LIMNOLOGY OF SELECT FRESH WATER SYSTEMS NEAR THE ANTARCTIC PENINSULA--FIELD AND LABORATORY STUDIES

by

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Thesis submitted to the Graduate Faculty of the
Virginia Polytechnic Institute and State University
in partial fulfillment of the requirements
for the degree of
Doctor of Philosophy

in

Botany

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December, 1970

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ACKNOWLEDGMENTS

I am sincerely grateful to Dr. Bruce C. Parker for his encouragement and guidance throughout this study and particularly during the preparation of this manuscript. This work was supported by the National Science Foundation grant GA 323318-1, awarded to Dr. Parker.

I am most indebted to my wife, Candi, whose understanding, encouragement, and assistance were a great inspiration.

I am indebted to Dr. E. R. Stout, Dr. G. W. Prescott, and Mrs. Barbara Mross for their valuable technical and field assistance. Thanks are also due to Drs. R. A. Paterson, D. M. McLean, J. Cairns, Jr., and R. S. Mitchell for their roles as reviewers and dissertation committee members.

TABLE OF CONTENTS

LIST OF TABLES

Page

LIST OF FIGURES

GENERAL INTRODUCTION

Since the early 1900's, there has been a growing scientific interest in the continental flora and fauna of Antarctica. However, even with extensive study of the continent and coastal areas during the International Geophysical Year 1957-58, relatively few detailed ecological observations and measurements have been reported (e.g., Siple, 1938; Giesseth and Leech, 1961; Armitage and House, 1962; Llano, 1962; Goldman, 1963; Goldman, et. al., 1963; and Wilson and Wellman, 1962).

Relatively limited limnological investigations and partial identifications of fresh-water algae from the western portion of the Antarctic Peninsula and sub-Antarctic islands in the vicinity of Palmer Station-Anvers Island have been reported previously by Wildemann (1900), Nordenskiold (1902), Fritsch (1903), Hariot (1908), Gain (1909), West and West (1911), all according to Hirano (1965), Bryant (1945), Holdgate (1964), and Cameron (1966). Besides temperature and general habitat descriptions, the earlier reports of these lakes and melt pools lack detailed information of physical, chemical and biological features. This information gap coupled with our detection of several apparent natural lakes in aerial photographs of the U. S.

Palmer Station area, encouraged this investigation toward understanding the fresh-water phytoplankton ecology of the areas near the Antarctic Peninsula.

Because of the scarcity of ecological observations concerning the biota of the remote lakes and pools of Antarctica, it is important to make observations available to interested scientists for reference and future study. Antarctic research is arduous and expensive and therefore requires unique preparation and planning. For this, an extensive backlog of reference material is necessary but not always available.

Continental Antarctica is predominantly an ice-covered cold desert with few habitats for living organisms (Allen, et. al., 1967). In contrast, the coastal zone and off-shore islands (The Maritime Antarctic of Holdgate, 1964) have a milder climate, much ice-free lowland, and a variety of plant and animal life. The flora and fauna are undoubtedly influenced by many factors, one of which concerns the chemical nutrient levels emphasized in this study. The range in differences among the several lakes studied near the U. S. Palmer Station is considered sufficiently representative for the data to be fairly widely applicable.

The field research was aimed at correlating certain physical, chemical, geological, and biological parameters to better understand the limnology of Palmer Station area fresh water systems; this was done jointly with Dr. Bruce C. Parker. From this study, several new areas of laboratory study arose to which special attention was devoted. These particularly included investigations of ^{14}C primary productivity in laboratory aquatic ecosystems which simulated Antarctic conditions to ascertain the effects of certain chemical nutrient factors on biological productivity of the Palmer Area fresh-water lakes and ponds.

Although these studies have centered around the general problem of biological productivity under the rigorous conditions of Antarctica, we have also considered a number of environmental variables, such as the study of penguins' contribution to the system in the form of ammonia nitrogen; while it may be peripheral to productivity, leads to a better understanding of the unusual Antarctic fresh-water ecosystem.

Also, an investigation was initiated to determine the merit of the standard 300 ml primary productivity bottle so long in use by many limnologists to measure the uptake of ^{14}C. Investigations on productivity as measured by ^{14}C were carried out, both in the field and at the laboratory, employing several commonly used productivity bottles and results can be found in Appendix III.

During the summer of 1970 at the University of Montana Biological Station, with the help of G. W. Prescott, an attempt was made to identify the Antarctic algae collected during our visit to the Palmer area and to correlate these algal communities with certain physical, chemical, and geologic parameters of the various lakes studied. From this work, we were able to construct a fairly complete list of algae genera reported from the Palmer Station area.

To ensure clarity, this thesis will be divided into several parts representing the specific research projects involving this author. Part I will include aspects of the field research conducted in the Antarctic during the austral summer 1969-70. Part II will concentrate on the laboratory ecosystem studies on nutrient levels, while Part III will survey the fresh-water algae of the Antarctic Peninsula.

PART I

LIMNOLOGICAL INVESTIGATIONS IN THE AREA OF ANVERS ISLAND, ANTARCTICA

INTRODUCTION

This paper reports on the limnological investigation of several fresh-water systems of Palmer Station and adjacent areas off the western coast of the Antarctic Peninsula. The field work occurred during the austral summer of 1969-70. The work reported here was aimed at understanding the biology of the Antarctic inland waters and includes both field and laboratory data. More specifically, I sought to identify the phytoplankton and attached algae; to measure physical and chemical parameters, such as light, temperature, oxygen, pH, and various nutrient levels; to ascertain the photosynthetic rates of phytoplankton communities by using the *in situ* ^{14}C and chlorophyll methods, and to correlate the physical and chemical data with the biological observations.

Between November and February numerous shallow fresh-water ponds and lakes near the Palmer Station area are melted completely or partially and contain a limited biota. The fresh-water habitats studied occurred within two miles of U. S. Palmer Station, constructed in 1967 on Anvers

Island (67^{o} 46' E; 60^{o} 05' W) off the Western Coast of the Antarctic Peninsula. Since none of the six ponds studied had been named previously, they were designated according to some prominent feature as geography, bird habitation, etc. This report deals primarily with two of the ponds investigated. The features of other ponds mentioned briefly throughout the study are summarized in Part III, with brief descriptions and data. These are included to provide a basis for contrast and generalization made from the data presented in the main body of this thesis.

"Skua Lake", located behind the abandoned United Kingdom and old U. S. Base at Norsel Point, Anvers Island, was named for the dominant resident bird population (Stercocarius skua) which frequented it. "Humble Lake" was located on adjacent Humble Island. These names are unofficial, but are used here merely to facilitate discussion.

General features of the Palmer Station area have been described by Gain (1909) and Hooper (1962) and, so far as is known, have not been discussed by others. Hooper (1962) discussed general glacial history of the Palmer Station area, which Scharon elaborated (1970--pers. comm.). They postulate that Anvers and adjacent islands are related to the Antarctic Peninsula with the islands resulting from a metasomatic process by which water covered the rest of the land mass, leaving the high altitude topographic region, as the present day islands of Anvers, Humble, etc. It is probable that the recent glacial events have opened virgin areas to biotic colonization. Llano (1959) estimates from studies of lichens that the current exposure of the Palmer Area Islands may date back no more than 500 years.

"Humble and Skua Lakes", although different in morphometric, chemical, and biological parameters, are similar in various other facets. Both receive their input from snow drifts and glacial ice, and output is by way of shallow channels directed toward the bay. The two lakes are approximately 1/4 mile apart, separated by Arthur Harbour. Scharon (pers. comm., 1970) considers the geological structure of the two lake basins to be identical. During our visits to this area in January, 1970, we noted certain striking differences between the two lakes. "Skua Lake", the largest and deepest of all lakes in the area, was almost entirely ice-covered. Nutrient levels in "Skua Lake" were lower than in "Humble Lake", but nevertheless approached or exceeded those found in many mesotrophic and eutrophic temperate lakes (Hutchinson, 1957; Reid, 1961). Biological productivity in "Skua Lake" was extremely low, and could for this reason be considered oligotrophic, based on temperate lake standards. "Humble Lake" was considerably smaller than "Skua Lake" and very shallow, with less than one-third of its surface ice covered. Nutrient concentrations of "Humble Lake" were consistently higher than those of "Skua Lake", although the difference in the nutrient levels were not extreme in many instances. Goldman, et. al., (in press), for example, reported greater variation in nutrient concentrations in a single Antarctic lake than the variations we found between these two lakes over a two-week period.

MATERIALS AND METHODS

Morphometric measurements were made on all lakes during the 1970 summer season. A pyranometer /Model 68--Yellow Springs Instrument Company (YSI), Yellow Springs, Ohio/ was operated periodically throughout the season, giving values for total incident radiation to approximately 4 μ. The manufacturer claimed 5% precision and ± 0.1 langley·min^{-1} accuracy. Light penetration in the lakes was also measured with the YSI pyranometer, having a neutral density selenium photronic cell probe. Ambient and water temperatures were regularly measured with ± 0.1° C accuracy with a YSI Model 41 thermistor unit calibrated against a standard mercury thermometer. Chemical and nutrient levels were determined both in the field and at the Palmer Station laboratory with a Hach chemical "Direct Reading" Portable Engineers laboratory, replicate samples having less than 10% variation. Phytoplankton densities were accomplished by direct counts, with Nikon field and binocular phase microscopes at 100-1000 x and concentrated with a Foerst continuous-flow centrifuge and 76 μ plankton net. Plankton samples from the lakes were preserved and shipped back to VPI with 3-4% formaldehyde. Algae samples cultured at Palmer Station and live collections were carried back to VPI for further culturing in Bozniak's (1969) community medium and an enrichment media designed to approximate closely those of the particular habitats. Phytoplankton were collected with a Model 40 Wildlife Supply Company Plankton Tow.

Water samples were collected and placed in acid-cleaned 250 ml opaque polyethylene bottles pre-rinsed with demineralized water. Soon after collection, samples were analyzed at Palmer Station for chlorophyll a and total chlorophyll concentration as well as for the phytoplankton concentration. Chlorophyll concentrations were measured with a B & L Spectronic 20 and Beckman Model DU Spectrophotometer, according to the method of SCOR/UNESCO cited by Strictland and Parsons (1968). Using the following equations:

$$\text{m-SPU/m}^3 = \frac{C}{V}$$

$$C\ (\text{Chlorophyll a}) = 11.64\ E_{6630} - 2.16\ E_{6450} + 0.10\ E_{6300}$$

$$C\ (\text{Chlorophyll b}) = 20.97\ E_{6450} - 3.94\ E_{6630} - 3.66\ E_{6300}$$

$$C\ (\text{Chlorophyll c}) = 54.22\ E_{6300} - 14.81\ E_{6300} - 5.53\ E_{6630}$$

and V is the volume of sample filtered in liters. E is the extinction value at the wave length indicated by the subscript.

Primary productivity studies followed the in situ ^{14}C method of Steeman-Nielsen (1952), with modifications by Goldman (1963) and Strictland and Parsons (1968). We modified this method still further in using transparent 250 ml pharmaceutical bottles with the thin, slightly convex side oriented upward. All opaque productivity bottles were painted black and wrapped with aluminum foil so that the "black body effect" would not raise the temperature of the bottles' content during the incubation period. Glass ampoules --each containing 1 ml and 10 micro-curies of $Na_2{}^{14}CO_3$ were obtained from New England Nuclear.

In the field, the $Na_2{}^{14}CO_3$ solution was removed from the ampoule by using a 5 cc syringe equipped with a 14 gauge, 4 inch long laboratory cannula and carefully deposited at the bottom of the productivity bottle. The ampoule was rinsed once with 2 ml of water drawn into the syringe from the top of the productivity bottle. The rinse solution was redeposited into bottles from which it was removed. The bottle was capped, shaken, and placed in situ at the same depths from which their contents were initially collected. Duplicate bottles were used frequently with less than 5% variation. During ^{14}C experiments, oxygen, temperature, and light measurements were made near productivity bottles.

Four hours later, the productivity bottles were brought to the surface and 10 ml of 40% formalin were added to each bottle to stop all carbon assimilation.

Upon return to the Palmer Station laboratory, the contents of each productivity bottle was filtered through a 25 mm 0.22 HA millipore filter at a vacuum not exceeding 350 mm of Hg. All filters containing organisms exposed to $Na_2{}^{14}CO_3$ were rinsed with about 5 ml of 0.003 N.HCl to remove precipitated $Na_2{}^{14}CO_3$. All filters were air-dried and dissolved in a screw-top scintillation vial containing 10 ml of 1.4 dioxose (p-dioxone) containing 7 gms of 2.5-diphenyloxozole (PPO)/1 and 100 gms of napthalene/1. Scintillation counting of ^{14}C was completed at VPI. Primary productivity was calculated as mg C/m^3/hr from the following modified formula of Saunders, Franc, and Bachman (1962).

$$P = \frac{r \times c \times f}{R \times hr}$$

Where:

P = carbon fixation in mg C/m^3/hr

r = assimilated ^{14}C in cpm

R = total available ^{14}C in cpm

C = total available stable inorganic carbon in mg/m^3

f = isotope correction factor

m = total incubation time in hours

The counts per minute of $Na_2{}^{14}CO_3$ assimilated by the plankton were recorded with a Beckman CPM-100^{tm} Liquid Scintillation System.

To ascertain the amount of available $Na_2{}^{14}CO_3$ (R) that was injected into each productivity bottle, the contents of an ampoule which was prepared from the original lot was added to a 250 ml volumetric flask containing a buffer solution at pH 8. The procedure and equipment in transferring each ampoule's contents into productivity bottles in the field were also employed in transferring the contents of the ampoule to be assayed. The resulting volume was brought to 250 ml. One half of this solution was pippetted into each of three scintillation vials containing the scintillation cocktail. The cpm were averaged and the total cpm per ampoule computed.

The total available stable inorganic carbon (C) in mg/m^3 was calculated from the data on temperature, pH, total alkalinity, and a table of conversion factors constructed by Saunders, et. al., (1962). The isotope correction factor (f) used was 1.06, also according to Saunders, et. al.

The standing crop of plankton by extractable chlorophyll and the photosynthetic carbon uptake were determined periodically under measured conditions of light and temperature. Both methods employed 0.22 micron millipore filters as recommended by Parker (1967). All measurements were made periodically for the two lakes during two weeks including a series of diurnal studies of chlorophyll and primary productivity and collections were made from approximately 20 cm depth in ice-free water. Other methods will be cited concurrently with the data.

RESULTS

General Features of "Skua and Humble Lake" Basins

Both lakes are located within a two-mile radius of the new Palmer Station. "Skua Lake" is the larger (Fig. 1), located directly behind the then unoccupied United Kingdom Base at Norsel Point, Anvers Island. A resident bird population of about 60 Sterococarius skua, some of which nested at the rim of the lake basin, frequented the shallow, open water and ice-covered portion of this lake. The smaller and more shallow "Humble Lake" (Fig.2) is located about 1/4 mile away on Humble Island. Figures 1 and 2 show also "Skua Lake" had less than 90% ice cover throughout the summer season, while "Humble Lake" had less than 30% ice cover, which decreased somewhat during our study. "Humble Lake" basin also possessed appreciable numbers of Skua, and in addition, Antarctic terns (Sterna paradisaea) and giant petrels (Macronectes giganteus), representing both greater bird species number and biomass than for "Skua Lake".

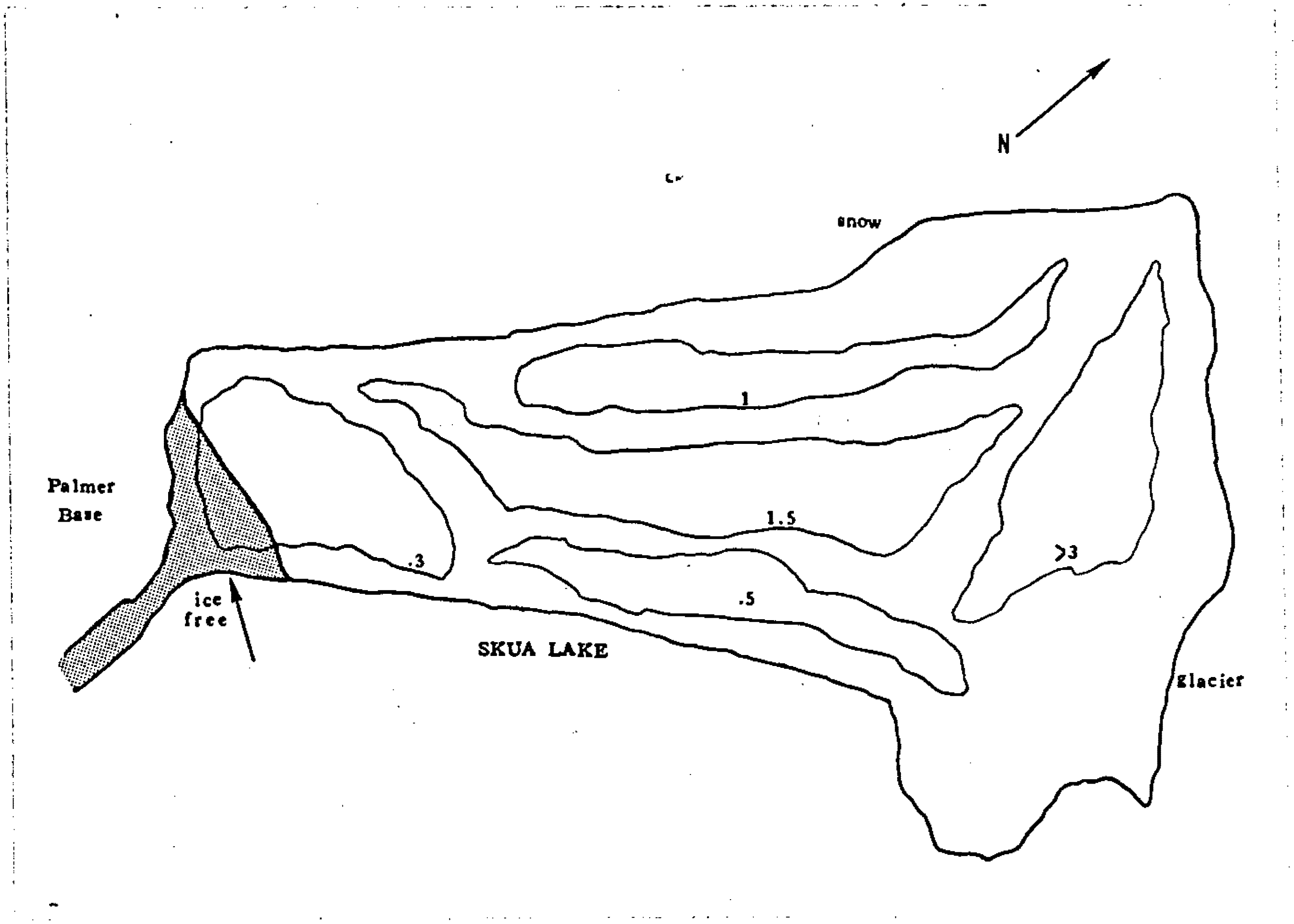

FIG. 1. Map of "Skua" Lake, Norsel Point, Anvers Island, Antarctica.
Scale: 1.0 inch = 10 meters

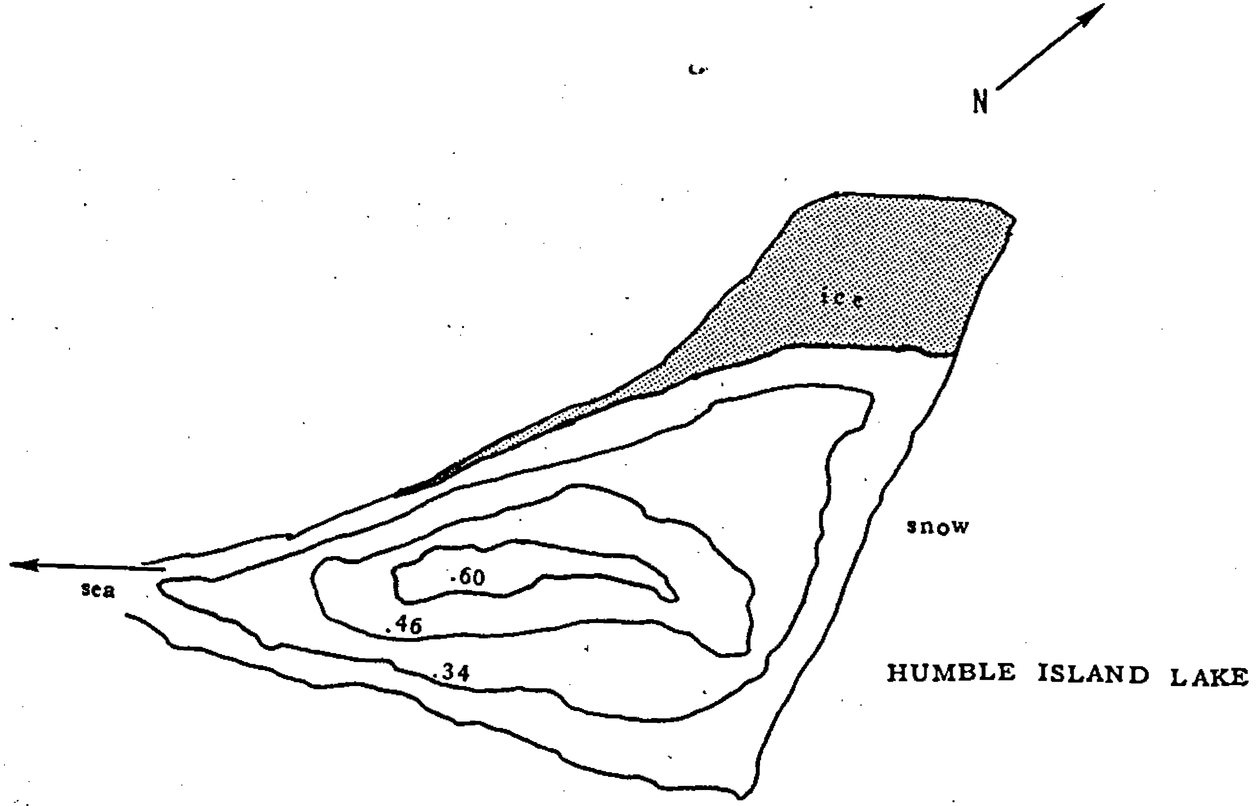

FIG. 2. Map of "Humble" Lake, Humble Island, near Norsel Point, Anvers, Island, Antarctica. Scale: 1.0 inch = 10 meters

These, like other Antarctic lakes on the coastal plain, were formed as thaw lakes, resulting from the melting of large masses of ground ice and glacial melt as described for Arctic lakes by Hopkins (1949) and Wallace (1948). Both lakes overflowed continuously during our visits as a result of rain and meltwater from glaciers and snow banks. Visual observations of the major overflow streams from each lake indicated that the volume of water leaving "Skua Lake" was many times greater than that of "Humble Lake", although on the basis of overflow per lake volume, the values were much closer. "Skua Lake", at the base of a glacier, exceeded three meters in depth, while "Humble Lake" had a maximum depth of 0.6 meters. These basic differences in size and shape of the two lakes are apparent from Figs. 1 and 2. To our knowledge, no official names have been given to these lakes by the Antarctic Treaty Organization.

Both lake basins contain an igneous, intrusive, quartz-rich granite with traces of biotite and appreciable sodium plagioclase and from extensive collections of rocks in the area, there is no reason to expect the geological structure of the two lake basins to differ appreciably.

Much of the basin and periphery of "Humble Lake" was colonized densely with the bryophytes Calliergidium austrostramineum C. Mull., Polytrichum juniperinum Hedvi, and lichens such as Caloplaca and Xanthoria spp. on rocks.

The edge of an adélie penguin (*Manchot adélie*) colony occupied one small portion of the upper rim of "Humble Lake" watershed, with occasional individuals sliding down the snow toward the lake. In striking contrast, "Skua Lake" lacked a luxuriant bryophyte and lichen development, with only occasional rock-adcrusting forms. Snow algae were not obvious on the extensive snow banks surrounding 75% of "Skua Lake", which further contrasted with the patches of pink snow at one end of "Humble Lake."

Physical and Chemical Parameters

Temperatures ranged from -1.0 to 3.5° C in "Skua Lake" and from $\overset{3}{1}.0$ to 8.0° C in "Humble Lake" during the January 10-26 period of the studies. These ranges resemble that reported by Boyd (1959) for a series of shallow Arctic lakes. At least four modes of heat transfer into ice-covered and partially ice-covered lakes must be considered: (1) surface advection; i.e., melt water streams from glaciers, (2) subsurface advection; i.e., thermal springs, (3) solar radiation penetrating the ice and absorbed by the water on the bottom, and (4) conduction of geothermal heat from the bottom. One and three seem to be the most logical means of heat transfer for "Skua and Humble Lakes." Radiation varied from negligible to 0.5 langley/min. at approximately 20 cm depth where productivity measurements were made.

Except for two days during our visit, skies were overcast with incident surface radiation below 0.6 langley/min. Table I summarizes additional physical and chemical data for these lakes. Note that both ponds had similar pH's (6.3 and 6.4)

Although levels of most nutrients were generally lower in "Skua" than in "Humble Lake", they approached or exceeded those found in some eutrophic temperate lakes (Hutchinson, 1957; Reid, 1961). In interpreting these chemical data, one should realize that melting proceeded from the lake margins toward the center, with approximately 70% of "Humble Lake" melted and only a small portion of "Skua" devoid of ice. Also, our collections were taken chiefly from the subsurface water at the melted edges.

As Mawson (1916) stressed in his studies of Antarctic coastal ponds, the rock chemistry of lake basins can represent significant sources of nutrients for such lakes. Table II summarizes the composition of a quartz-rich granite considered typical of the predominant rocks collected near the rims of both lakes. Note especially that these granites, as compared with lava and other quartz-rich diorites, contain significantly lower levels of phosphate and iron. Furthermore, nitrogen and chloride compounds are virtually absent from granites. Physical processes appear to dominate the initial breakdown of rock on Humble and Anvers Islands,

TABLE 1

Some physical and chemical parameters of "Skua Lake" and "Humble Lake", (mg/l, or as indicated; chemical parameters are means of at least duplicate samples, with a variation of ≤ 10%)

Parameter	"Skua Lake"		"Humble Lake"	
Maximum depth	3.00 M		0.60 M	
Mean depth	1.00 M		0.20 M	
Maximum length	95.00 M		43.00 M	
Maximum breadth	25.00 M		20.00 M	
pH	6.40		6.30	
Turbidity	15.00 JTU*		63.00 JTU*	
Dissolved O_2	14.00		13.00	
Total alkalinity	10.00		12.00	
Total hardness	10.00		15.00	
NH_4^+-N	0.1		2.5	
NO_2^--N	nil	1.1	0.05	4.30
NO_3^--N	1.0		1.75	
Ortho $PO_4^{\equiv}$ -P	0.02		1.0	
Total $PO_4^{\equiv}$ -P	0.03		1.7	
Cl^-	7.5		35.0	
$SiO_2^=$	1.0		1.5	
Ca^{++}	5.0		10.0	
Fe^{++}	0.02		0.02	
$SO_4^=$	4.0		6.0	

*JTU = Jackson turbidity units

TABLE II

Chemical composition of Antarctic lava (after Goldman, et. al., in press) and granite, considered comparable to that in the Palmer Station area, Antarctica (after Turner and Verhoogen, 1960).

	Lava	Granite
Mineral	Portion of Weight (%)	Portion of Weight (%)
SiO_2	49.65	72-75
Al_2O_3	16.31	11-14
CaO	9.07	0.6-1.0
MgO	6.14	0.0-0.2
FeO	6.45	0.5-1.0
Fe_2O_3	5.47	0.5-1.5
Na_2O	3.24	3.5-4.5
K_2O	1.66	4.2-4.9
TiO_2	1.41	0.1-0.3
P_2O_5	0.48	nil
MnO	0.30	0.0-0.4
Total	100.18	92.4-102.8

especially at and just below the surface where repeated freeze-thaw cycles are very effective (Chambers, 1966). A similar predominance of mechanical weathering was reported by Kellogg and Nygard (1951) and Kelly and Zumberge (1961), and has generally been considered wide-spread in polar regions. Glacial action has been important in mixing the primary rock fragments. The fragments have been further mixed with silts and clay to form the mineral soils of the two islands which are mainly at an early age and show little profile development. There is none to very little incorporation or organic matter into the mineral soil.

Biological Features of the Lakes

Only four algal genera were found in "Skua Lake", while the algal community of "Humble Lake" included twenty-one frequently observed genera in plankton tows and water edge collections (Table III).

Both lakes contained an abundance of gram-negative bacilli which grew at low temperatures on Difco nutrient agar plates. Only one colony color and form grew from "Skua Lake" water, while at least ten different colony types grew from "Humble Lake" water inocula. Abundant bryophyte mats and large numbers of a small aquatic crustacean found in "Humble Lake" were absent in the waters of "Skua Lake."

TABLE III

Algal genera in "Skua Lake" and "Humble Lake"

Genus (reference**)	"Skua Lake"	"Humble Lake"
Oscillatoria (2,4)	+	+
Phormidium (4)		+
Mastigocladus		+
Trachychloron		+
Chlamydomonas (1,4)	+	+
Prasiola (2)		+
Chlorella (4)	+	+
Ellipsoidion		+
Trochiscia (3,4)		+
Navicula (3)		+
Chroococcus	+	+
Scotiella (1,4)		+
Merismopedium		+
Chlorosarcina (4)		+
Chrysococcus		+
Dactylococcopsis		+
Monostroma		+
Aphanocapsa		+
Palmellopsis		+

* Identifications tentative, see text.

** References cited represent previous works reporting these genera in Anvers Island area, Antarctica: (1) Wildemann, (1900); (2) Nordenskiold (1902); (3) West and West (1911); (4) Gain (1913); according to Hirano (1965).

Following combustion at 500 C, pale, sandy "Skua Lake" bottom sediment, dried previously at 100 C, lost less than one percent of its weight, while the dark brown mud from "Humble Lake" lost 34%. Table IV shows that total chlorophyll content for "Skua Lake" fluctuated diurnally between 35-41 mg/m^3, while that of "Humble Lake" for the same time period ranged between 37-112 mg/m^3. Diurnal carbon fixation for "Skua Lake" ranged between 0.78-3.3 mg C/m^3/hr. Note also in Table IV that peaks in chlorophyll concentrations and carbon uptake rates at the 20 cm depth occurred in afternoons and early evening when radiation levels were less than 0.25 langleys/min. No obvious correlation existed between chlorophyll content and carbon fixation for either lake, nor between diurnal concentrations of sestonic chlorophyll, rate of carbon fixation, and either light intensity or temperature.

DISCUSSION

"Humble and Skua Lakes" exhibited the extremes in different conditions found among the shallow water bodies near Palmer Station. The slightly colored, more turbid water of "Humble Lake", containing significantly higher concentrations of phosphate (50X), inorganic nitrogen (4X), and chloride (5X), had up to 20 times the phytoplankton primary productivity at 20 cm depth per unit area of ice-free water than "Skua Lake." "Skua Lake" water was clearer

TABLE IV

Diurnal measurements of temperature, radiation, total extractable chlorophyll, and primary productivity of open waters at 20 cm depth in "Skua" and "Humble" Lakes, January 18-19, 1970

Lake	Time	Temperature C	Radiation (langley/min)	chlorophyll (mg/m^3)*	Photosynthetic CO_2 Fixation mg C/m^3/hr**
"Skua"	0940	3.5	0.38	37	0.78
	1340	0.0	0.085	41	1.7
	1800	-1.0	nil	35	1.0
	0200	0.0	0.12	36	1.6
	0800	0.0	0.18	36	3.3
"Humble"	1215	7.5	0.5	112	72.0
	1615	4.0	0.25	56	40.0
	2000	2.2	0.175	37	19.0
	0100	4.5	0.13	45	16.0

* Chlorophyll values refer to first time in each interval.

** Values for C fixation are means of duplicate light bottles less the dark bottle values; values for dark bottles and for filterable (extracellular), fixed organic matter were always $\leq$ 5% of the total productivity.

throughout the season and contained a relatively small biomass and low species diversity of plankton, including bacteria, even in the ice-free shoreline areas of the lake visited by Skuas. Possibly micro-algae were present in "Skua Lake", but escaped plankton net capture and subsequent detection. It is unlikely, however, that other species of phytoplanktonic microalgae occur abundantly in ice-free subsurface water of "Skua Lake", because a 76 µ pore-size plankton net revealed the genera Chlorella and Chlamydomonas which have cell sizes below this pore diameter, and these were the only algae observed in Foerst centrifuged water samples.

Water temperature probably is not the chief factor inducing nutrient and biological differences between the two lakes, for daily temperatures fluctuated in both lakes with maximum water temperatures approaching 8° C only briefly during our studies in the shallower, more open "Humble Lake." During periods of bright light in both lakes, water temperatures were usually highest at the bottom in shallow areas, where much of the radiant energy is absorbed and converted to sensible heat; this heating effect on the bottom no doubt contributed to nutrient mixing, as found by Goldman, et. al., (in press). Differences in water temperature also seem not to explain the great variations in plankton content between the two lakes, because at any given temperature, there may be many or few plankton.

Thus, the extreme cold of the Antarctic does not seem to have a great direct effect, except perhaps at the shore, upon the life in the water. The lakes are not very large, and they attain summer temperatures of 8-10° C. This is no colder than many of the deep lakes of the temperate zone. For example, Lake Superior, at a latitude of about 48°, attains a maximum open water surface temperature of only about 10°C (Millan, 1952). The well-known thermal properties of water act to buffer aquatic organisms against the regional thermal environment and the actual temperatures to which aquatic organisms are subjected are as much a function of lake size and shape as of latitude. This is not to say that the length of the growing season is not affected by the shortness of the Antarctic summer; it is, but a short growing season is not restricted to the Antarctic. In ephemeral lakes of the temperate and trophic zones, the length of the growing season is limited by summer drought and most aquatic organisms, at least the smaller algae, are adept opportunists, able to take advantage of favorable circumstances when they occur and to endure long resting phases of very low activity with little ill effect.

Also, a living organism may according to Oppenheimer (1959), have more than one optimal temperature for activity in the natural environment. If microorganisms in general have the ability to grow or be active optimally in different environments, this may account for increase in activity at certain periods of the annual cycle corresponding to the predicted optimal temperature. It may also account for microbial activity at cold and warm latitudes and suggest that the microorganisms which are optimally active in the Antarctic regions may also be active in the tropical environments.

Because of the thermal capacity of the deeper "Skua Lake", the ice cover forms in the fall and disappears in the spring more slowly than it does in the shallow "Humble Lake." This must be of some importance in the illumination of the water, for it keeps "Skua Lake" ice-covered almost the entire summer. The separate crystals of melting spring ice reflect a good proportion of the incident light income of the two lakes. Our data on productivity of "Skua and Humble Lakes" is in agreement with that of Comita and Edmondson (1953) who concluded that the summer productivity and summer standing crop of Arctic lakes did not differ markedly from those of temperate lakes; a great deal of solar energy enters a low latitude lake during the summer.

Goldman, et. al., (in press) found that ice surfaces on Alga Lake and "Skua Lake" at Cape Royds reflected 58% of the incident radiation. Nil readings for radiation penetrating the expanse of snow-covered ice on most of "Skua Lake" may therefore have a greater influence on the lower chlorophyll content and carbon uptake rates for this lake than the temperature differences. In one trial ^{14}C experiment under the ice, we obtained the significant fixation rate of 2.0 mg $C/m^3/hr$, but this value may not represent exclusively under-ice productivity due to ice hole reflectance. Goldman, et. al., (1963) found that radiation values above 0.2 langleys/min. appeared inhibitory to both chlorophyll production and carbon uptake by Antarctic freshwater algae. Data from "Humble Lake" do not agree with this interpretation, but the low primary productivity of "Skua Lake" water at the higher radiation values recorded could reflect light-inhibition of photosynthesis.

Biological production seems to be limited by certain nutrient factors. The data for "Skua Lake" suggest limiting reserves of both phosphate and nitrogen. Between the two nutrients, however, phosphate seemed to be more limiting in "Skua Lake" because the ratio of inorganic N/orthophosphate-phosphorus is 55:1, while in "Humble Lake", it is 4:1. However, nutrient studies in the laboratory showed that this was not the case.

It appears that there are three sources of nutrient supply on Humble and Anvers Island. The first is rock breakdown. The frequency of the freeze-thaw cycle on the islands suggests that physical weathering is dominate, although not exclusive. This action continually exposes fresh surfaces to water seepage. The second and third sources of nutrient supply are directly or indirectly marine. The sea contributes almost all the salt constituents of precipitation (Sugawara, 1965) in oceanic areas such as the Antarctic, where industrial fumes and soil dust are not significant. In addition, the abundant marine life is the food supply of the birds and mammals that frequent the two islands and in turn provide the nutrient resevoirs there.

Atmospheric precipitation can be an important factor in the supply of chemical nutrients to an ecosystem. Unfortunately, few data are available for the chemical content of precipitation in the Antarctic. Recent publications include that of Brocas and Delwiche (1963) who report a high mineral content for snow near the coast. Gorham and Cragg (1960) showed that bog water in the Falkland Islands contained high concentrations of elements of marine origin, particularly sodium (26-63 ppm). Wilson (1959) reported that the surface of the ocean in the southern hemisphere is important as a source of air-borne nitrogenous material and other plant nutrients. Most precipitation on Humble and Anvers Islands, however, falls as snow, with a lower nutrient content than rain and, therefore, atmospheric precipitation as a nutrient addition source is likely to be relatively unimportant.

Allen, et. al., (1967), point out that of the three above mentioned sources of nutrient addition, the contaminated areas appear to offer the greatest potential but their actual significance cannot be estimated until the distribution pattern has been clearly established. The volatile nature of the nitrogen compounds and the damp conditions appear to facilitate their distribution. The mechanism of the PO_4 distribution is even less clear, but the contrast between the high levels in the soils and vegetation and the low levels in the rocks suggest a faunal source. It is interesting to note that the major sources of the principal nutrient elements are complementary --sodium and magnesium have a largely marine origin, potassium and some of the calcium come from the rocks while the fauna provide phosphorus and nitrogen.

On the bases of wind direction, similar altitude, insulation from wind and similar rock composition, we see no obvious explanation for the different levels of these elements between the lakes. In fact, nitrogen and chloride are essentially absent from the rocks. However, the proximity of "Humble Lake" to a large penguin rookery and the greater abundance of other birds on Humble Island suggest that chemical-enrichment of "Humble Lake" may have been caused directly by runoff from bird waste products. The data of Allen, et. al., (1967) suggest also this source of nutrients for lakes in the Cape Royds area of Antarctica.

They report findings by which, in particular, phosphorus (75%) and nitrogen (71%) are extremely high in the penguin rookeries and the cations moderately so. Their results also confirm ours for Elephant Seal Pool, when they say the seals' wallow grounds contain even higher nitrogen levels together with appreciable amounts of the cations and phosphorus. "Skua Lake" may receive nutrients from bathing Skuas, but this must be slight when compared with the penguins' contribution to "Humble Lake." Uric acid, a chief nitrogenous waste products of birds, is only slightly soluble in cold water (Baldwin, 1959). When penguin guano accumulates during the nine month frozen part of the year, we propose that when the melt occurs, a significant quantity of nitrogen- and phosphorous-containing compounds reach "Humble Lake." The main organic nitrogen source in penguin guano, however, is uric acid--essentially insoluble in water. We propose, therefore, that appreciable uric acid is decomposed _in situ_ by bacteria and/or fungi during the Antarctic summer. A manor decomposition product of uric acid is NH_3, which under alkaline conditions of the guano, enters the atmosphere as NH_3 gas. Winds blowing over "Humble Lake" carry the NH_3 a portion of which is picked up by the slightly acid lake water as NH_4^+. Recall the work of Junge (1954), who showed that atmospheric NH_4^+ was low in areas of low pH soils, and high in areas of high pH soils. Experiments with acid-moistened filter paper confirm that the air above penguin rookeries contain enormous quantities of NH_3 gas. Also a limited amount of data collected during an austral summer 1969-70 visit to the Antarctic (Parker, unpublished) tends to support the NH_3 enrichment theory.

Water flowing over areas of scree and silt, bare of vegetation as at "Skua Lake", according to Heywood (1964), had low concentrations of nitrate and phosphorus unless contaminated by bird droppings, etc. If water flowed through stands of moss, it gained appreciable amounts of nutrient salts. The nitrates and phosphates may be leached out of the underlying plant or be produced by the fungal-bacterial fauna associated with the moss. They may even be extracted from the wind borne sea spray by the moss stands. This no doubt accounts in part for the greater productivity found in Humble waters.

On the basis of the preceding data and discussion, it is concluded that "Humble Lake" is eutrophic during the austral summer, as judged by temperate lake standards of and productivity levels (Hutchinson, 1957 and Reid, 1961). Contrastingly, "Skua Lake" is oligotrophic. On the basis of temperature maxima above 4° C and temporary cooling in summer with frequent mixing, "Humble Lake" fits Yoshimura's (1936) classification as a "subpolar" lake, while "Skua Lake" typlifies a "polar" lake. Comparing these lakes with other studies in Antarctica, "Humble Lake" resembles Goldman's Alga Lake in its biological productivity, while "Skua Lake" approaches the productivity levels reported in numerous ice-covered, melt water ponds of the Cape Royds area of Antarctica (Goldman, et. al., in press). However, nutrients and extractable chlorophyll in both "Humble and Skua Lakes" were orders of magnitude lower than those observed by the author for Alga and "Skua" Lakes in the Cape Royds area. Order of magnitude discrepancies between carbon fixation and both chlorophyll and nutrient levels of these Antarctic lakes cannot be explained on the basis of our use of different primary productivity bottles for in situ ^{14}C measurement. While our ^{14}C fixation values obtained consistently in 250 ml screw-cap pharmaceutical bottles generally are 25-50% higher than those obtained in the more standard 300 ml BOD bottles (Parker and Samsel, unpublished), we have never found order-of-magnitude differences.

The presence of many cosmopolitan genera in Antarctic assemblages near Palmer Station raises the question of how they were introduced into the south polar region. Several means of distribution have been suggested.

(1) Continental association. According to Kuenen (1950), there are several theories to account for the dispersal of plants and animals to (and from) Antarctica; of these, the continental drift hypothesis of Wegener (1924) appears to be the most popular. It postulates the Palezoic existance of Gondwanaland from which, in the early Mesozoic, the continents of the southern hemisphere broke off and drifted apart. Stille (1944) and others deduce from seismic evidence that much of the area between Antarctica and Australia is a slumped continent.
Hedley (1911) and his school beleive in an ancient isthmian link between Australia, Antarctica and South America.
Hedley's thesis is invoked by Du Rietz (1940) and others to explain the bipolar distribution of common plants.

(2) Dispersal by the wind. Allee, et. al., (1950) mention "plankton of the air" consisting of desiccated animals and plants, cysts, eggs, etc., which drift with the air currents, sometimes as high as the stratosphere. Upon falling to earth, they resume normal activity where the environment is favorable.

(3) Distribution by birds. According to Hesse, et. al., (1958), water birds are transportation media for aquatic microorganisms. Not only may biota be carried externally, but cysts and eggs may be eaten and excreted. Eklund (1961) says skuas were often seen to drink at fresh-water ponds. According to Stead (1932), *Cataracta antarctica* (*C. skua lonngergi*) range from New Zealand to Antarctica. It seems logical that all of these theories, especially 2 and 3 could account for the algal genera reported during the study of the areas near Anvers Island.

PART II

LABORATORY ECOSYSTEM STUDIES ON NUTRIENT FACTORS LIMITING PRODUCTIVITY IN ANTARCTIC FRESH WATER SYSTEMS

INTRODUCTION

Because of the vast difference in biological productivity, and by contrast, slight differences in other related parameters, "Skua and Humble Lakes" were chosen to initiate a thorough study of the chemistry and biology of Palmer Station lakes to determine whether "limiting nutrient factors" were important in causing Antarctic lakes to change from a state of oligotrophy to eutrophy. To confirm these observations, an attempt was made to design closed laboratory systems to monitor changes in productivity levels resulting from chemical enrichment of Antarctic waters. The microcosm or micro-community appears to be the only environment in which a reliable check of the total procedure can be made. For this reason, simílated aquatic systems were set up in the laboratory at VPI to ascertain the nutrient factors which may be limiting to Antarctic productivity.

According to Livingstone (1958) temperature within normal limits has less effect on the development of polar phytoplankton studied than does light intensity or chemical nutrient levels. Growth is always favorable to increase in light up to a point. My experiments, thus, were concerned solely with the effect of the chemical composition of the aquatic system, under similar conditions of temperature and illumination, on the productivity of Antarctic algae.

The sensitivity of culture techniques for determining the availability of nutrients for phytoplankton growth has been recognized for many years. Schreiber (1927), working with sea water, Strom (1933) using Schreiber's approach in fresh-water, Chu (1942), Edmondson and Edmondson (1947), Rodhe (1948), Potash (1956) and Provasoli, et. al., (1957), to name a few, have developed and used culture techniques of the type used in this experiment with considerable success.

Phytoplankton population growth has been measured most frequently by direct cell counts (Sterfling, 1949), although light extinction coefficients (Aberg and Rodhe, 1942), chlorophyll (Ryther and Yentsch, 1957), volumetric and gravimetric measurements, as well as the oxygen, CO_2, and pH methods, have been used. The low plankton concentrations encountered in the natural Antarctic waters and in the earlier weeks in the artificial water used as media and similar CO_2 content and saturation of oxygen rendered all these techniques less applicable than the ^{14}C method of Steeman-Nielsen (1955). Therefore, the main productivity experiments in this study involve a comparison of the rate of carbon assimilation in the different nutrient level cultures. The measurement of growth was not as greatly dependent upon a significant increase in cell numbers during the culture periods, as upon an increase in the rate of photosynthetic accumulation of organic carbon which may not be immediately manifest in a numerical increase.

It has been suggested by Talling (1957) that results of culture experiments may not be readily applied to the natural environment because restriction of plankton in a container does not duplicate the natural conditions and may favor the development of atypical forms. To offset this, in addition to using the natural lake plankton, every attempt was made to duplicate the natural lake light and temperature conditions in the experimental cultures. However, to strengthen the findings, tests will be conducted in both "Skua and Humble Lakes" in Antarctica on levels of nutrients found to be limiting in the laboratory. Also, several tests were initiated to determine the effect of size of container and volume on enrichment studies.

MATERIALS AND METHODS

Live communities brought to VPI were grown in enrichment media in a growth chamber at 8-10° C and 500 ft.-c.

from a bank of "long wave length" fluorescent lights.[1] A series of experiments were set up in the laboratory at VPI to determine the nutrient factors which could explain the eutrophication of various lakes in the Palmer Station area. Assimilated aquatic systems comparable to those of "Skua and Humble" Lakes were constructed in the laboratory first from 500 ml flasks and then from 3000 ml wide-mouth beakers, and finally from 5 gallon aquaria. Natural water from "Humble and Skua" Lakes was simılated in the laboratory by adding the major nutrients (Appendix I) and a trace element-vitamin mixture from Goldman, et. al., (in press).

The salts used for the artificial media of "Skua and Humble" water were CP or reagent grade, dissolved in deionized and redistilled water. Since Arnon (1938) found that the trace elements that were necessary for higher plants are apparently present as impurities in these salts in sufficient quantities to permit normal growth, only some trace elements necessary for growth were added as

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[1] For planktonic fresh-water algae, Algeus (1951) states that fluorescent lamps rich in long-wave-length are preferable to the light of the "daylight" type. Lesser differences in the intensity of illumination seem to be of no consequence, according to Algeus (1951).

necessary. All media were autoclaved-sterilized one day before use. Cultures were swirled manually every 24 hours and air bubbled through to insure adequate supply of CO_2.

Solutions of pure chemicals, similar in composition and concentration to those occurring in natural waters, were essential in order to investigate the effect of varying the concentration of a salt, (Chu, 1942). Efforts were therefore especially directed during this work towards preparation of media, which would imitate the two types of natural waters ("Skua and Humble") as closely as possible. Artificial solutions, based on the normal composition of "Skua and Humble" water, were prepared after numerous experiments, so that ultimately the planktonic community from each lake could be successfully grown in the artificial cultures. A continuous-flow device was constructed to permit constant input and output of the nutrients into the experimental vessels. The experimental systems were returned to the growth chamber and kept at 5° C under fluorescent lights at 0.15 langley/min. illumination for 12 hours and .05 langley/min. illumination for 12 hours. After the systems had set for several days, a Hach chemical analysis of various nutrients was run to ascertain the nutrient level of each assimilated lake system. Upon verification that concentration of nutrients found in the Antarctic lakes were the same as those of laboratory systems, pre-cultured, equilibrated communities composed of algae with their associated native bacteria, fungi, and protozoa (Table V), from each Antarctic lake were added to the respective systems.

The biotic communities were allowed to equilibrate and primary productivity ^{14}C measurements were made in situ to ascertain the level of biological productivity found in each of the two systems. Controls and replicas of each system were likewise evaluated. These levels of productivity were then compared with those of the natural respective Antarctic lakes to verify that levels of productivity of natural and assimilated systems of the two environments were respectively similar. Nutrient concentrations were then added, both singularly and compounded, to the laboratory "Skua Lake" microcosm to approach those in "Humble." Sufficient equilibration time was allowed for the algae community to respond to the new concentration for each nutrient addition. Hach analyses of simulated media water and ^{14}C measurements were determined every five days for the duration of the nutrient studies. Productivity values were compared to determine the degree of variation between the enriched "Skua" system with that of "Humble." Once the limiting nutritional factors of the oligotrophic "Skua Lake" had been determined, an attempt was made to

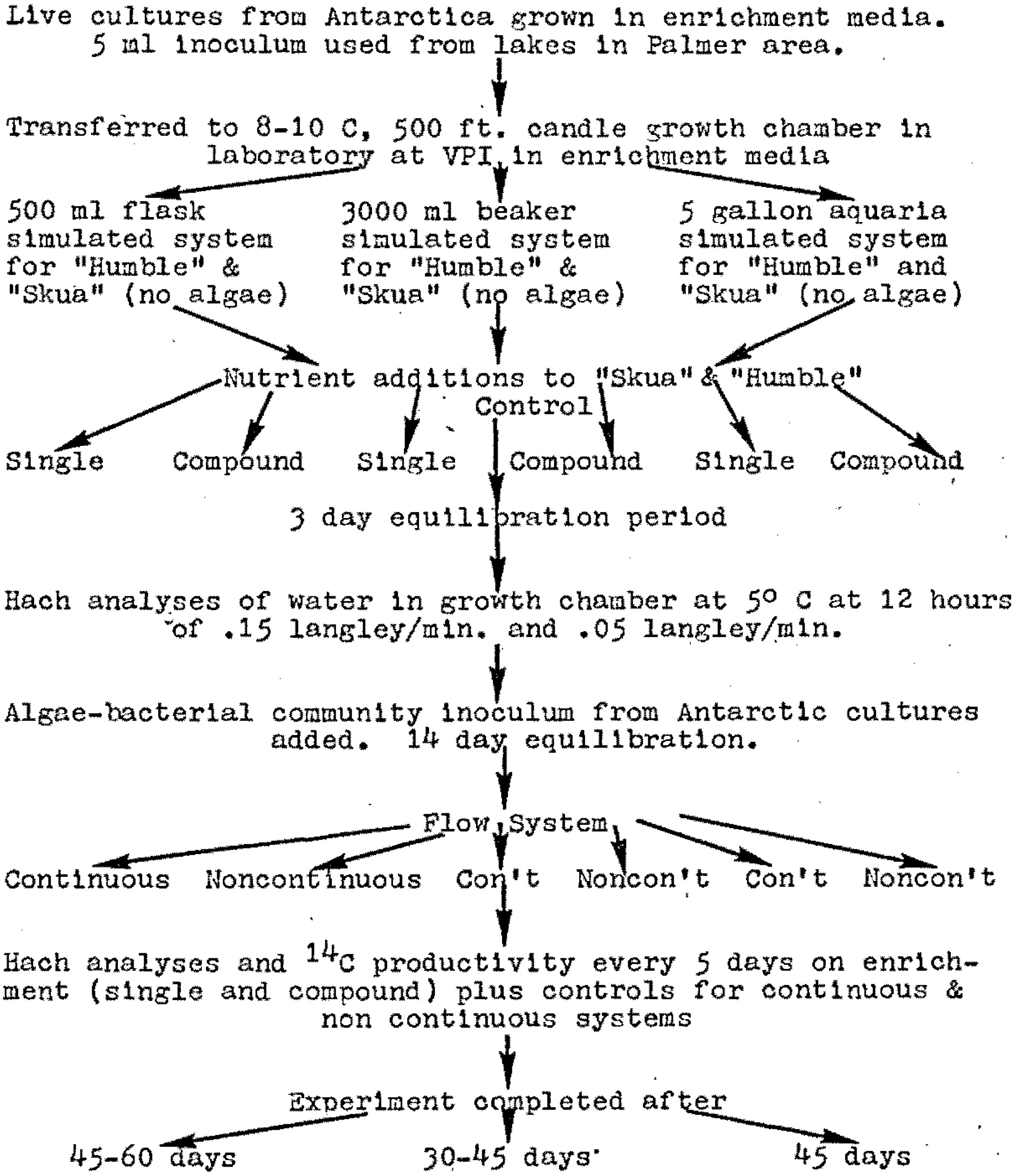
TABLE V

Algal genera reported in field for "Humble and Skua" Lakes during January 10-26 study; genera used for artificial media inoculum; genera present in artificial lakes after 6 week enrichment period

Genus	Skua Antarctica	Skua inoculum	Skua after 6 weeks	Humble Antarctica	Humble inoculum	Humble after 6 weeks
Chlamydomonas	+	+	+	+	+	+
Chlorosarcina				+		
Oscillatoria	+			+	+	+
Chryscoccocus				+		
Dactylococcopsis				+		
Merismopedium				+		
Prasiola				+		
Navicula				+		
Monostroma				+		
Troschicia				+		
Chroococus	+	+	+	+	+	+
Aphanocapsa				+		
Palinellopsis				+		
Phormidium				+		
Scotiella				+		
Ellipsoidion				+		
Trachychloron				+		
Chlorella	+	+	+	+	+	+
Chrysopsis				+	+	+

isolate the nutrient or nutrients which influenced the degree of eutrophication of "Humble Lake." The same procedure was followed in all sets of experiments mentioned above. Figure 3 summarizes the general procedure followed in experiments on laboratory ecosystem studies of nutrient factors.

In addition to the enrichment of "Skua Lake" water to ascertain the nutrients limiting to biological productivity (as compared with eutrophic "Humble Lake" water), several other short-term experiments were initiated to enable a better understanding of the problem of eutrophication in the Antarctic. An experiment was initiated by which the algal community of "Humble Lake" was grown in artificial "Skua Lake" water and vice versa to ascertain the effects of the community structure on the level of nutrient addition to each lake system. Also, a series of experiments were begun to determine the level of Fe^{++} enrichment to both "Skua and Humble", which would be needed to provide an increase in productivity. Data for all experiments, including inoculum size, duration of experiment, replicate numbers, productivity and chemical analysis, etc., can be found under "Results."



Live cultures from Antarctica grown in enrichment media. 5 ml inoculum used from lakes in Palmer area.

Transferred to 8-10 C, 500 ft. candle growth chamber in laboratory at VPI, in enrichment media

500 ml flask simulated system for "Humble" & "Skua" (no algae)

3000 ml beaker simulated system for "Humble" & "Skua" (no algae)

5 gallon aquaria simulated system for "Humble" and "Skua" (no algae)

Nutrient additions to "Skua" & "Humble"

Control

Single

Compound

Single

Compound

Single

Compound

3 day equilibration period

Hach analyses of water in growth chamber at 5° C at 12 hours of .15 langley/min. and .05 langley/min.

Algae-bacterial community inoculum from Antarctic cultures added. 14 day equilibration.

Flow System

Continuous

Noncontinuous

Con't

Noncon't

Con't

Noncon't

Hach analyses and ^{14}C productivity every 5 days on enrichment (single and compound) plus controls for continuous & non continuous systems

Experiment completed after

45-60 days

30-45 days

45 days

FIG. 3. Flow sheet of procedure followed in laboratory ecosystem experiments.

RESULTS

Experiments on Nutrient Factors Limiting Productivity

The algal community of both "Humble and Skua Lakes" was transported to the laboratory at VPI from the Antarctic in media comprised of a similar nutrient composition as that of each natural lake with 5 ml inocula from the respective systems. Upon arrival at VPI, cultures were kept under light and temperature regimes which approached those of their natural habitat. Microscopic identifications were made periodically throughout all experimental runs to determine if community structure of either community ("Humble" or "Skua") changed to any appreciable degree throughout enrichment tests. It is obvious from Table V that the algal genera as well as bacterial community of both lake systems used for the initial inoculum of all experimental enrichment studies were the same as those reported from laboratory culture examinations of the natural "Skua and Humble Lake" biota. Also note that after the 5-7 week nutrient experiment, with the exceptions of some disappearance of sub-dominant species in the "Humble Lake" system, all algal bacterial communities remained the same as the original community found in the Antarctic.

The mere presence of chemical substances in the environment, although recognized as a valuable guide for pure culture studies (Pinter, 1953), does not necessarily prove their biological availability (Potash, 1956). Furthermore, because of the complexity of growth factors in natural waters (Hutchinson, 1944), bioassay may be expected to reflect limiting factors better than chemical analyses of the environment. As described under "Materials and Methods" culture experiments were run to identify the role of various nutrient factors in phytoplankton production in "Humble and Skua Lakes." Although cultures were maintained for longer periods, the effect of specific nutrients on carbon fixation rates was detectable (with ^{14}C) within a few hours after their addition to the media.

Steemann-Nielsen and Al Kholy (1956) have demonstrated that the ^{14}C technique is applicable under conditions of phosphorus and nitrogen deficiency, although the discrepancy between the ^{14}C and O_2 determination of photosynthesis is reduced by nitrogen and phosphorus addition (Ketchum, et. al., 1958). This is an important consideration since some of the measurements in the Antarctic lake studies, as well as in cultures, were made under suboptimal concentrations of these two elements.

Also, much criticism (e.g., Emerson and Green, 1934; Emerson, 1935) has been leveled against measurements of photosynthesis by aquatic plants in unshaken and sealed vessels. Limitations of gaseous diffusion in unstirred media are likely to be minimal for dilute suspensions of unicellular algae, but few tests of this point are recorded in the abundant ecological literature (Talling, 1957; Doty and Oguri, 1958). An experiment was therefore run to test whether rates of photosynthesis differed between previously unshaken suspensions in which cells were allowed to settle and attach at least superficially to vessel walls and suspensions in which shaking by hand every hour during a 4-hour period prior to ^{14}C experiments maintained cells in free circulation. Continuous mixing by currents in the flasks was also tested. The experimental results in Table VI show almost identical rates of carbon fixation in shaken and unshaken flasks, despite considerable settling and adhering of cells to the vessel walls, especially after the latter period of the 12 hour experiment. Nevertheless, during the following experiments, all vessels were shaken twice a day and aerated to insure free circulation.

Similated aquatic ecosystems comparable to those of "Skua and Humble Lakes" were constructed in the laboratory, first from 500 ml flasks, then from 3000 ml wide-mouth beakers and finally from 5 gallon aquaria, to ascertain the effect of various nutrient levels on biological productivity. In addition to these enrichment studies, several

TABLE VI

Mean carbon fixation uptake rate (mg $C/m^3/hr$) for shaken and unshaken vessels and current mixing; 3000 ml beakers

Sample	Unshaken hours				Hand Shaken hours				Current mixing hours			
	0	4	8	12	0	4	8	12	0	4	8	12
"Humble"	8	8.4	8.4	8.2	7.7	8.0	8.0	7.9	8	8.0	7.8	8.0
"Skua"	2	2.0	1.9	2.1	2.0	2.1	2.3	1.9	2	1.7	2.0	2.0

short term experiments were initiated. An experiment was begun by which the algal community of "Humble Lake" was grown in artificial "Skua Lake" water and vice versa to determine the effects of community structure on the level of nutrient addition to each lake system. Also, a series of experiments were begun to determine the level of ferrous iron enrichment to both "Skua and Humble" which would be needed to provide an increase in productivity. The results of the above are reported separately in the following section.

500 ml Flask--Nutrient Level Experiment

Three separate experiments, each with three replicas, were run in 500 ml flasks on March 20-April 30; April 15-June 1, and June 1-July 9. Inoculum size was adjusted to give representative values for both "Humble and Skua Lakes", which ranged between 1 ml to .2 ml for "Skua and Humble", respectively. The number of algae cells found in the inoculum for all experiments were approximately 200-300 cells/ml with five genera in "Humble" and three in the "Skua" inoculum. A two-week equilibration period was used for each system before inoculation occurred and another equilibration period of one week elapsed before nutrient enrichment was begun. Separate enrichment of $PO_4^{\equiv}$-P,

NH_4^+-N, NO_3^--N, Cl^- and $SiO_2^=$ were added to synthetic "Skua" water to approach the nutrient concentration found in "Humble." Nutrients were added both continuously throughout two experiments and initially only in a third experiment to facilitate determination of the degree of nutrient depletion. Also, a combined nutrient level experiment with $PO_4^{\equiv}$ + NO_3^-; $PO_4^{\equiv}$ + Cl^-; $PO_4^{\equiv}$ + $SiO_2^=$; $PO_4^{\equiv}$ + NH_4^+; $PO_4^{\equiv}$ + NO_3^- + NH_4^+; NH_4^+ + Cl^-; and NH_4^+ + $SiO_2^=$ was run.

In all experimental runs, after the equilibration period and before enrichment of synthetic "Skua" water, the observed $^{14}CO_2$ uptake rates in synthetic "Humble" water were 5-10 times higher than that of synthetic "Skua." The addition of NH_4^+-N to "Skua Lake" had the greatest effect of any single nutrient toward increasing the productivity of the algal community in the artificial system with greater than 2 times the productivity over control in all three runs. Besides NH_4^+-N, the addition of $PO_4^{\equiv}$-P to artificial "Skua" water showed the next greatest stimulation with productivity being 1.2-1.5 that of the control. Enrichment of Cl^-, $SiO_2^=$, and NO_3^--N, Fe^{++} resulted in no increase in carbon fixation in any of the experiments. The only "positive" result obtained from the combined nutrient experiments was with the addition of $PO_4^{\equiv}$-P + NH_4^+ to "Skua" media, where levels of productivity approached those of "Humble" in all instances. In one case, the "Skua" enriched water (NH_4^+ + $PO_4^{\equiv}$-P) resulted in exactly the same rate of carbon fixation as did the "Humble" community. Table VII shows the effects of enrichment of "Skua" water with the various single nutrient levels. Note in Table VIII the effects of combined nutrient levels on the algal community of "Skua Lake." It is obvious from Table IX that in all the continuous-flow vessels, nutrient levels remained relatively constant throughout the experiments. However, small changes may have occurred during the intervals between additions of nutrients to the continuous flow vessels.

The nutrient depletion results show $PO_4^{\equiv}$-P values for "Skua" water never drop below the original value of 0.1 ppm, and enrichment values up to 5.1 ppm fell to 0.1 for "Skua" water within 30-45 days. The average rate of $PO_4^{\equiv}$-P consumption for "Skua" water is 0.15 ppm $PO_4^{\equiv}$-P/day. The $PO_4^{\equiv}$-P values for "Humble" water never dropped below .4 ppm and usually not lower than 1.0 ppm over a 60 day period. The average consumption rate for "Humble" water was .11 ppm $PO_4^{\equiv}$/day. Figure 4 summarizes the above $PO_4^{\equiv}$-P depletion values. One can see similar changes in NH_4^+-N levels, with

TABLE VII-A

Mean carbon fixation uptake rate (mg C/m^3/hr) for enrichment with single nutrient level to "Skua" water to approach "Humble" concentration --500 ml flask; trial #1

	days								
Sample	0	5	10	15	20	25	30	35	40
Humble	5.2	64.0	81	90	116	120	---	106	110
Skua Control	.75	8.2	10	16	20	19	---	25	24
Skua + NH$_4^+$-N	1.4	24.1	35	41	59	60	---	51	50
Skua PO$_4^{\equiv}$-P	.81	10.6	17	17	27	24	---	30	27
Skua + NO$_3^-$-N	.72	8.0	11	15	19	17	---	19	18
Skua + SiO$_2^=$	.74	7.8	9	17	23	19	---	24	25
Skua + Cl$^-$	.70	8.4	12	16	20	21	---	20	24

TABLE VII-B

Mean carbon fixation uptake rate (mg C/m^3/hr) for enrichment with single nutrient level to "Skua" water to approach "Humble" concentration--500 ml flask; trial #2

				days					
Sample	0	5	10	15	20	25	30	35	40
Humble	6.1	70.0	91	124	131	125	141	120	120
Skua Control	.90	7.6	12	26	29	29	31	24	28
Skua + NH_4^+-N	1.7	28.0	39	50	34	60	50	47	41
Skua + $PO_4^{\equiv}$-P	1.1	9.0	13	37	35	39	31	28	28
Skua + NO_3^--N	.81	7.0	11	29	24	27	27	20	24
Skua + $SiO_2^=$	.94	8.0	12	25	26	27	26	20	29
Skua + Cl^-	.83	8.0	11	26	28	25	30	25	31

TABLE VII-C

Mean carbon fixation uptake rate (mg C/m^3/hr) for enrichment with single nutrient level to "Skua" water to approach "Humble" concentration--500 ml flask; trial #3

Sample	days 0	5	10	15	20	25	30
Humble	4.1	51.0	84	93	100	104	96
Skua Control	0.40	5.1	9	8	12	12	10
Skua + NH_4^+-N	1.0	19.0	25	24	36	41	29
Skua + $PO_4^{\equiv}$-P	0.7	7.0	12	15	10	20	18
Skua + NO_3^--N	0.43	5.0	8	10	13	12	11
Skua + $SiO_2^{=}$	0.37	6.0	9	9	13	11	12
Skua + Cl^-	0.5	5.0	10	10	10	11	10

TABLE VIII-A

Mean carbon fixation uptake rate (mg C/m^3/hr) for combined enrichment of "Skua" water to approach "Humble" concentration--500 ml flask; trial #1

	days						
Sample	0	5	10	15	20	25	30
Humble	10.0	96	134	150	161	141	151
Skua Control	2.5	19	21	20	27	27	24
Skua + $PO_4^{\equiv}$-P+NO_3^--N	3.0	21	30	32	24	34	31
Skua + $PO_4^{\equiv}$-P+$SiO_2^=$	2.7	20	34	30	24	27	30
Skua + $PO_4^{\equiv}$-P+Cl^-	3.1	24	30	31	30	30	35
Skua + $PO_4^{\equiv}$-P+ NH_3^+-N	5.1	71	108	121	100	120	117
Skua + NH_3^+-N + Cl	4.6	51	80	80	84	71	80
Skua + $PO_4^{\equiv}$-P + NO_3^--N + NH_4^+-N	5.0	61	120	130	100	110	113

TABLE VIII-B

Mean carbon fixation uptake rate (mg $C/m^3/hr$) for combined enrichment of "Skua" water to approach "Humble" concentration--500 ml flask; trial #2

	days						
Sample	0	5	10	15	20	25	30
Humble	9.0	70	150	160	140	120	150
Skua Control	2.1	20	30	34	29	30	26
Skua $+PO_4^{\equiv}-P+NO_3^{-}-N$	2.8	29	30	40	35	36	36
Skua $+PO_4^{\equiv}-P+SiO_2^{=}$	2.8	24	31	38	38	40	37
Skua $+PO_4^{\equiv}-P+Cl^{-}$	2.7	24	34	37	39	27	35
Skua $+PO_4^{\equiv}-P+NH_4^{+}-N$	3.1	55	91	130	140	105	100
Skua $+NH_4^{+}-N+Cl^{-}$	5.0	41	80	75	91	100	82
Skua $+PO_4^{\equiv}-P+NO_3^{-}-N$ $+NH_4^{+}-N$	6.4	70	81	115	135	100	120

TABLE VIII-C

Mean carbon fixation uptake rate (mg $C/m^3/hr$) for combined enrichment of "Skua" water to approach "Humble" concentration--500 ml flask; trial #3

Sample	0	5	10	15	20	25	30
Humble	11.0	90	145	161	120	140	160
Skua Control	3.0	20	30	34	27	31	35
Skua + $PO_4^{\equiv}$-P + NO_3^--N	3.6	24	34	35	30	37	38
Skua + $PO_4^{\equiv}$-P + $SiO_2^{=}$	3.4	26	36	39	30	36	36
Skua + $PO_4^{\equiv}$-P + Cl^-	3.0	29	35	37	34	30	36
Skua + $PO_4^{\equiv}$-P+NH_4^+-N	5.4	80	110	150	118	120	120
Skua + NH_4^+-N + Cl^-	4.4	50	70	90	110	100	108
Skua + $PO_4^{\equiv}$-P + NO_3^--N + NH_4^+-N	4.5	60	82	100	100	104	98

TABLE IX-A

Mean nutrient concentration levels of "Skua" and "Humble" media in continuous flow 500 ml flasks; trial #1

	days						
Sample	0	5	10	15	20	25	30
Humble							
$PO_4^{\equiv}$-P	1.7	1.6	1.8	1.7	1.5	1.7	1.5
NH_4^{+}-N	2.5	2.5	2.3	2.4	2.5	2.4	2.6
NO_3^{-}-N	1.75	1.6	1.8	1.7	1.7	1.5	1.8
$SiO_2^{=}$	1.5	1.4	1.5	1.6	1.5	1.6	1.4
Cl^{-}	40.0	38.0	35.0	42.0	40.0	45.0	40.0
Fe^{++}	0.02	0.02	0.01	0.03	0.02	0.02	0.02
pH	6.3	6.35	6.4	6.25	6.3	6.4	6.3
Skua Control							
$PO_4^{\equiv}$-P	0.03	0.03	0.025	0.04	0.03	0.025	0.03
NH_4^{+}-N	0.1	0.1	0.08	0.08	0.1	0.12	0.14
NO_3^{-}-N	1.0	1.0	1.25	1.0	1.0	1.1	1.0
$SiO_2^{=}$	1.0	1.0	1.0	1.0	1.0	1.0	1.1
Cl^{-}	8.0	7.0	9.0	8.0	7.0	8.0	8.0
Fe^{++}	0.02	0.02	0.02	0.01	0.03	0.02	0.02
pH	6.3	6.3	6.3	6.3	6.3	6.35	6.3
Skua + $PO_4^{\equiv}$-P							
$PO_4^{\equiv}$-P	1.7	1.6	1.7	1.7	1.7	1.8	1.7
Skua + NH_4^{+}-N							
$PO_4^{\equiv}$-P	1.7	1.6	1.7	1.7	1.8	1.7	1.7
Skua + NH_4^{+}-N							
NH_4^{+}-N	2.5	2.4	2.4	2.4	2.6	2.5	2.4
Skua + Cl^{-}							
Cl^{-}	40.0	38.0	40.0	42.0	45.0	45.0	38.0
Skua + $SiO_2^{=}$							
$SiO_2^{=}$	1.5	1.5	1.5	1.5	1.5	1.5	1.5

TABLE IX-B

Mean nutrient concentration levels of "Skua" and "Humble" media in continuous flow 500 ml flasks; trial #2

				days			
Sample	0	5	10	15	20	25	30
"Humble"							
$PO_4^{\equiv}$-P	1.7	1.8	1.7	1.7	1.6	1.5	1.7
NH_4^+-N	2.5	2.4	2.4	2.4	2.4	2.6	2.5
NO_3^--N	1.75	1.8	1.5	1.6	1.6	1.9	1.8
$SiO_2^=$	1.5	1.4	1.4	1.6	1.5	1.5	1.4
Cl^-	40.0	30.0	41.0	38.0	38.0	40.0	40.0
Fe^{++}	0.02	0.02	0.02	0.02	0.02	0.04	0.02
pH	6.3	6.5	6.3	6.3	6.4	6.3	6.4
"Skua" Control							
$PO_4^{\equiv}$-P	0.03	0.03	0.03	0.02	0.01	0.03	0.03
NH_4^+-N	0.1	0.09	0.12	0.08	0.07	0.1	0.1
NO_3^--N	1.0	1.0	1.1	1.2	1.0	1.0	0.9
$SiO_2^=$	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Cl^-	8.0	7.0	6.0	9.0	10.0	9.0	8.0
Fe^{++}	0.02	0.02	0.02	0.02	0.02	0.01	0.03
pH	6.3	6.3	6.4	6.2	6.3	6.3	6.3
"Skua" + $PO_4^{\equiv}$-P							
$PO_4^{\equiv}$-P	1.7	1.6	1.8	1.9	1.6	1.7	1.7
"Skua" + NH_4^+-N							
NH_4^+-N	2.5	2.4	2.4	2.4	2.4	2.6	2.5
"Skua" + Cl^-							
Cl^-	40.0	35.0	45.0	38.0	40.0	40.0	41.0
"Skua" + $SiO_2^=$							
$SiO_2^=$	1.5	1.6	1.5	1.5	1.5	1.5	1.5

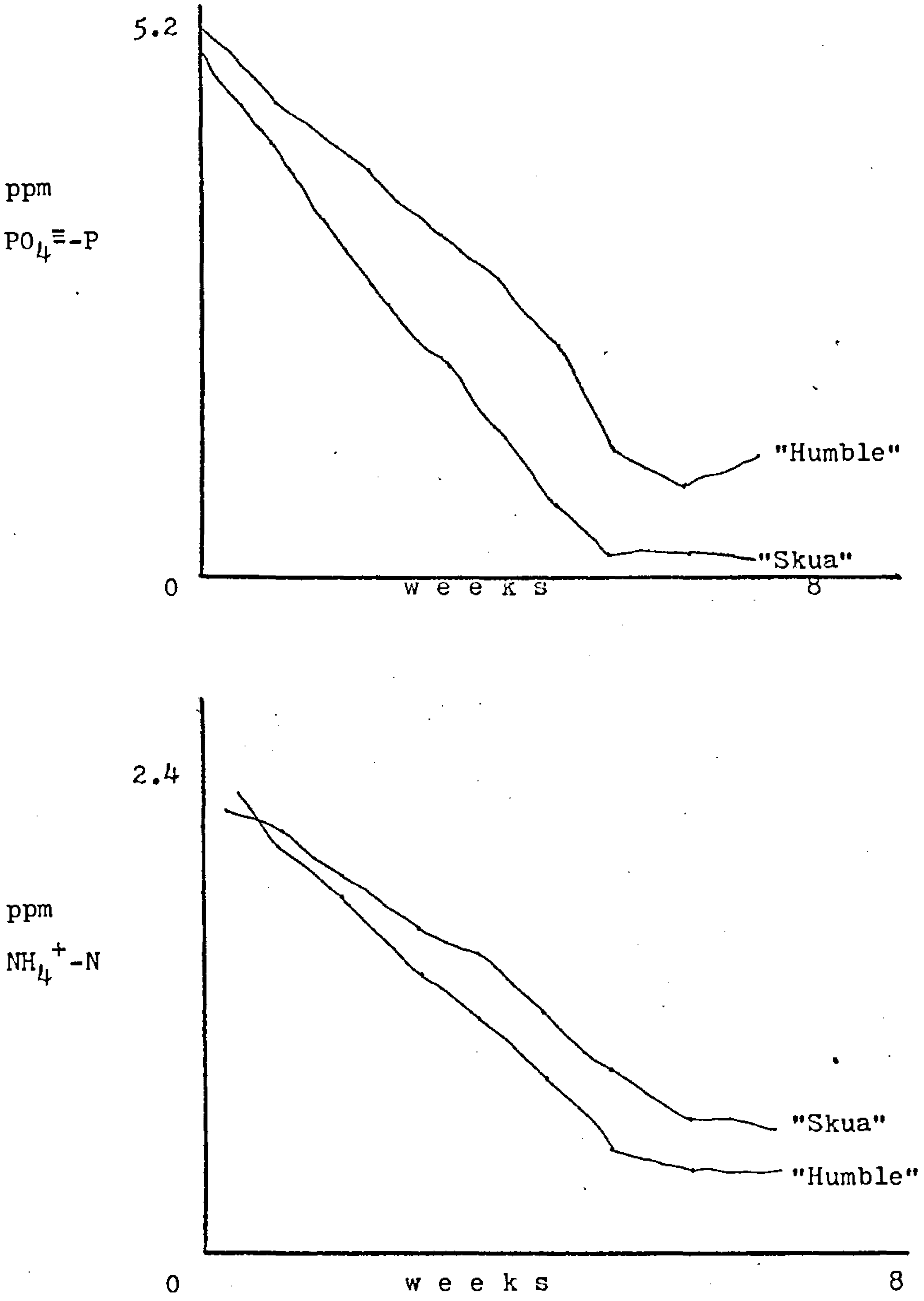


FIG. 4. Mean $PO_4^{\equiv}$-P and NH_4^+-N consumption for "Skua" and "Humble" media; 500 ml flask and 3000 ml beaker

the exception that levels of this nutrient remain higher in "Skua" water after enrichment than in natural "Humble" water over the same period (Fig. 5). Average NH_4^+-N consumption for the "Humble" system was .05 ppm NH_4^+/day, while "Skua" consumed less than .04 ppm NH_4^+/day in "Humble" and .012 ppm NO_3^-/day in "Skua." Likewise, Fe^{++} values for consumption were almost nil with rates of .00012 ppm Fe^{++}/day in "Humble" water and .0002 ppm Fe^{++}/day reported in "Skua" (Fig. 5). $SiO_2^=$ and Cl^- were not consumed at all in any of the depletion experiments. Table X shows carbon fixation rates for the nutrient depletion experiment for "Humble and Skua" waters. Productivity bottles used in all carbon uptake experiments were of the same size (70 ml) to facilitate in situ measurements.

3000 ml Beaker--Nutrient Level Experiment

Three separate experiments, with three replicas, were run in 3000 ml wide-mouth beakers on March 1-April 22, April 1-June 1, and June 1-July 9. The inoculum size was 2 ml for "Skua" and .4 ml for "Humble." The same equilibration periods were used as those for the 500 ml flask experiments. No obvious differences appeared in either the single nutrient depletion experiment between the two different size experimental vessels. Carbon fixation

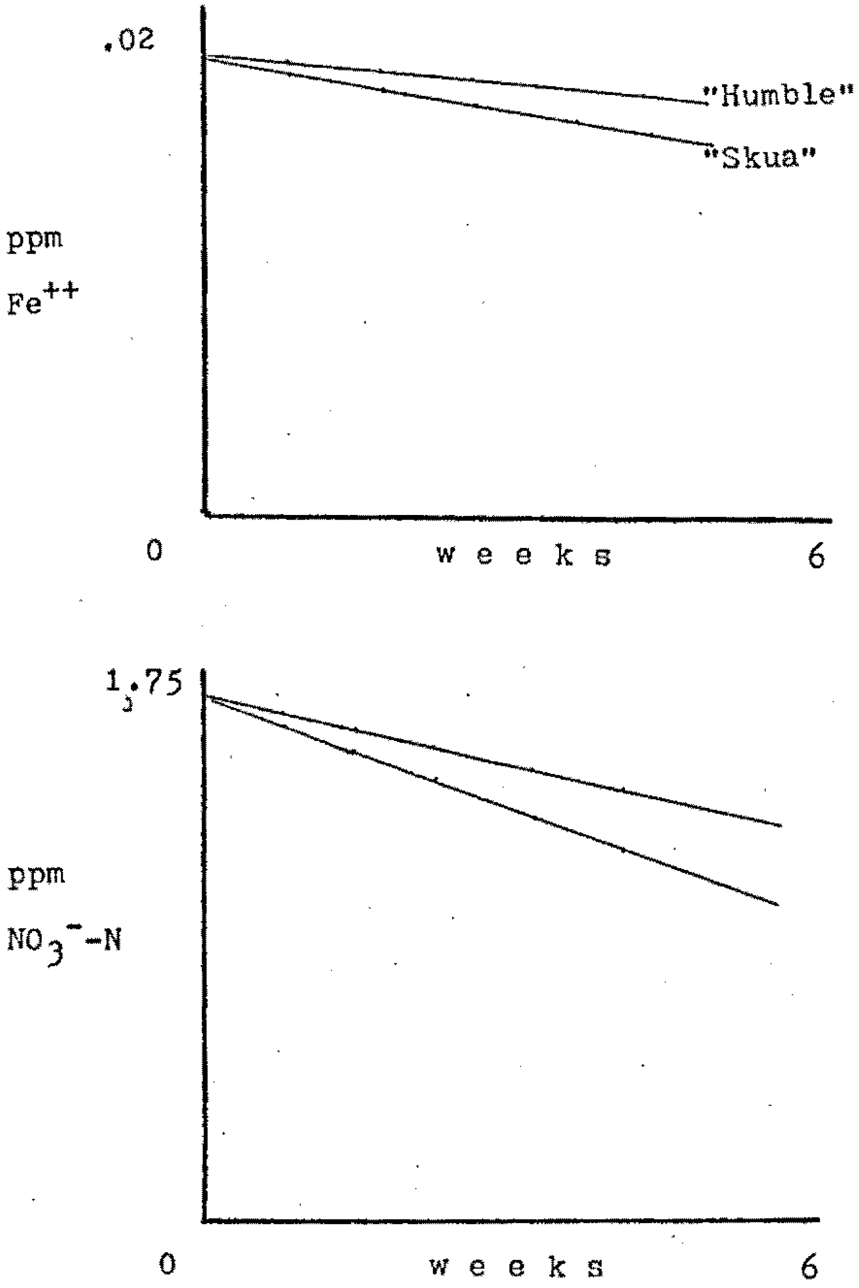


FIG. 5. Mean consumption of Fe^{++} and NO_3^--N for "Humble" and "Skua" media--500 ml flask and 5000 ml beakers

TABLE X-A

Mean carbon fixation uptake rate (mg C/m^3/hr) for nutrient depletion of "Skua" and "Humble" waters--500 ml flask; trial #1

	days							
Sample	0	5	10	15	20	25	30	35
"Humble"	6.1	40.0	51.0	81.0	86.0	80.0	74.0	60.0
"Skua" Control	1.4	15.0	32.0	45.0	47.0	39.0	37.0	30.0
"Skua" + NH_4^+-N	3.8	26.0	45.0	60.0	54.0	69.0	60.0	49.0
"Skua" + $PO_4^{\equiv}$-P	2.4	12.0	37.0	51.0	46.0	45.0	41.0	39.0
"Skua" + $SiO_2^{=}$	1.6	10.0	30.0	40.0	45.0	40.0	27.0	30.0
"Skua" + Cl^-	1.4	15.0	29.0	42.0	49.0	40.0	36.0	37.0
"Skua" + NO_3^--N	1.5	18.0	31.0	48.0	40.0	47.0	41.0	32.0

TABLE X-B

Mean carbon fixation uptake rate (mg C/m^3/hr) for nutrient depletion of "Skua" and "Humble" water--500 ml flask; trial #2

					days			
Sample	0	5	10	15	20	25	30	35
"Humble"	1.8	7.0	28.0	91.0	84.0	59.0		
"Skua" Control	0.9	2.1	7.0	40.0	27.0	29.0		
"Skua" + NH_4^+-N	1.2	4.0	17.0	60.0	51.0	45.0		
"Skua" + $PO_4^{\equiv}$-P	0.94	2.0	12.0	47.0	31.0	27.0		
"Skua" + $SiO_2^{=}$	0.8	2.6	8.0	30.0	29.0	27.0		
"Skua" + Cl^-	0.85	1.8	9.0	36.0	31.0	29.0		
"Skua" + NO_3^--N	0.0	2.1	8.0	41.0	29.0	20.0		

rates were usually 2-4 times higher in the 3000 ml beakers than the 500 ml flask; however, the inoculum size was at least this amount greater in the larger vessels to compensate for the larger volume. Productivity levels before enrichment were 3-7 times higher in "Humble" media than in "Skua." As in the 500 ml flask experiments, NH_4^+-N showed the greatest stimulatory effect with increases as high as eight times over the control vessel (no enrichment). $PO_4^{\equiv}$-P showed some stimulation with values as high as two times over control. It is interesting to note that the response to enrichment seemed somewhat quicker in the larger 3000 ml beakers than in the 500 ml flasks. Again, $SiO_2^{=}$, NO_3^--N, Cl^-, and even increase in pH had no effect on productivity in the "Skua" enrichments. Table XI summarizes the effects of single nutrient additions to "Skua" media. Note in Table XII that the effects of combined nutrient additions (the same used in the 500 ml flask experiment) were almost identical to the values reported from those of the smaller vessels, adjusted for inoculum size. Again, it is obvious that the $PO_4^{\equiv}$-P + NH_4^+-N enrichment produced productivity values in close accord with those of the "Humble Lake" standard. The chemical nutrient levels in the continuous-flow vessels were identical to those of the 500 ml flask run (Table IX), and likewise,

TABLE XI-A

Mean carbon fixation uptake rate (mg C/m^3/hr) for enrichment with single nutrient level to "Skua" water to approach "Humble" concentration--3000 ml beakers; trial #1

Sample	0	5	10	15	20	25	30	35	40	45
"Humble"	6.0	74	200	304	400	400	390	405	400	400
"Skua" Control	1.0	10	26	30	34	39	29	34	29	39
"Skua" + NH_4^+-N	3.0	41	120	200	180	190	200	200	220	175
"Skua" + $PO_4^{\equiv}$-P	1.6	14	40	60	55	60	60	71	54	60
"Skua" + NO_3^--N	1.0	9	24	34	30	34	29	30	38	30
"Skua" + $SiO_2^=$	0.9	8	27	30	30	31	27	24	30	27
"Skua" + high pH	1.0	10	25	40	31	30	27	28	40	33

TABLE XI-B

Mean carbon fixation uptake rate (mg C/m^3/hr) for enrichment with single nutrient level to "Skua" water to approach "Humble" concentration--3000 ml beakers; trial #2

	days									
Sample	0	5	10	15	20	25	30	34	40	45
"Humble"	10	102	260	308	450	400	421			
"Skua" Control	2	12	36	45	42	40	37			
"Skua" + NH_4^+-N	3	50	160	190	200	200	175			
"Skua" + $PO_4^=$-P	2	20	60	70	65	70	80			
"Skua" + NO_3^--N	1.6	15	30	41	50	40	35			
"Skua" + $SiO_2^=$	2	13	30	40	37	26	41			
"Skua" + Cl^-	1	20	40	50	37	31	40			
"Skua" + high pH	2	19	45	30	34	36	41			

TABLE XI-C

Mean carbon fixation uptake rate (mg $C/m^3/hr$) for enrichment with single nutrient level to "Skua" water to approach "Humble" concentration--3000 ml beaker; trial #3

						days				
Sample	0	5	10	15	20	25	30	35	40	45
"Humble"	12	100	190	340	400	410	360			
"Skua" Control	4	20	30	41	50	45	50			
"Skua" + NH_4^+-N	6	41	100	141	170	150	150			
"Skua" + $PO_4^{\equiv}$-P	3	10	50	81	70	75	69			
"Skua" + NO_3^--N	4	20	40	50	40	41	39			
"Skua" + $SiO_2^{=}$	3	12	50	40	40	45	41			
"Skua" + Cl^-	3.1	15	40	50	35	41	39			
"Skua" + high pH	3	17	35	40	31	45	41			

TABLE XII-A

Mean carbon fixation uptake rate (mg C/m^3/hr) for combined enrichment of "Skua" water to approach "Humble" concentration--3000 ml beaker; trial #1

	days							
Sample	0	5	10	15	20	25	30	35
"Humble"	7	80	160	270	410	420	400	405
"Skua" Control	1	8	32	59	71	63	70	65
"Skua" + $PO_4^{=}$-P + NO_3^{-}-N	3	20	49	81	90	76	84	80
"Skua" + $PO_4^{\equiv}$-P+$SiO_2^{=}$	3	17	50	70	81	64	90	78
"Skua" + $PO_4^{\equiv}$-P+Cl^{-}	2	15	41	62	90	90	84	80
"Skua" + $PO_4^{\equiv}$-P+NH_4^{+}-N	5	51	110	210	319	376	294	358
"Skua" + NH_4^{+}-N+Cl^{-}	4	41	81	97	114	174	161	172
"Skua" + NH_4^{+}-N + $SiO_2^{=}$	4	60	72	100	119	181	174	168
"Skua"+$PO_4^{\equiv}$-P NO_3^{-}-N+NH_4^{+}-N	5	49	137	200	227	184	261	200

TABLE XII-B

Mean carbon fixation uptake rate (mg $C/m^3/hr$) for combined enrichment of "Skua" water to approach "Humble" concentration--3000 ml beaker; trial #2

				days			
Sample	0	5	10	15	20	25	30
"Humble"	10	90	190	294	460	417	450
"Skua" Control	3	15	48	84	90	86	97
"Skua" + $PO_4^{\equiv}$-P + NO_3^--N	5	30	69	100	114	95	112
"Skua" + $PO_4^{\equiv}$-P + $SiO_2^=$	5	27	70	91	94	86	90
"Skua" + $PO_4^{\equiv}$-P + Cl^-	4	23	87	100	100	94	108
"Skua" + $PO_4^{\equiv}$-P + NH_4^+-N	8	70	187	276	410	319	384
"Skua + NH_4^+-N + Cl^-	6	50	164	215	370	294	318
"Skua" + NH_4^+-N + SiO_2	6	41	117	200	304	306	300
"Skua" + $PO_4^{\equiv}$-P + NO_3^--N + NH_4^+-N	7	58	129	197	291	300	300

nutrient depletion values for NH_4^+-N, $PO_4^{\equiv}$-P, NO_3^--N and Fe^{++} were similar to those of the smaller vessel size (Fig. 4, 5). In the 3000 ml beaker experiment, the productivity in control "Skua" was at least 10 times lower than that for "Humble." Replicas showed less than 15% variation between 500 ml flask and 3000 ml beakers for both nutrient level determinations and rates of carbon fixation.

5 Gallon Aquaria--Nutrient Level Experiment

One experiment, with replicas, was run September 20-November 1, in 5 gallon continuous-flow aquaria. Only NH_4^+-N, $PO_4^{\equiv}$-P separately and combined were used to enrich the "Skua" water. Similar equilibration times and inoculum ratios were employed; 10 ml inoculum for "Skua" and 1 ml for "Humble." No tests were made on depletion rates, as they remained the same during the past experiments in various size vessels.

As in the previous experiments (500 ml and 3000 ml vessels) productivity as observed $^{14}CO_2$ uptake was several times higher in the "Humble Island Lake" synthetic water than that of the "Skua Lake" media control samples. Note in Table XIII that the greatest increase in productivity occurred with enrichments of NH_4^+-N both separately

TABLE XIII

Mean carbon fixation uptake rate (mg C/m^3/hr) for enrichment with single and combined nutrient levels to "Skua" water to approach "Humble" concentration --5 gallon aquaria

					days				
Sample	0	5	10	15	20	25	30	35	40
"Humble"	7.8	9.2	18.0	24.0	29	37	41	56	60
"Skua" Control	0.9	1.6	2.7	4.1	6	9	11	12	14
"Skua" + NH_4^+-N	3.6	6.0	8.1	14.6	19	26	33	36	51
"Skua" + $PO_4^{\equiv}$-P	1.1	2.0	3.6	5.0	9	11	10	17	19
"Skua" + NH_4^+-N + $PO_4^{\equiv}$-P	5.0	6.0	11.0	20.0	27	34	34	46	57

and combined with $PO_4^{\equiv}$-P. Additions of NH_4^+-N separately increased ^{14}C uptake rates 3-4 times over control "Skua" water. $PO_4^{\equiv}$-P additions to the synthetic "Skua Lake" media increased productivity 1.3 times that of the control "Skua" system. Enrichment of both NH_4^+-N and $PO_4^{\equiv}$-P to the artificial "Skua" water in the 5 gallon aquaria came within 15% of equaling the rate of carbon fixation in the control "Humble Lake" system. Uptake rates as mg $C/m^3/hr$ were somewhat lower in the larger volume 5 gallon aquaria vessels than those reported for both the 500 ml flasks and the 300 ml beakers (Table XIII). However, if the 45 day experiment had been allowed to run for a longer period of time, the ^{14}C fixation rate values would no doubt be equal or higher than those reported in the smaller container experiments. It is obvious from Table XIII that fixation rates did not reach a peak and level off as seen in the previous experiments. Therefore, it seems apparent that the algae-bacteria community in this experiment had not yet reached equilibrium with contained size and volume as noted in the 500 ml and 3000 ml experiments. Also, it can be noted from Table XIII that increases in ^{14}C uptake were not as rapid in the larger 5 gallon vessels than those for either the 500 ml or 3000 ml containers.

TABLE XIV

Mean carbon fixation uptake rate (mg C/m^3/hr) for "Humble" algal community in "Skua" water and "Skua" algal community in "Humble" water --3000 ml beaker

Sample	days 0	5	10	15	20	25	30
"Humble" Control	10.0	119	308	482	319	341	318
"Skua" Control	2.4	37	84	139	100	92	102
"Humble" algae in "Skua" water	1.9	29	71	128	108	85	100
"Skua" algae in "Humble" water	6.0	71	267	390	300	264	290

Community Structure Experiments

"Skua" algae with the same inoculum size as in the previous 3000 ml beaker experiment were grown in synthetic "Humble" water in 3000 ml beakers. In contrast, "Humble" algae of similar inoculum size as previous experiments were grown in artificial "Skua" media. Similar equilibration periods were used. All vessels were under continuous flow regime to ensure constant nutrient levels approaching those of the natural Antarctic systems. Immediately after the equilibration period, the "Skua" algae-"Humble" water community increased to 3 times the productivity of the "Humble" algae-"Skua" water community and after the 5 week experimental run, the carbon fixation rate of the "Skua" algae-"Humble" water community was almost the same as the "Humble" algae-control water system. Replicate samples showed almost no variation with differences of less than 4% between samples, Table XIV.

Fe^{++} Enrichment of "Humble and Skua" Media

Fe^{++} enrichments to 0.1 and 1.0 ppm were added to both "Skua and Humble" water for a 30 day test. The containers used were 500 ml flasks and 3000 ml beakers. Inoculum size and equilibration periods were consistent with previous experiments. Controls and replicas were used.

TABLE XV-A

Mean carbon fixation uptake rate (mg C/m^3/hr) for "Humble" and "Skua" systems with Fe^{++} enrichments of 0.1 and 1.0 ppm--3000 ml beakers; 0.1 ppm Fe^{++}

				days			
Sample	0	5	10	15	20	25	30
"Humble" Control	8.0	90	200	319	340	297	300
"Humble" + Fe^{++}	7.0	100	196	341	390	300	281
"Skua" Control	1.0	14	41	78	100	92	90
"Skua" + Fe^{++}	1.2	10	39	91	112	84	91

TABLE XV-B

Mean carbon fixation uptake rate (mg C/m^3/hr) for "Humble" and "Skua" systems with Fe^{++} enrichments of 0.1 and 1.0 ppm--3000 ml beakers; 1.0 ppm Fe^{++}

Sample	0	5	10	15	20	25	30
"Humble" Control	12.0	114	208	370	410	400	398
"Humble" + Fe^{++}	13.0	150	190	318	400	390	410
"Skua" Control	1.0	14	41	78	100	92	90
"Skua" + Fe^{++}	1.2	10	39	91	112	84	91

The enrichment of both systems to 0.1 ppm after 30 days showed no stimulation in either "Humble or Skua", and with the 1.0 ppm enrichment, there was no increase in the "Humble" system and a decrease over control in the "Skua" media, (Table XV).

DISCUSSION

Experiments which combine both laboratory and field exposures have relevance for the various recent attempts to use laboratory data for extending phytosynthetic productivity in nature (Ryther, 1956; Ryther and Yentsch, 1957; Rodhe, Vollenweider and Nauwerck, 1958; Cushing, 1958). A principal difficulty here is the comparison of light intensities measured in the two situations, particularly in view of the progressive spectral modification of underwater light with depth, which cannot be reproduced by a single color filter as used by Cushing (1953, 1958). A full comparison would require evaluation of the effects of differing qualities of vector and spectral distribution of radiation in laboratory and in the lake, the latter considered in relation to the action-spectrum of photosynthesis. The present assessment of effective light intensities, by the total energy flux of photosynthetically active radiation (Talling, 1960) is only an approximation but has value for interpreting field experiments under different conditions.

Based on present knowledge, field experiments involving exposures <u>in situ</u> still provide the most direct estimation of photosynthetic productivity by natural populations of phytoplankton (Talling, 1960). With suitable design, they can also allow the observed behavior to be interpreted in terms of limited number of variables, from which photosynthetic behavior in other field situations can be estimated (Manning and Juday, 1941; Edmondson, 1956; Talling, 1957). The application of laboratory measurements involves still wider extrapolation, but has been used in recent work with ^{14}C, in view of the saving of time and greater ease of measurement. Nevertheless, the significance of the measurements are often uncertain, partly on purely physiological grounds such as the unknown effects of temperature and the incomplete attainment of light, saturation, and partly from uncertainties from the wide-spread applications of formulae (e.g., those of Steeman-Nielsen, 1952; Ryther, 1956; Ryther and Yentsch, 1957) without sufficient testing of the validity of the basic assumptions for local conditions. Other attempts to simplify field conditions of exposure, using photosynthetic rates measured only near the water surface are still far from satisfactory, in view of the unknown significance of photo-inhibition in such exposures. A need exists for the greater development of analytical studies of photosynthetic productivity by phytoplankton, broadly based upon both laboratory and field experiments and involving short exposures under conditions better defined than in most previous field experiments.

An attempt was made here to point out several of the drawbacks for use of laboratory models in extending field observations of phytoplankton productivity and indeed bioassay using photosynthetic productivity to determine effects of nutrient levels in laboratory systems. An effort was made during this experiment to alleviate as many of these shortcomings as possible. It is my belief that many more intensive investigations should be undertaken to bring laboratory microecosystem studies and field studies into harmony. It was the purpose of this paper to further this goal.

The inhibitory effects of sunlight above 0.1 langley/min. upon photosynthesis in natural water (Talling, 1961) and algal cultures (Sorokin and Krauss, 1958) are well known. This inhibition is expressed as a depression of carbon uptake at the surface, with a subsurface maximum where the light intensity has decreased to an optimal value.

The effect of increased temperature on photosynthetic uptake of carbon by unshielded plankton in inhibiting light is very pronounced with a photosynthetic Q_{10} ($4-{}^{14}C$) between 5 and 9 (Goldman, 1963). The high Q_{10} values indicate the extremely sensitive response of the plankton to heat, as well as tolerance of temperature greatly in excess of environmental ranges. In this way, they do not appear to be "cold adapted" forms with a photosynthetic temperature optimum near that of the environment.

With reference to Goldman, et. al., (1963) our productivity studies were carried out in subsurface waters with light intensity values, in general, below the level influencing photooxidation and inhibition of photosynthetic pigments. Also, an intensive collection of data on light intensities for both lakes during several diurnal studies was undertaken to aid in duplicating the natural illumination conditions of "Skua and Humble Lakes" as nearly as possible in the laboratory systems. The growth chamber used for all nutrient experiments, we feel, approaches more closely the intensity and spectral properties of the natural illumination characterizing the Antarctic environment.

From laboratory microecosystem studies on nutrient levels, NH_4^+-N appears to be a nutrient in critical supply, because additions of NH_4^+-N to "Skua" water produce by far the greatest increases in carbon fixation uptake rates on the algal community. It would seem that $PO_4^{\equiv}$-P, with an inorganic N:P ratio of 55:1 in "Skua Lake", as compared to 4:1 in "Humble Lake", would be the logical candidate for the single most important limiting nutrient reserve between the two systems. Nevertheless, additions of NH_4^+-N to "Skua" water in quantities necessary to approach the levels found in "Humble Lake" showed increases in excess of 3 times the primary productivity of control "Skua" waters (no enrichments). In comparison, the highest increase in fixation of $PO_4^{\equiv}$-P enrichment to "Skua" was less than 1.5 times over the control sample. Likewise, with additions of NH_4^+-N and $PO_4^{\equiv}$-P combined in experimental vessels, productivity rates comparable and in a few cases exactly the same as those found in the naturally eutrophic "Humble Lake" were observed. Additions of Fe++, Cl^-, $SiO_2^=$, NO_3^--N and increase in pH had no stimulating effect whatsoever on the artificial "Skua" water-algal community complex. Also, combined nutrient studies with these nutrients and $PO_4^{\equiv}$-P and NH_4^+-N had no effect on increased primary productivity above that observed for single nutrient additions of either $PO_4^{\equiv}$-P or NH_4^+-N.

It appears that the algal community of "Humble Lake" in the midst of plentiful supplies of both NH_4^+-N and $PO_4^{\equiv}$-P from the nearby faunal and floral associations thrives with a possible luxury consumption of these essential nutrients; and when these supplies are used up; i.e., under nutrient depletion studies, there is little or no reserve of either nutrient and productivity soon falls well below that found under natural Antarctic conditions. The bacterial algal community of "Skua Lake", on the other hand, living in an impoverished area of lower NH_4^+-N and almost nil values of $PO_4^{\equiv}$-P, in comparison with "Humble" values, has built up a reserve system for use of these nutrient levels and under conditions of nutrient depletion, maintain rates of carbon fixation comparable to those of natural conditions for several weeks. Also, under luxury consumption a rapid rate of increase is evident with enrichments of these two nutrients, as well as a reserve mechanism by which $PO_4^{\equiv}$-P and NH_4^+-N are maintained in quantities above natural levels for considerable periods of time with levels never falling below those reported <u>in situ</u> in the Antarctic. An operational system of this type for the biotic community of "Skua Lake, receiving only small quantities of nitrogen and phosphate from the fauna and flora would seem necessary from an evolutionary standpoint for the survival of the ecosystem.

From observations of pools near Palmer Station, which are enriched with nutrients from the biota, it would appear that "Humble Island Lake" is on the upper asymtote side of Lindeman's (1942) oligotrophic-eutrophic curve and with additional enrichments will decrease in species diversity and increase in population numbers of one or two dominate algal genera; i.e., Elephant Seal Pool (Part III). "Skua Lake", on the other hand, would appear to be on the ascending side of the curve and with nutrient additions over time would increase in species diversity and subsequently in total population.

Upon looking at the mineral composition of the intrusive rocks underlying the basins of both "Humble and Skua Lakes", it becomes obvious that a possible explanation for the greater increase in productivity in "Humble Lake" with enrichments of NH_4^+-N for "Skua Lake" can be visualized (see Part I, Table II). Small quantities of $PO_4^=$-containing apitite, etc., are found under both lake basins and through the intensive mechanical weathering processes occurring in the Antarctic and with the cold, slightly acid waters slowly dissolving portions of $PO_4^{\equiv}$-P out into the water, an equal supply of this nutrient could be available to both lakes for a considerable period of time before the invasion of the fauna and flora to the area. Thus, a biological community could have established itself with similar composition, utilizing the small, but possibly adequate amounts of $PO_4^{\equiv}$-P and small amounts of nitrogen (from sea spray, etc.) in both "Humble and Skua Lakes." Eventually, penguins and other birds could have invaded the smaller, more open and easily accessible Humble Island, deposited their guano, providing nutrient additions for the formulation of bryophyte and lichen development; thus enriching the waters of "Humble Lake" and causing a considerable increase in both diversity of organisms and population size. "Skua Lake", however, much less accessible to the sea, with its large glacier and almost constant ice cover, was never colonized by flightless penguins, etc., and thus lacked the higher level of NH_4^+-N from guano deposits, with subsequent lack of bryophyte and abundant lichen development.

These laboratory bioassay studies used to determine levels of nutrients limiting to the primary productivity of the Antarctic Peninsula fresh waters have provided a case which points out that although many limnologists believe that $PO_4^{\equiv}$-P is the ultimate limiting factor for fresh-water phytoplankton productivity, much more attention should be paid to other nutritional constituents, expecially the much overlooked NH_4^+-N component. It is obvious from this study that although addition of $PO_4^{\equiv}$-P to "Skua" water indeed increased the productivity, that NH_4^+-N enrichments play a much greater role in the increased rates of carbon uptake. Thus, one may conclude that extreme caution must be taken before concluding that a certain nutrient is the one that ultimately causes increased productivity for any aquatic microecosystem, whether in the laboratory or in the field.

The data suggest that the levels of Fe^{++}, $SiO_2^{=}$, Cl^-, and NO_3^--N are either sufficiently high in "Skua Lake" so that additions do not cause an increase in productivity or that these are not essential nutrients to the system; and that CO_2, which was kept the same under laboratory conditions plays only a minor role, if any, in the increased productivity of "Humble Island Lake." This would seem likely, as at the lower pH and colder temperature, CO_2 would not be readily kept in solution.

Upon comparison of "dark bottle" respiration of the bacterial flora both in the field at Palmer Station and in experimental microecosystems in the laboratory, there was very little difference in ^{14}C uptake rates between natural algae-bacteria communities and enrichment simulated communities in their respiration rates.

The size of container used for nutrient evaluation studies seems to have no direct effect on the productivity rate of the algal community of either lake. Although greater values (mg $C/m^3/hr$) were found in the larger experimental vessels, there was little difference in carbon uptake rate per unit volume in any of the three containers. There seemed to be a point at which the bacterial-algal community reached a level at which no more increase in carbon fixation rate occurred and was then followed by a gradual leveling off. This, no doubt, was the point at which population size was in proportion with unit volume and no further increase could occur without overcrowding; resulting in death, etc. However, it is this author's belief that for laboratory microecosystem studies of the type described here, containers should be used, if possible, which facilitate the use of formulae designed for determination of mass/unit area measurements; i.e., gms/m^3, etc. Thus, large containers, i.e., cubic meter, made of some inert substance, as teflon for example, should be used to better enable comparisons of field and laboratory studies that make use of bioassay for nutrient studies and related parameters.

PART III

FRESH-WATER ALGAE OF THE ANTARCTIC PENINSULA. PRELIMINARY OBSERVATIONS IN THE PALMER STATION AREA, ANVERS ISLAND

INTRODUCTION

Since the early works of Wildemann (1900), Fritsch (1903), Hariot (1908), Gain (1909), West and West (1911), and the more recent works of Bryant (1945), Holdgate (1964), and Cameron (1966), few systematic, distributional and ecological studies of algae from the Antarctic Peninsula have been reported. This report constitutes the first in a series to survey the fresh-water algae of the Antarctic Peninsula along with select physical, geological, chemical, and biological features associated with their habitats. These studies aim at the long-range goals of understanding dispersal mechanisms, environmental adaptation and evaluation, roles in the food chain, etc., of algae in Antarctica.

Approximately 50 fresh-water habitats were visited during the 1970 austral summer (January 10-26). Of these, 15 sites contained well developed algal communities or algal genera considered to be probably taxonomic and ecologically of interest to the area. These habitats are located in approximate positions on the map (Fig. 6). Seven habitats

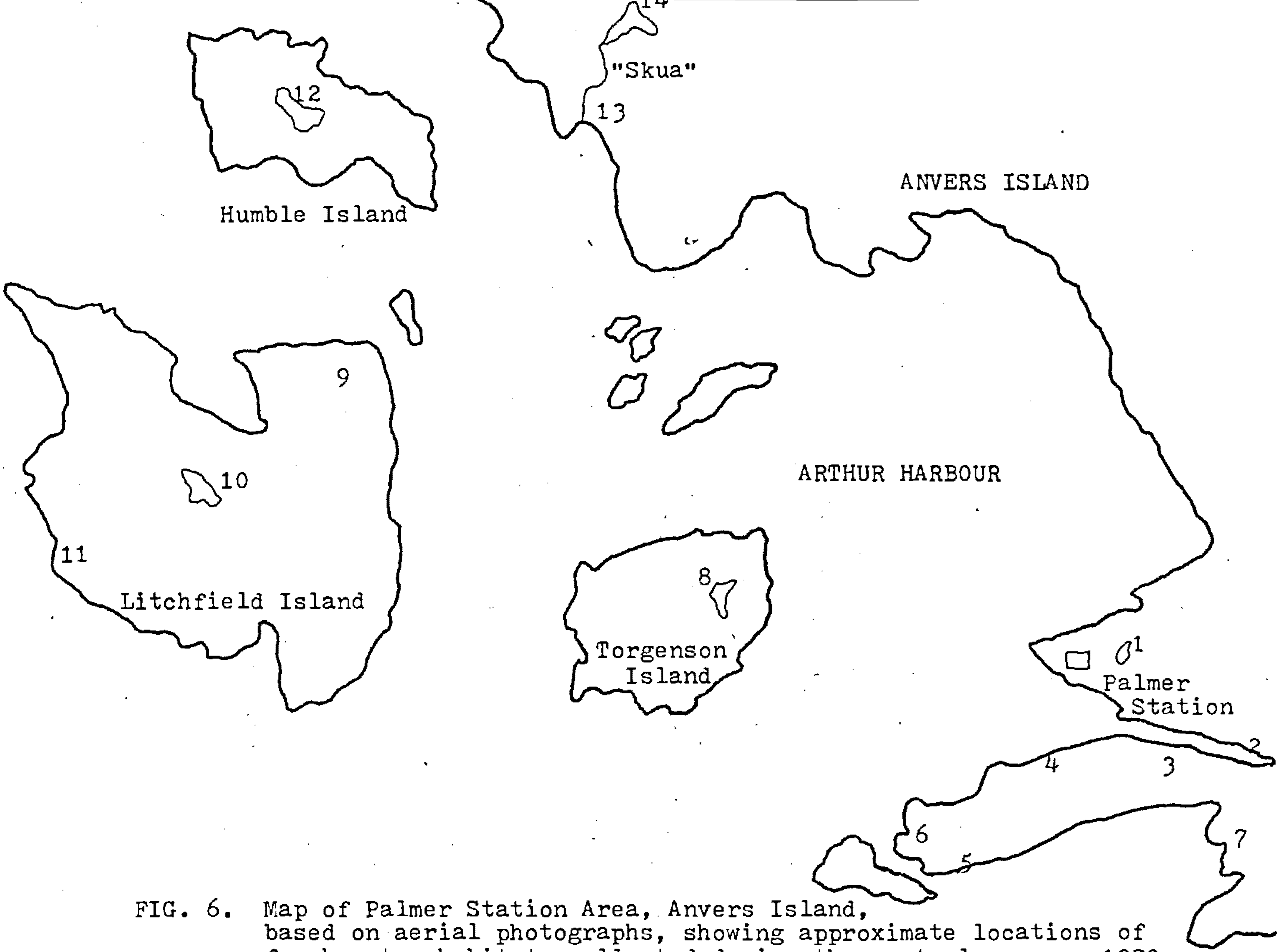


FIG. 6. Map of Palmer Station Area, Anvers Island, based on aerial photographs, showing approximate locations of fresh water habitats collected during the austral summer, 1970

were selected for more detailed study, including physical, geological, and chemical features, on the basis of their size, apparent permanency and/or unusual biological content.

Names for the fresh-water habitats are unofficial, and used here to facilitate discussion. Algal identifications were made jointly with Drs. G. W. Prescott and B. C. Parker.

MATERIALS AND METHODS

Physical, geological, chemical, and biological features examined in the seven more thoroughly studied habitats included the following:

1) Morphometric measurements;

2) Identification of parent rock type composing the lake basin;

3) Analyses of select inorganic ions, dissolved O_2, pH, etc. with Hach chemical "Direct Reading" Portable Engineers laboratory, replicate samples having less than 10% variation;

4) Radiation with a Yellow Springs Instrument Co. model 68 pyrelometer, having 5% precision and ± 0.1 langley$\cdot$min^{-1} accuracy, for both incident and subsurface (20 cm) measurements;

5) Air and water temperatures with a YSI thermister (Model 41) and probe, having ± 0.1° accuracy;

6) Chlorophyll via extraction of 0.22 μ GS millipore membranes, through which water had been filtered, in acetone, and subsequent chlorimetric determination, all according to the SCOR/UNESCO formula and methods of Strickland and Parsons (1968).

7) Primary productivity, using the ^{14}C method described by Steeman-Nielsen (1952) and as modified by Strickland and Parsons (1968), and employing 250 ml screw-cap pharmaceutical bottles which have been found superior in their optical properties to many other types of glass containers (Parker and Samsel, unpublished).

Values here reported for both chlorophyll and carbon fixation are means of duplicate samples having less than 5% variation.

Algae were obtained for direct observation in a Nikon field microscope and on return to the laboratory in a binocular phase microscope via 76 μ pored plankton net towing, scraping of rocks, mud and vegetation sampling. Also, water and plankton net samples were often concentrated in a Foerst continuous flow centrifuge. Following microscopic examination, portions of collections were preserved with 5% formalin. Other portions of collections were inoculated into various media for culturing at ambient temperatures of the Palmer Station area, and subsequently at 8-10° C, continuous cool-white fluorescent lighting of about 500 ft-c. at the Virginia Polytechnic Institute laboratory. Two media were Bozniak's Community Medium (Bozniak, 1969) and Modified Bristol's Solution (Bold, 1942). In addition, several media used possessed nutrients closely matching the concentrations of the specific fresh-water habitats under study. Other media are omitted here, as they did not yield viable algal cultures.

RESULTS

Appendix II summarizes data on algal genera and species near Palmer Station, including those cited by previous investigation and those identified in our fresh collections, live community cultures, and preserved samples.

Original collecting sites are listed. Also, a general habitat description of each location where algae were collected including habitat features are listed.

General Features of Collection Locations

I. CB Pond (1)*

Physical: Located at base of glacier directly behind Palmer Station and adjacent to CB hut. Supplemental summer water supply for the Station. Input from runoff and melt water from glacier constitutes only detected source for this pond. Maximum depth = 1.5 m; maximum length = 21 m; maximum width = 24 meters. Bottom igneous with less than 5 cm of accumulated mud and silt, largely inorganic. Secci disc visibility to maximum depth.

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*Collecting site no., Figure 1

Chemical: (ppm unless stated)

	CB Pond	Stream	Glacial Snow	Mud-Water
pH	6.35	6.6	6.3	6.4
O_2(saturated)	14.0			
Total alk.	15.0	10.0	10.0	10.0
Total hard.	5.0	5.0	5.0	10.0
Calcium hard.	5.0	0.0	0.0	5.0
Chloride	2.5	5.0	5.0	7.5
Fluoride	0.28			
NH_3-N	0.01	0.02	0.04	8.5
NO_3-N	0.095	0.05	0.1	1.0
NO_2-N	0.005	0.0	0.0	0.0
Ortho-PO_4-$P^{\equiv}$	0.01	0.03	0.025	0.06
Total-PO_4-$P^{\equiv}$	0.02	0.07	0.05	0.09
Silica	0.1	0.12	0.31	1.3
Fe^{++}	0.01			
$SO_4^{=}$	2.0			

Additional tests were run on snow melt, stream, and mud water from CB Pond.

Geological: Quartz-diorite = tonalite, less than 5% acid feldspars: biotite, pyroxene. Tonalite-plagioclase less than 5%. $SiO_2^{=}$ greater than 50%. Small amounts of biotite, pyroxene, hornblende, hypersthene containing Fe, Mn, SiO_3, Al, etc.

Biological:

Total Chlorophyll = 26 m-SPU/m^3

Carbon Fixation = 1.2 mg C/m^3/hr

Total organic matter (on combustion) 1.13%

Species Diversity--no algae. Bacteria 70 colonies/plate

II. Frost Pool (2)

Physical: Small pool, near Palmer Station, with rapid inflow from snow melt stream, igneous rock bottom with some sediment, maximum depth 0.6 m; maximum length 7 m; maximum width 4 m. Secci disc visibility to maximum depth.

Chemical:

pH	6.4	Chloride	10.0	Ortho-PO_4-$P^{\equiv}$	0.02
O_2(saturated)	---	Fluoride	15.0	Total-PO_4-$P^{\equiv}$	0.06
Total Alk.	10.0	NH_3-N	0.02	Silica	0.05
Total Hard.	5.0	NO_3-N	1.99	Fe++	0.01
Calcium Hard.	5.0	NO_2-N	0.01	$SO_4^{=}$	2.0

Geological: Same as CB Pond

Biological:

Total Chlorophyll = nil; for benthic algal mats, = 814 m SPU/m^3

Carbon Fixation for benthic algal mats, = 340 mg C/m^3/hr

Species Diversity = No phytoplankton, only several benthic algae

III. Bonaparte Pool #4 (3)

Physical: Small pool in rocks on Bonaparte Point, about 8 m long by 4 m wide with maximum depth of 0.3 m. Received input from precipitation and snow melt; bottom igneous with little accumulation of moss debris and slight addition of Skua excrement. Secci disc visibility to maximum depth.

Chemical:

pH	6.35	Chloride	25.0	Ortho-PO_4-$P^{\equiv}$	0.47
O_2 (saturated)	14.0	Fluoride	0.38	Total-PO_4-$P^{\equiv}$	0.47
Total Alk.	10.0	NH_3-N	0.35	Silica	1.3
Total Hard.	10.0	NO_3^--N	1.8	Fe^{++}	0.0
Calcium Hard.	5.0	NO_2^--N	0.0	$SO_4^=$	2.0

Geological: Tonalite (= quartz diorite); main minerals: SiO_2, greater than 60% less than 5% acid feldspars, some Na plagioclase; less than 1% biotite (Fe^{++}, Mn, SiO_3).

Biological:

Total Chlorophyll = 683 m-SPU/m^3

Carbon Fixation = 3.0 mg C/m^3/hr

Species Diversity = 8 planktonic genera including 6 genera of diatoms

(4,5,6)

In addition to Bonaparte #4, several other small pools, Bonaparte #1, 2, 3, were visited during our short visit to the area. These pools were smaller than Bonaparte #4, with similar geological and chemical parameters. Silica was higher in these small water bodies located on Bonaparte Point, than in any of the other pools visited.

IV. Elephant Seal Pool (7)

Physical: Small "pea soup green" pool in igneous intrusive rock on Bonaparte Point. Size = 3 m wide by 6 m long. Maximum depth 1 m, receiving precipitation and snow melt input with considerable quantities of seal waste. Secci disc visibility less than 10 cm.

Chemical:

pH	8.9	Chloride	117.5	Ortho-PO_4-$P^{\equiv}$	2.0
O_2 (saturated)		Fluoride	0.65	Total-PO_4-$P^{\equiv}$	2.5
Total Alk.	70.0	NH_3-N	3.2	Silica	1.35
Total Hard.	80.0	NO_3^--N	3.8	Fe^{++}	0.0
Calcium Hard.	50.0	NO_2^--N	0.069	$SO_4^{=}$	17.0

Geological: Same as Bonaparte #4

Biological:

Total Chlorophyll = 2,194 m SPU/m^3

Carbon Fixation = 830 mg C/m^3/hr

Species Diversity = 3 planktonic algal genera

Adjacent to Elephant Seal Pool there was a small pocket of blood-red water which received runoff from a nearby elephant seal herd. Collections were made in this area which exhibited nearly the same general features as the adjacent, larger Elephant Seal Pool.

V. Torgenson Island Melt Pool (8)

Physical: Shallow lake system, maximum width 8 m; maximum length 12 m; maximum depth 0.2 m. Located at base of a penguin rookery, with snow melt and precipitation as source of water; considerable penguin excrement and large patches of snow algae on banks. Secci disc visibility to maximum depth. Located on Torgenson Island.

Chemical:

pH	6.25	Chloride	---	Ortho-PO_4-$P^{\equiv}$	7.0
Dissolved O_2 (sat.)	13.0	Fluoride	1.05	Total-PO_4-$P^{\equiv}$	19.0
Total Alk.	80.0	NH_3-N	---	Silica	0.7
Total Hard.	25.0	NO_3-N	3.0	Fe^{++}	0.01
Calcium Hard.	---	NO_2-N	0.11	$SO_4^{=}$	12.0

Geological: Glacial scouring-volcanic, acidic type granite, probably porphyritic tuff = riolite; some Na plagioclase, high in Si, low in Fe. Also, hypersthene, hornblende, magnetite, hematite, illimite.

VI. "Skua Lake" (14)

This lake, the largest of all the water bodies visited, was located about 1.5 miles from the new Palmer Station and directly behind the now unused United Kingdom Base at Norsel Point, on Anvers Island. Located at the base of a large glacier, "Skua Lake" had a maximum depth of over 3 meters, with a mean depth of 1 m and a maximum length and breadth of 95 m and 25 m respectively. Other data on general parameters of this lake can be found in Part I.

Old Palmer Stream was a small channel that directed runoff and overflow from "Skua Lake" toward Arthur Harbor. The chemistry and geology were similar to that of "Skua Lake", with the exception of added nutrients from sea spray, providing a more diverse algal flora to this collection site.

VII. "Humble Lake" (12)

"Humble Lake," located just 1/4 mile from "Skua Lake" on nearby Humble Island, exhibited a rich variety of algal biota in comparison to the oligotrophic "Skua Lake." The maximum depth of "Humble Lake" was less than 0.6 m with maximum length and breadth 25 m and 20 m respectively. Extensive collections were made at this lake located near a large penguin rookery and in the midst of lush bryophyte and lichen vegetation. Secci disc visibility to maximum depth. More details on productivity levels, chemical and geological data can be found in Part I.

(9, 10, 11)

Several small pools located in the midst of shallow rock depressions on Litchfield Island about 2 miles from Palmer Station were visited briefly during our study. Geological and chemical features were similar to the water bodies of Bonaparte Point, including silica values in excess of 1.2 ppm.

CONCLUSIONS

Of the 31 genera and 75 species of algae identified from the Palmer Station area, 45% were placed in the division Chlorophyta, 35% in Cyanophyta, and less than 20% in the division Chrysophyta. There were approximately 17 genera and 41 species not previously reported from the areas near the Antarctic Peninsula. Likewise, there were 14 genera which we failed to find, but had been identified by previous workers in the peninsula area. The majority of all green algae identified were in the genera Chlamydomanas, Prasiola, Chlorella, and Chlorococcum. The genera Oscillatoria and Phormidium comprised over 95% of all algae in the Cyanophyta with several species of diatoms comprising the majority of the Chrysophyta division.

With the exception of 5 species, all algae identified were cosmopolitan and the majority of these could be found widely dispersed throughout the temperate zone. Even though the five species identified are at the present time endemic to the Palmer Station area, there is strong historical evidence that with continued exploration, particular species will be found elsewhere; thus, not being truly endemic.

Another interesting outcome of this work was the identification of several species of desmids in the area.

Only recently have these algae been evidenced in the Antarctic, and for many years phycologists have reported this as one of the few families of algae absent in the Antarctic. Our work supports the few explorers who have reported desmids in this cold habitat.

It appears that because almost all the algae reported were indeed cosmopolitan, one may conclude that Antarctic algae have more than one temperature optima, as reported by Oppenheimer (1959), or that they are merely expressions of ecotype deviations from other species types. Much more work needs to be conducted before we answer these questions satisfactorally and determine the environmental tolerences of these uniquely adapted organisms.

GENERAL CONCLUSIONS AND FUTURE STUDY

In summary, the fresh water lakes of Anvers and Humble Islands, and comparable maritime Antarctic localities derive nutrients from rocks and land drainage, the latter materially affected by input from marine sources. Furthermore, the breeding bird populations contribute phosphate, nitrate, and ammonia directly while wallowing elephant seals play a major part in determining the characteristics of some pools.

The data collected and presented in this paper have considerable significance for understanding the ecology of phytoplankton productivity in the Antarctic environment. Furthermore, lakes such as "Humble" and "Skua" are sufficiently abundant in the Antarctic to provide the variety of fresh water ecosystems required to study the physiological ecology of the remarkedly well-adapted biota.

From laboratory microecosystem studies on nutrient levels, it appears that NH_3-N is the primary cause for many of the natural lakes of the Antarctic Peninsula to change from a state of oligiotrophy to that of eutrophy. Although $PO_4^{\equiv}$-P definitely has a stimulating effect on algal-bacterial fauna of these lakes, it is slight when compared with the NH_3-N stimulation.

Ultimately, the results of all laboratory experiments with ecological objectives should be tested in the field, possibly in small artificially restricted areas (e.g., as in plastic cylinders as we plan to do during the Antarctic summer of 1970-71) of the lake itself. That this bioassay of "Skua and Humble Lake" waters is purely exploratory should be emphasized. Not only is the scope of the work limited, but different results might be expected during different times of the year. Nevertheless, this experiment has elucidated some heretofore unknown aspects of the problem of eutrophication on the Antarctic Peninsula by demonstrating the effects due to natural enrichments of various chemical nutrient levels on the primary productivity of several lakes and pools of the Palmer Station area.

The majority (45%) of the Antarctic algae identified from cultured and preserved field samples were placed in the division chlorophyta, 35% in the cyanophyta and less than 20% of the Antarctic algae were placed in the chrysophyta. At least 90% of all species identified were of cosmopolitan origin, with only five species endemic to the Antarctic Peninsula area. These data enable some understanding of phytoplankton ecology and dispersal in the fresh waters of the Antarctic control areas.

Problems concerning the future study of Antarctic algae can be divided into two classes. First, a systematic investigation and critical appraisal of all the known species based on preserved specimens. Second, surveys of the unexplored regions, both geographically and ecologically.

The coast line of the Antarctic Continent is very extensive and there is much barren land along the coastal plain and in the interior of the continent. Most of this land still remains unexplored biogeographically and ecologically. Islands adjacent to the continent and islands in subantarctic regions strangely enough have not as yet been well investigated. Future studies should concentrate on the regions of Antarctica not yet surveyed for algae. Suitable places for the growth of algae are known; for example, the innumerable pools, ponds, and lakes caused by thawing found by Antarctic explorers. However, collections from these areas are extremely poor and many remain merely a photographic record.

Very little attention has been paid to the ecology and limnology of Antarctic inland waters in the past. It is important to clarify the algal distribution and the changes in composition of the flora with changes of latitude, as mentioned above.

It is particularly important to study the algal flora of the subantarctic islands around Antarctica because these subantarctic islands lie in the path of algal transportation to the Antarctic, from other continents. Detailed surveys of the Palmer Peninsula might be useful in explaining changes in flora composition, because the Palmer Peninsula would be preferable to surveys of the islands lying randomly in the oceans of the subantarctic. Previous studies have been based on preserved materials and older collections.

Studies on the influence of environmental factors on Antarctic algae have hitherto been inadequate, except for the report, by West (1911) on ponds and lakes of Ross Island, and Goldman (1963) on Lake Bonney and Vanda, and Goldman, et. al., (in press) on Algal and "Skua" Lakes at Cape Royds. The daily and monthly variations in temperature and the chemical constituents of water on the whole Antarctic continent are not satisfactorily reported, and they have a direct influence on aquatic plant life. Comparative stidues on the habitats of algae, especially pools, lakes and running water are necessary to help explain the adaptation of algae to the Antarctic environment.

Most biological research in Antarctica is conducted during the period of continuous illumination. The Antarctic winter, with its period of continuous darkness, places severe, but no insolvable limitations on man's ability to conduct field research. Biological studies of the Anvers Island area lakes during the winter have not been pursued and the kinds of biological activities which occur during this period remain enigmatic. If one assumes that "Humble and Skua" algae live autotrophically during the summer, then how do these organisms survive during the long period of continuous darkness and what percentage of these organisms survive heterotrophically? One suggestion is that heterotrophic carbon fixation may explain their survival when photosynthetic carbon reduction is impossible. They might also become encysted and simply remain dormant. The survival of bacteria populations could be easily explained by heterotrophic utilization of organic compounds. Although this question can only be answered by experimentation in the winter, experiments will be conducted during the Antarctic summer of 1971 to ascertain the occurrance of heterotrophic utilization of ^{14}C labeled acetate in "Humble and Skua Lakes." A need exists for more intensive experimentation in an effort to separate and measure bacterial and possible algal heterotrophic activity.

It is likely that aquatic areas around the bases of Antarctica are gradually being polluted by human activity. Vigorous growth of blue-green algae in polluted waters has been observed around some bases. Although an attempt was made in this paper to ascertain several factors which may cause Antarctic lakes to become eutrophicated, much more intense investigations must be undertaken by qualified scientists to combat the ever growing problem of pollution in Antarctica.

APPENDIX I

SALTS USED FOR ARTIFICIAL "SKUA" AND "HUMBLE" MEDIA*

"Humble" Water		"Skua" Water	
Na_2SiO_3	3.05 mg/l	Na_2SiO_3	2.3 mg/l
H_2SO_4	3.47 ml of 1:1000 con.	H_2SO_4	2.5 mg/l
CaCl2	27.7 mg/l	$MgCl_2$	5.2 mg/l
$MgCl_2$	11.1 mg/l	Na_2HPO_4	.14 mg/l
Na_2HPO_4	6.4 mg/l	Na_2CO_3	18.0 mg/l
$KHCO_3$	2.6 mg/l	$FeCl_2$	.417 mg/l
Na_2CO_3	13.45 mg/l	$MnCl_2$	.410 mg/l
$FeCl_2$	.417 mg/l	KCl	2.2 mg/l
MnCl	.410 mg/l	NH_4Cl	.25 mg/l
$NaNO_2$	2.01 mg/l	$CaOH_2$	8.0 mg/l
NH_4NO_3	10.0 mg/l	HCl	1.5 ml of 1:1000 con.
HCl	1.5 ml of 1:1000 con.		

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*Salt concentrations were determined empirically from analyses of respective lakes conducted January 10-20. Other nutrients were approximated from a knowledge of the rocks, proximity to the sea, and data of Goldman, et. al., for apparently similar aquatic ecosystems in the Cape Royds area.

APPENDIX II

FRESH WATER ALGAE OF THE ANTARCTIC PENINSULA NEAR PALMER STATION, ANVERS ISLAND

Genus and Species	Preserved	Cultured	Location**
Chlorophyta			
Chlamydomonadaceae			
Chlamydomanas spp.* (1,4)	+	+	7,12,11,3,4
Chlamydomanas basimaculatus Pasch et. Jod.	+		12
Chlamydomanas caudata wille	+		10
Chlamydomanas elliptica korch.	+		14
Chlamydomanas gracilis	+		7
Chlamydomanas snowiae printz	+		14
Polytoma spp.		+	14
Chlorosphaenaceae			
Chlorosarcina elegans Gerneck	+		4,12,13
Gloeocystaceae			
Palmellopsis gelatinosa Korch.	+		12
Pallmellaceae			
Sphaerocystis Schroeteria Chodat	+		12,4
Hormotilaceae			
Palmodictyon varium naeg.	+		4
Oocystaceae			
Ankistrodesmus setigerus (Schrored.) G. S. West	+		13
Chlorella spp.		+	4,7,14
Chlorella vulgaris Beig.	+	+	2,7,13,12,3,4
Oocystis Borgei	+		4

Genus and Species	Preserved	Cultured	Location
Oocystis lacustris chodat	+	+	4
Scotiella spp.		+	3,4
Scotiella antarctica Fritsch*	+		12
Trochiscia granulata (Reinsch) Hansgrig	+		12
Troschiscia zachariasi Lemmermann	+		12
Troschiscia spp.*(4)			12
Chlorococcaceae			
Chlorococcum infusionum (Schrank) menegl.	+	+	4,3,12,14
Chlorococcum spp.	+	+	
Spongiochloris sp.		+	4
Coccomyxaceae			
Nannochloris bacillaris (naumann) Bourn		+	4,3,13
Dictyosphaeriaceae			
Westella botryoides (West) de Wild.	+		13, 14
Ulotrichaceae			
Binuclearia tatrana Wittr.	+		4
Stichoccus flaccidus (Kuetz) Gay.		+	4
Chaetophoraceae			
Gongrosira-like branched filament		+	4
Prasiolaceae			
Prasiola spp.* (4)	+		13,4
Prasiola crispa (Light of) Menegh.	+		12,4,3,13
Prasiola fluviatilis (Sommer.) Aresch.	+		13
Prasiola tesselata Kuetz.	+		11
Monostroma sp. (Recheck)	+		12
Mesotaeniaceae			
*Cylindrocystis brebissonii menegh	+		13
Desmidiaceae			
Staurastrum dilatatum var. insignias Raciborski	+		13

Genus and Species	Preserved	Cultured	Location
Cyanophyta			
Chroococcaceae			
Aphanocapsa Grevillei (Hass.) Rab.	+		12
Aphanotheca microscopica naeg.	+		11
Aphanotheca microspora (menegh.) Rab.		+	7,10
Chroococcus limneticus var. carneus (chodat) Lemm.	+		13
*Chroococcus minor (Kuetz) Naeg. (4)	+	+	4
Chrococcus minutis (Kuetz) Naeg.	+		4,12,14,13
Chrococcus pallidus Naeg.	+		12
*Chroococcus varius A. Braun. (4)		+	7
Dactylococcopsis raphidiodes Hansging	+		12
Merismopedium elegans A. Braun	+		12
Merismopedium spp.	+		12
Entophysalidiceae			
Heterohormogonium spp.	+		11
Pleurocapsaceae			
Myxosarcina concinna Printz	+		4
Oscillatoriaceae			
Oscillatoria angustissima	+		13
*Oscillatonia brevis (Kuetz) Gomont (2,4,5)	+		12,11
Oscillatoria granulata Gardner	+		12
Oscillatoria granutata var.	+		13,14
Oscillatoria hormogenea Fremy.	+		11
Oscillatoria meslinii Fremy	+		13
Oscillatoria profunda Kirchner	+		4
*Oscillatoria subbrevis Schm. (2)	+		14,12
Oscillatoria splendida Grev.	+		12
*Oscillatoria tenuis (2,4,5) var. levis Gard.	+	+	2,12,7
Oscillatoria terebriformis Ag.	+		7

Genus and Species	Preserved	Cultured	Location
*Phormidium spp. (2,4,)			
Phormidium mucicola Hub-Pest.	+		12
Phormidium tenuissimum wokon.	+		12
Schizotrix calcicola (Ag.) gomont	+		12,4,2
Chrysophyta			
Chrysococcaceae			
Chrysococcus Sp.	+	+	4,12
Chrysococcus tesselatus Fritsch	+		4
Chromulina minima			4,3
Chrysapsidaceae			
Chrysapsis Spp.		+	12
Pleurochloridaceae			
Ellipsoidion solitare (Geitler) Pascher	+		12
Trachychloron ellipsoideum Pascher	+		12
Melsina Borron, Grev. Bacillariophyceae	+		4
Achnantheses sp.	+		13
Fragilaria virescens Ralfs	+		13
Surirella sp.	+		13
*Navicula spp. (2,3)	+		12,13,4

Identified by Previous Investigation:

Cosinodiscus Spp. (2)
Diploneis sp. (2)
Pinnelaria sp. (2)
Cocconeis spp. (2)
Denticula sp. (2)
Diatomella sp. (2)
Grammatophora sp. (2)
Tabellaria spp. (2)
Microcoleus sp. (5)
Gleocapsa sp. (4)
Lyngbya spp. (4)
Nostoc spp. (4)
Anabaena (4)
Calothrix sp. (4)
Cosmarium sp. (4)
Pleurotaeniopsis sp. (4)
Pteromonas sp. (4)
Ulothrix spp. (1,4)
Penium sp. (4)

The previous identifications were made by the following investigators:

(1) Wildemann (1900), (2) Nordenskiold (1902),
(3) West and West (1911), (4) Gain (1913)
(5) Carlson (1907).

* Identifications made previously by the above mentioned investigators.

**See Fig. 6, p. 89.

APPENDIX III

The following data summarizes the differences in rates of photosynthesis which one can obtain employing typical primary productivity bottles for the ^{14}C method.

SPECTRAL DATA ON GLASS PIECES FROM
5 PRIMARY PRODUCTIVITY CONTAINERS

CONTAINER AND WAVE-LENGTH RANGE	$\bar{x}$* CM^2	CONTAINER AND WAVE-LENGTH RANGE	$\bar{x}$* CM^2
250 ml, 700-400mμ	89.1	300 ml, 700-400mμ	79.0
400-300	66.2	400-300	59.0
700-300	83.3	700-300	74.0
125 ml, 700-400mμ	87.0	500 ml, 700-400mμ	74.3
400-300	74.6	400-300 400-300	52.2
700-300	83.9	700-300	68.8
70 ml, 700-400	88.9		
400-300	54.6		
700-300	80.3		

* $\bar{x}_{cm^2}$ = means of $\geq$ 3 planimeter measurements with $\leq$1% variation of areas of % transmission

PRIMARY PRODUCTIVITY AND ANTHRACENE POLYMERIZATION FOR AN ANTARCTIC FRESH-WATER POND

(January 20, 1970; 25 hr exposure; 0.28 to nil langleys at 20 cm depth)

Container	mg C/m³/hr	Anthracene % Transmission	Antracene % Transmission, Jan. 22, 25 hr
250 ml light	3.65	70 (rounded)	23
	3.67	63 (flat)	---
Dark	0.18		1
300 ml light	2.60	37	14
light	---	37	---
dark	0.15	0	---
dark	---	1	3

PRIMARY PRODUCTIVITY AND ANTHRACENE POLYMERIZATION

FOR VPI DUCK POND

(April 19, 1970; 8 hr exposure; 3500-5000$^+$ ft-c at surface)

Container	mg C/m^3/hr*	$\bar{x}$	% of 250 ml	Anthracene, % Transmission	
				Set 1, Apr.19	Set 2,
250 ml light	34.2 30.1	32.2	100	75	75
300 ml light	25.6 22.4	23.8	74	45	38
125 ml light	22.4 19.1	20.7	61	40	35
70 ml light	11.6 10.4	11.0	34	34	25
500 ml light	3.6 3.4	3.5	11	38	42

* Dark bottle values ≤ 5% of light values

CHANGE IN CHLOROPHYLL a DURING CONTAINER INCUBATION

(July 23, 1970; 6 hr. incubation;
2625 ft-c; temp. ca. 21-2 C)

Container	Chlorophyll a m-SPU pigment/m^3	Container	Chlorophyll a m-SPU pigment/m^3
None, fresh collection	792, 836		
250 ml light	823	250 ml dark	1,020
300 ml light	820	300 ml dark	1,016
125 ml light	843	125 ml dark	998
500 ml light	697	500 ml dark	1,048
70 ml light	786	70 ml dark	962

Chlorophyll a = $11.64\ E_{663} - 2.16\ E_{645} + 0.10\ E_{630}$

CHANGE IN CHLOROPHYLL a DURING CONTAINER INCUBATION

(July 21, 1970; 6 hr incubation;
1700 ft-c cloudy-rainy, temperature ca. 20C)

Container	Chlorophyll a m-SPU pigment/m3	Container	Chlorophyll a m-SPU pigment/m3
None, fresh collection	261*		
250 ml light	574	250 ml dark	550
300 ml light	502	300 ml dark	616
125 ml light	316	125 ml dark	542
70 ml light	506	70 ml dark	537
500 ml light	486	500 ml dark	484

*Possibly due to larger volume filtered and 6 hour longer exposure to acetone.

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LIMNOLOGY OF SELECT FRESH WATER SYSTEMS NEAR THE ANTARCTIC PENINSULA--FIELD AND LABORATORY STUDIES

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Abstract

We compared primary productivity and nutrients in two lakes of different trophic levels during the Antarctic summer of 1969-70 at Anvers Island, Antarctica (64° 46' S, 60° 05' W). Algae collected and cultured in the field were identified. "Skua Lake" and "Humble Lake", about 1/4 mile apart, had partial ice cover the entire season. Both were underlain with a silica-rich granite. Striking nutrient concentration differences were Cl^- (7.5 and 35.0), NH_4^+-N (0.1 and 2.5), total $PO_4^{\equiv}$-P (0.03 and 1.7 mg/l) respectively for "Skua" and "Humble" Lakes. Diurnal ranges in extractable total chlorophyll in subsurface water were 35-41 mg/m^3 in "Skua Lake" and 37-112 mg/m^3 in "Humble Lake." Diurnal ranges in net photosynthesis were 0.78-3.3 mg C/m^3/hr ("Skua") and 16-72 mg C/m^3/hr ("Humble"). Somewhat broader ranges for chlorophyll and carbon fixation were obtained at specific times during this two-week investigation. On return to the laboratory, we established in vitro microecosystems containing native Antarctic algae and

bacteria to determine effects of various environmental factors on algal primary productivity rates for each lake. Of the numerous factors tested, only NH_4^+-N and $PO_4^{\equiv}$-P enrichments of artificial "Skua Lake" water increased significantly productivity rates in control enriched microecosystems, as measured by ^{14}C uptake. Enrichment of artificial "Skua Lake" water with NH_4^+-N to approach the level in "Humble Lake" water resulted in productivity increases 1.5-4 times that of the control, while comparable enrichments with $PO_4^{\equiv}$-P caused increases in ^{14}C-fixation rates of 1.2-1.5 times that of the controls. NO_3^--N, Cl^-, SiO_2^{--}, and Fe^{++} additions and pH fluctuations produced no productivity rate changes in the two artificial microecosystems. Also, varying the container size, shaking, and aerating microecosystems had no effect on ^{14}C uptake rates or on algal community structure. The microbial communities of the two lakes, while different in species composition, gave the same responses to nutrient additions when transplanted reciprocally into the foreign artificial microenvironment; this result further demonstrated that the nutrient composition, rather than the community structure formed the main basis for the differences observed in these two natural Antarctic ecosystems. The majority of the Antarctic algae identified from the field were placed in the division chlorophyta with numerous genera in the cyanophyta and a relatively few algae in the chrysophyta. At least 90% of all species identified were cosmopolitan, with only four species endemic to the Antarctic coastal area. These data enable some understanding of phytoplankton ecology and natural eutrophication in fresh waters of the Antarctic Peninsula.