Latitudinal relationships among temperature and selected plant nutrients along the west coast of North and South America

by S.-J. Zentara[1] and D. Kamykowski[1]

ABSTRACT

The relationships among temperature and selected plant nutrients (nitrate, phosphate and silicate) were determined in marine waters for 10° latitudinal (longitudinal) bands along the west coast of North and South America. Data within each 10° band were obtained from the U.S. National Oceanographic Data Center, the Canadian Oceanographic Data Center or major oceanographic institutions.

A number of trends appear in the temperature-nutrient and nutrient-nutrient scatter diagrams. Temperature and plant nutrients follow an inverse monotonic relationship at tropical and temperate latitudes. The range of nutrient concentration at a temperature varies with latitude and depends on the complexity of the local hydrography. A nutrient concentration occurs at successively colder temperatures as latitude increases. Specifically, the temperature at which each nutrient depletes decreases from the equator to the poles. The latitudinal comparison of the nutrient depletion temperature with the mean surface temperature divides the Pacific Ocean into regions of nutrient abundance and nutrient deprivation. Silicate and nitrate exhibit a biologically significant relationship in the eastern Pacific Ocean. The pattern across the equator follows a smooth sigmoid curve representing an increasing excess of silicate to the north and an increasing excess of nitrate to the south.

The relationships among temperature and the plant nutrients supplement the oceanographic parameters that are directly available through remote sensing, clarify the temperature relationships of a fishery and characterize the environmental milieu within which phytoplankton communities develop.

1. Introduction

Global patterns of physical or chemical factors are usually presented as contour plots on axes of depth and latitude. This approach surveys parameter distribution. The covariance patterns of different factors, however, are best described through interactive analyses. The classic discussion of the inverse relationship between apparent oxygen utilization and dissolved phosphorus by Redfield *et al.* (1963) is

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Table 1. The information used within each latitudinal band is categorized by data source, months represented, years represented, number of stations and number of samples. The data source codes are referenced after the text bibliography.

Latitude	Source*	Months†	Years (19)	Number of Stations	Total Number of Samples††
75N	CODC	9,10	70	17	88
65NA	CODC	10	70	26	131
65NB	CODC	8	70	27	249
55NA	CODC	4,5,6,7	66,67,68,69	27	153
55NB	CODC	2,5,6,7,8,9,10,12	66,67,68	33	228
45N	OSU	6	67	11	75
35N	CALC	6	68	14	157
25N	CALC	4,5,6	68	17	118
15N	EAST	2,3	67	6	59
5N	EAST,NODC	2,3,5,8	65,67,68	10	97
5S	EAST,NODC	2,3,4,8,9	66,67,68	11	110
15S	EAST,PIQ	2,3	67,69	17	265
25S	SCORP	6	67	9	73
35S	SCORP,NODC	1,5	66,67	8	78
45S	SCORP,ELT	5,10	66,67	10	92
55S	ELT	1,4,10,11	63,65,66	11	118
65S	ELT	1,10,11	63,64	24	183

* Data Sources: See Appendix I.

† The months of the year are represented by numbers January (1)-December (12).

†† All samples within each band were scrutinized. Though the accompanying plots are limited to 100 points, they accurately represent the total data.

a well-known example. In the present paper, scatter diagrams are used to investigate the relationships between temperature and nitrate, phosphate and silicate and between silicate and nitrate. The properties of the scatter diagrams are analyzed for latitudinal trends.

The biological relationship between temperature and plant nutrients in the photic zone was first examined by Strickland *et al.* (1970). They reported on a six-month series of weekly cruises off La Jolla, California, during 1967. The station profiles extended from the surface to the depth at which plant pigment was negligible, a close approximation to the photic zone. Scatter diagrams of the T-N relationships were constructed from selected profiles. During the first three months (April, May, June) of the program, the persistent negative correlation between temperature and plant nutrients allowed a nearly analytical prediction of nutrient concentration from temperature. Occasional significant variations from the norm were observed that appeared to be related to high phytoplankton crops. In general, Strickland *et al.* found a surprisingly good relationship between the heating of the water column and plant nutrient utilization.

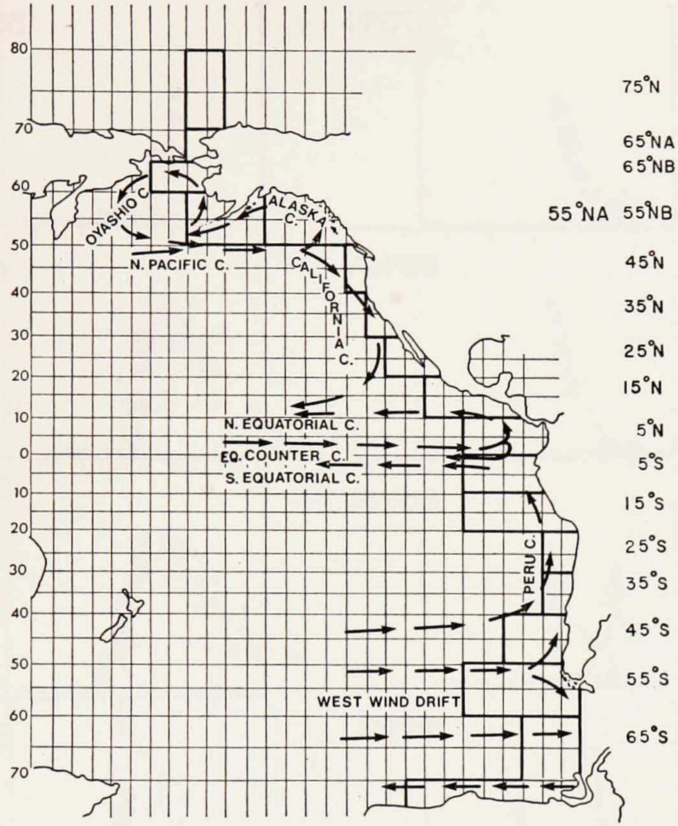


Figure 1. A map of the eastern Pacific Ocean depicting the latitudinal or longitudinal bands from which data were considered. The approximate surface current systems are displayed.

Kamykowski (1973) investigated the annual range of plant nutrient concentration observed at a temperature off La Jolla, California, during 1971. Semiweekly samples were collected throughout the year from the surface, the thermocline and 15 meters below the thermocline. At temperatures below 14°C, the annual range of nitrate-nitrogen was ± 4 μg-at N l^{-1} and the annual range of reactive phosphorous was ± .25 μg-at P l^{-1}. The annual range of reactive silicate was ± 6 μg-at Si l^{-1} at temperatures below 10°C but was considerably greater at temperatures above 10°C. Though temperature does not provide an analytical prediction of nutrient concentration over extended time periods, the annual range of plant nutrient concentration (especially nitrate and phosphate) at a temperature is confined to definable limits for any depth or season. Similar temperature-nutrient plots generated for geographic bands off the Pacific coast of the Western Hemisphere allow an analysis of latitudinal trends.

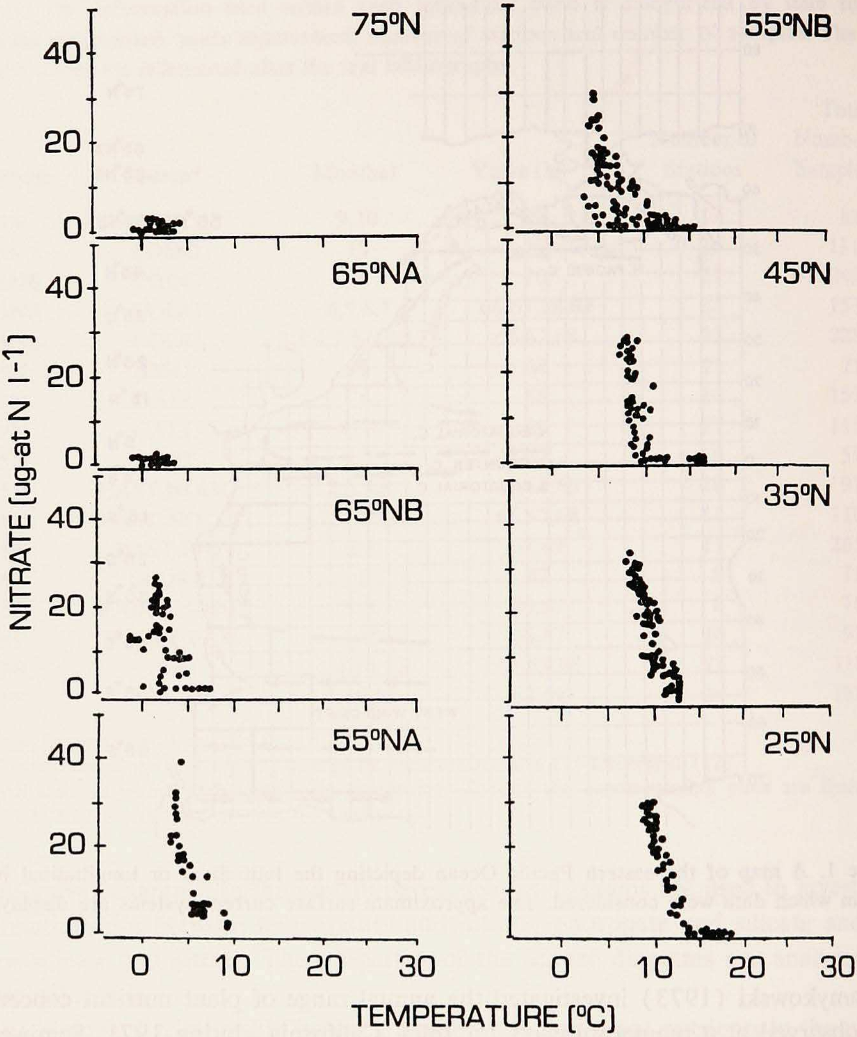
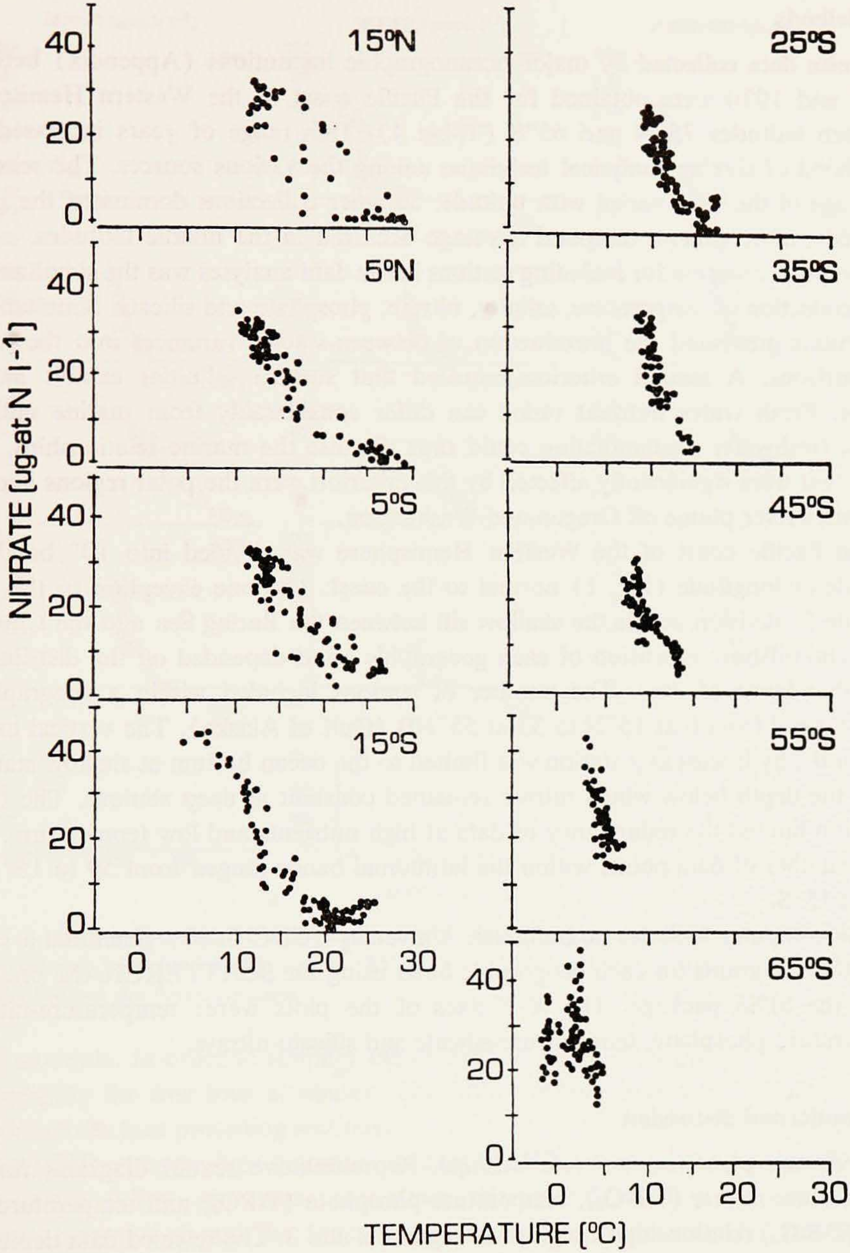


Figure 2. Scatter diagrams of temperature (*x* axis) versus nitrate (*y* axis) for each latitudinal or longitudinal band depicted in Figure 1. The details of the data are given in Table 1.

The enrichment of the Pacific Ocean with plant nutrients was documented by Berger (1970). The estuarine-type flow (the basin collects deep water) that characterizes the Pacific Ocean results in higher deep water concentrations of dissolved phosphate (2-3:1), nitrate (2-3:1) and silicate (4:1) than are found in the Atlantic. A comparison of the data given in Dugdale (1972) collected off Peru (15°S) and in Kamykowski (1974) collected off California (30°N) focuses on the pattern in the eastern Pacific Ocean. In the coastal waters off Peru, silicate is generally depleted from the surface waters before nitrate; off California, nitrate is



generally depleted from the surface waters before silicate. This dichotomy suggests a latitudinal trend in the relative abundances of these nutrients. The same data used to investigate the latitudinal patterns of temperature and plant-nutrients are applied to a detailed analysis of the silicate-nitrate relationship in the eastern Pacific.

2. Methods

Cruise data collected by major oceanographic institutions (Appendix) between 1963 and 1970 were obtained for the Pacific coast of the Western Hemisphere between latitudes 75°N and 65°S (Table 1). This range of years increased the likelihood of similar analytical technique among the various sources. The seasonal coverage of the data varied with latitude. Summer collections dominated the polar latitudes; more general temporal coverage occurred in the middle latitudes.

The main criterion for including stations in the data analyses was the simultaneous data collection of temperature, salinity, nitrate, phosphate and silicate. Simultaneous collections prevented the introduction of between-station variances into the factor comparisons. A second criterion required that surface salinities exhibit marine values. Fresh water nutrient ratios can differ considerably from marine nutrient ratios; freshwater contamination could thus disguise the marine relationships. The areas that were significantly affected by this criterion were the polar regions and the Columbia river plume off Oregon and Washington.

The Pacific coast of the Western Hemisphere was divided into 10° bands of latitude or longitude (Fig. 1) normal to the coast. The one exception to this rule was the 5° division across the shallow sill between the Bering Sea and the Chukchi Sea. The offshore extension of each geographic band depended on the distribution and abundance of data. The number of stations included within a geographical band ranged from 6 at 15°N to 33 at 55°NB (Gulf of Alaska). The vertical extension of the hydrocast at a station was limited to the ocean bottom at shallow stations or to the depth below which nitrate remained constant at deep stations. The latter criterion limited the redundancy of data at high nutrients and low temperature. The total number of data points within the latitudinal bands ranged from 59 to 15°N to 265 at 15°S.

The computer facilities at Dalhousie University (CDC 6600) generated a series of scatter diagrams for each geographic band using the SCATTERGRAM program from the SPSS package. The *X-Y* axes of the plots were: temperature-nitrate, temperature-phosphate, temperature-silicate and silicate-nitrate.

3. Results and discussion

Temperature-plant nutrient relationships. Representative scatter diagrams for the temperature-nitrate (T-NO_3), temperature-phosphate (T-PO_4) and temperature-silicate (T-SiO_3) relationships are given in Figures 2 and 3. The selected data depict the trend of the temperature-plant nutrient (T-N) relationships between 75°N and 65°S in the eastern Pacific. Five attributes of the scatter diagrams are discussed: (1) the general curvilinear shape of the data, (2) the intercept on the temperature axis, (3) the variability of the data within each graph, (4) the pattern in the slope of the T-N relationship, and (5) the temperature relationships among the three

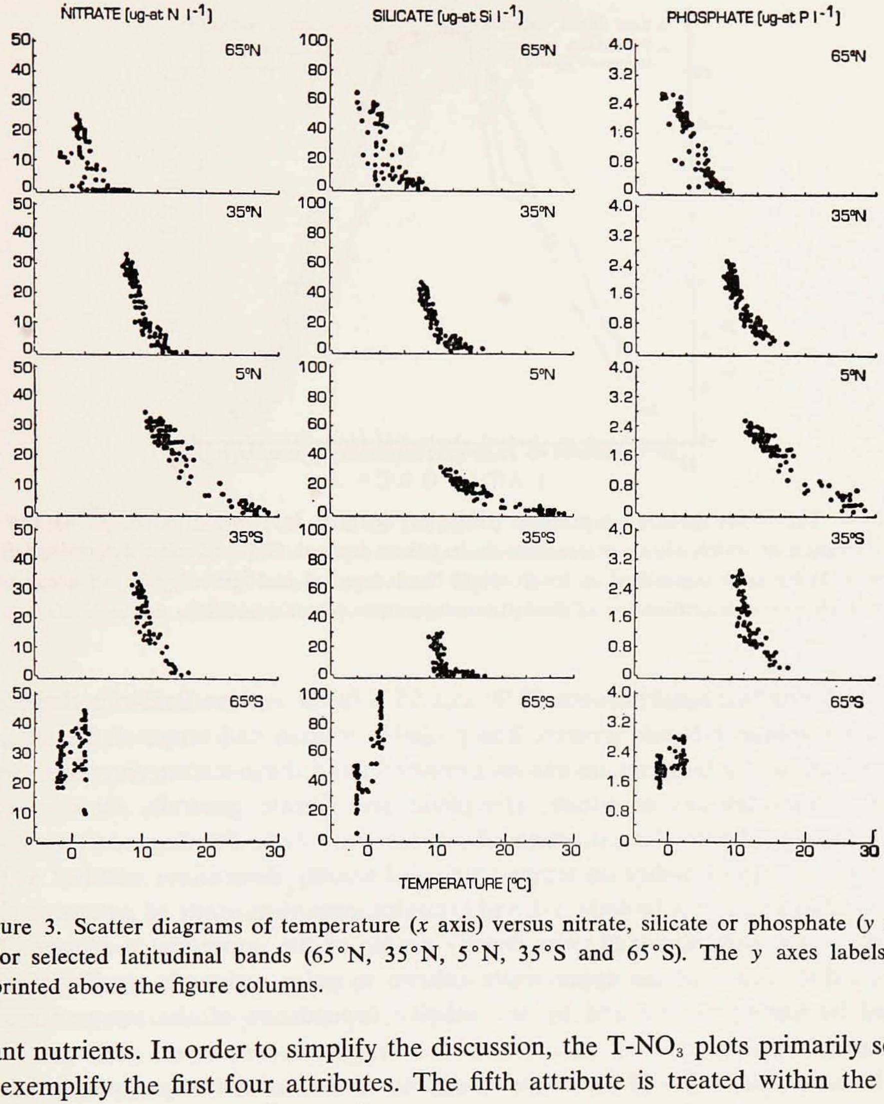


Figure 3. Scatter diagrams of temperature (x axis) versus nitrate, silicate or phosphate (y axis) for selected latitudinal bands (65°N, 35°N, 5°N, 35°S and 65°S). The y axes labels are printed above the figure columns.

plant nutrients. In order to simplify the discussion, the T-NO_3 plots primarily serve to exemplify the first four attributes. The fifth attribute is treated within the discussions of the four preceding sections.

The T-NO_3 relationships between latitudes 65°NB (Bering Sea) and 35°S (Fig. 2) generally follow an inverse monotonic relationship between the lowest temperature represented and the intercept on the temperature axis. An increase in temperature is matched by a corresponding decrease in nitrate. South of 35°S the T-NO_3 relationship remains curvilinear but does not intercept the temperature axis. The T-PO_4 and T-SiO_3 (Fig. 3) scatter diagrams parallel the T-NO_3 discussion. The change in slope within the T-N graphs may be related to depletion of one of the nutrients (i.e., nitrate in the Northern Hemisphere).

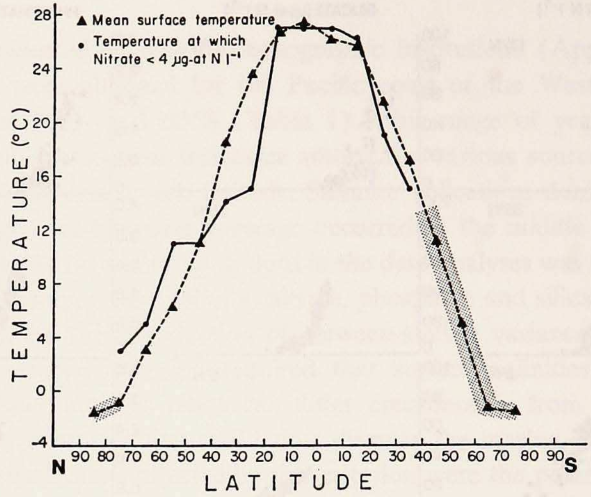


Figure 4. The mean surface temperature (triangles; adapted from Wust *et al.*, 1954) and the temperature at which nitrate is consistently less than 4 μg at N l^{-1} (circles; determined from Figure 2) for each latitudinal or longitudinal band depicted in Figure 1. Shaded areas mark zones where the determination of the latter temperature was not possible.

Each latitudinal band between 65°N and 55°S in the eastern Pacific is characterized by a unique T-N relationship. The probable median and range of the nutrient concentration at a temperature can be predicted from these scatter diagrams. Since marine concentrations of nitrate, phosphate and silicate generally increase with depth associated with the extinction of incident radiation, the dependence of seawater density and stability on temperature and salinity determines whether a T-N relationship exists at a latitude. At mid-latitudes, except in areas of extensive river runoff, temperature dominates the density profile of the upper water column. The density distribution of the upper water column in polar regions is significantly affected by salinity *per se* and by the salinity dependence of the temperature of maximum density.

The second attribute of the scatter diagrams is the latitudinally dependent temperature intercept. The T-NO_3 graphs in Figure 2 depict a successive decrease in intercept temperature between the equator and the poles. Actually this trend of decreasing temperature is true for all nitrate concentrations. The decreasing temperature intercept is also seen in both the T-PO_4 and T-SiO_3 scatter diagrams (Fig. 3).

Figures 4 and 5 investigate the latitudinal relationships between the T-NO_3 and T-SiO_3 temperature intercepts and the mean surface water temperature (Wust *et al.*, 1954). Due to scatter in the data, the nutrient depletion temperature is represented by that temperature at which these nutrients did not exceed 4 μg-at l^{-1}. A T-PO_4 figure closely parallels the T-NO_3 discussion, except the concept of preformed

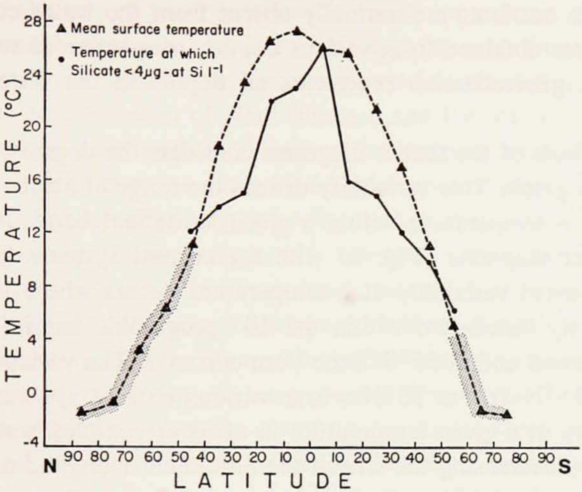


Figure 5. The mean surface temperature (triangles; adapted from Wust *et al.*, 1954) and the temperature at which silicate is consistently less than 4.0 μg at Si l^{-1} (circles) for each latitudinal or longitudinal band depicted in Figure 1. The shaded areas mark zones where the determination of the latter temperature was not possible.

phosphate (Redfield *et al.*, 1963) coincides with nitrate depletion. The solid line connects the latitudinal temperature intercepts that occur in the eastern Pacific. The shaded areas depict zones where a temperature intercept does not occur because (1) no T-NO_3 or T-SiO_3 relationship occurs (75°N, 65°S); or (2) nitrate (45°S, 55°S) or silicate (65°N, 55°N) are always abundant.

The T-NO_3 comparisons (Fig. 4) show that nitrate is generally available in the surface waters of the eastern Pacific between 75°N and 45°N; the surface waters are generally depleted in nitrate between 45°N and 15°N. In the tropics (15°N to 15°S) the T-NO_3 intercept approximates the average surface temperature. Since the isothermal mixed layer in tropical regions can extend far into the water column, this result does not necessarily mean that nitrate is available near the surface. The similarity between the mean surface temperature and the NO_3 intercept temperature suggests a steady state water column in a climatically stable area. Between 15°S and 35°S, the surface waters are generally nitrate depleted.

The T-SiO_3 comparisons (Fig. 5) show that silicate is generally available in the surface waters north of 45°N. Between 45°N and 25°N, silicate depletes from the surface water at somewhat higher temperatures than nitrate. Surface silicate normally occurs at low concentrations within this latitudinal range. Between 25°N and 45°S, silicate generally depletes from the surface waters at lower temperatures than nitrate. South of 45°S, silicate is usually present in the surface waters.

The temperature intercept of the T-N graphs emphasizes the temperature above which the various nutrients are normally absent from the water column. Since the available data were obtained from various depths irrespective of season, the depletion temperature generalization represents all depths in the water column at all seasons.

The third attribute of the scatter diagrams considers the degree of the data variability within each graph. This variability defines the range of nutrient concentrations that characterize a temperature within a given latitudinal band. A comparison of the T-NO_3 scatter diagrams (Fig. 2) with the current systems (Fig. 1) suggests that the least nutrient variability at a temperature occurs where the water masses are most uniformly distributed within the 10° geographic band (i.e., at 35°N in the California current and at 35°S in the Peru current). The variability is somewhat greater both at 15°N and at 55°N where various current systems converge. The nutrient variability at a given temperature in areas of complex water mass interaction is reduced by decreasing the size of the latitudinal (longitudinal) subdivisions. Some geographic areas always display a temporal variability associated with the migration of various water masses across the boundary lines. Stefansson and Atkinson (1971) discuss the water mass properties of density-plant nutrient relationships.

The change in slope is a fourth attribute of the T-N graphs. The slope of the T-NO_3, T-PO_4 and T-SiO_3 relationships (Fig. 3) decreases at 5°N compared to 35°N and 35°S. The explanation for this change in slope probably lies in the climatic stability and photic zone depth of tropical areas, but a definitive explanation is not available.

The negative correlation that exists between temperature and plant nutrients in the marine water column is a complex observation. The processes that influence these two oceanographic factors are considered separately. The actual causality of the T-N relationship lies in their mutual dependences.

LaFond (1962) considered the factors that control the temperature structure of the water column in two categories: (1) energy transfer processes at the sea surface, and (2) advective transfer processes below the sea surface. The first category concerns water column heating (absorption of radiation from sun and sky, convective sensible heating from the atmosphere, and condensation of water vapor) and cooling (back radiation from sea surface, convection of sensible heat to the atmosphere, and evaporation) across the atmosphere-ocean interface. The second group of factors (tide current and wind current) affect temperature by water movement without transfer of heat between the atmosphere and the ocean. The temperature structure of the water column in a geographic area is dominated by the first category but perceptibly influenced by the second.

Riley and Chester (1971) discuss plant nutrient cycles in the sea. The nitrate component of the nitrogen cycle is an appropriate focus since nitrogen is considered the ocean's primary limiting nutrient. The rate of nitrate utilization in the upper water column is overwhelmingly dependent on photosynthesis. Sverdrup (1953) demonstrated that the rate of photosynthesis in the water column depends on solar radiation both through available absolute light intensity and through the effect of surface heating on mixed layer depth. Sverdrup's model included a feedback mechanism between the concentration of plant biomass and the water column extinction coefficients for various wavelengths of light. After nutrient depletion in the upper layers, the peak in plant biomass descends in the water column growing at a rate determined by the quantity of penetrating solar radiation. Following photosynthetic utilization of nitrate by phytoplankton, the nitrogen passes through a series of reduced forms. Another possible feedback mechanism in nitrate utilization depends on the fact that the concentration of ammonium affects the rate of nitrate uptake (Caperon and Ziemann, 1976). The cycling of reduced nitrogen within the food web is generally most important at temperatures above the T-NO_3 temperature intercept at a given latitude. Below the photic zone, nitrate continues its relationship with temperature. Except for nitrate reduction by bacteria, nitrate utilization is usually insignificant below the zone of active photosynthesis. The T-NO_3 relationship in the aphotic zone ordinarily depends on the balance between bacterial denitrification and nitrate regeneration from decomposing organic matter and on physical processes (density advection and vertical mixing). The complex biological events that occur between nitrate utilization and regeneration are related to the temperature dependence of detrital sinking rates and of the bacterial nitrification rate.

The latitudinal interdependence between temperature and the concentration of plant nutrients in the water column is thus related to the heating effect of solar radiation, vertical mixing, advection, photosynthesis, the feedback between plant production and extinction coefficients for light, the interactions among the various forms of nitrogen, and the temperature dependence of the rates of biological processes in the aphotic zone. These generalizations merely list some of the components of the energy relationships that yield a latitudinally specific T-N pattern. A detailed study of the characteristics of the latitudinal T-N relationships will form the basis of a model of the global patterns.

Silicate-nitrate relationship. Figure 6 exemplifies the general pattern of the silicate-nitrate (SiO_3-NO_3) scatter diagrams for 10° bands of latitude (longitude) along the Pacific coast for the Western Hemisphere. A SiO_3-NO_3 relationship exists between 65°N and 55°S. Scatter varies with latitude depending on the hydrographic regime and the specificity of the silicon requirement to diatoms. The latitudinal pattern of the intercepts throughout the eastern Pacific is given in Figure 7. The excess silicate or nitrate remaining in the water after nitrate or silicate is depleted is determined from the graphs in Figure 6 and is plotted for each geographic band investigated. The sigmoid curve is a smoothed fit to the observed data. The pattern of excess silicate in the northern latitudes and excess nitrate in the southern latitudes confirms

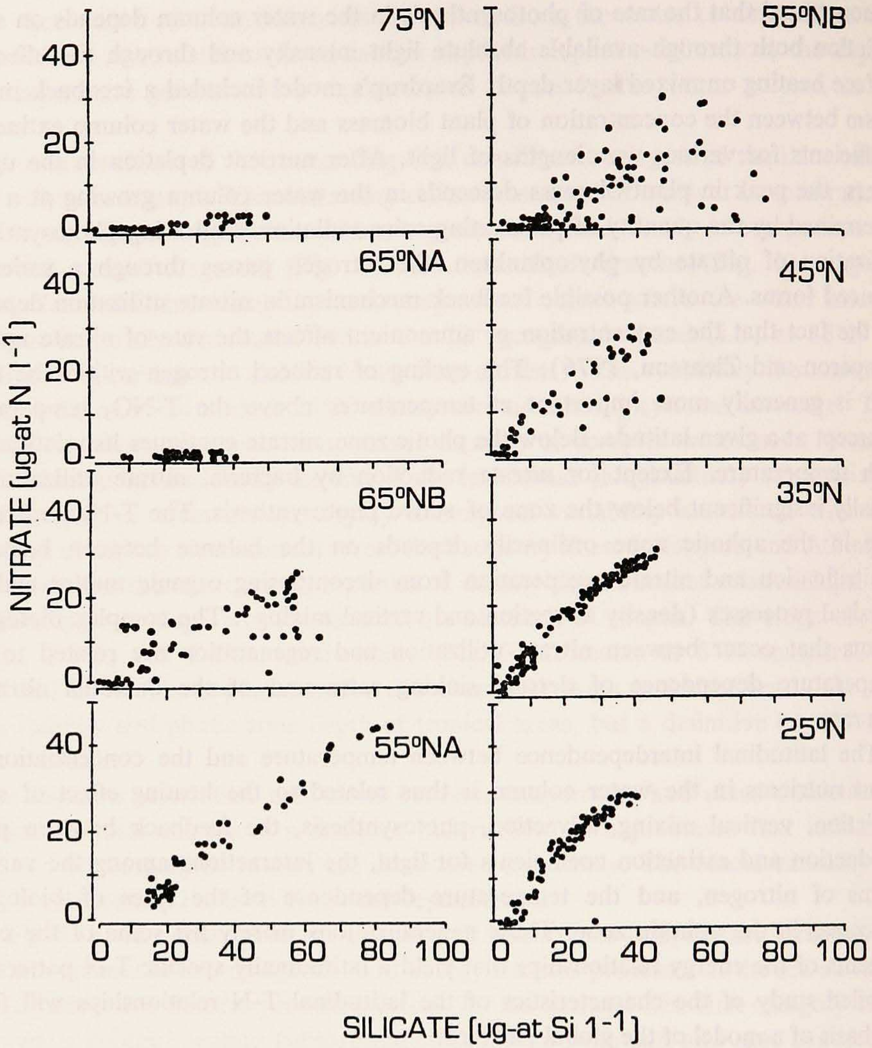
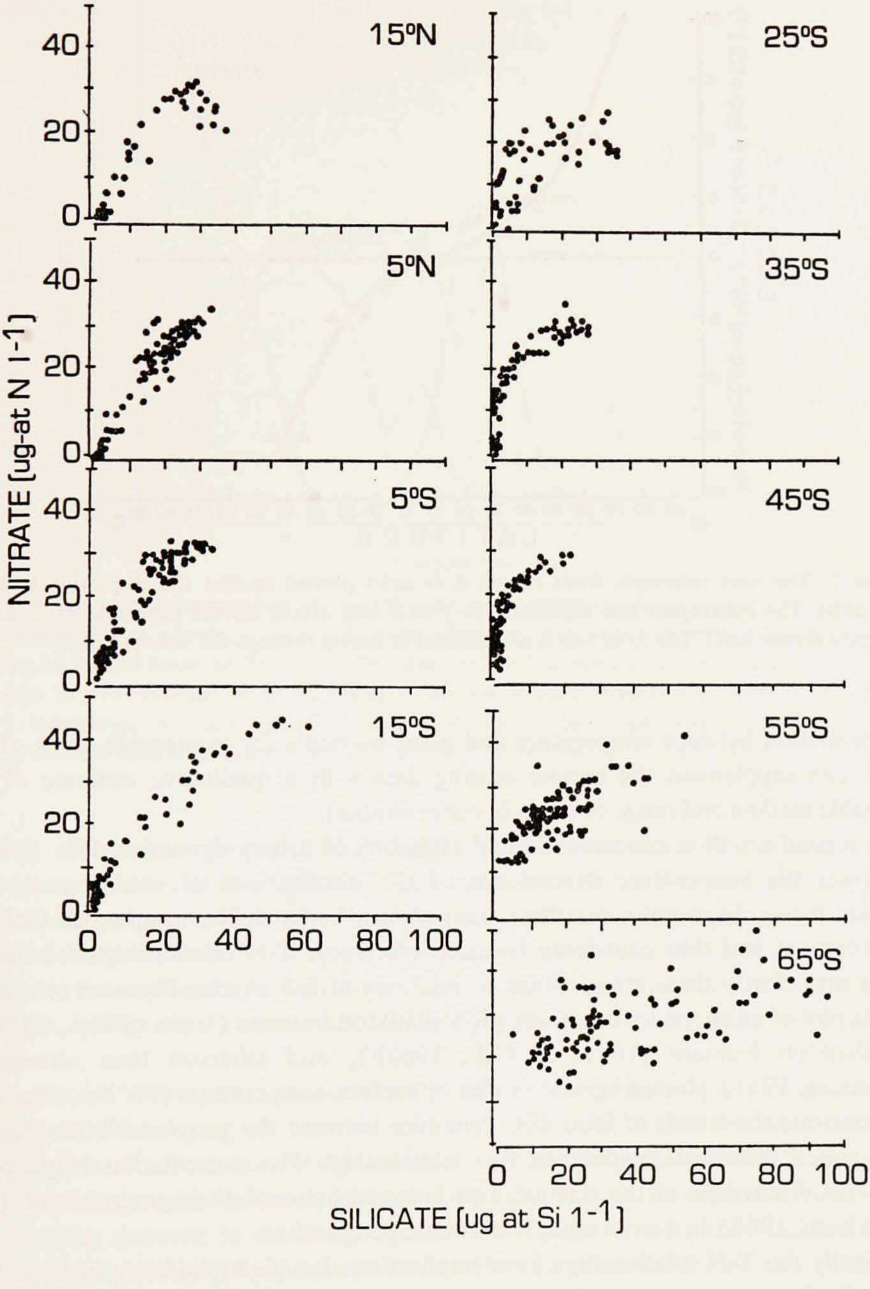


Figure 6. Scatter diagrams of silicate (x axis) versus nitrate (y axis) for each latitudinal or longitudinal band depicted in Figure 1.

the extension application of Berger's (1970) deep water enrichment presentation to the surface waters of the Pacific. The surface waters become silicate depleted as they flow south toward Antarctica.

4. Conclusions

The recognition of a latitudinal pattern of T-N relationships generates speculation on potential utility. The direct application concerns the prediction of plant nutrient concentration from temperature. Situations presently exist where it is



impossible or inconvenient to measure plant nutrients. One of these situations is the advancing ability to measure oceanographic factors from airplanes or satellites. Current techniques yield information on temperature, salinity and chlorophyll *a*.

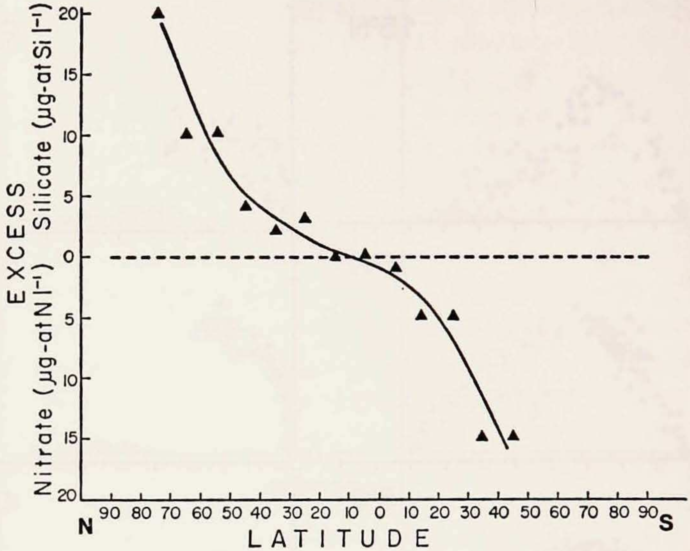


Figure 7. The axes intercepts from Figure 6 (y axis) plotted against the respective latitudes (x axis). The interrupted line separates the y axis into excess silicate (upper half) or excess nitrate (lower half). The solid line is a smoothed fit drawn through the data points.

A correlation between temperature and plant nutrients for geographic areas of the earth can supplement the remote sensing data with a qualitative estimate of the probable median and range of nutrient concentration.

A second situation concerns the understanding of fishery dynamics. Uda (1960) discusses the temperature dependence of the distributions of commercially important fishes. In many cases these temperature limits define a subsection of the environment and thus contribute to catch efficiency. T-N relationships for fishery areas may clarify these temperature correlations of fish stocks. Figure 8 is a composite plot of mean values of nitrate, phytoplankton biomass (Univ. of Cal., 1968a), zooplankton biomass (Univ. of Cal., 1968b), and albacore tuna abundance (Clemens, 1961) plotted against *in situ* or surface temperature (33°N). The data demonstrate the trends of food web dynamics between the proposed T-N relationship and a historical temperature-fish relationship. The presentation helps place previous discussions of the relationships between fish and their environment (*i.e.*, Blackburn, 1969) in a more complete trophic perspective.

Finally the T-N relationships have implications for phytoplankton ecology. The latitudinal patterns suggest that the temperature and nutrient combinations that occur at a geographical location fall in a limited range. Different phytoplankton species exhibit differences in their ability to utilize a specific concentration of a nutrient at a constant temperature (20-21°C) (Eppley *et al.*, 1969). The com-

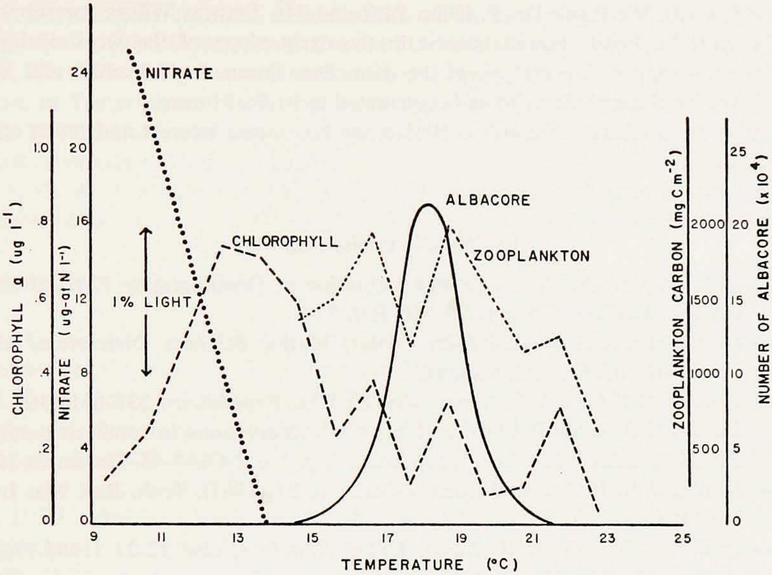


Figure 8. The mean temperature at the 1% light level within the water column and the mean concentration of nitrate, chlorophyll *a*, zooplankton and albacore tuna occurring over a range of temperatures at 33°N, 117°W. The nitrate line summarizes the data for 35°N in Figure 2. The chlorophyll *a* line connects the mean concentration observed for successive 1°C increments of temperature irrespective of depth. The zooplankton and albacore tuna lines connect the mean biomass at successive 1°C increments of surface temperature.

petitive advantages observed might change if the temperature and nutrient concentrations of the cultures simultaneously adjust to natural T-N relationships. The T-N relationship could contribute to the seasonal successional pattern at a geographic location and to differences in the successional patterns at different latitudes. The T-N relationships could be combined with appropriate daylength, light intensity, and light quality data to more accurately simulate growth conditions at a chosen latitude.

The pattern of SiO_3-NO_3 concentrations can affect the composition of phytoplankton communities during the annual production cycles in North and South Pacific coastal waters. In the north Pacific there is adequate silicate for the nitrate available. Silica-requiring organisms competitively utilize the nitrate to depletion since it is their limiting nutrient. In the south Pacific a large reservoir of nitrate remains after silicate depletion. Since diatoms have an absolute requirement for silicate (Thomas and Dodson, 1974), this nitrogen resource is available to phytoplankton (i.e., dinoflagellates, coccolithophorids) that do not require silica. If the expected differences in phytoplankton species composition do occur, repercussions may appear through the food web.

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In particular we thank Dr. Richard T. Barber for his sincere interest and much appreciated encouragement.

APPENDIX: Cruise Reports

CALC — University of California. Scripps Institution of Oceanography Physical and chemical data, CalCoFI Cruse 6806, SIO Ref. 71-3.

CODC — Canadian Oceanographic Data Center, Marine Sciences Directorate, 615 Booth Street, Ottawa, Ontario, Canada.

EAST — University of California, 1968. EASTROPAC Expedition I 23F-8M 1967.

ELT — Jacobs, S. S. 1965. Physical and chemical observations in southern oceans. USNS *Eltanin* Cruises 7-15 (1963-1964). Tech. Rep. No. 1-CU-1-65. December 1965.

— Jacobs, S. S. 1966 USNS *Eltanin* Cruise 16-21 (1965). Tech. Rep. No. 1-CU-1-66. May 1966.

— Jacobs, S. S. and A. F. Amos. USNS *Eltanin* Cruise 22-27 (1966-1967). Tech. Rep. No. 1-CU-1-67. November 1967.

NODC — National Oceanographic Data Center, U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Environmental Data Service, Washington, D.C.

OSU — Barstow, D., W. Gilbert, and B. Wyatt. 1969. Hydrographic data from Oregon waters 1967. Data Report No. 35 *Yaquina.* OSU Ref. 69-3.

PIQ — University of California, Scripps Institution of Oceanography. Physical and chemical data. PIQUERO Expedition. Sio Ref. 74-27.

SCORP — Scripps Institution of Oceanography. Physical and chemical data from the SCORPIO expedition in the South Pacific Ocean aboard USNS *Eltanin* Cruises 28-29. SIO Ref. 69-15.

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