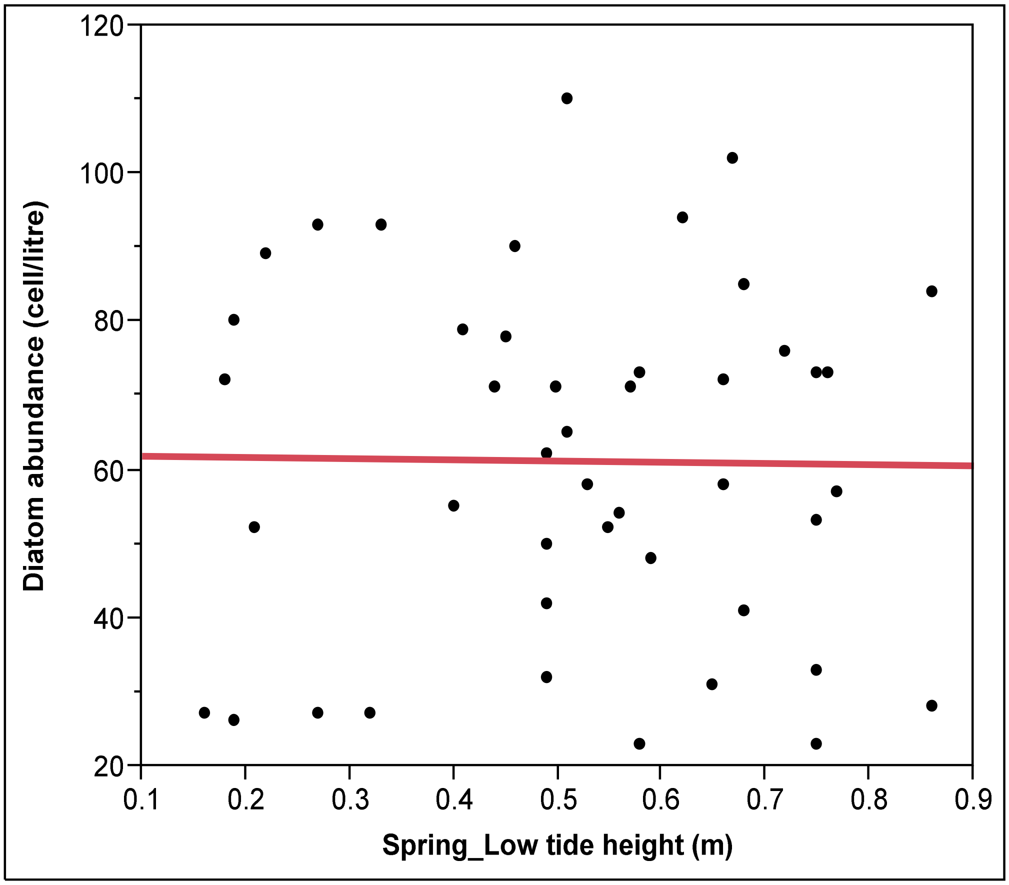
RSquare	0.004367
RSquare Adj	-0.06675
Root Mean Square Error	27.59785
Mean of Response	61.125
Observations (or Sum Wgts)	16

Fig. 9. Matrix of diatom abundance in relation to neap low tidal height

value of 0.0002 implies that spring low tidal height could only determine the abundance of diatom by 0.02%

Fig. 11 shows the relationship between diatom abundance and neap high tidal height. The scatterplot matrix and the line of best fit show a positive relationship between both parameters. The result produced a slope of 60.7, an intercept of -83.5 and an R^2 value of 0.03. The R^2 value of 0.03 implies that 3% of the variability in the diatom abundance is explained by the neap high tidal height.

Fig. 12 shows the relationship between diatom abundance and spring high tidal height. The scatterplot matrix and the least squared



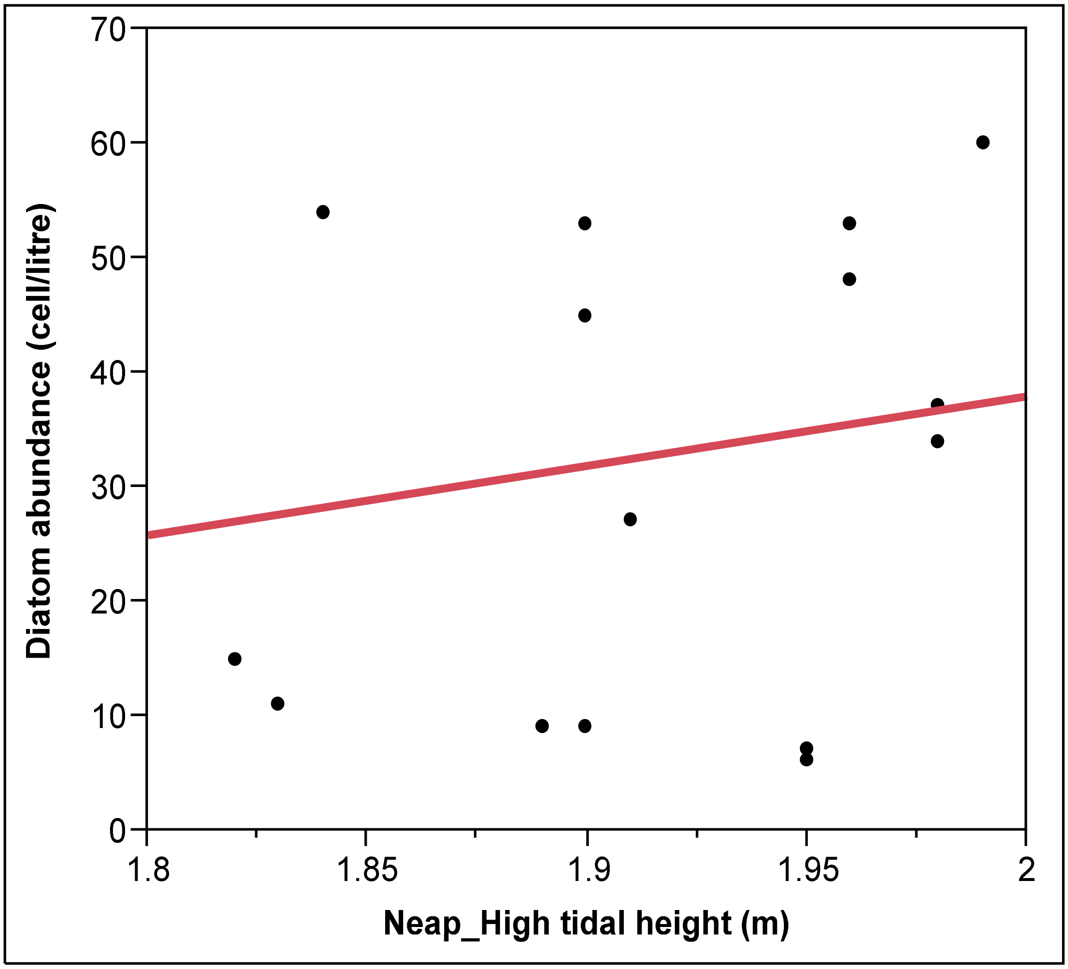
Linear Fit

Diatom abundance = 62.009533 - 1.5906919*Spring_Low tide height

Summary of Fit

RSquare	0.000169
RSquare Adj	-0.02308
Root Mean Square Error	23.97886
Mean of Response	61.17778
Observations (or Sum Wgts)	45

Fig. 10. Matrix of diatom abundance in relation to spring low tidal height



Linear Fit
Diatom abundance = -83.56034 + 60.750507*neap high tidal height

Summary of Fit

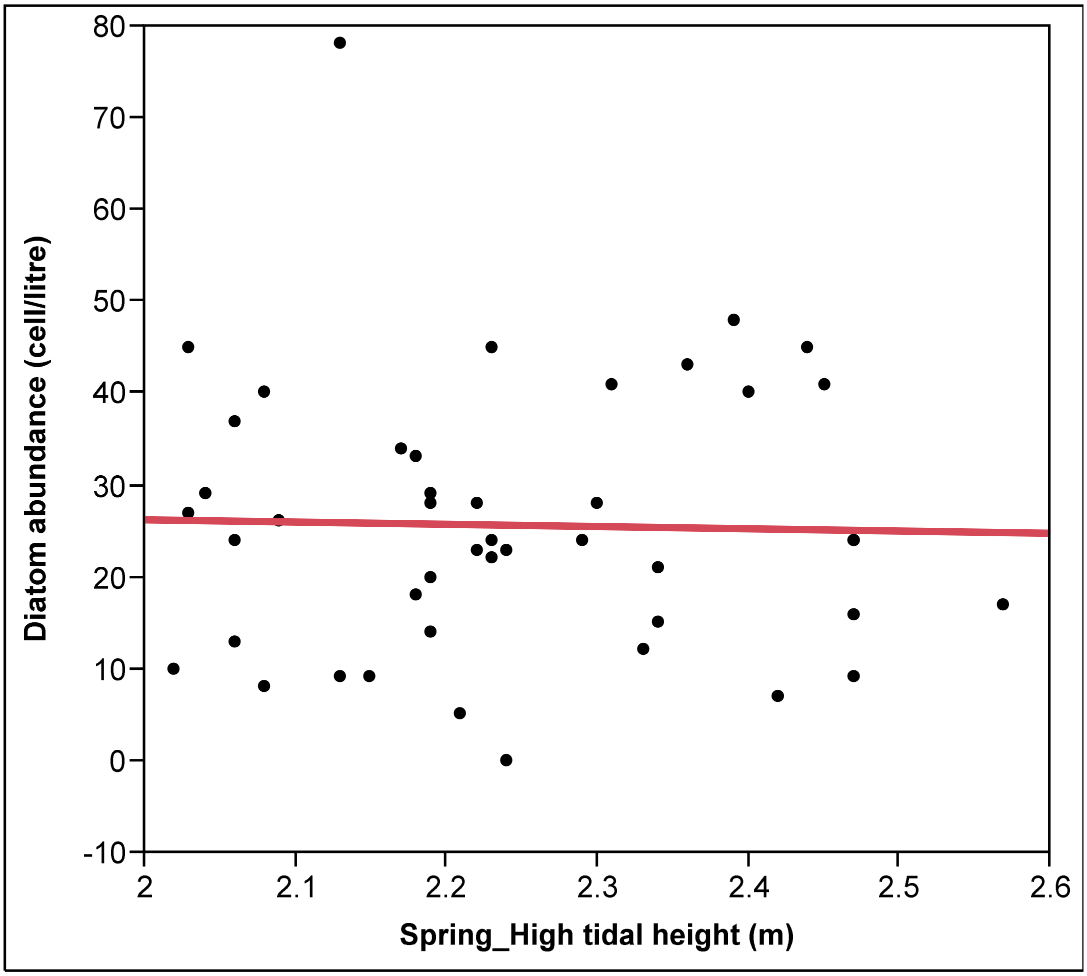
RSquare	0.029367
RSquare Adj	-0.03996
Root Mean Square Error	20.72576
Mean of Response	32.625
Observations (or Sum Wgts)	16

Fig. 11. Matrix of diatom abundance in relation to neap high tidal height

regression line show an inverse relationship between both parameters. This means that an increase in the height of tide resulted in a decrease in the abundance of diatom during the spring period. More so, the R^2 value of 0.001 implies that high tidal height could only determine the abundance of diatom by 0.1%.

Fig. 13 shows the scatter plot matrix of low tide diatom abundance in relation to low tide salinity values. The least square regression line indicates that there is a negative relationship between diatom abundance and the salinity during low tide. The R^2 value of 0.027 indicates that the salinity can predict the abundance of diatom by only 3% at low tide; while the regression equation produced a negative slope value of -2.66 and an intercept of 78.44.

Fig. 14 shows the scatter plot matrix of high tide diatom abundance in relation to high tide salinity values. The least square regression line indicates that there is a negative relationship between diatom abundance and the salinity during high tide. The R^2 value of 0.002 indicates that 0.2% of the diatom abundance is predictable by the high tide salinity; while the regression equation produced a negative slope value of -0.89 and an intercept of 42.27.



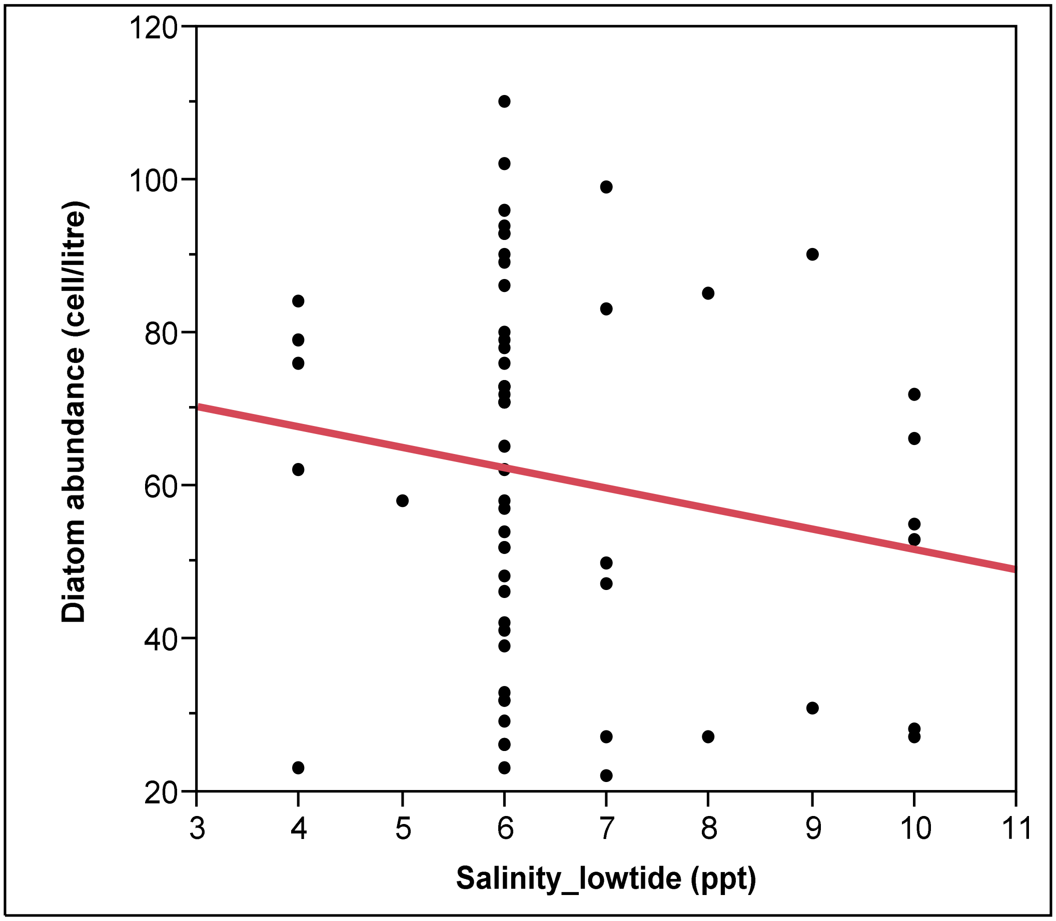
Linear Fit

Diatom abundance = 31.213471 - 2.4641311*spring high tidal height

Summary of Fit

RSquare	0.000597
RSquare Adj	-0.02264
Root Mean Square Error	14.91988
Mean of Response	25.68889
Observations (or Sum Wgts)	45

Fig. 12. Matrix of diatom abundance in relation to spring high tidal height



Linear Fit

Diatom abundance = 78.440592 - 2.6680407*Salinity lowtide

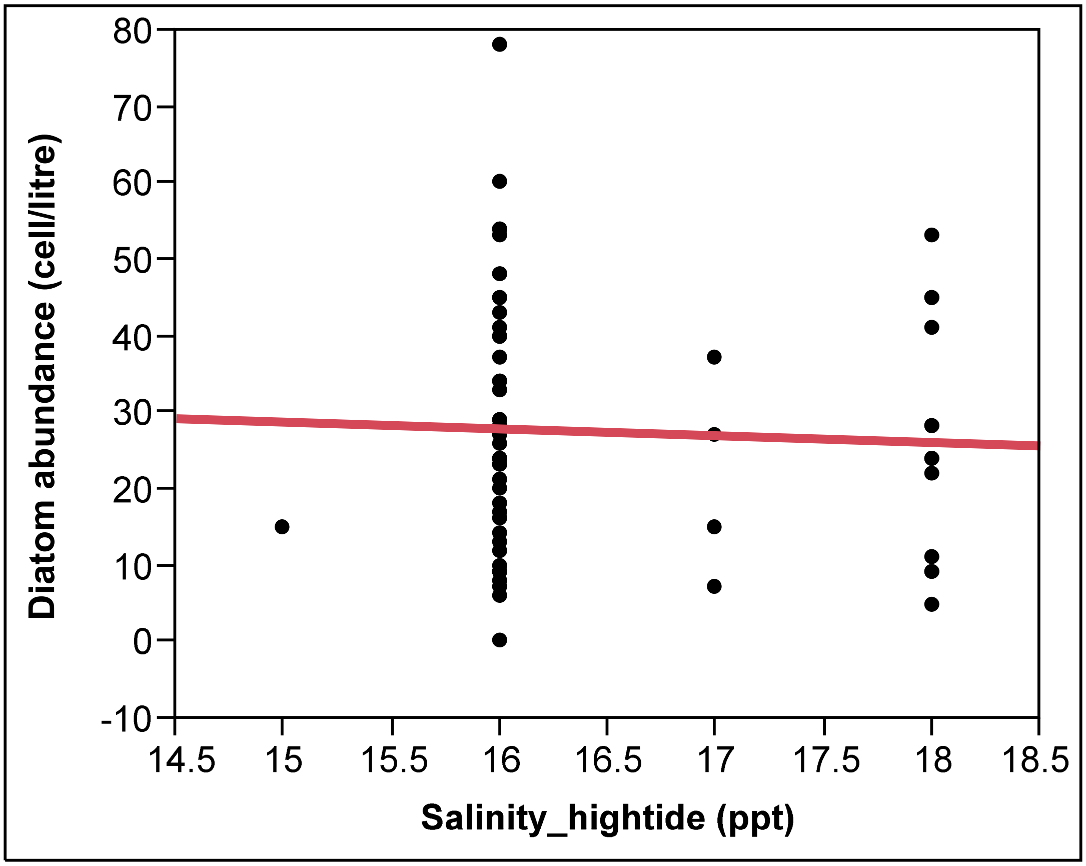
Summary of Fit

RSquare	0.02716
RSquare Adj	0.010671
Root Mean Square Error	24.17305
Mean of Response	61.16393
Observations (or Sum Wgts)	61

Fig. 13. Matrix of low tide diatom abundance in relation to salinity

4. DISCUSSION

The study has shown evidence of changes caused by tidal variations on the diatom community within the study area. A strong tidal influence was found in the diatom abundance and distribution on a two weeks' time scale (spring-neap tidal cycles) and at six hour time scale (high-low tidal cycle). The abundance of diatoms was higher during low tide than the high tide periods which indicated differences caused by heights and water volume. This is in contrast with the findings of Davies and Ugwumba [24,25] who found significant differences between tides with high diatom diversity at high tide; higher dominance index at low tide, but lower abundance and species diversity at low tide. Other studies however have collaborated



Linear Fit
Abundance = 42.277314 - 0.896434*Salinity high tide

Summary of Fit

RSquare	0.002125
RSquare Adj	-0.01479
Root Mean Square Error	16.62473
Mean of Response	27.5082
Observations (or Sum Wgts)	61

Fig. 14. Matrix of high tide diatom abundance in relation to salinity

higher abundances at low tide on the shores of Baja California [33-35]. The evidence of diatom abundance at low tides can be interpreted from reports by Smetacek [36] which show that diatoms have a physiological control over buoyancy with the frustule acting as ballast. Higher abundance during low tidal periods in this study can therefore be argued as linked to this unique sinking behaviour of diatoms. Such sinking can be facilitated by a number of factors such as size, morphological and physiological responses of the frustule to the advection cycle, settling and re-suspension during the ebb, slack, and flood tidal stages. The study which also observed differences in abundance between the moon phases provided another aspect to be given due consideration. A number of studies have given attention to day-night changes in plankton form and distribution in shallow coastal waters in concert with both solar and lunar cycles of illumination [37-42]. In the studies of Quinn and Kojis [37] in Australia there was no significant difference in the abundance of diatoms between full and new moon. Anny and Ara [42] showed, however, a relationship between phytoplankton and lunar phases which varied with highest abundance in first quarter phase followed by full moon phase, new moon phase and last quarter phase. In this study lunar related variation had highest abundance at the full moon followed by first quarter, new moon and last quarter. Noteworthy is the observation that the abundance relationship in Anny and Ara [42] was indicated for the Chlorophyceae in contrast to the Bacillariophyceae in this study. Others such as Dhua and Patra [40] indicated a less defined lunar phase influence, but nonetheless with phytoplankton increasing with advancing lunar period. Dhua and Patra [40] had therefore argued that the lunar cycle imparts certain stimulatory effects on the rhythmic behaviour of plankton and their life processes by which they actively migrate to the surface and gradually sink as the moon fades. These two findings are crucial for ecological inference during environmental assessment surveys. The activities that accompany short term sampling during environmental surveys are fast track and rapid without the benefit of daily scale (flood-ebb-flood) or fortnightly (neap-spring-neap) involvement, which are in alignment with lunar cycles. The implication of such snapshot data can provide poor estimates that can drastically alter the conclusions and inference necessary for decision making concerning environmental impacts.

5. CONCLUSION

Diatoms were sampled through a spring-neap-spring cycle to determine the relationship with physical factors such as water volume (tidal height), tidal periods (neap and spring) and lunar cycles. The study has shown higher abundance during low tide periods at both neap and spring tides. This has been interpreted to be linked to the baffling physiological behaviour of diatom sinking in response to certain stimulatory effects induced by water flow of the tidal phases. The study also indicated there is an influence on abundance by lunar phases being highest at full moon followed by first quarter, new moon and last quarter. This suggests the need to consider incorporation of these factors during environmental surveys in order to reduce the potential of fallacious conclusions. Sampling events for environmental monitoring could therefore occur on the same tidal period and moon phase to remove such interferences.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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