

FOODWEB AND NUTRIENT DYNAMICS IN
NEARSHORE ALASKA BEAUFORT SEA WATERS

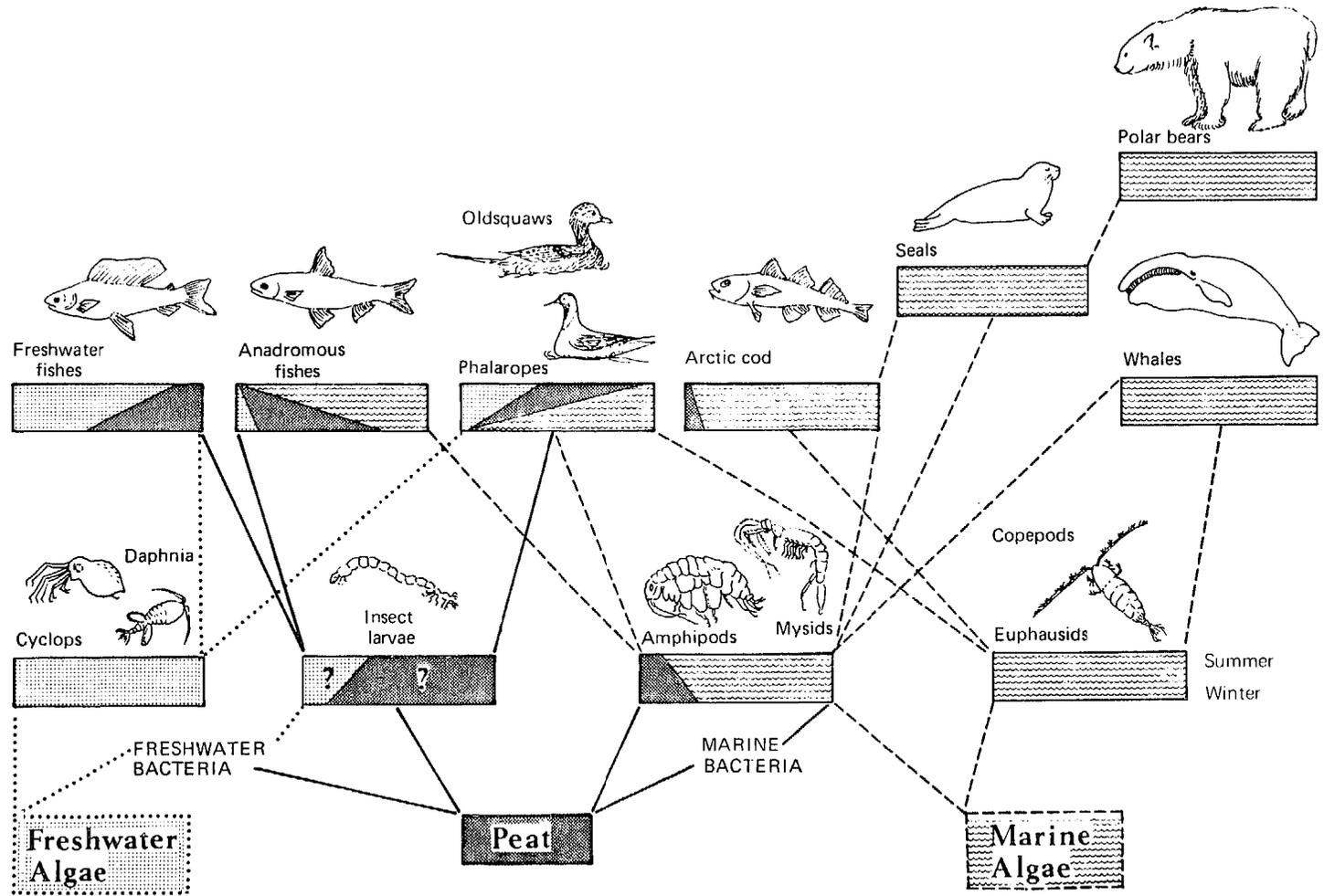
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Frontispiece Generalized foodweb structure and major seasonal energy dependencies in Alaska Beaufort Sea coastal ecosystems.

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I. SUMMARY OF OBJECTIVES, CONCLUSIONS AND IMPLICATIONS
WITH RESPECT TO OIL AND GAS DEVELOPMENT

Objectives

The overall objective of RU 537 was to describe the principal, processes supplying energy (i.e., fixed carbon) to the biota of the Beaufort Sea coastal zone and to estimate transfer efficiencies of this energy through the foodwebs of the nearshore zone. In addition, this research unit has investigated the nutrient dynamics of coastal waters and related the nutrient regimes to this production of energy. Both terrestrially derived and offshore derived nutrient sources are considered. The information obtained was initially for integration into the overall structure of the LGL Barrier Island study group, RU 467. Their efforts related this information to: 1) description of the overall ecosystem, 2) possible OCS direct impacts on the nearshore biota by offshore oil and gas development, and 3) possible impacts on the nearshore biota caused by "upstream effects" on land which would change the character of terrestrial input of nutrients and/or carbon to the marine ecosystem via erosional processes or runoff.

In addition, this research unit has cooperated with units 356 (Dr. Carter Broad) and 359 (Dr. Rita Homer) with the following objectives: 1) to seek information on the rates of macrofloral primary production in the "boulder patch" of Stefansson Sound (RU 356); 2) investigate the ability of indigenous species of amphipods to utilize peat carbon through symbiotic intestinal cellulose-degrading microfloral populations, (RU 356); and 3) cross calibrate estimation techniques for ice algal biomass and seasonal production (RU 359) with the goal of developing methods that would allow estimation of annual ice algal production based on observed standing stocks at particular intervals of the spring season.

Overview

The conclusions to date give evidence that **trophic interdependencies** of the nearshore Beaufort Sea are decidedly different from more temperate Alaska coastal zones with regard to the energy sources supporting the **biota**. Although the inputs of terrestrial peat to the marine waters do not contribute major amounts of energy to marine organisms, the peat is directly linked to the **anadromous** fishes and birds via the freshwater foodwebs. This is a most important point -- the reproductive success of oldsquaws and **phalaropes** and the overwintering success of **anadromous** fishes are established upon freshwater peat-based foodwebs. When these fishes enter the marine environment, their food shifts to marine invertebrates (**mysids**, **amphipods**, etc.) which derive their carbon from the phytoplankton, ice algae and benthic **microalgal** primary producers. The carbon isotope compositions of arctic marine and freshwater **biota** lead us to hypothesize that a major separation exists in the **trophic** system of the arctic coastal zone. Even though there is peat carbon available to organisms in the marine environment, due to the input from coastal erosion and the **Colville** River, utilization of this large reservoir of organic matter is limited by invertebrate assimilation capabilities. The strictly marine organisms, therefore, rely on the more variable supply of marine **microalgal** primary production. It may be significant that apical organisms of the pelagic foodweb (such as seals, whales and polar bears) are typified by large energy storage capacities which may assist in smoothing out the pronounced seasonal and, perhaps, annual variations in food supplies. The obligate freshwater fishes, on the other hand, have been shown to be heavily dependent on peat carbon which appears to be made available through the critical link of insect larvae (probably **chironomids**). Superimposed on these two schemes are the **anadromous** fishes, oldsquaws, and **phalaropes**. It is through the movement of these upper **trophic** level organisms that two energetically independent systems interact. Although this type of interaction certainly occurs elsewhere, the importance to both migrating species and prey organisms on which they feed cannot be underestimated in an

environment where primary production 'is essentially nil for seven months of the year. It is reasonable to assume that the successful ecological adaptation of marine birds, such as the oldsquaws and phalaropes, to rearing their young on tundra ponds is in part in response to this reliable food source. Similarly, the anadromous fish populations overwintering in the arctic rivers can expect a relatively constant peat-based -food supply independent of the variable seasonal microalgae production. The frontispiece shows the relationships of organisms to the energy sources supporting -the nearshore and freshwater ecosystems.

The estimates of energy input to nearshore waters have been revised as new data obtained by this research unit and RU 530 are utilized to appraise the various input sources. These estimates show that over 50 percent of the carbon input to nearshore marine biota (within approximately 10 km of shore) is terrestrially derived from two primary processes, fluvial transport and coastline erosion. The rivers carry large quantities of organic matter during spring breakup and coastal erosion occurs during summer months, resulting in the deposition of large amounts of organic carbon along the shoreline. This carbon is composed primarily of peaty material that has been accumulating on land for up to 12,000 years. The freshwater and nearshore marine ecosystems are apparently "fossil fuel" subsidized, wherein the meager annual primary production by ice algae and phytoplankton is supplemented by organic carbon eroded from coastal peat bluffs and transported by river flow into the coastal zone. The distinctive carbon isotopic signatures of the materials from terrestrial and marine sources allow detection and quantitation of the source fractions in the tissues of the fauna comprising the foodwebs built upon these sources.

The input of allochthonous carbon to the Harrison Bay (Sale 71) area by the Colville River causes a disproportionate increase in terrestrial carbon relative to marine primary production. Over 85 percent of the fixed carbon budget is terrestrially derived, which readily accounts for the high percentages of peat carbon found in organisms collected from Harrison Bay in November 1979. If the detrital foodweb dependencies increase during winter in Harrison Bay (as has been

found to occur in the freshwater habitats), the terrestrial carbon inputs may be even more critical than currently indicated.

Highlights and Conclusions

Since 1977, this research unit has sought to quantitate the energy inputs to the foodwebs of the nearshore Beaufort Sea and to determine the relative significance of peat detritus to higher trophic levels. Beginning with a limited investigation of the role of ice algal primary production and related nutrient cycling, this work expanded into a broad investigation of the major processes supplying energy to the ecosystem. The findings have been reported in past annual reports and have been modified as new data have been acquired.

An overall picture of nearshore arctic marine energy flow is emerging. The marine and freshwater ecosystems are remarkably different, but they are inseparably linked by the anadromous fishes and migratory birds that use both habitats and are apex organisms in arctic foodwebs. Arctic marine fauna are almost totally dependent upon marine primary production and have not adapted to direct utilization of the large inputs of terrestrial organic matter that enter nearshore waters via fluvial transport and coastline erosion. Presumably, this is because few of the indigenous invertebrates can utilize cellulosic matter as an energy source. An exception is the amphipod *Gammarus setosus* which has been shown to assimilate cellulose, but this organism is not a principal prey species of the fishes or birds that feed in the coastal Beaufort Sea.

In contrast, the freshwater aquatic fauna are heavily dependent upon detrital peat as a primary energy source, and the success of overwintering fish populations requires an almost complete shift to detrital foodwebs. The anadromous fishes which overwinter in the Colville River have been shown to continue feeding over the winter months and to rely almost entirely upon a food chain based on peat carbon. Similarly, oldsquaw ducks breeding on the coastal tundra in the small ponds and lakes have been found to contain as much as 20-60

percent peat carbon indicating that aquatic primary production is responsible for a variable fraction of their food requirements in summer months. Terrestrial carbon in the form of peat may, therefore, supply a significant fraction of the energy requirements of the freshwater ecosystem. Several highlights of the research results follow. For detailed descriptions of methods and results, the reader should seek the appropriate section in the report body.

The conclusions presented herein, especially with regard to the carbon isotope studies, are based upon samples analyzed to date. Some samples are still being processed, and our conclusions will be modified as new information is acquired.

Ice Algae

November 1980 sampling of sea ice cores north of Stefansson Sound yielded a surprisingly large population of ice algae at the ice-water interface. The ice algae layer was readily discernible to the eye, and chlorophyll-a concentrations averaged 87 mg/m^3 in the bottom 5 cm of ice. Integrating the bottom 10 cm of ice yielded a standing stock of 4.7 mg Chl-a/m^2 which translates into approximately 0.2 g C/m^2 . No data are available as to year-to-year variation in arctic ice algal blooms during fall; indeed, to the author's knowledge, this is the first report of its occurrence. It is interesting that the documentation of Canadian arctic microalgae (Hsiao, 1980), which includes the Eskimo lakes area of the nearshore Beaufort Sea, makes no note of any bloom of ice algae in the fall, but instead found the minimum annual concentrations of ice algae during November. This marked contrast to our findings in November off Narwhal Island cannot be explained without better understanding of the environmental differences between the areas. Similar blooms have been reported in the Antarctic, and the author is indebted to Dr. Mitsuo Fukuchi of the Japan Polar Research Institute (with whom this was a joint effort) for the suggestion to look for their occurrence. Due to the low light intensities, short day length, and rapid rate of ice formation, it had been assumed that ice algae would not have time to

grow before incorporation into congelation ice. The fall of 1980 was characterized by an unusually warm period in late October that may have contributed to favorable growth conditions.

The distribution and productivity of ice algae over much of the coastal zone between Cape Halkett and Stefansson Sound has been estimated from chlorophyll concentrations and from direct carbon measurements. Ice algal populations are highly variable as a result of sediment inclusion in the ice cover and other environmental variables such as hypersalinity, freshwater stress during runoff, and variable snow cover. Considerable effort has been directed toward obtaining a better estimate of the annual contribution of ice algae to the energy budget of the marine ecosystem. Based upon our efforts and the literature data, ice algae are believed to contribute 1-6 g C/m² to the nearshore Beaufort Sea, with the higher values occurring 20 or more kilometers offshore where the ice is free from sediment inclusions. In the nearshore areas, sediment-laden ice is very common and prevents light transmission through the ice cover over much of Harrison Bay and Stefansson Sound.

Although the area of sediment-laden ice varies greatly from year to year, and sampling density is insufficient to accurately quantify the total area covered, we feel that approximately one-third to two-thirds of the Stefansson Sound and Harrison Bay area are typically rendered unsuitable for ice algal growth. Progressing seaward, sediment in the ice diminishes and the increasing clarity of the ice and decreasing snow cover enhance growth conditions. At 160 km offshore (the farthest distance sampled), virtually all annual sea ice showed visible evidence of an ice algal layer on the bottom where pack ice motion had overturned pieces.

Estimation of annual production was accomplished using two methods. Observed standing stocks of chlorophyll-a were halved to approximate a seasonal average density and the equivalent carbon fixation rates were integrated over a 60 day season using assimilation efficiencies obtained from literature data. The alternate technique involved converting observed chlorophyll concentrations to carbon by measuring carbon/chlorophyll ratios in ice algal samples. By multiplying the

maximum standing stocks of ice algal carbon by a factor of 5, annual production was obtained. The factor 5 was an approximation derived from averaging several annual productivity/maximum standing stock values from the literature. We feel reasonably confident in these estimation techniques, since they agree with both our own and literature data. There are several pitfalls, however, that limit their usefulness. These are explained in detail in Section VI.

Chukchi Sea Ice Algae Studies, 1981

During trafficability studies in the Chukchi Sea during Spring 1981, the U.S. Coast Guard icebreaker Polar Sea sustained damage to the propeller shaft and became immobilized in the ice of Wainwright, Alaska. The termination of the trafficability studies afforded the opportunity to place graduate student Daniel Parrish on board to conduct ice algal studies over the course of the spring bloom. The situation did not prove very successful, however, due to severe fuel shortages on the " vessel and the fact that whenever a lead opened, the vessel moved southward as rapidly as possible. As a result, only four ice stations were occupied yielding a very limited sampling density. Ice algal densities were variable reflecting ice rafting and snow depth, but were generally higher than observed in the Beaufort Sea. Maximum chlorophyll concentrations were found beneath smooth ice pans and ranged from 24.9 to 78.3 mg chl-a/m², equivalent to 1.2 to 3.9 g C/m². Assuming an annual productivity equal to 5x the maximum standing stock, nearly 20 g C/m² were fixed under optimal conditions in the Chukchi Sea. This value agrees well with the 24 g C/m² estimated by McRoy and Goering (1976) for the Bering Sea, although their figure was listed as an average value. The overall trend, therefore, in ice algal productivity is a gradual decrease in annual production along a line northward from the Bering Sea into the Chukchi and then, presumably, north and eastward into the Beaufort Sea. This trend is due to the thicker ice, lower nutrient concentrations, deeper snow cover, and lower solar angles that prevail on a progression northward.

Phytoplankton Production

Field measurements of phytoplankton productivity under sea ice and during the open water months were undertaken on a limited scale by this research unit. Data have been obtained from Simpson Lagoon, Harrison Bay, Prudhoe Bay, Stefansson Sound, and offshore. Four sampling trips (17-18 June and 2 July, 1980; 24-28 May and 22-24 June, 1982) were specifically made to obtain chlorophyll fluorescence and primary production beneath melting sea ice late in the spring season.

All samples obtained confirm the hypothesis that primary production rates are low, but that shade adaptation allows active carbon fixation beneath the ice. Nevertheless, no evidence of a "spring bloom" was apparent during any sampling period, although fixation rates were highest in nearshore waters. This may mean that phytoplankton populations gradually increase during June and July as light intensities increase with the melting ice cover. The nutrients available for growth are also depleted during June and July, and thus prevent any major pulse of production as the ice cover disappears.

Estimates of total annual phytoplankton production were obtained by two techniques. The first method integrated average primary productivity rates over the summer season and adjusted the effective euphotic zone depths in response to the presence or absence of ice cover. The second method involved calculating a phytoplankton crop based upon maximum nutrient availability in the spring and then using approximations for turnover times based upon zooplankton standing stocks and estimated consumption rates. Both methods contain major uncertainties and the approximations obtained are most useful in a qualitative sense in determining which areas of the Beaufort Sea are most biologically productive.

Based upon the literature data available (Alexander, 1974; Homer, 1981) and our findings, we conclude that seasonal primary productivity in the coastal Beaufort Sea is typically between 0-2 g C/m²-yr for ice algae and 5-20 g C/m²-yr for phytoplankton for the nearshore areas such as Stefansson Sound, inner Harrison Bay, and Simpson Lagoon. Outside of the barrier islands and further offshore, ice algal

productivity increases to 2-6 g C/m²-yr and phytoplankton productivity increases to over 40 g C/m²-yr. These increases reflect the clearer ice cover and the deeper water column which, when integrated over the euphotic zone, yield higher total primary productivity values. It is assumed that far offshore (beyond about 200 km) where pack ice is perennial, phytoplankton productivity decreases to very low annual totals of less than 1 g C/m²-yr (Apollonio, 1959; English, 1959).

Erosional and Fluvial Inputs of Carbon to the Nearshore Marine Environment

Carbon, nitrogen, and phosphorus analyses on peat soil section samples have been completed for a large selection of sites along the Colville River, Simpson Lagoon, and the Beaufort Sea coastline west to the Cape Halkett area yielded a reasonably comprehensive picture of the nutrient content of the allochthonous matter entering the marine environment. In addition, S. Rawlinson of RU 530 has completed estimations of shoreline erosion rates for the entire coastline between Point Barrow and the Canadian border. Approximately 2.6×10^9 kg/year of peat soils erodes into the nearshore marine waters carrying 158×10^6 kg carbon, 10×10^6 kg nitrogen and 0.69×10^6 kg phosphorus. On an atom ratio basis, the C:N:P ratios are approximately 558:31:1. The peat soils have been shown to be readily oxidized microbiologically; thus mineralization of the incorporated nutrients would make them available for phytoplankton uptake.

Fluvial input of carbon and nitrogen has been determined for the Colville River discharge, and extrapolations were made to estimate total North Slope inputs to the Beaufort Sea. Annually, approximately 230×10^6 kg C and 15×10^6 kg N enter via river flow. Of this amount, about half is transported by the Colville River. This 115×10^6 kg C/year entering Harrison Bay compares with an estimated 20×10^6 kg C/year from ice algal and phytoplankton primary production. This high input of terrestrial carbon is reflected in ¹⁴C content of the invertebrates sampled near Thetis Island which were found to contain

over 25 percent peat carbon. The low efficiency of detrital foodwebs in the marine environment is probably responsible for the terrestrial carbon not comprising an even larger fraction.

Energy Flow and Trophic Relationships

Carbon isotope tracer techniques have revealed that the foodweb pathways of energy transfer into the fishes and birds of the nearshore Beaufort Sea are almost totally based upon marine primary production in spite of the large quantities of terrestrial carbon available to the nearshore ecosystem.

The organic matter transported by the Colville and Kuparuk Rivers was found to be strongly depleted in ^{14}C , and the depletion increased as breakup progressed. Thus, the major fraction of fluvially transported carbon is derived from eroded peat from river banks, and the input of surficial vegetative material is pronounced only during the initial stages of breakup in the rivers. The Kuparuk River contained the lowest quantity of ^{14}C in river particulate matter, approximately 71 percent of the 1950 standard radiocarbon activity compared to 65 percent for the mean radiocarbon content of Simpson Lagoon soil sections

Refined estimates of the mean ^{14}C content of the allochthonous carbon sources, and the determination of ^{14}C activity in several additional species of marine and freshwater fauna of the coastal zone and rivers, have revealed startling variations with regard to the utilization of eroded peat carbon. Anadromous fishes from the Colville River (arctic cisco, least cisco, humpback whitefish) are almost entirely dependent upon the marine ecosystem for their nutrition during summer as evidenced by $^{13}\text{C}/^{12}\text{C}$ isotope ratios of specimens collected from Simpson Lagoon and Harrison Bay in August and September.

After the anadromous fishes enter the Colville River during the fall, however, their food habits shift to a nearly complete dependence on detrital peat foodwebs. By the following June, the $^{13}\text{C}/^{12}\text{C}$ ratios of the fishes recentering saltwater are typical of obligate freshwater fishes, and the ^{14}C content has fallen to concentrations

equivalent to approximately 45-50 percent peat carbon. However, some samples of anadromous fishes obtained in June 1982 showed evidence of feeding in marine waters over the entire winter. Whether these fish wintered in saline delta channels or offshore is not known. This information is important in that it shows 1) the anadromous fishes are actively feeding during winter months, and 2) peat-based detrital foodwebs are the most important pathways of energy flow during winter in the freshwater aquatic ecosystem. Since fish can be presumed to be feeding on insect larvae and other invertebrates, the lower trophic levels must in turn be almost totally dependent upon peat carbon inputs.

Further evidence of the role of peat carbon in freshwater foodwebs came from an oldsquaw duck collected after nesting on the tundra for the summer. The $^{13}\text{C}/^{12}\text{C}$ ratio of this bird was typical of terrestrial carbon sources and the ^{14}C content ratio was equivalent to 60 percent peat carbon. Thus, some of the small ponds and lakes on which these birds live during the summer must be energetically supplied to a large extent by eroded peat carbon, and phytoplankton production inputs are exceeded by the vast quantities of peat. These tentative conclusions are supported by documented oldsquaw specimens collected from the Teshekpuk Lake area.

Marine Detrital-based Production

Laboratory' experiments in cooperation with Dr. David Schneider (RU 356) were conducted at the Naval Arctic Research Laboratory in July 1979 to determine the cellulose oxidation capabilities of in situ populations of marine microflora and resident populations of amphipods. The experiments confirmed previous findings that active microbial oxidation occurs in the water column, but that *Onisimus* sp. amphipods do not have the ability to utilize cellulose (or peat) directly.

In contrast, experiments run with *Gammarus setosus* showed rapid cellulose uptake and metabolism. At 8°C, the average adult *Gammarus setosus* oxidized approximately 1.6 µg peat/hr to carbon dioxide. Microbial oxidation rates of peat in seawater yielded turnover times of

about 1,050 days at 0°C and 640 days at 8°C. This turnover time implies that the fate of most eroded peat is microbial oxidation within the lagoon-nearshore system, since transportation offshore in this low energy environment is slow.

The collection problems associated with acquiring sufficient specimens of *Gammarus setosus* from the lagoon environment to perform radiocarbon activity determinations (for high precision, 5 g of carbon is required) have prevented the acquisition of isotopic data on these animals until recently. A sample collected by Dr. Schneider during July from the Chukchi Sea at Barrow showed a radiocarbon content of 96.6 percent modern, equivalent to approximately 30 percent peat carbon, the highest fraction in any marine organism analyzed to date. In addition, baited traps set in Simpson Lagoon during November 1979 yielded sufficient adult amphipods of *Atylus*, *Gammaracanthus*, and *Weyprechtia* spp. to obtain radiocarbon activities. These adult organisms also contained the low radiocarbon activities corresponding to body compositions of 16-23 percent peat carbon. These organisms are apparently partially dependent upon detrital peat and reflect the high inputs of terrestrial detritus to the nearshore environment.

Further work on measuring the rates of microbial oxidation of peat in offshore marine waters and in the freshwater environment confirmed that the oxidation of cellulose occurs in both marine and freshwater at temperatures down to freezing. Kuparuk River water collected in September 1980 oxidized cellulose at nearly twice the rate as marine water collected offshore of Reindeer Island and at approximately the same rate as marine waters from Simpson Lagoon. The addition to the water samples of small quantities of peat detritus collected from the shoreline increased oxidation rates, indicating active populations of bacteria associated with peat in seawater.

The Stefansson Sound Boulder Patch

The Boulder Patch is an area of pebbles, cobbles, and boulders in Stefansson Sound that provide a substratum for a diverse assortment of invertebrates and several species of algae. Linear growth in the

kelp, *Laminaria solidungula*, is greatest in winter and early spring when nutrients are available for new tissue growth. The plant draws on stored food reserves to complete over 90% of its annual linear growth during the nine months of darkness under a turbid canopy. These reserves are accumulated by photosynthetic activity during the previous summer. The total carbon fixed by kelp in the Stefansson Sound "Boulder Patch" is approximately 146×10^6 g/yr (equivalent to $7 \text{ g/m}^2 \cdot \text{yr}$). This annual carbon input is roughly equivalent to that of phytoplankton in the overlying water column and provides a year-round energy source for consumers. Most of this carbon is released in dissolved or particulate form and appears to be a potential food source for filter-feeding animals and detritivores.

Stable carbon isotope ratios ($^{13}\text{C}/^{12}\text{C}$) have provided evidence that kelp carbon ($\delta^{13}\text{C} = -14.8$) is being utilized by many consumers in the Boulder Patch kelp community, including organisms that typically rely on phytoplankton ($\delta^{13}\text{C} = -24$ to -26) as an ultimate food source. The $^{13}\text{C}:^{12}\text{C}$ ratios of organisms examined to date reflect their known diets from in situ behavioral observations, with a notable exception showing a higher than expected dependency on kelp carbon. *Mysis litoralis* ($\delta^{13}\text{C} = -19.1$), an important crustacean in arctic foodwebs, is more enriched in ^{13}C than individuals collected some distance from the kelp community ($\delta^{13}\text{C} = -23.6$) which may indicate a change in feeding strategy for this predominantly filter feeding organism. In general herbivores (chitons and snails) exhibited the highest carbon isotope ratios and filter feeders the lowest. The importance of kelp as a winter food source may be seen in the shift of the carbon-isotope composition of mysids from summer to winter. The $^{13}\text{C}/^{12}\text{C}$ ratio in mysids is lowest in summer (most negative $\delta^{13}\text{C}$ values) when phytoplankton productivity is greatest, but this ratio increases during the winter as phytoplankton production ceases and the available food contains a greater proportion of kelp carbon relative to phytoplankton carbon. In respect to its carbon inputs, the relative simplicity of this community makes it an ideal system in which to examine foodweb structure and the importance of kelp carbon in trophic dynamics, a role that is not well understood.

Implications with Respect to Oil and Gas Development in the Coastal Beaufort Sea

Detrimental impacts on the primary producers and detritivores within the lease area could result from either spills of hydrocarbons or petroleum-related development. Since the range of specific insults to the environment is extreme, we will deal with the direct and indirect effects of developmental activities in a general sense. The research results of this RU have shown that: 1) most of the higher organisms including the larger invertebrates are dependent primarily upon marine primary production for their food during "summer; 2) primary production in the nearshore zone is very low by most coastal standards; 3) extreme variability exists in the nearshore aquatic environment due to such natural phenomena as river breakup, daylight extremes, ice turbidity, solute exclusion during ice formation, and strong winds. It is reasonable to expect, therefore, that the microflora and fauna living in this environment are some of the most opportunistic and resilient organisms extant, for their living conditions demand flexibility. There are probably exceptions. The Boulder Patch floral and faunal densities and assemblages are anomalous and very likely unique due to the protected environment they enjoy and the paucity of similar areas free of ice gouging in deep (6 m) water with rocky substrate along the Alaska Beaufort coast. These same rigorous environmental conditions also imply, however, that the organisms living therein are periodically stressed. The fact that this coastline is a range limit for several species also implies that the stresses can be severe, and in some cases, limiting. In this context, the implications of petroleum development acquire a greater potential for impact. If the environmental stresses are increased through the addition of man-produced insults such as might result from toxic waste inputs, increased turbidity, radical changes in circulation patterns, or oil spills, the impacts on some species could be direct, with foodweb dependencies passing on the interspecific change. For example, an impact such as shoreline stabilization along the lease area would radically change the gross energetic input to the nearshore ecosystem by eliminating erosion of the peat bluff shorelines.

This impact might not become apparent in the higher organisms such as fishes due to their almost exclusive dependency upon marine primary production foodwebs. Some invertebrates, however, could be adversely impacted insofar as terrestrial peat has been found to supply over 20 percent of the energy requirements of some amphipods taken from Harrison Bay.

Major impacts would result from perturbations that altered the summer primary productivity of phytoplankton and ice algae. Oil spills, phytotoxic chemical discharges, or other impacts that decreased primary production in a significant fraction of the coastal zone would be felt by the entire foodweb, including all the anadromous fishes. Other direct effects on primary producers, such as uptake of toxic substances from low ambient concentrations, could indirectly produce severe impact at the higher trophic levels due to the biomagnification of toxicants during foodweb transfers. Toxic heavy metals or halogenated organic compounds are potential problems given the limited circulation that occurs during winter months in the lease area.

Long-range environmental impacts resulting from energy development in arctic Alaska may directly perturb the anadromous fishes and detritivores of the coastal zone through disturbances in freshwater habitats. Deep pools in the larger rivers and lakes are critical overwintering areas for the anadromous fishes which use the marine environment for feeding in summer months. River channel disturbances, increased organic loading in tributaries, nutrient loading from sewage effluents, etc. , can all impact overwintering populations through oxygen depletion in under-ice waters. These potential impacts have been identified previously (Schell, 1974, p. 662-663). As, for example, dredging operations begin in the Colville Delta near Nuiqsut, the biological hazards associated with these activities will require continued monitoring.

In the more distant future, the vast arctic reserves of peat may be used as feedstock for synthetic natural gas production to replace declining production of North Slope fossil gas supplies. This will present a direct conflict through the appropriation for man's usage of an energy source now important to freshwater foodwebs and indirectly to

marine foodwebs as a nutrient source. As our understanding of the interactions between terrestrial and marine ecosystems clarifies, further areas of potential developmental impacts will surely become evident.

II. INTRODUCTION

General Nature and Scope of Study

This research unit originally proposed to look at a very specific aspect of the nearshore primary production regime, namely the contributions of ice algae and the effects of thermohaline convection in supplying nutrients to ice algal populations. At that time, the importance of terrestrial detritus as an energy source became more evident, and this research unit began to consider the possible magnitude of its significance through the use of data collected previously by the author. These results, which have been refined and presented below (see Fig. 2), show the approximate magnitudes of carbon inputs to the Simpson Lagoon ecosystem and set forth an outline of isotopic techniques that allow determination of the relative inputs of peat carbon versus modern primary production carbon (Figs. 3 A, B). Using carbon isotope techniques, this research unit has undertaken the task of determining the significance of each of the carbon sources to the fauna of the coastal Beaufort Sea.

Specific Objectives

The specific objectives of this research unit included:

1. Determine the role of terrestrial allochthonous carbon versus marine primary production in the trophic energetic of marine

organisms in the nearshore Beaufort Sea through use of carbon isotopic tracer techniques.

2. Determine the total inputs of energy to the coastal ecosystem, including allochthonous carbon and nitrogen entering the system via terrestrial runoff and coastline erosion.
3. Compare standing stocks of epontic algae in relation to under-ice nutrient concentrations and ice turbidity.
4. Collect data delineating temporal and spatial variability in ice algal blooms in the nearshore Beaufort Sea.
5. Relate the observed patterns in nutrient availability over the annual cycle to the heterotrophic utilization of detrital carbon within the coastal ecosystem.

Relevance to Problems of Petroleum Development

An ecosystem with a substantial detrital component along large portions of the Beaufort Sea could be readily altered directly or indirectly through OCS-related petroleum development. A summary of the specific impacts that might affect the various sources of energy into the ecosystem includes:

Ice algal productivity:

1. Oil spills on or under the spring ice cover would diminish primary production through either phytotoxic effects or by attenuation of light passing through the ice sheet.
2. Alteration of bottom topography by dredging channels or constructing causeways could alter ice algal production by changing patterns of thermohaline convective flow beneath the

ice cover. Prevention of brine drainage by closing off deeper channels would lead to brine accumulation on the bottom which could seriously impact both fauna and flora.

Phytoplankton production: Open water primary production would be most sensitive to such impacts as phytotoxicity resulting from oil spills. The rapid lateral transport of water along the Beaufort Sea coast may, however, serve to minimize this aspect of potential impact. Potential impacts could also result from the input of nutrients, particularly nitrogen, as a result of secondary sewage effluent discharge. The increased nutrients would stimulate plant growth in summer and could have localized impact on primary and secondary production with possible alternation of the species composition in the area. These effects would not necessarily be classified as detrimental to the marine ecosystem.

Detrital-based production and heterotrophic productivity: Impacts upon the heterotrophic organisms that depend upon eroded and transported peat materials as their energy source would occur primarily through OCS-related developments that impinged upon the sources of detritus. Such procedures as shoreline stabilization could alter the food base by eliminating eroded materials. Causeway construction could change wave energy regimes and thus decrease shoreline erosion. Stabilization or channelizing of streambeds might add to or subtract from the total organic load carried by runoff waters.

Chronic toxicity and increased stress on microbial populations: An indirect impact due to developmental activity effects on the nearshore biota may arise through the physico-chemical interactions of peat detritus and pollutants in under ice waters. The high cation exchange capacity and the hydrophobic nature of the lignins and humic acids associated with peat make it act as an effective scavenger for multivalent cations, chlorinated hydrocarbons, and other polar and hydrophobic molecules. Chronic discharges of toxic

or mutagenic substances into the shallow water column may lead to rapid scavenging of these substances by the detritus. During winter, the limited circulation beneath the ice may result in accumulation through chemical and physical processes to levels toxic to the microbial component. We have not addressed this potential problem in this study beyond showing that the peat supports an active microbial population throughout winter and summer. Although peat appears to be a minor input to total energy requirements of nearshore higher trophic level organisms, we do not know what effects may arise from alteration or inhibition of microbial populations in this component of the energy supply.

The Boulder Patch

A distinctive feature of the Alaska Beaufort Sea shelf biota is the absence of kelp and other species of benthic macroalgae. Pieces of kelp and red algae have been found only as drift on beaches between Pt. Barrow and the United States--Canadian border, and entire plants are seldom observed in significant numbers in driftlines. Collins (1927), in the last major account of benthic algae of the Alaska Beaufort Sea, indicated that no extensive stands of laminarioids were found between Pt. Barrow and the MacKenzie River, NWT. In contrast, many species of sublittoral benthic algae grow in the Canadian Arctic (Lee, 1973; Wilce, 1964).

The ecology of arctic kelp communities has not been studied, mainly due to the large amount of logistic support needed for a diving operation in the Arctic. Therefore, we know little about the energetic contribution made by sublittoral benthic algal communities to the arctic nearshore environment and the fauna associated with large stands of macroalgae. Lee (1973) postulated that colonization of submerged rocks in the Canadian Arctic by fast-growing ephemeral plants takes place after they are no longer icebound, but this hypothesis has not been tested. In temperate regions, subtidal field studies have addressed the temporal and spatial aspects of recolonization, the interaction among organisms, the importance of physical parameters, and the productivity

of the algae in respect to its carbon or energetic input (Foster, 1975; Hatcher et al., 1977; Vadas, 1977).

In August 1971, Erk Reimnitz discovered abundant kelp and a diverse invertebrate fauna attached to cobbles and boulders near Prudhoe Bay in Stefansson Sound, Alaska, in an area now designated the "Boulder Patch" (by the U.S. Board of Geographic Names). The Boulder Patch has been the subject of cooperative geological (RU 205, E. Reimnitz and P. Barnes, principal investigators) and biological studies (RU 356, C. Broad, principal investigator) since 1978. These studies resulted from the need to provide adequate protection to sensitive biologically productive regions, while allowing simultaneous exploration of oil reserves in the immediate area. The Boulder Patch lies on top of promising offshore oil reserves, as evidenced by some tracts in this area receiving the highest bids in the joint State-Federal Beaufort Sea lease sale in December 1979 (Wilson, 1979).

The Boulder Patch is a rare feature of the Alaska Beaufort Sea shelf, which is blanketed predominantly by silty sands and mud (Barnes and Reimnitz, 1974). Most macroalgae depend on hard rock substrates for attachment, since they require a stable base for successful colonization, growth and reproduction. This fundamental need for a hard substratum was recognized by Kjellman (1883), in his classic treatise on arctic algae.

Mohr et al. (1957) first reported the existence of a kelp bed in Arctic Alaskan waters. Using a dredge, they collected a large amount of seaweeds, fishes and invertebrates at 13 meters depth about 50 miles southwest of Pt. Barrow in the Chukchi Sea. Collection of algae elsewhere in the Alaska Arctic has been limited to drift material picked up by various Canadian and American arctic expeditions during the late 19th and early 20th centuries (for complete review, see Mohr et al., 1957).

III. CURRENT STATE OF KNOWLEDGE

Primary Production

In comparison to the warmer waters along the more southern Alaska coastlines, the Beaufort Sea supports a relatively sparse biota. No appreciable harvests of renewable marine resources are made, with the exception of small commercial fisheries operated principally by residents in the estuaries along the coast, and seasonal harvesting of bowhead whales and seals. The zone of maximum biological productivity is confined to a relatively narrow strip along the coast wherein the interaction of terrestrial influences ameliorates and somewhat enhances the sparse oceanic regime.

The primary production supporting the pelagic community occurs in two distinct phases in the Beaufort Sea (and other polar waters). The initial algal bloom in the spring occurs well before the 2 m ice cover has begun to melt, and after the returning daylight reaches crucial intensities sufficient to supply the necessary energy beneath the ice (Bunt, 1963; Apollonio, 1965). Epontic attached algal populations grow on the ice-water interface and thrive until the melt begins around the beginning of June. Literature estimates of the carbon fixed during this period range from about $1 \text{ g/m}^2\text{-yr}$ in the shallow Prudhoe Bay area (Homer et al., 1974) to $5 \text{ g/m}^2\text{-yr}$ Point Barrow (Alexander et al., 1974). Little is known about spatial variability in ice algal production along the Beaufort Sea coast.

Ice algal production has been assumed to be a strictly spring phenomenon in arctic waters (Alexander, 1974) in contrast to the Antarctic, where the onset of freeze-up occurs a full month earlier in the solar year, and thus considerably more light is available for epontic algal production. The conditions of the freeze-up algal bloom in the Antarctic are well documented (Hoshiai, 1969a, b, 1977), but no reports of a similar bloom in arctic waters has been reported. In November 1980, sampling of sea ice north of Narwhal Island near Prudhoe Bay yielded ice cores visibly laden with ice algae, the first evidence

of an arctic freeze-up bloom. These samples are described in detail in the Results section of this report.

As the ice cover melts following the spring ice algal bloom, phytoplankton production assumes the major role in energetic input, although the stability of the water column caused by the melting of the nutrient-poor ice hinders the advection of deep-water nutrients to the photic zone. Only in limited areas near Barter Island has Hufford (1974) identified possible upwelling of deep waters. As a result, primary productivity of phytoplankton is low. Estimates range from less than $1 \text{ g C/m}^2\text{-yr}$ in the central Arctic Ocean (Apollonio, 1959; English, 1959; Melnikov, 1980) to about $20 \text{ g C/m}^2\text{-yr}$ on the coastal zone near Barrow (Alexander et al., 1974).

Input of Terrestrial Carbon to the Nearshore Coastal Zone

The enhancement of biological activity in the proximity of land has been long attributed to various factors among which are the provision of suitable habitat for both benthic flora and fauna, substrate for macrophytes and input of terrigenous nitrogen, phosphorus, and carbon via runoff from land. The arctic coastline provides very limited habitat for macrophytes or benthic infauna due to the 2 m freeze depth, which effectively eliminates the shallow nearshore zone as a year-round environment for marine organisms. In the deeper water, ice scouring creates sufficient habitat disturbance to account for the paucity of observed infauna. The exception to this generalization is the area of dense macrophytic algae that has been described by RU 356 in the central region of Stefansson Sound. This area has relatively deep lagoon waters (6 m) with protection from ice scouring afforded by the offshore barrier islands. In addition, a rocky substrate is available on the sea bottom in the form of relict cobbles and boulders. Dense stands of *Laminaria* are present, and this research unit has participated with RU 356 in assessing the contributions of this biologically rich community to the surrounding coastal waters.

The shallow lagoon areas with mud bottoms are characterized by low infaunal densities and a dearth of macroflora. Below the 2 m contour in the bays and lagoons, however, large standing stocks of invertebrates (amphipods, mysids, and isopods) are common and the LGL-Barrier Island Study (RU 467) personnel have documented the biomass in Simpson Lagoon. These invertebrates are commonly found in close association with eroded organic material from the shoreline. Studies by Broad (RU 356) have shown that certain gammarid amphipods and isopods do ingest and degrade the peat. This ingestion is probably accompanied by the removal and digestion of heterotrophic microflora and microfauna that are attached to the peat particles.

Using data obtained by Lewellen (1973) and the first author during an earlier study of the Simpson Lagoon shoreline (Schell, 1975), erosion rates and the resulting quantities of carbon and nitrogen washed into the lagoon were estimated for the shoreline between Oliktok Point and Beechey Point. These estimates have been expanded by Cannon and Rawlinson (RU 530) to include all of Simpson Lagoon and are presented in Section VI. Further estimates of the total input of allochthonous carbon to the Beaufort Sea have been made by the first author and S. Rawlinson (RU 530), showing that much of the total carbon input is terrestrially derived. Additional information on the coastal erosion rates in the Elson Lagoon area near Pt. Barrow are available from Lewellen (1970), and average coastal erosion rates are presented in Lewellen (1977). Hopkins and Hartz (1978) prepared a map of mean erosion rates along the boundaries of the National Petroleum Reserve - Alaska. All of these data are derived from the comparison of aerial photo profiles of beaches made in 1949, 1955, and within the last few years.

The other data required for accurate estimates of erosional inputs of carbon are the stratigraphic section compositions of the eroding bluffs. We have obtained eight profiles of eroding bluffs along the coast between Cape Halkett and Simpson Lagoon, including two from the Colville River at Ocean Point and Sentinel Hill. S. Rawlinson (unpublished data) has approximately 100 vertical bluff sections obtained between the Colville River and Flaxman Island, and has found

the peat layer thickness to range between 10 and 220 cm and average about 50 cm. The thickness of the peat layer is highly variable along a small length of beach due to ice wedges and surficial relief of the polygons. Yet for the purpose of calculating gross peat inputs, the usage of this mean thickness of 0.5 m seems reasonable based upon the stratigraphic data. The implications of this compartmentalization of the energy input to the marine ecosystem are discussed in Section VI.

Natural Carbon Isotope Abundances

The usage of natural carbon isotope abundances to trace foodwebs is a relatively recent development, and this study is the first to successfully use both $^{13}\text{C}/^{12}\text{C}$ and $^{14}\text{C}/^{12}\text{C}$ ratios simultaneously. The rapid expansion of the literature on isotopic fractionation in foodwebs during the past few years is testimony to the desirability of new techniques in this field, although there have been conflicting interpretations in some of the studies (see, for example, Peterson et al., 1980). Most of the work to date has arisen from the usefulness of $^{13}\text{C}/^{12}\text{C}$ ratios separating vegetative carbon arising from C-3 and C-4 plants (Haines, 1976a, b; DeNiro and Epstein, 1978; Teeri and Schoeller, 1979). Where the inputs of terrestrial carbon constitute a significant fraction of the energy supporting nearshore marine ecosystems, such as in estuaries, stable carbon isotopes have proven somewhat useful in delineating probable energy sources to higher organisms (Haines and Montague, 1979). But as Peterson et al. (1980) pointed out, there is considerable ambiguity arising from the usage of a single isotopic marker in environments where a wide range of natural abundances may be found due to biochemical fractionation in foodwebs and differing photosynthetic pathways.

Within the marine environment, fractionation of stable carbon isotopes due to temperature effects has been documented (Sackett et al., 1965), and the contribution of terrestrial carbon to marine sediments was demonstrated by Gearing, et al. (1977). McConnaughey and McRoy (1979a, b) used $^{13}\text{C}/^{12}\text{C}$ isotope ratios to trace the importance of

eelgrass (*Zostera marina*) to Bering Sea foodwebs and documented the natural isotopic abundances for many Bering Sea organisms. Carbon isotope ratios in deep sea hydrothermal vent mussels have been used to imply chemosynthetic food sources for organisms in this unusual environment (Rau and Hedges, 1979).

Although the preceding samples of studies using stable carbon isotope ratios demonstrate a growing interest in this technique, the carbon storage pools of the arctic environment have allowed us to take advantage of a second natural isotopic marker to determine foodweb pathways and to quantitate inputs with much greater precision. The great chronological age of the peat deposits has resulted in a marked ^{14}C depletion in this carbon source that is easily distinguished from modern sources. This radioactive marker, when used in conjunction with the stable isotope abundances of the various primary producers, has offered considerable insight into the interdependencies of nearshore arctic foodwebs.

IV. STUDY AREA: BEAUFORT SEA (90 PERCENT) CHUKCHI SEA (10 PERCENT)

The study area for this project has been shifted from the originally proposed Elson Lagoon-Dease Inlet area near Point Barrow to the Stefansson Sound-Simpson Lagoon area approximately 60 km west of Prudhoe Bay, and then to the Sale 71 area in Harrison Bay. This shift in siting was made to allow integration with the tasks being undertaken by other OCSEAP investigators. The principal data collection and detailed analyses on primary production and heterotrophic production have now been made along most of this coastline. However, in conjunction with RU 530, estimates of terrestrial input of carbon along the entire Beaufort Sea coast via runoff and erosion have been undertaken in a much less detailed program west of Cape Halkett.

Laboratory experiments to determine the mechanisms by which trophic movement of peat carbon occurs were conducted at the Naval Arctic

Research Laboratory at Point Barrow. The ready availability of amphipods and isopods in Elson Lagoon allowed controlled laboratory experiments on cellulose biooxidation with freshly collected animals.

Stefansson Sound

Stefansson Sound extends from the Midway Islands in the west to Tigvariak Island in the east, and is enclosed by the protecting barrier island chain that consists of the McClure Island, Dinkum Sands, Cross Island, and the Midway Islands (Fig. 1k). Water depths in Stefansson Sound do not exceed 10 meters, and range from three to nine meters within the Boulder Patch. Waves have a short period because of shallow depth and limited fetch. Even during storms, waves rarely exceed 1.5 meters. Currents are predominantly wind driven during the open-water period, when easterly winds dominate. Therefore, the net drift is westward during the summer (Barnes et al., 1977; Matthews, 1981a, b). The rivers discharging into the sound supply only sand-size and finer materials. Peak discharge occurs in June following the river breakup, but very little sediment accumulates within the sound (Reimnitz and Ross, 1979). Currents are very weak to undetectable during the period of total ice cover (from mid-October through June). Bottom water temperatures in the vicinity of the Boulder Patch range from a nearly constant -1.9°C under the sea ice to 7°C during the open-water period. Salinity varies from 14 to 35 ‰ (Barnes et al., 1977). With the exception of the Boulder Patch, the bottom is characterized by silty sands and mud, and an infaunal assemblage dominated by polychaete worms, small molluscs and crustaceans (Feder and Schamel, 1976; Broad et al., 1978).

Freeze-up is usually complete by mid-October, and breakup begins in late June or early July. The benthic environment is largely protected by the offshore islands and shoals from gouging by deep draft ice. The winter ice field within Stefansson Sound is shorefast (i.e., attached to the shore), with minimal movement from early November through June. Ice thickness reaches a maximum of 2 m in early May before deterioration of the ice canopy begins.

v. SOURCES, METHODS, AND RATIONALE OF DATA COLLECTION

Primary Production by Epontic (Ice) Algae

The sampling program for ice algal production and spatial distribution occurred during the spring months and involved sampling the ice-water interface before and after the ice algal bloom. The first sampling period was during early April and yielded water chemistry data representing the maximum nutrient concentrations and salinities of the annual cycle. Fall 1980 saw the first ice algae sampling during freeze-up.

The second sampling trip of the spring, in late May, coincided with the maximum standing stocks of ice algae. Ice cores, water samples, and nutrient samples were taken at this time to estimate ice algal and **phytoplankton biomasses** in the water column. In order to expedite sampling and handling of collected ice cores, the ice algal **biomasses** were estimated via indirect techniques. Total in vivo fluorescence measurements were made on the melted core samples (or on diluted aliquots) and converted to dry weight by cross calibration with laboratory cultures of known algal populations. Since fluorescence is dependent upon many factors (among which physiological state, algal morphology, and past light history are very important), the algal biomasses shown are primarily for comparison and secondarily for quantification. These data are useful in projecting primary productivity estimates for the lease area.

Annual primary productivity by ice algae was also estimated using indirect methods based upon algal biomass and short-term primary productivity measurements. Our summarized results are semi quantitative at best (see Table 5 in Results and Discussion section). The estimates by Homer et al. (1974); McRoy and Goering (1976); Homer (1980), and this study are all based upon the extrapolation of standing stock data and short-term primary productivity experiments. Errors due to grazing, diurnal variations in light, loss of standing stock during sampling, etc. , were approximated, but the paucity of data does not allow

meaningful confidence levels. Station maps and sample locations are shown in Figure 1.

Analytical methods employed for nitrate, ammonia, and phosphate analyses are similar to those utilized by Alexander et al. (1974) for their ice algal studies. Particulate nitrogen analyses were run on glass fiber filters containing particulate material from melted ice cores or underlying water. The filters were burned, and the evolved nitrogen gas was measured using a Coleman Nitrogen Analyzer.

Phytoplankton Primary Productivity

Primary productivity measurements were made by filling three 150 ml glass bottles with water from each sample depth. A dark bottle blank (non-photosynthetic uptake correction) and two clear bottles were injected with 5.0 μCi of ^{14}C -labelled sodium bicarbonate, placed in a plastic basin under 5-10 cm of cold ($<10^\circ\text{C}$) water, and incubated in sunlight. In June and July 1980, the samples were incubated for 24 hours with enough window screening covering the basin to set the light intensity at 425 microeinsteins at 1400 hours local time. The August 1980 samples were also incubated for 24 hours, but no screening was used since the skies were heavily overcast. In August 1981, the incubation period was reduced to 5 hours and the light intensities were adjusted to simulate in situ conditions by adding layers of screening until the same percentage of surface light (measured just below the water surface) was removed by the screens as was removed by the column of water above the sample depth. The light intensities in the tubs were 60 percent, 20 percent, 10 percent, 1 percent and 0.1 percent of surface light, and corresponded well with the light intensities measured in situ. In May and June 1982, the incubation period was 18 and 24 hours at simulated in situ light intensities.

At the end of an incubation, samples were filtered through 0.45 μm Millipore filters using weak suction, fumed with HCl vapors, and the filters were placed in scintillation vials. In Fairbanks, scintillation cocktail was added to the vials and the samples were counted in a Beckman LS-100 Liquid Scintillation System. Sample counting rates were

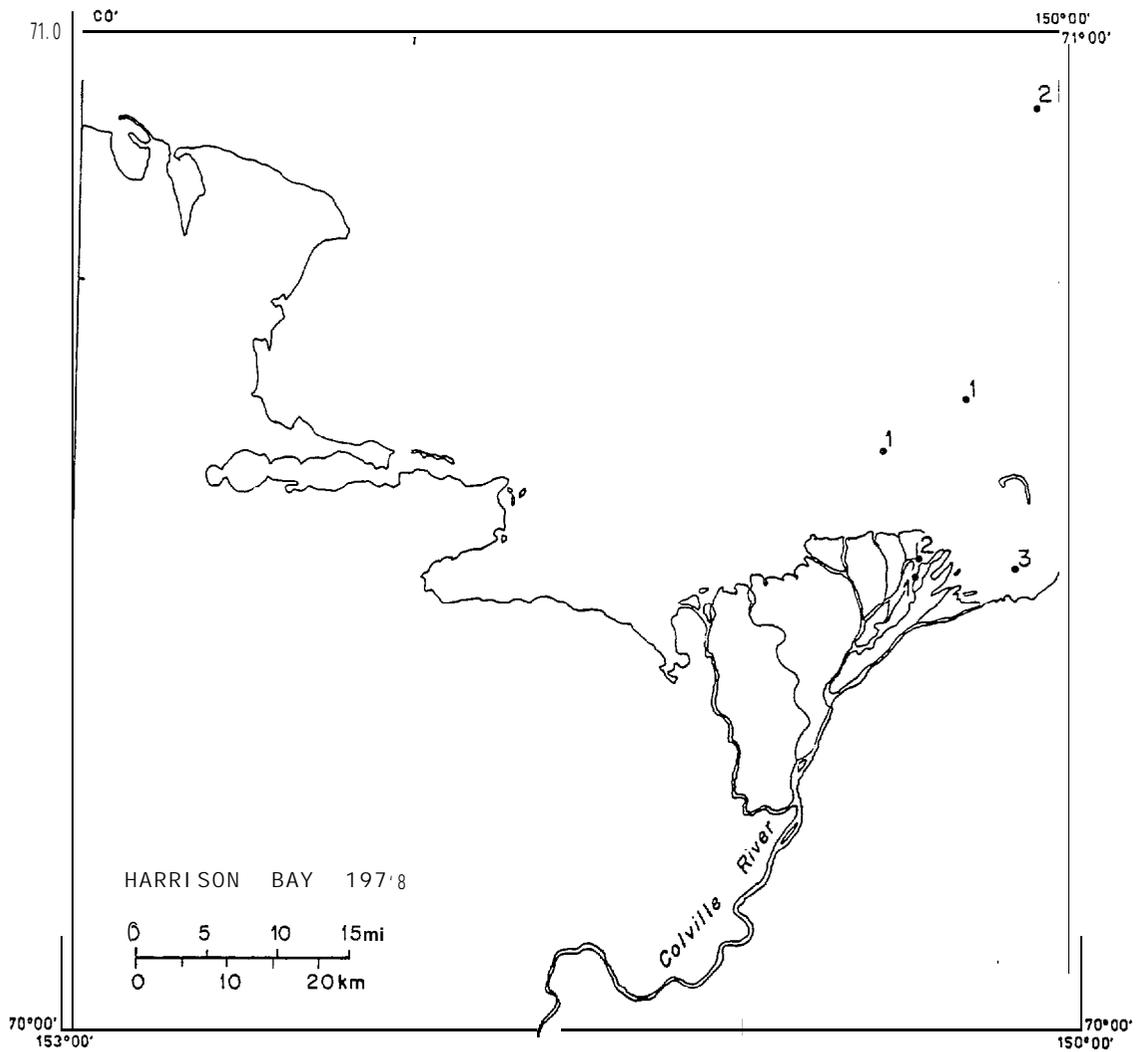


Figure 1A. Station locations and number of times occupied, 1978

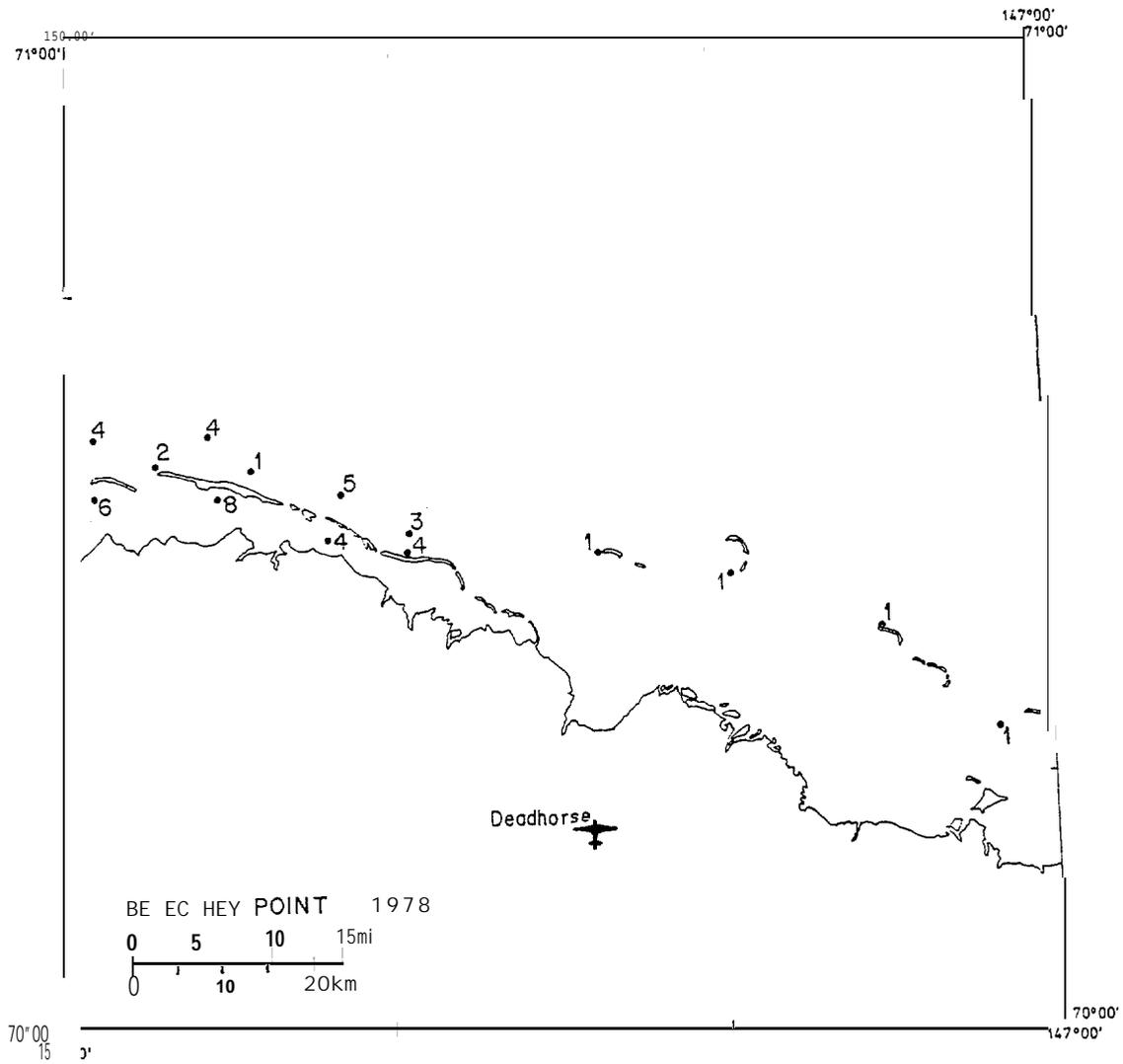


Figure 1B. Station locations and number of times occupied, 1978.

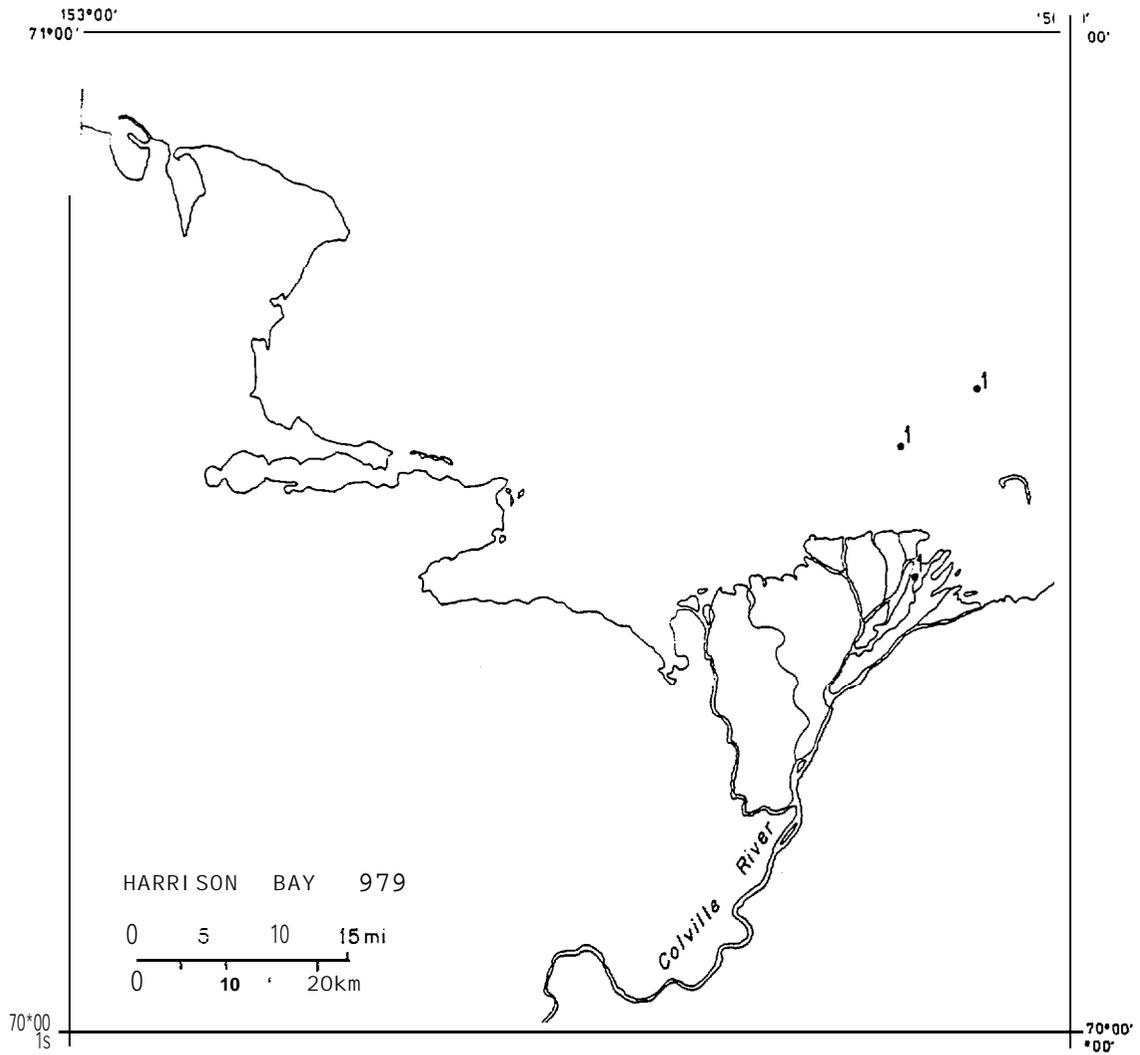


Figure 1C. Station Locations and number of times occupied, 1979.

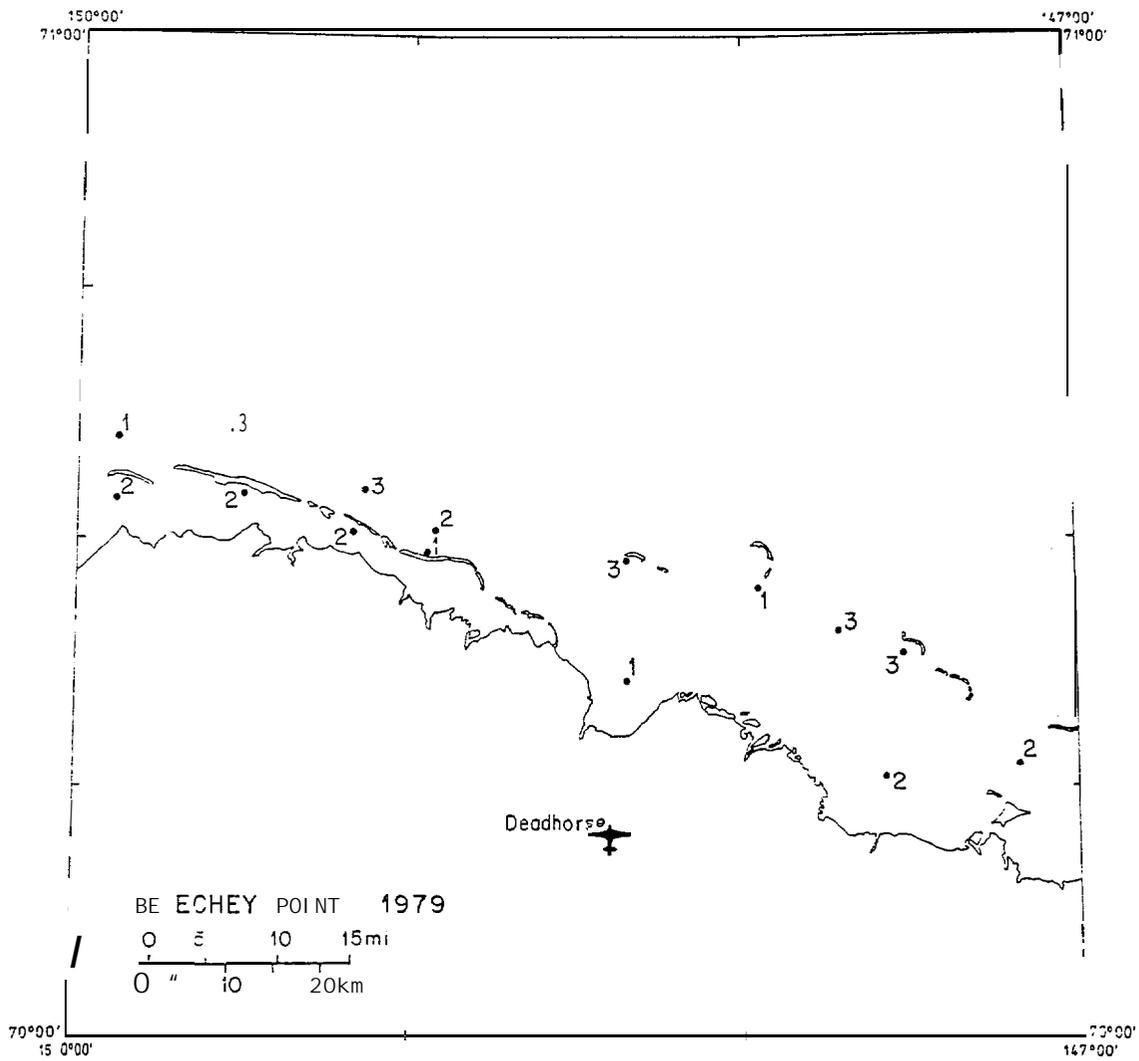


Figure 1D. Station locations and number of times occupied, 1979.

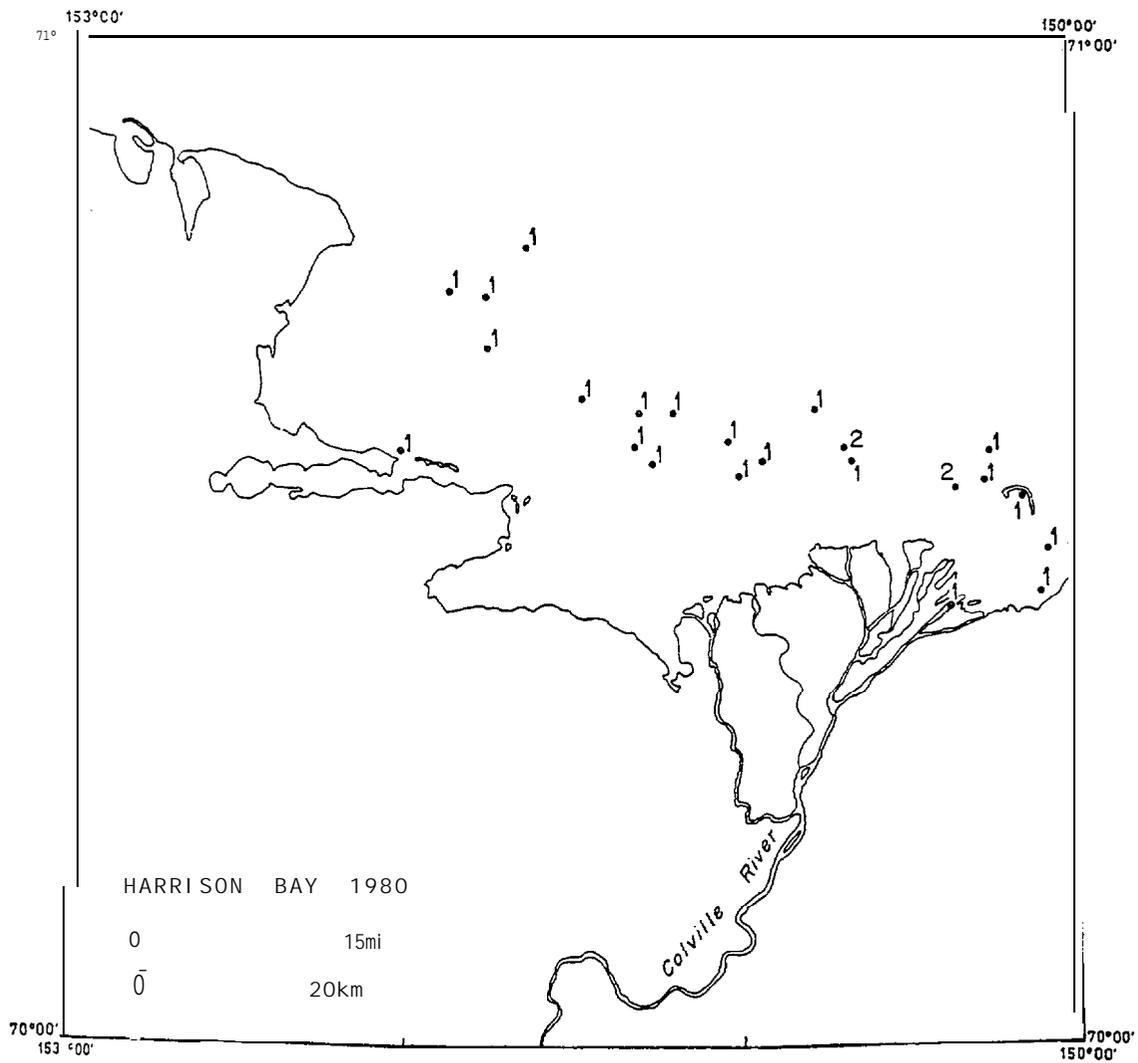


Figure 1E. Station locations and number of times occupied, 1980.

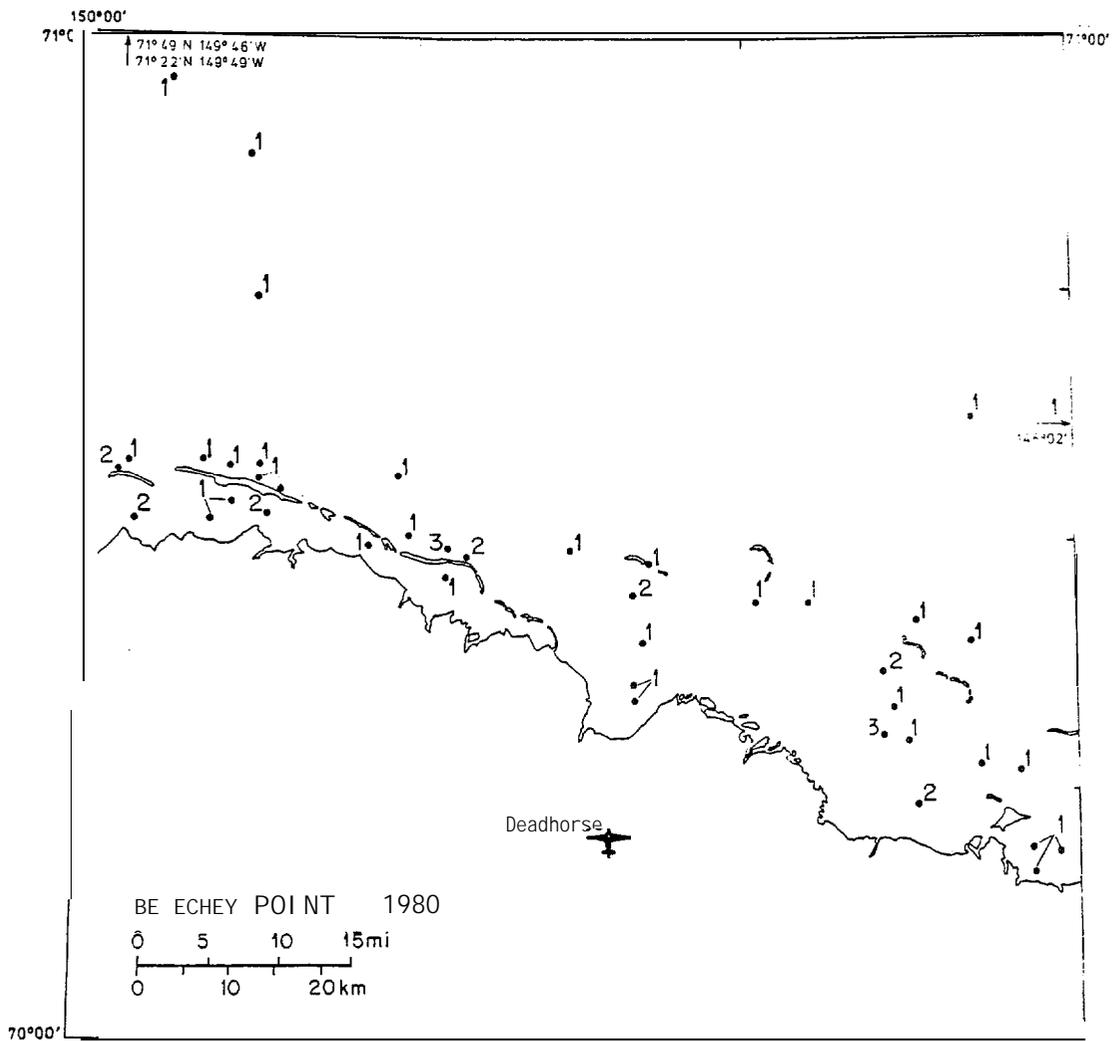


Figure 1F. Station locations and number of times occupied, 1980.

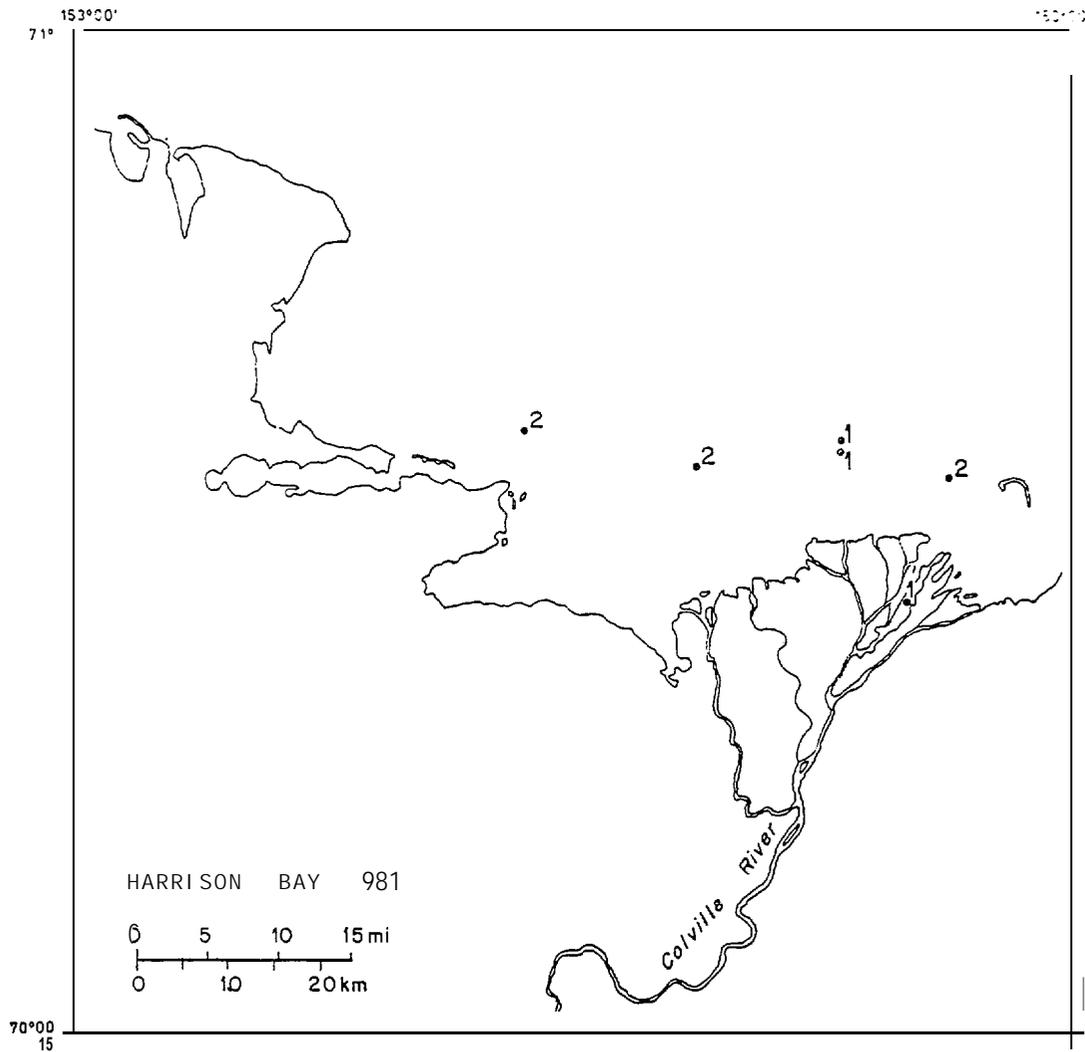


Figure 1G. Station Locations and number of times occupied, 1981.

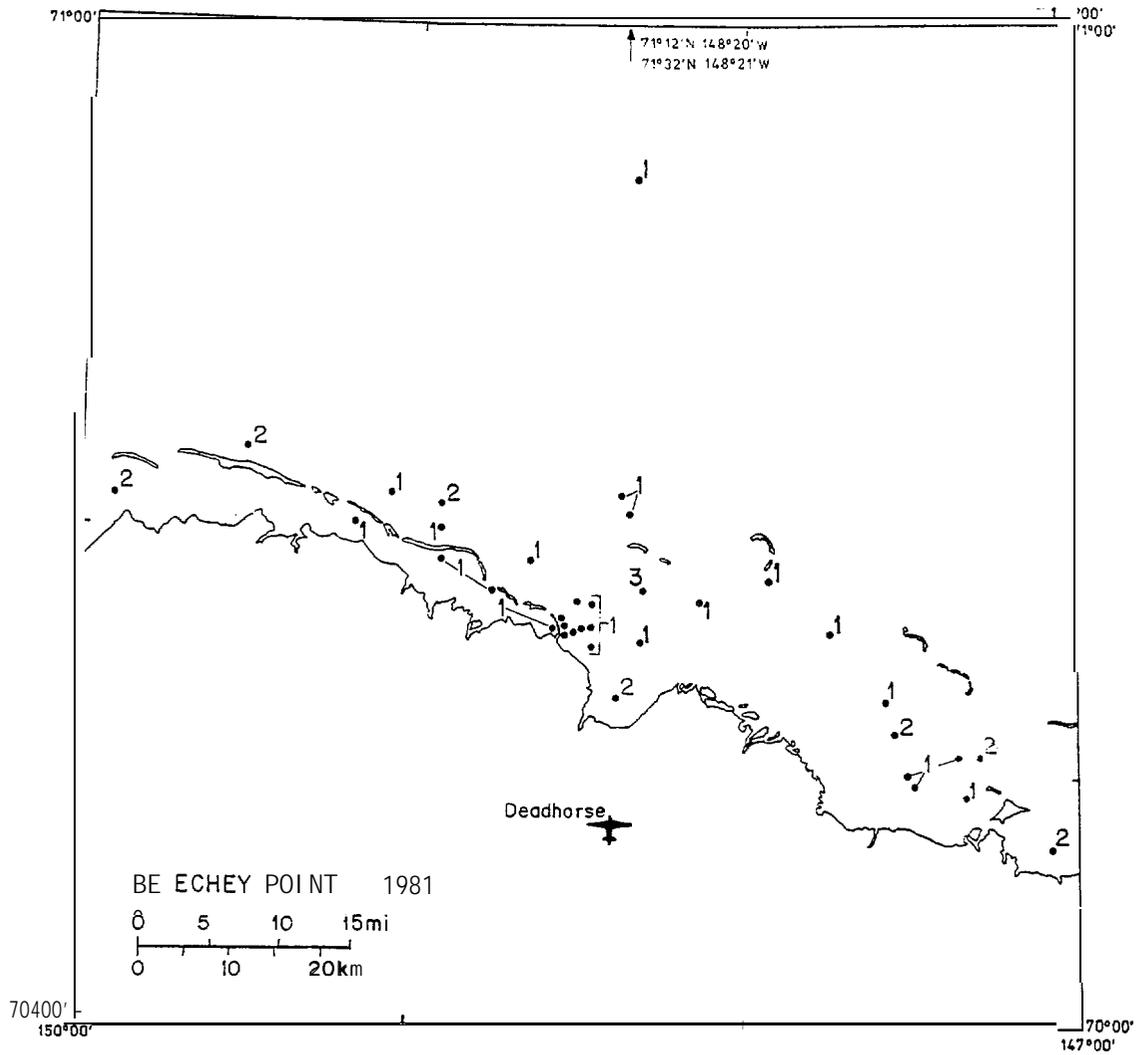


Figure 1H. Station locations and number of times occupied, 1981.

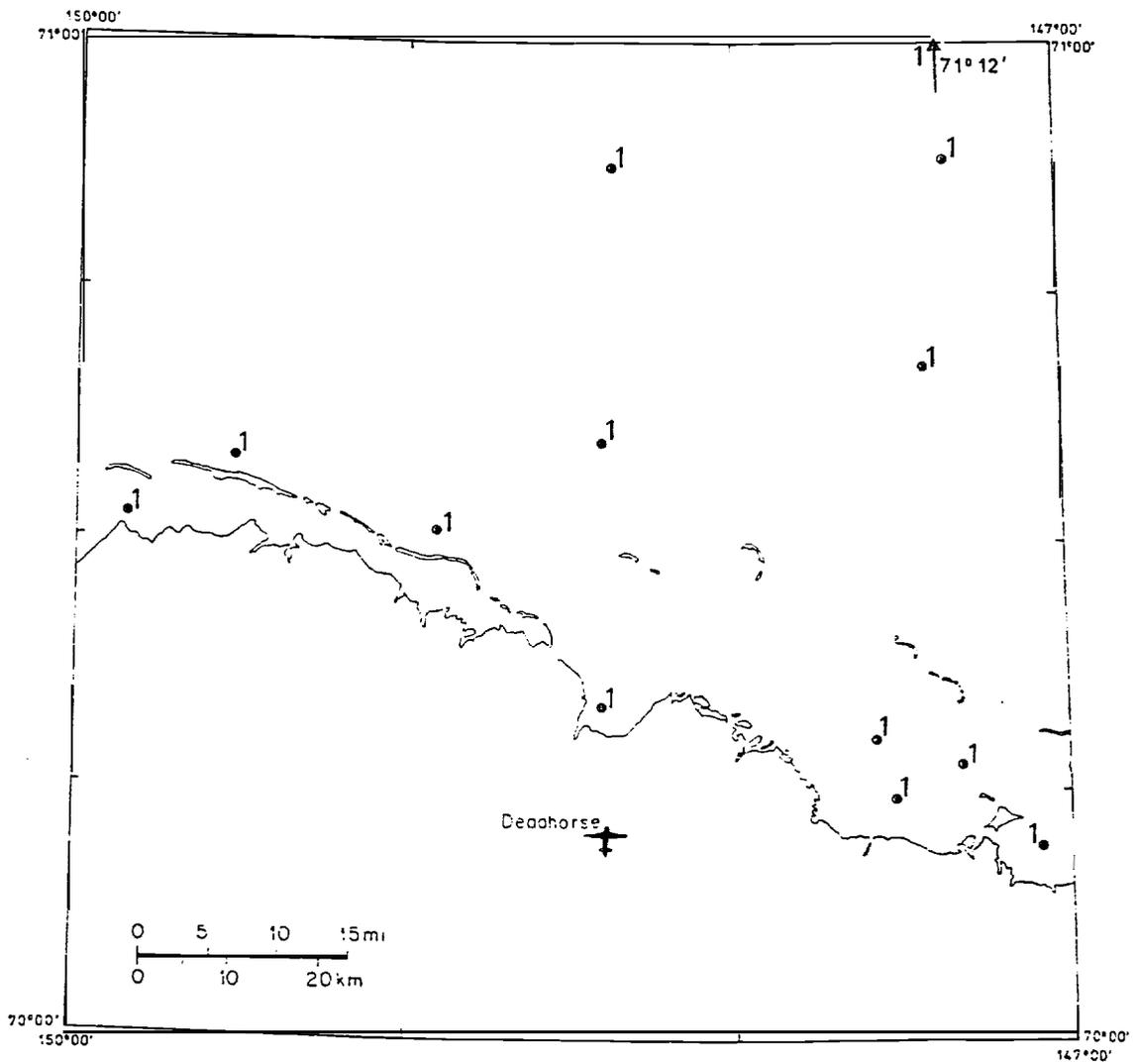


Figure 11. Station locations and number of times occupied, 1982.

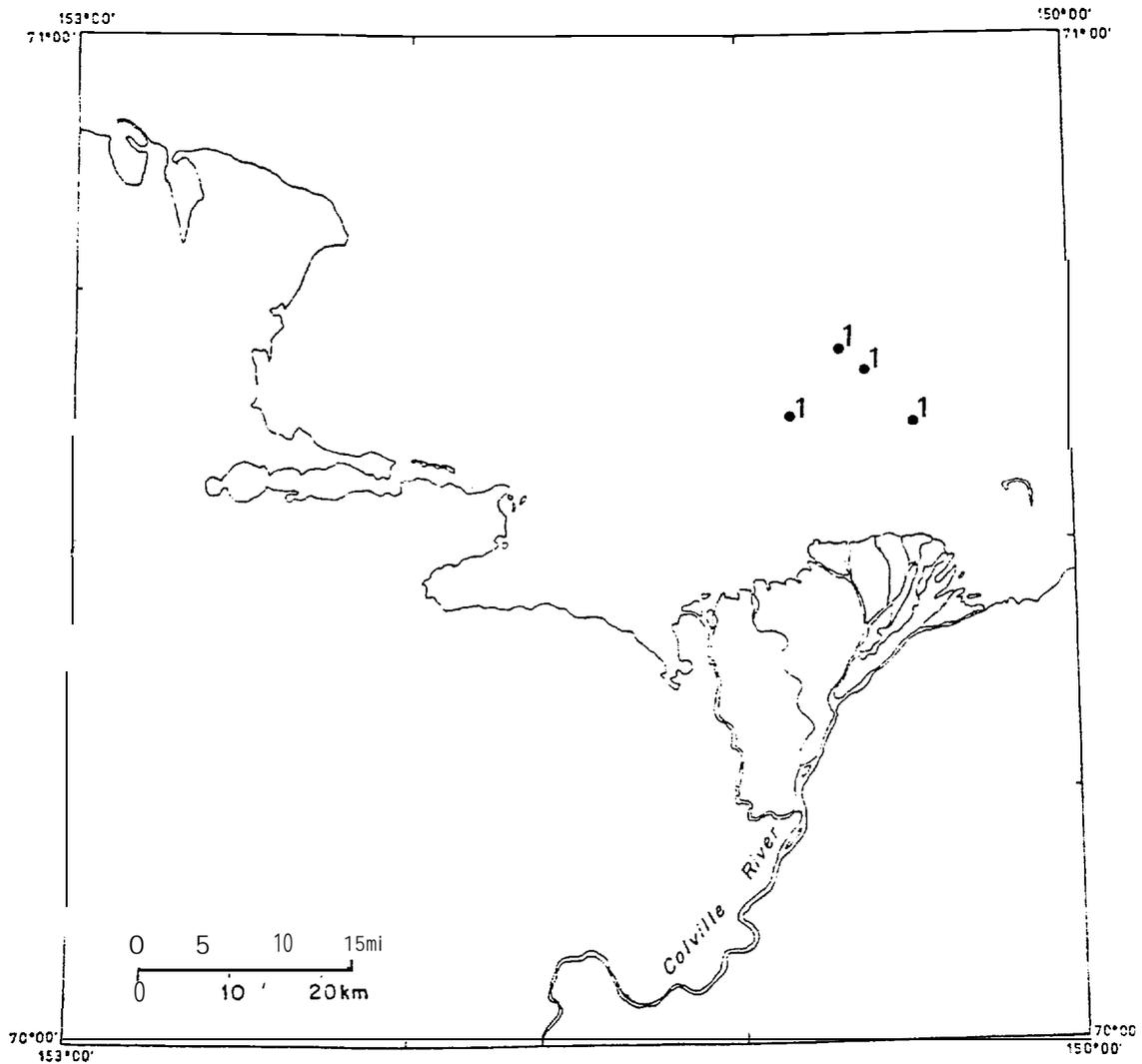


Figure 1J. Station locations and number of times occupied, 1982.

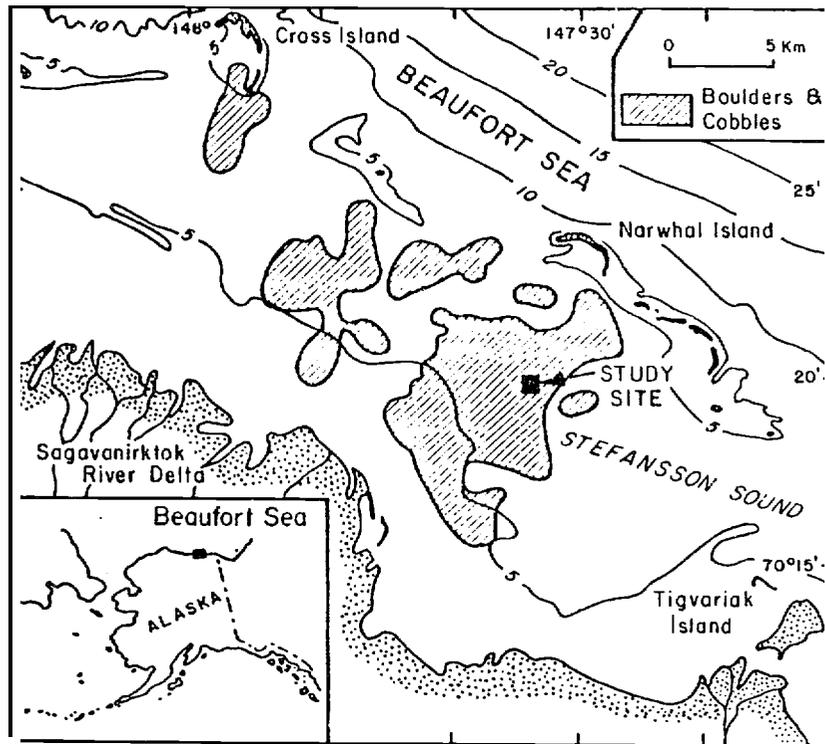


Figure 1K. Location of the Boulder Patch in Stefansson Sound (from Reimnitz and Ross, 1979). Depths in meters.

corrected for quench using a regression equation ($r = 0.98$) developed from the external standard channels ratios and the counting rates of standards of known quench. The photosynthetic rate was then calculated according to Strickland and Parsons (1972).

Annual Primary Production Estimates

Seasonal production was estimated by two methods: 1) integration of ^{14}C uptake rates over monthly intervals with a correction for ice cover; and 2) by calculating the biomass that could be supported through uptake of the available inorganic nitrogen. Since late-winter water column samples were characterized by high nitrate concentrations relative to ammonia, nitrate depletion was used as the principal indicator of uptake. Although there appears to be considerable variation in maximum nitrate concentrations in late winter from year to year, concentrations were sufficiently uniform spatially and with depth to allow area-wide extrapolation of uptake rates.

The ^{14}C uptake data used to calculate seasonal production have been summarized in Table 4. The major task in the extrapolation of integrated uptake rates over a wide area was to account for the variable ice cover and low solar angles over the summer. We used the data compiled by W. Stringer et al. (1981) to obtain average and dominant ice concentration data in the Harrison Bay-Prudhoe Bay area, and large-scale satellite imagery (Defense Meteorological Satellite Program)(see below) from the period 1978-1980 to establish ice-cover patterns over the entire Beaufort Sea region. Although cloudy weather prevented data acquisition over much of the summer, the generalized patterns of ice retreat were readily evident. Based upon these images, average ice retreat curves were drawn over a contour chart of the area. Integrated daily primary productivity rates were then multiplied by the period of open water available. Beneath ice cover, the light intensity was assigned a value of 10 percent of open water values based upon measurements made through offshore sea ice north of Narwhal Island in June and early June, 1980. An additional problem in calculating euphotic zone depths arises from the high incidence of cloudy, dark

weather and the effects of low solar angles on light transmission to deep water.

Instantaneous ^{14}C data were obtained by "correcting" the rates given by Homer, 1980. We assumed that the methodology employed, in which the filtered cells were rinsed with 0.01 HCl , resulted in a loss of about 25 percent of the photosynthate (Allen, 1971).

Nimbus-7 Coastal Zone Color Scanner (CZCS) and Defense Meteorological Satellite Program (DMSP)

The possibility of obtaining wide scale estimates of phytoplankton standing stocks in the Beaufort Sea through use of the CZCS led us to attempt to acquire imagery from the Beaufort Sea in 1981 and 1982. Beginning on 26 July 1981, weekly pictures were taken from north of Alaska and accumulated at the Scripps Remote Sensing Facility at the University of California. Unfortunately, very poor weather conditions prevented the acquisition of even one image of wide scale usefulness. Furthermore, ground haze and the extreme variations in reflectivity between ice cover and the sea surface complicated the areas which were relatively clear in the images. Although one of us (DP) has been trained in CZCS data processing, the very poor image quality obtained and sharp increase in computer facility costs at Scripps caused us to drop this approach in favor of using information from large scale imagery.

We were fortunate to have access to a comprehensive selection of Defense Meteorological Satellite Program (DMSP) imagery in the library of the Geophysical Institute, University of Alaska. By reviewing the images available over the period 1978-1980 we were able to estimate the "average" position of the ice edge during the summer months. We then used this information to calculate ice-free days for projecting euphotic zone depths.

Utilization of Detrital Carbon and Transfer Efficiency Determination

The magnitude of detrital carbon input to the nearshore zone of Simpson Lagoon (Figure 2) required that the effects of this energy source be evaluated with respect to the inputs of primary production. Detrital input occurs through essentially two sources -- coastal erosion and runoff from the tundra. Thus, assessment of these inputs becomes a geomorphological problem for the former source and a hydrological problem for the latter. Chemical data on the eroded tundra have been previously obtained by Schell (1975) and have been refined through additional work since beginning this study. Vertical profiles of newly exposed permafrost shoreline bluffs at Milne Point and Pingok island were obtained in August 1978. Additional profiles of carbon content in eroding peat were obtained along the Colville River and western Harrison Bay during summer 1980.

Refinements in shoreline erosion rates along the Beaufort coast were determined by Cannon and Rawlinson (RU 530). Total organic carbon data for the Colville River waters have been kindly provided by the U. S. Geological Survey (Charles Sloan, personal communication) and flow data are available from the literature (Arnborg et al., 1967; Walker, 1974).

The utilization of detrital organic carbon by heterotrophs and the further transfer of this carbon into the foodweb has been investigated through the use of carbon isotope ratios in the various coastal marine living and nonliving organic materials. Figure 3A shows the three fractions that can comprise the organic carbon of a detritivore or their predators. The analytical techniques employed to identify these fractions are shown in Figure 3B. If the carbon in the eroded peat materials of the shoreline is incorporated to a significant extent into heterotrophic microorganisms, and these are then consumed and assimilated by benthic invertebrates such as amphipods, isopods, and mysid shrimp, then isotopic abundances in the higher organisms should reflect this food source with some variation ($\pm 1^0/00$) due to biochemical fractionation. The data described below support this premise.

ENERGY SOURCES FOR SIMPSON LAGOON-BARRIER ISLAND ECOSYSTEM

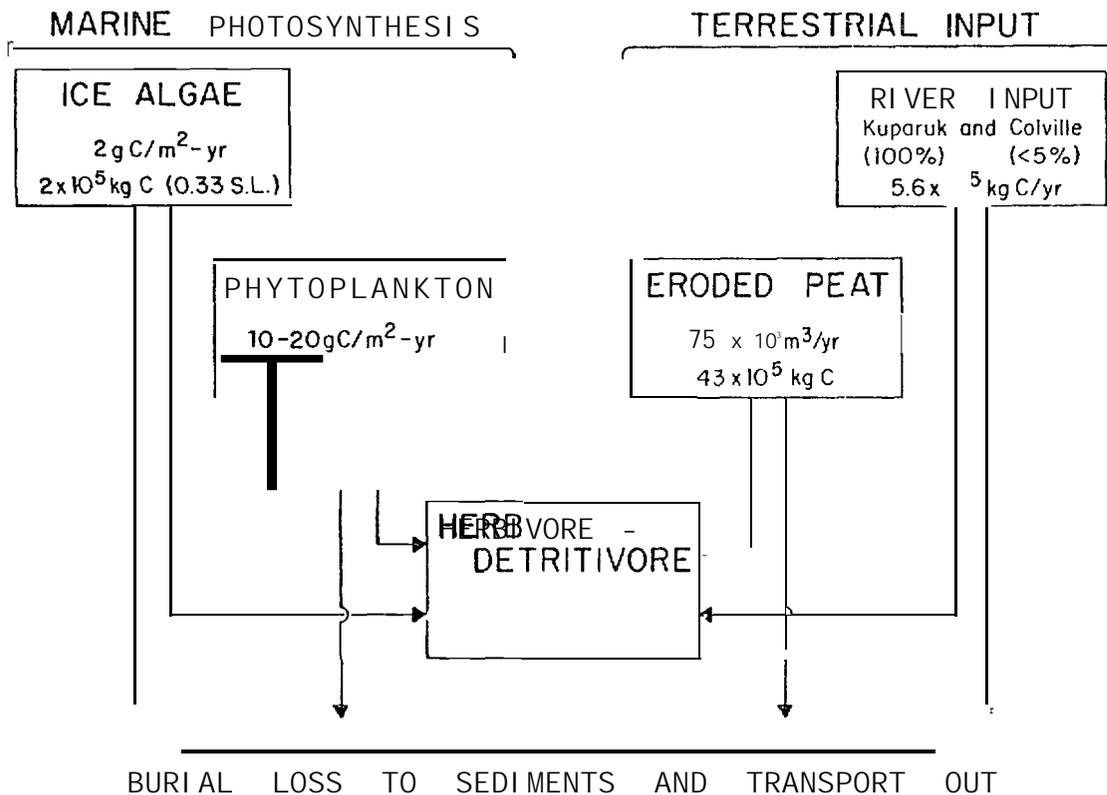


Figure 2. Box model of annual energy inputs to the Simpson Lagoon-Barrier Island ecosystem.

Stable isotope techniques allow the discrimination of food sources in ecosystems where the source materials (primary producers) have significantly different $^{13}\text{C}/^{12}\text{C}$ ratios. By comparing $^{13}\text{C}/^{12}\text{C}$

DETERMINATION OF HERBIVORE - DETRITIVORE CARBON SOURCE

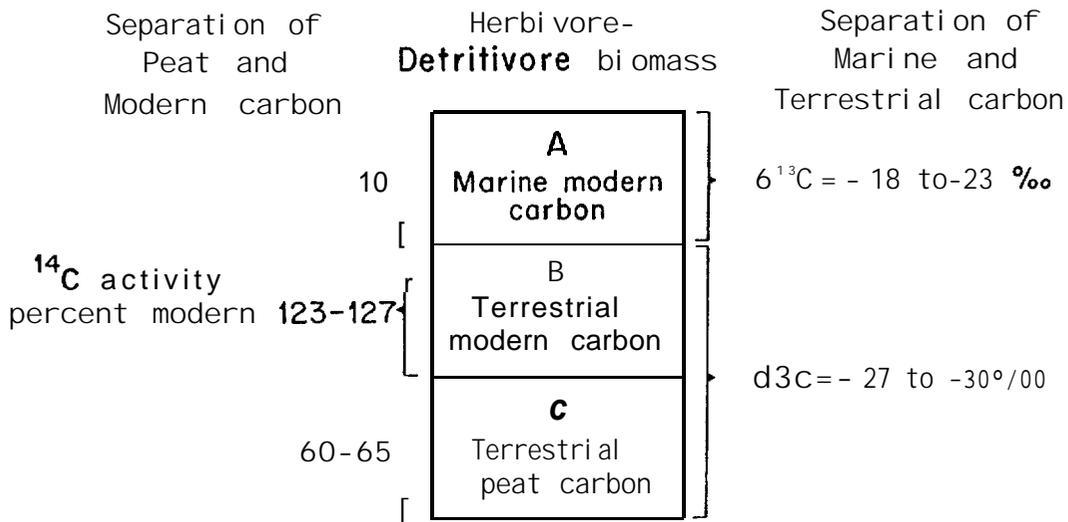


Figure 3A. Isotopic techniques for allocation of energy sources to consumers.

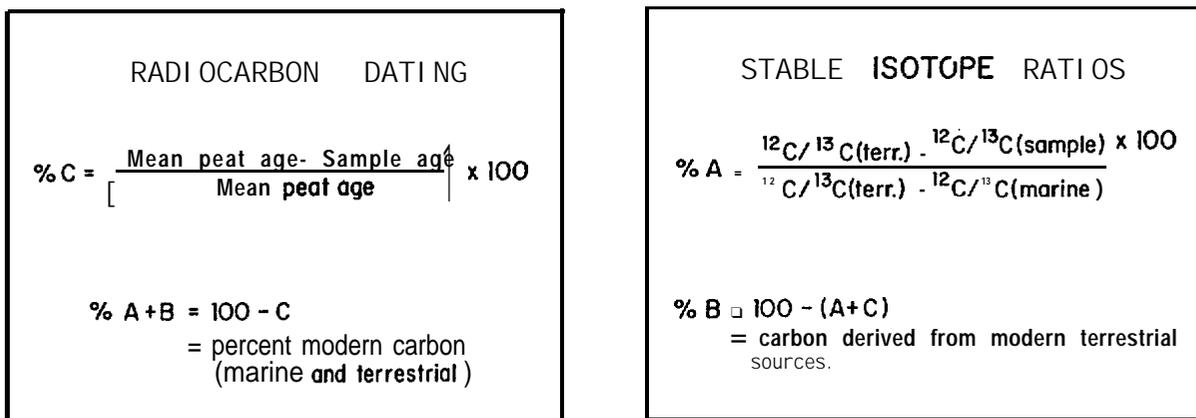


Figure 3B. Allocation of carbon fractions in Figure 3A.

ratios of organisms at different trophic levels, the food sources of the higher organisms can be apportioned. This technique has been used by McConnaughey (1978) to study the detrital input of eelgrass beds in Izembek Lagoon to the fauna of the lagoon and nearshore Bering Sea. Although the method is acknowledged to be less sensitive than ^{14}C dating, the applicability to modern carbon sources increases its desirability and analytical cost is low compared to ^{14}C dating.

Samples for stable carbon isotope and radiocarbon analyses were treated as follows.

Lake sediments: Samples were collected either by Ekman dredge or by cores pushed by hand into the bottom. Samples were sectioned horizontally in sufficient size to yield at least 5 g of carbon. After suspension in dilute hydrochloric acid to remove carbonates, samples were settled, decanted, rinsed with distilled water, and dried (70°C) in a vacuum oven.

Peat soils: Sample sites were chosen where erosion had exposed a fresh break in the permafrost. Pick and shovel were used to dig to undisturbed permafrost and a vertical section was made at 10 cm intervals from beneath the vegetation surface mat to basal mineral soils. In some cases, layers of mineral soils were interposed between peat layers, and the gradation into basal mineral soils was indefinite. Samples were kept frozen until returned to the laboratory where they were thawed and the moisture contents were determined. A subsample of the dry peat was ground to a powder for carbon, nitrogen, and phosphorus determination, and further subsamples were used for loss-on-ignition, radiocarbon content, and stable carbon isotope ratios.

Animal tissues: Organisms collected for isotopic analysis were kept frozen in sealed polyethylene bags until returned to the laboratory. After thawing, small organisms such as mysids, amphipods, isopods, lemmings, and *Daphnia* were dried whole in a vacuum oven (70°C). Since these animals were not acidified prior to combustion an error in $\delta^{13}\text{C}$ due to carbonate inclusions may have occurred in amphipod samples. Subsequent analyses have shown this error to be $+1.58$. Larger organisms such as fishes and birds were skinned, and the muscle tissue dried for analysis. Large animals such as caribou, bowhead whales, and seals were subsampled for muscle and fat tissue. The whale and seal oil

was rendered by heating to 80°C in a vacuum oven, and the oil poured off into a vial.

Vegetation: Fresh samples of aquatic and terrestrial plants were collected from the tundra at Milne Point and at Colville Village in the Colville River Delta. Samples were cleaned of foreign matter and dried.

Particulate matter: Samples of riverborne detritus were collected by suspending a 120 micrometer mesh plankton net in the Colville and Kuparuk rivers until sufficient material had been collected to assure 5 grams of carbon. No attempt was made to isolate any insect larvae or other living organisms from the collected material, since inspection did not reveal significant quantities present. Samples were dried in vacuo prior to analysis.

Carbon Isotope Analyses

All samples were sent to commercial laboratories specializing in radiocarbon analyses. Stable carbon isotope ratios were run on the same samples. Laboratory identification in the table of carbon isotope data (see Section VI) can be made from the second identification number with each sample: GX = Geochron Laboratories Division, Kreuger Enterprises, Cambridge Massachusetts; UM = University of Miami, Department of Geology, Miami, Florida; I = Teledyne Isotopes, Westwood, New Jersey; Beta = Beta-Analytic, Inc., Coral Gables, Florida. Radiocarbon activity was reported as percent modern normalized to $\delta^{13}\text{C} = -25\text{‰}$ to allow direct comparison among samples. Where the analytical precision was reported by the company, it is included in the data listing.

Cellulose Biodegradation Studies

Process studies to measure the rate of cellulose biodegradation in the under-ice waters of the Beaufort Sea were undertaken at the Naval Arctic Research Laboratory at Barrow. Water samples were collected at stations in Elson Lagoon, Smith Bay, and Dease Inlet. A big-tired truck

was used for transportation on Elson Lagoon ice and a Cessna 180 ski-equipped aircraft was used to sample the latter two locations. In July 1979, hand netting of amphipods was employed to collect specimens of *Gammarus setosus*.

A baited trap was set overnight in Elson Lagoon. Upon retrieval, approximately 200 *Onisimus* and *Boeckosimus* amphipods were captured. These animals were used to investigate their ability to digest cellulose through a series of experiments employing ^{14}C -labeled cellulose mixed with peat samples obtained from Simpson Lagoon. Similarly, the microbial activity in the detrital peat was studied by measuring the production of radiolabeled CO_2 from added ^{14}C -labeled cellulose. Samples of seawater were incubated with ^{14}C -labeled cellulose, and aliquots were taken at approximately 1-hour intervals. These aliquots were acidified and stripped with nitrogen to remove the carbon dioxide fraction, which was subsequently absorbed in phenethylamine liquid scintillation cocktail. These experiments, conducted at 0° and 20°C , showed active microbial decomposition and oxidation of the labeled cellulose, with the fastest rates occurring at 20°C .

To test the hypothesis that *Onisimus* and *Boeckosimus* spp. possessed intestinal microflora which were active cellulose degraders (and thus were able to symbiotically contribute to the nutrition of the amphipods), an experiment was conducted using freshly captured animals fed on radiolabeled cellulose. Animals were offered both carrier-free and a mix of labeled cellulose and peat aged in seawater. A control of peat plus labeled cellulose without amphipods was used to determine the oxidation rate due to microflora alone. At 12 hour intervals, animals were sampled, and aliquots of seawater were stripped for radiolabeled carbon dioxide as described above.

Similar experiments were repeated in July 1979 at the Naval Arctic Research Laboratory in cooperation with Dr. David Schneider (RU 356) to test if the known detritivorous amphipod, *Gammarus setosus* could utilize cellulose. Experiments were conducted as described above using both *G. setosus* and *Onisimus* spp. at 0° and 8°C . The intestinal tracts of the *G. setosus* amphipods were surgically removed and the radioactivity of the guts and bodies determined separately. Each sample of tissue was

TABLE 1: Percent moisture, loss-on-ignition, carbon, nitrogen, and phosphorus in Beaufort Sea coastline and Colville riverbank soils.

STAT 10N	LOCATION	DATE	DEPTH INTERVAL (cm)	SOIL MOISTURE (-----Percent)	LOSS ON IGNITION	CARBON	NI TROGEN of dry weight	PHOSPHORUS	
OCEAN POINT	70°4.3'N 151°22.5'W	5 AUG 80	0-10	35	8.7	3.0	0.14	0.09	
			20-30	61	15.4	6.8	0.37	0.08	
			40-50	118	26.5	15.7	0.69	0.07	
			60-70	171	26.0	10.9	0.74	0.08	
			110-110	148	15.5	6.2	0.39	0.08	
			130-140	44	6.2	2.1	0.15	0.09	
ATIGARU POINT	70°33.3'N 151°42.1'W	6 AUG 80	0-10	71	26.1	9.9	0.89	0.04	
			20-30	23	8.9	6.1	0.24	0.03	
			40-50	6	1.6	0.7	0.17	0.04	
CAPE HALKETT	70°48.0'N 152°10.0'W	6 AUG 80	0-10	393	50.0	33.3	2.24	0.18	
			10-20	66	16.2	4.5	0.51	0.06	
SENTINEL HILL	69°51.0'N 151°36.0'W	5 AUG 80	0-10	30	38.7	17.9	1.03	0.07	
			50-60	166	74.0	31.1	2.00	0.04	
			180-190	424	56.0	31.2	2.24	0.05	
ESOOK	70°08.1'N 152°33.8'W	5 AUG 80	0-10	57	3.5	5.1	0.49	0.07	
			20-30	167	8.5	22.2	1.80	0.06	
			50-60	26	2.3	1.6	0.04	0.07	
MILNE	70°31.0'N 149°27.6'W	9 AUG 78	0-10	71	35.6	19.6	1.13	0.03	
			30-40	57	38.6	20.8	1.15	0.03	
			60-70	320	55.1	25.2	1.46	0.03	
			90-100	436	84.5	37.8	2.33	0.02	
			120-130	216	42.6	19.5	1.12	0.03	
			150-160	258	57.7	28.2	1.59	0.02	
			*160-170	135	35.8	18.1	0.88	0.02	
PEAT ISLAND	70°34.2'N 149°34.4'W	9 AUG 78	0-10	40	15.1	5.1	0.57	0.02	
			30-40	250	71.4	34.5	2.07	0.01	
			50-70	373	33.3	15.5	0.85	0.03	
			90-100	350	33.2	16.0	0.83	0.03	
			120-130	148	19.6	9.0	0.47	0.03	
			*150-160	279	64.3	32.4	1.82	0.03	
			(BASAL PEAT)						
			170-180 (BASEMENT MINERAL)	256	4.0	3.4	0.06	0.04	
SAGAVANIRKTOK RIVER	70°04.1'N 149°38.0'W		*BASAL PEAT	104	20.1	13.1	0.77	0.02	

*Radiocarbon dates determined.

oxidized with a Harvey Biological Oxidizer to carbon dioxide. The labeled gas was collected quantitatively in phenethylamine cocktail for scintillation counting.

Composition of Peat Soils

Peat soil samples were oven dried at 105°C for 8-10 hours to determine moisture content. Subsamples of 2-6 g were weighed in tarred crucibles, and combusted in a muffle furnace for 3 hours at 550°C, and reweighed to determine the loss-on-ignition. A longer combustion time was found to have no effect on the loss of weight. Subsamples of 10-100 mg were also combusted in a LECO TC-12 Automatic Carbon Determinator to measure the percent carbon content. Total nitrogen and total phosphorus in peat samples were determined on a Technicon II Autoanalyzer following Kjeldahl digestion.

The results of the carbon, nitrogen, phosphorus, and organic matter (as loss-on-ignition) analyses are listed in Table 1. The average for 33 peat soil samples is $16.0 \pm 11.1(\pm 1)$ percent carbon. A plot of percent carbon vs. percent loss-on-ignition fits the regression equation

$$y = 0.475X + 0.14 \quad (r = 0.97)$$

where y is the percent carbon, and x is the loss-on-ignition. This yields an ash-free dry weight (AFDW) carbon content of 47.5 percent. although the temperature is high enough ($\sim 400^\circ\text{C}$) to remove CO_2 from some carbonates and water from clays, the y -intercept of almost zero and the excellent fit of the equation imply that these effects on the loss-on-ignition are small in these peaty soils. It is reasonable then that our equation should be similar to that of Ball (1964)

$$y = 0.458x - 0.4$$

in which the loss-on-ignition was determined by combusting a variety of soils at 375°C for 16 hours. This relationship will allow the estimation of carbon content in our future soil samples by measuring the

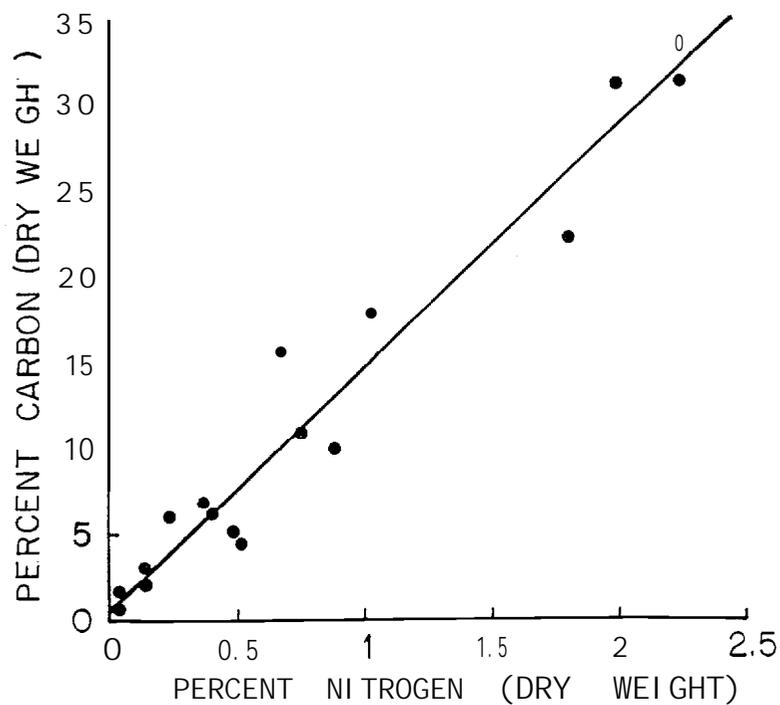


Figure 4. Carbon-nitrogen relationships in coastal and riverbank soils.

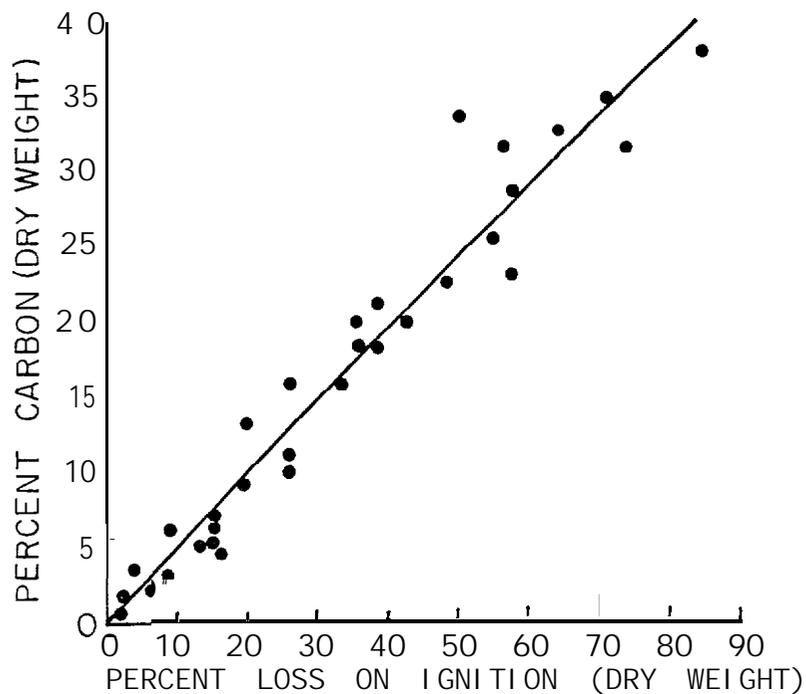


Figure 5. Loss-on-ignition and percent carbon in peat soils.

Loss-on-ignition. A plot of the percent carbon vs. percent nitrogen yields the regression equation

$$y = 14.0x - 0.75 \quad (r = 0.98)$$

where y is the percent carbon, and x is the percent nitrogen. The organic matter of these samples is, therefore, 3.4 percent nitrogen with a C:N atomic ratio of 16.3:1. The data on C:N relationships and loss-on-ignition versus carbon content are shown in Figures 4 and 5.

Chemical Analyses for Total Dissolved Phosphorus and Total and Dissolved Phosphate

A limited study of phosphate uptake kinetics was performed in 1978 in Simpson Lagoon to test if peat detritus was actively taking up phosphate from the overlying water column. Portions of bottom and surface water were analyzed for total and dissolved inorganic phosphate by the calorimetric method of Murphy and Riley (1962). The total phosphorus procedure involved a persulfate oxidation step to convert all of the phosphorus present to phosphate prior to calorimetric analysis (Gales et al., 1966). Total (persulfate labile) phosphorus was also determined on weighed portions of oven-dried peat.

Radiophosphate Uptake Measurement

For analysis of radiophosphate (^{32}Pi) uptake rates in seawater, samples of water from Simpson Lagoon (9 August 1978), and peat-amended seawater in duplicate 250 ml subsamples were removed from five gallon carboys and placed into glass bottles which had been carefully washed and pre-rinsed with the appropriate water.

To the duplicate 250 ml subsamples, amounts to equal final concentrations of 0.2 μM phosphate (^{31}Pi) plus 0.05-0.1 microcuries of ^{32}Pi were added (Rigler, 1966). Controls were poisoned with three drops of 10^{-2} M mercuric chloride, and all were incubated under

constant illumination. At intervals (from 10 minutes to one day after the addition of ^{32}Pi and ^{31}Pi), 10 ml aliquots were removed and passed through 0.45 micrometer membrane filters using a constant suction of 400 mm Hg. The filters were placed in 10 ml of toluene-Triton X-100 counting cocktail, and the radioactivity was measured in a liquid scintillation counter to give (after correction for background radiophosphorus on the filter and subtraction from the total ^{32}Pi added), the amount of radiophosphorus in solution at different times after the addition.

Phosphate Uptake Rate Determinations

The rate of ^{32}Pi uptake (v^*) was determined as a function of either exponential (first order) or linear (zero order) ^{32}Pi removal from solution according to Brown et al. (1978). The rate of ^{31}Pi uptake (v) was then calculated from

$$v = v^* \frac{S_n + A}{C}$$

where S_n was the indigenous ^{31}Pi level, A was the added ^{31}Pi level at time zero, and C was the total added ^{32}Pi at time zero.

Salinity Determination

Salinities were determined using a Grundy Model 6230 N salinometer to measure the conductivity ratios.

Light and Ice Sediment Load

Light measurements were made above and beneath the ice using a Photomatic light meter. Ice cores were collected with a 75 mm SIPRE corer and water samples were taken with a Van Dorn sampler. Sediment and ice algal layers observed in cores were sectioned, melted, and

filtered onto precombusted, preweighed, Whatman 47 mm, glass fiber filters. When sediment content was high, the sample was well stirred to suspend the sediment, and an aliquot was removed for filtration. Filters were dried at 105°C for 8 hours and weighed to determine the amount of sediment. They were then placed in a dessicator with concentrated HCl and fumed for 4 hours to remove carbonates, reweighed, and combusted in the LECO Carbon Determinator to measure the carbon content. The change in weight caused by fuming was negligible.

Chlorophyll-a and Phaeopigments

A Turner Designs Fluorometer (Model 10-005) was used to measure the in vivo fluorescence in sectioned and melted cores. The melt water was then filtered on Gelman Type A/E 47 mm glass fiber filters with a few drops of MgCO₃ suspension added as a preservative. The filters were folded in half, placed in glassine envelopes, and frozen for subsequent pigment extraction.

The extraction procedure and equation for calculation of chlorophyll-a were those of Strickland and Parsons (1972), and the calculation for phaeopigment was that of Lorenzen (1966).

Chlorophyll-a concentration was determined with the Turner Designs fluorometer that was cross calibrated against a Beckman DB and later a Bausch and Lomb Spectronic 2000 spectrophotometer. The equation used to determine chlorophyll-a spectrophotometrically was

$$C = 11.6 \left(\frac{E_{665}}{E_{645}} - 1 \right) \left(\frac{E_{665}}{E_{630}} - 1 \right)$$

where C is the chlorophyll-a in micrograms and E is the extinction at the indicated wavelengths.

The equation used to determine phaeopigments was

$$\text{mgP/m}^3 = \frac{F_o/F_a \text{ max}}{F_o/F_a \text{ max} - 1} (K_x) [F_o/F_a \text{ max}(F_a) - F_o]$$

where F_0/F_A max is the maximum chlorophyll a:phaeopigment fluorescence ratio (2.0), F_0 is the fluorometer reading before acidification, F_A is the fluorometer reading after acidification, K_x is the calibration constant, and V is the volume of water filtered in liters (Lorenzen, 1966). K_x was calculated from the chlorophyll data.

Field Logistics for Boulder Patch Studies

During the open-water period, sample was carried out from a 6 m Boston Whaler (the R.V. Arctic Char; National Oceanic and Atmospheric Administration). During ice covered periods most of the diving occurred at an acoustically marked study site, 'Dive Site 11 (DS-11; 70°19.25'N, 147°35.1'W; Figure 1k), where divers entered the water through holes cut in the ice using augers and ice chisels. Ice blocks were removed by helicopter or multiterrain vehicle (Rolligon). A heated insulated hut (Parcoll, Panebec Ltd., Montreal) placed over the dive hole functioned as a dive shelter and laboratory. Each diver wore a dry suit, a primary and backup breathing system, and headphones for wireless underwater communication with the surface (UDI-SUBCOM, Aberdeen, Scotland). Liquid silicone injected into the barrel of the first stage of the regulator prevented freezeups in the breathing system, especially when diving without a shelter. Divers were tethered to the surface and usually limited to a 25 m radius of the hole, although occasional ventures were made up to 50 m distant for short periods under special circumstances.

Primary Production in *Laminaria solidungula*

Linear growth of *Laminaria solidungula*, the predominant kelp, was followed by punching holes in the base of the blade, above the meristematic region (Chapman and Craigie, 1977). Production-to-biomass ratios were calculated to determine the total carbon input made by the brown algae to the marine environment. Since *L. solidungula* constitutes over 90% of the brown algal biomass, we focused on the productivity of this plant. The blade of *L. solidungula* is divided into distinct ovate segments of different sizes by constrictions that form annually. The

growth of a new basal blade segment starts in November and continues until the following November. Since attrition occurs at the distal portion of the blade, the biomass of the basal segment is an accurate measurement of the plant's annual production. Seventeen plants, weighing between 1.5 and 33 grams, were carefully detached from their substratum in November 1979, and banded to a large plastic Vexar cage anchored to the seafloor for one year. Following retrieval of the cage in November 1980, the new basal segments of the plants were individually removed and weighed. These wet weights represented the annual production of the plant. The average annual production-to-biomass (P:B) ratio was obtained by dividing the biomass of the first blade segment by the initial plant weight. The percentage of dry weight to wet weight was determined by drying algal tissue in an oven at 30°C for 48 hours. The plants used for wet weight to dry weight determinations were collected haphazardly by divers at DS-11.

VI. RESULTS AND DISCUSSION

Ice Algae Distribution and Production

Prior to last year, it had been assumed that the low light intensities and rapid rate of ice accretion in the nearshore Arctic effectively prevented the appearance of a fall ice algal bloom, although freeze-up blooms were known to be an annual occurrence in the Antarctic. The Southern Ocean begins to freeze over a month earlier in the solar year, and the higher light intensities and very light snow cover readily account for the bloom. Logistically, the later freeze-up in the Arctic and thin ice cover prevented access to offshore ice and hindered ice algae research during this period of the year.

In cooperation with Dr. Mitsuo Fukuchi of the Japan Polar Research Institute, we were able to core new sea ice north of Narwhal Island and discovered a pronounced ice algal bloom on 7 November 1980. Vertical chlorophyll *a* concentrations and associated nutrient concentrations in the underlying water are given in Table 2. The appearance of this bloom

TABLE 2. Fall ice algae samples, 9 November 1980.
 Station Location: Narwhal Island, 70°25.3'N, 147°27.6'W

<u>Core NI-1</u>			<u>Core NI-2</u>		
<u>Ice Depth</u> (cm)	<u>Chl orophyll I -a</u> (mg/m ³)	<u>Phaeopigments</u> (mg/m ³)	<u>Ice Depth</u> (cm)	<u>Chl orophyll I -a</u> (mg/m ³)	<u>Phaeopigments</u> (mg/m ³)
1-7	0.9	0.5	0-8	0.8	0.5
7-14	0.1	0.1	8-16	1.1	0.5
14-20	2.0	0.4	16-23	2.2	0.4
20-25.5	7.4	2.3	23-30	20.5	5.0
25.5-31	87.7	1.9	30-34	7.1	1.2
20-31	3.9 ⁽¹⁾	0.2 ⁽¹⁾	23-34	1.4 ⁽¹⁾	0.3 ⁽¹⁾
20-31	195.0 ⁽²⁾		23-34	70.0 ⁽²⁾	
<u>Core NI-3</u>			<u>Core NI-4</u>		
0-7	1.2	0.4	0-10	1.0	0.3
7-13.5	2.4	0.1	10-20	1.4	0.2
13.5-20.5	3.5	1.5	20-27	2.6	0.6
20.5-27	3.2	0.1	33-38	101.9	4.9
13.5-27	0.4 ⁽¹⁾	0.1 ⁽¹⁾	27-38	4.7 ⁽¹⁾	0.4 ⁽¹⁾
13.5-27	20.0 ⁽²⁾		27-38	235.0 ⁽²⁾	

(1) Sum of bottom two intervals expressed as mg/m².

(2) Biomass (mg C/m²) calculated as 50 x chl-a.

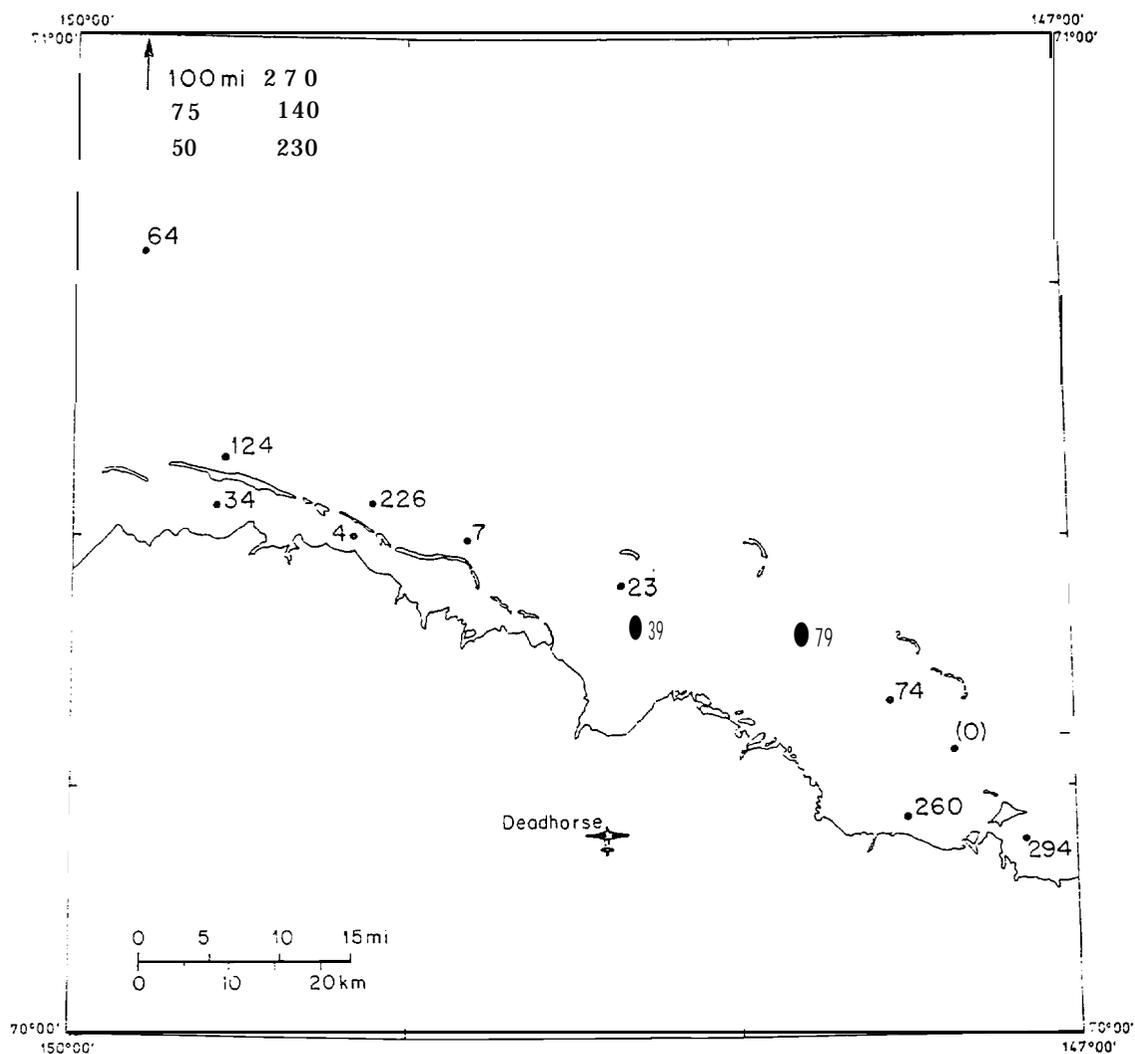


Figure 6. Ice algae standing stocks, May 1979. Values shown are estimates of plant carbon (mg C/m^2) determined from chlorophyll concentrations. Offshore stations (upper left) are measured from the shoreline.

may not be an annual occurrence in that an unusually warm spell of weather had preceded the sampling date and may have retarded ice growth sufficiently to allow development of the bloom. Normal ice accretion rates are on the order of 1 cm/day and it is hard to conceive of a dense algal bloom having time enough to form under these conditions. This bloom (fall 1980) was not as large as the spring ice algal bloom, and the observed chlorophyll-a concentrations were about 10 percent of maximum concentrations in May, corresponding to about 0.2 g C/m² standing stock. No data are yet available as to spatial or annual variability in the fall bloom, and further investigation of this phenomenon is a high priority for future studies. Lack of logistic support prevented any sampling in November 1981.

The major field effort in spring 1979 was directed toward obtaining a representative number of ice algal samples such that standing crop estimates could be projected for the lease area. Sixteen stations were occupied with triplicate cores obtained from each site. One transect was run approximately 100 miles north of the lease area to attempt to delineate trends in distribution with distance from shore. In addition, visual observations were made along lead and pressure ridge systems to obtain qualitative information regarding ice conditions and ice algae presence. The cores obtained were used to estimate standing stocks as described above and the data obtained are shown in Figure 6. The Stefansson Sound area showed the greatest variability in standing crops as might be expected from the large patches of turbid ice.

Offshore, the ice algae generally increased although patches of turbid ice were visible as far as 25 miles offshore. Along lead systems, overturned pieces of annual sea ice were often heavily discolored by algal populations. A general observation was that algae were present on ice of sufficient thickness (>1.0 m) such that the sheet represented all or most of the winter freezing season. No ice algae were visible on thin sheets which represented ice less than 2 months old. Cores cut from the fast-ice sheet near the open leads off Harrison Bay had dense populations and may represent a large area of uniformly high populations.

Closer to shore, the variability in algal biomass sharply increases. Simpson Lagoon was sampled at only two locations, but in

TABLE 3. Carbon content, sediment load, and light penetration in coastal Beaufort Sea ice. Intervals are for visible sediment bands.

Station	Date	Location	Ice depth (cm)	Snow depth (cm)	Integrated ice sediment load (g/m^2)	Percent surface light	Ice depth interval (cm)	Sediment load* (g/m^3 of ice)	Percent carbon in sediment (dry weight)
PB	12 APR 81	70°19.7'N 148°22.4'W	150	20	42	0.001	0-27	99	4.0
HB1	12 APR 81	70°36.0'N 151°38.0'W	170	20	145	0.0001	0-20 32-34, 53-57, 59-68, 97-102	390 125	5.8 3.2
HB2	12 APR 81	70°33.9'N 151°08.0'W	150	20	104	0.003	27-31 12-14, 20-22, 33-36	1660 325	3.2 4.1
8	14 APR 81	70°31.0'N 148°55.0'W	160	20	21	0.200	19-21	247	4.6
15	14 APR 81	70°26.4'N 148°19.0'W	160	20	51	0.084	22-88	53	7.0
18	13 APR 81	70°16.7'N 147°17.3'W	160	30	53	0.001	17-28 28-40	64 250	7.0 3.1
BP	13 APR 81	70°18.0'N 1117°32.3'W	160	25	86	0.001	10-100	77	7.4
2	14 APR 81	70°35.1'N 149°28.6'W	160	20	26	0.290	15-20	196	3.7
3	14 APR 81	70°32.0'N 149°51.7'W	130	25	13	0.110	----	----	----
19	13 APR 81	70°11.0'N 147°03.0'W	150	15	15	0.067	----	----	----
20	13 APR 81	70°14.2'N 147°29.8'W	150	25	15	0.021	----	----	----
12	14 APR 81	70°33.3'N 150°21.6'W	160	10	16	0.150	----	----	----
13	12 APR 81	70°34.9'N 151°41.4'W	170	20	17	0.270	----	----	----

* Clear ice, not listed, averaged less than $10 \text{ g}/\text{m}^3$.

TABLE 4. Carbon content and particulate load in coastal Beaufort Sea ice. Intervals are for visible sediment bands.

Station	Date	Location	Ice Depth Interval (cm)	Particulate load ₃ (g/m ³ of ice)	Percent carbon in particulate matter (dry weight)
19-2	30 MAY 81	70°11.1'N 147°03.0'W	154-160 (bottom of ice)	41*	14.6
HB1-3	31 MAY 81	70°36.2' N 151°38.4'W	166-170	150*	18.7
HB2-1	31 MAY 81	70°34.2'N 151°08.3'W	164.5-170 (bottom of ice)	64*	11.8
TR1	2 JUNE 81	70°32.1'N	148-155	110	2.4
TR1-2		148°23.3'W	107-110	122	3.9
TR2-3B	2 JUNE 81	70°52.6' N 148°22.2'W	143.5-150 (bottom of ice)	48*	16.6
TR2-5B			142.5-150 (bottom of ice)	77*	13.8
3-2	31 MAY 81	70°32.1'N 149°52.0'W	165.5-170 (bottom of ice)	66*	10.4
12-2	31 MAY 81	70°33.4' N 150°21.5'W	135-140 (bottom of ice)	55*	8.2

*Predominantly ice algae. Clear ice (not listed) averaged less than 10 g/m³.

both cases, algal populations were much lower than immediately outside of the barrier islands (see Figure 6). The ice in the lagoon was clear, but salinities in the underlying water were over 40‰ and may have been partially responsible for the low plant densities. Assuming that the water was at or near the freezing temperature, this would indicate ambient temperatures of about -2°C which may also inhibit growth.

Stefansson Sound yielded cores with plant biomasses ranging from nearly undetectable to almost 0.3 g C/m^2 in Mikkelson Bay beneath clear ice. Most of the central area of Stefansson Sound and Prudhoe Bay had less than 0.1 g C/m^2 beneath the ice.

The light measurements listed in Table 3 were taken at the same stations as the ice algal samples, but a month earlier and not at identical locations. They do not, therefore, describe light conditions at the place or time of ice algal sampling, but serve to illustrate the range of variability in light penetration through the ice. The presence of winter snow cover is sufficient to decrease incident light to about 0.5-1.0 percent of that striking the snow surface, but the presence of even small amounts of particulate matter in the ice causes the rapid extinction of light to intensities approaching the limit of detection. Since the particulate matter is often dispersed over much of the upper ice column, the associated drastic light attenuation can be expected to persist almost as long as the ice cover lasts. Thus, primary production by ice algae in April and May, and by phytoplankton in June and even early July is effectively prevented in areas of sediment-laden ice in the Stefansson Sound-Simpson Lagoon area. Estimating a 50-75 percent areal extent of turbid ice, this condition probably reduced the 1979 ice algal productivity and possibly phytoplankton productivity to as low as 25-30 percent of the maximum possible if snow cover alone were attenuating light penetration. At this time, very little data exist on year-to-year variability of sediment-laden ice and on the length of persistence of the opaque ice into the summer season. Duration estimates based on satellite imagery indicate that approximately 40-50 percent of the Stefansson Sound area is ice free by the first week of July, followed by rapid dispersal of the remaining ice during the month. Thus, sediment-laden ice could potentially prevent light penetration into the water column for two or more weeks past the solar solstice,

causing a large decrease in annual primary production. More detailed documentation on the ice retreat characteristics in relation to light penetration has been assembled using satellite imagery and field observation, and sediment-laden ice has been addressed as a topic in a previous workshop (Larsen, 1980). Although the mechanisms of incorporation are still unclear, turbid ice forms in the fall and is apparently related to the rate of freeze-up. Figure 7 shows a qualitative relationship between ice thickness and turbidity following fall freeze-up of 1978. The thicker ice is believed to have originated during super-cooling by fall storms over open water wherein rapid ice formation and sediment suspension occurred simultaneously.

The sediment loads listed in Tables 3 and 4 were calculated by multiplying the concentrations in each band by its volume. A sediment concentration determined to be 10 g/m^3 was used for clear ice and the total sediment in the core was found by summation of the individual bands. The load was placed on an areal basis by dividing this total by the area of the core barrel. The light and sediment data show that light penetration is strongly attenuated by the presence of sediment in the ice. The low extinction coefficients are for essentially clear ice and are comparable to those found by Homer and Schrader (1981) for ice of similar depth, but with twice as much snow cover (20-50 cm), whereas the high extinction coefficients are caused by the increased sediment load. Some of the higher percent carbon values from core sections arise from differences in the organic content of ice algae and sediment. The particulate matter in the bottom of the ice cores contained algae ranging from 8.2-18.7 percent carbon, while the upper core contained sediment of 2.3-7.4 percent carbon. These samples are shown in Table 4.

Ice algal primary production in the nearshore Beaufort Sea is a small fraction of the total annual primary production and is small relative to epontic algal production in the Bering and Chukchi seas, although very little data are available on the latter region. Table 5 compares the estimates of total annual production of epontic ice algae in other continental shelf waters of Alaska and the Antarctic with data obtained in the Beaufort Sea. Only the study by Alexander et al. (1974) represents integrated ^{14}C uptake measurements determined over the spring season. The remaining estimates are extrapolations made on

TABLE 5. Ice algae standing stock and primary productivity data.

	Maximum Chlorophyll <u>11-a</u> (mg Chl <u>11-a</u> /m ²)	Estimated standing stock (50 x Col. 1) (g C/m ²)	Estimated annual primary production (g C/m ²)	Ratio of annual production to standing stocks (Col. 3 divided by Col. 2)
Bering Sea				
McRoy and Goering (1974)	3.0	0.2	0.3 ⁽¹⁾	2
McRoy and Goering (1975, 1976, and personal communication [†])	50.0 - 100.0 [†]	2.5 - 5.0	24.0 ^{(2)*}	9.6 - 4.8
Chukchi Sea				
Alexander et al. (1974)	23.0	1.2	5.0	4.2
Schell (this study)	78.3	3.9	19.5**	
Beaufort Sea/Canadian Arctic				
Anderson (1977)	0.5	<0.1	0.2*	5.0
Homer (1980)	3.0	0.2	0.9*	6.0
Homer and Schrader (1981)	26.5	1.3	0.7	0.5
Schell, (this study) Harrison Bay, Outside the barrier island, Stefansson Sound	12.3 10.7 6.4	0.6 0.5 0.3	3.0** 2.5** 1.5**	
Hsiao (1980) Eskimo Lakes Frobisher Bay	5.7 25.3	0.3 1.3	1.5** 6.5**	
Grainger (1979) Frobisher Bay	4.6	0.2	1.0**	
Dunbar and Acreman (1980) Robeson Channel Barrow Strait/Austin Channel Hudson Bay Gulf of St. Lawrence	10.3 13.8 25.3 3.0	0.5 0.7 1.3 0.2	2.5** 3.5** 6.5** 1.0**	
Antarctic				
Burkholder and Mendilli (1965) ⁽³⁾	123.0	6.2	6.2 [†]	
Meguro (1962) ⁽³⁾	97.0	4.9	4.9 [†]	
Bunt (1963, 1964)	0.1	0.7	2.3*	3.5
Whitaker (1974)	1478.0	40.0 ⁽⁴⁾	40.0 [†]	
Whitaker and Richardson (1980)	244.0	9.1 ⁽⁵⁾	45.5**	

⁽¹⁾ Calculated by Homer and Schrader (1981) from data of McRoy and Goering (1974).

⁽²⁾ Calculated from total shelf ice algae productivity (24×10^6 metric tons C) divided by the shelf area ($1,000 \times 10^6 \text{ km}^2$).

⁽³⁾ Samples collected from "snow" communities.

⁽⁴⁾ Value reported by Whitaker (1974) for shelf on an ice berg.

⁽⁵⁾ Estimated using carbon-chlorophyll 11-a ratio of 37.1, from Whitaker and Richardson (1980).

* ¹⁴C incubated primary productivity.

** 5 x estimated standing stock.

† Grazing assumed negligible.

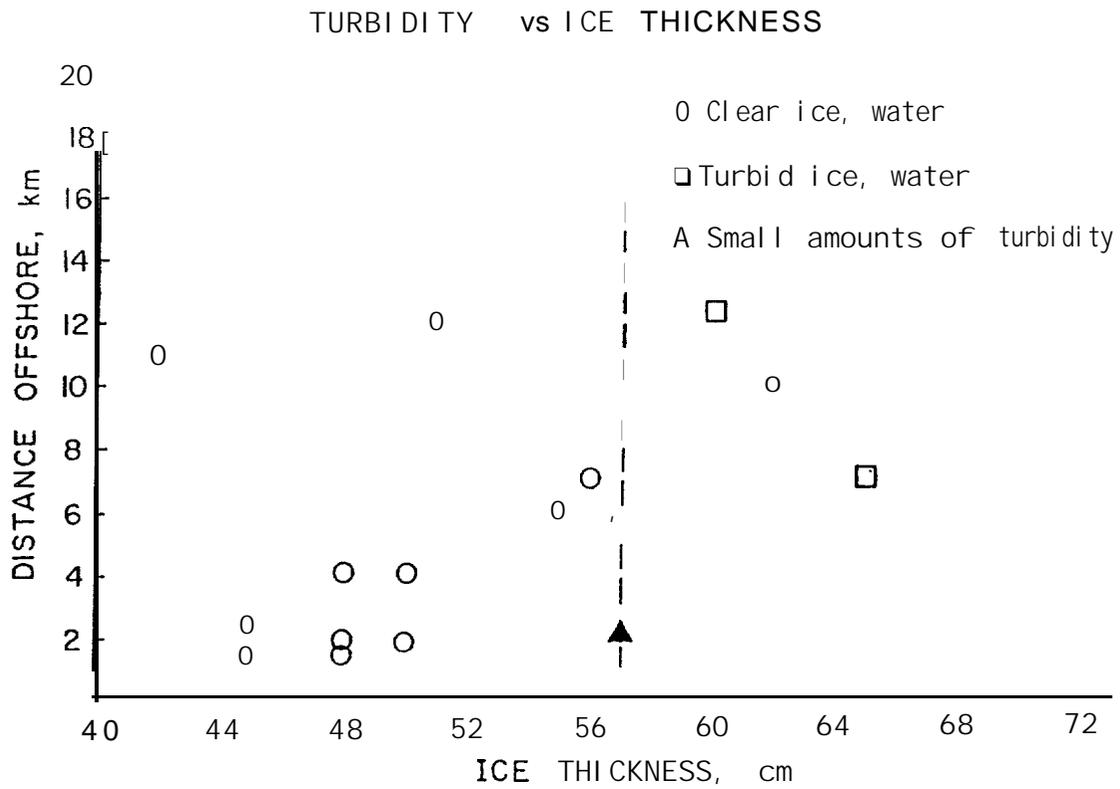


Figure 7. Fall 1978, ice turbidity and thickness in the Prudhoe Bay-Simpson Lagoon-Harrison Bay area.

either limited ^{14}C -uptake measurements or on standing stock measurements converted to productivity numbers by cross calibration with instantaneous productivity measurements and standing stocks estimated from chlorophyll concentrations.

The estimates of ice algal production for this study in Table 5 which are based in part on data from Table 6 are probably high since sampling is unavoidably biased by the choice of helicopter landing spots which are flat. Due to the roughness of pressure fields and the inaccessibility of the bottom surface of pressure ridges, there are no data on ice algae from these areas. Light attenuation would be greater in pressure fields due to the increased snow cover, and/or thicker ice would be expected to preclude ice algal growth. However, the estimates of annual production in Table 5 do not take ice morphology into account, but are based on the actual samples taken and may result in a systematic error. In the context of total annual primary production and the effects of sediment-laden ice, this error would probably have little effect.

Coastal Beaufort Sea Ice Algae Studies

Coring of ice algae samples in 1981 was accomplished on 30-31 May and 2 June. Logistic delays prevented sampling at the typical spring bloom optimum period of 7-10 days previous to these dates and several cores, especially those near shore, showed evidence of algal loss through melting and from river runoff. Further offshore, we are more confident that the observed populations are at or near annual maxima, and this is corroborated by the simultaneous studies by Homer and Schrader (1981) who observed the maximum standing stocks of ice algae of Narwhal Island at this time. Because of the uncertainties in nearshore samples, however, we are not attempting to use 1981 samples to establish distributional trends in maximum annual standing stocks. Previous estimates of standing stocks based on cores obtained in May 1979 and May 1980 showed an increase in biomass progressing offshore -- except in areas of moving ice, algal populations ranged from very low densities in new ice to high concentrations in areas of stable annual sea ice.

TABLE 6. Chlorophyll-a_ and phaeopigment data from Beaufort Sea ice cores collected May 30, 31 and June 2, 1981.

Prudhoe Bay Site 70°19.9'N 148°22.7' 11

Core	Snow cover (cm)	Ice depth interval (en)	Chlorophyll -s (mg/m ³)	Phaeopigments (mg/m ³)	Estimated standing stock (mg C/m ²)
	5	164-170	2.0	1.7	
		Total (mg/m ²)	0.1	0.08	5.0
PB 2	14	162-165	0.3	0.2	
PB 2	14	165-170	1.2	0.9	
		Total (mg/m ²)	0.006	0.05	3.0
Station 20 70°14.4'N 147°29.5'W					
20-2	35	158-166	1.0	0.2	
20-2	35	166-170	3.0	0.6	
		Total (mg/m ²)	0.2	0.03	10.0
Station 19 70°11.1'N 147°03.0' 14					
19-1	21	1535-160	14.6	1.5	
		Total (mg/m ²)	0.8	0.008	40
19-3	3	150-155	4.1	1.0	
19-3	3	155-160	46.1	10.2	
		Total (mg/m ²)	2.3	0.5	115
Station 18 70°16.6'N 147°17.2' 11					
18-1	4	1365-145	6.1	1.9	
18-1	4	145-150	38.4	0.9	
		Total (mg/m ²)	2.2	0.2	110
18-2	11	137-144	3.8	0.3	
18-2	11	144-150	3.7	0.7	
		Total (mg/m ²)	0.4	0.05	20
Station BP 70°17.9'N 147°31.9'W					
BP-2	8	165-170	0.05	0.4	
		Total (mg/m ²)	0.02	0.02	1.0

TABLE 6. (Continued)

Core	Snow cover (cm)	Ice depth interval (cm)	Chlorophyll <i>a</i> (mg/m ³)	Phaeopigments (mg/m ³)	Estimated standing stock (mg C/m ²)
Station 8 70°31.0'N 148°56.2'W					
8-2	1	149-156.5	2.7	0.9	
8-2	1	156.5-164	7.1	1.6	
8-2	1	164-170	24.3	3.6	
		Total (mg/m ²)	1.7	0.3	85
8-3	1	161-166	13.2	1.8	
8-3	1	166-170	227.8	18.7	
		Total (mg/m ²)	9.9	0.8	495
Station 3 70°32.1'N 149°52.0'W					
3-1	10	159-165	12.4	1.5	
3-1	10	165-170	68.8	6.2	
		Total (mg/m ²)	3.9	0.4	195
3-3	13	157-164	11.0	1.1	
3-3	13	164-170	37.1	4.7	
		Total (mg/m ²)	2.8	0.3	140
3-4	7	158-165	14.4	3.9	
3-4	7	165-170	109.5	17.1	
		Total (mg/m ²)	6.4	1.1	320
Station 12 70°33.4'N 150°21.5'W					
12-1	3	125.5-133	2.7	0.4	
12-1	3	133-138	4.0	0.6	
12-1	3	138-140	107.7	20.5	
		Total (mg/m ²)	2.8	0.5	140
12-3A	7	124-130	2.8	0.7	
12-3A	7	130-136.5	3.4	0.8	
12-3A	7	136.5-140	12.3	5.5	
		Total (mg/m ²)	0.8	0.3	40

TABLE 6. (Continued)

Core	Snow cover (cm)	Ice depth interval (cm)	Chlorophyll <i>l</i> - <i>q</i> (mg/m ³)	Phaeopigments (mg/m ³)	Estimated standing stock (mg C/m ²)
Station 13 70°35.1'N 150°41.1'W					
13-1	2	130-138	4.1	0.2	
13-1	2	138-144	1.5	0.3	
13-1	2	144-150	51.2	7.0	
		Total (mg/m ²)	2.1	0.3	105
13-2	2	138-146	8.4	0.0	
13-2	2	146-150	99.3	23.2	
		Total (mg/m ²)	4.2	0.8	210
13-3	20	139.5-145.5	3.1	0.6	
13-3	20	145.5-150	5.1	1.4	
		Total (mg/m ²)	0.4	0.1	20
13-4	30	138-144	1.5	0.4	
13-4	30	144-150	3.4	0.9	
		Total (mg/m ²)	0.2	0.06	10
13-5	2.5	142-147.5	8.8	1.1	
13-5	2.5	147.5-150	196.4	42.3	
		Total (mg/m ²)	53.	.1	265
Station HB2 70°34.2'N 151°08.3'1'1					
HB2-2	3	163-166	4.6	0.8	
HB2-2	3	166-170	182.4	50.0	
		Total (mg/m ²)	7.2	1.9	360
HB2-3	2	161-165	5.5	1.2	
HB2-3	2	165-170	108.6	26.3	
		Total (mg/m ²)	5.6	1.4	280
Station HB1 70°36.2'N 151°38.4'W					
HB1-1	2	152-159	12.6	1.5	
HB1-1	2	159-165	19.6	1.8	
HB1-1	2	165-170	206.1	34.0	
		Total (mg/m ²)	11.0	1.7	550

TABLE 6. (Continued)

Core	Snow cover (cm)	Ice depth interval (cm)	Chlorophyll <i>a</i> (mg/m ³)	Phaeopigments (mg/m ³)	Estimated standing stock (mg C/m ²)
Station HB1 (Continued)					
HB1-2	3	155-161.5	5.3	0.4	
HB1-2	3	161.5-167	15.0	-	
HB1-2	3	167-170	466.7	10.48	
		Total (mg/m ²)	12.3	2.6	615
Station TR1 70°32.1'N 148°23.3'W					
TR1-1	4	185-190	1.0	0.2	
TR1-1	4	190-194.5	3.1	1.5	
TR1-1	4	194.5-198.5	25.0	1.0	
TR1-1	4	198.5-200	333.8	57.1	
		Total (mg/m ² ; 194.5-200 cm)	0.2	0.03	10
TR1-2	4	184.5-192.5	2.9	2.4	
TR1-2	4	192.5-197.5	6.2	2.1	
TR1-2	4	197.5-200	125.0	34.3	
		Total (mg/m ² ; 192.5-200 cm)	3.1	0.8	155
TR1-3	4	187-191.5	4.5	1.1	
TR1-3	4	191.5-196	6.8	1.0	
TR1-3	4	196-200	19.8	3.4	
		Total (mg/m ² ; 191.5-200 cm)	0.8	0.1	40
TR1-4	4	186-191	1.2	0.7	
TR1-4	4	191-196	0.5	0.4	
TR1-4	4	196-200	1.1	.4	
		Total (mg/m ²)	0.1	0.01	5
TR1-5	4	187-193	1.9	0.4	
TR1-5	4	193-198	4.3	1.4	
TR1-5	4	198-200	93.4	20.4	
		Total (mg/m ² ; 193-200 cm)	2.8	0.6	140
Station TR2					
TR2-1	3	147-150	95.5	29.6	
		Total (mg/m ²)	4.1	1.3	205

TABLE 5. (Continued)

Core	Snow cover (cm)	Ice depth interval (cm)	Chlorophyll-a (mg/m ³)	Phaeopigments (mg/m ³)	Estimated standing stock (mg C/m ²)
Station TR2 (Continued)					
TR2-2	3	148-150	8.50	25.3	
		Total (mg/m ²)	10.7	3.2	535
TR2-3	3	132.5-139.5	2.2		
TR2-3	3	139.5-146.5	4.7	1.0	
TR2-3	3	146.5-150	98.9	16.7	
		Total (mg/m ²)	3.1	0.5	155
TR2-4	1	148-150	352.5	67.6	
		Total (mg/m ²)	4.4	0.8	220
TR2-5	1	135-141	2.1	0.4	
TR2-5	1	141-147	5.9	1.7	
TR2-5	1	147-150	332.7	65.4	
		Total (mg/m ²)	10.1	2.0	505
TR2-6	3	1-20	0.2	0.1	
TR2-6	3	10-20	0.4	0.3	
TR2-6	3	20-30	0.1	0.2	
TR2-6	3	30-40	0.2	0.1	
TR2-6	3	40-50	0.2	0.1	
TR2-6	3	50-60	0.1	0.1	
TR2-6	3	60-70	0.3	0.1	
TR2-6	3	70-80	0.8	0.4	
TR2-6	3	80-90	0.2	0.1	
TR2-6	3	90-100	1.3	0.3	
TR2-6	3	100-110	0.2	0.1	
TR2-6	3	110-120	0.1	0.0	
TR2-6	3	120-130	0.1	0.0	
TR2-6	3	130-140	0.3	0.0	
TR2-6	3	140-150	0.6	0.6	
TR2-6	3	150-163	1.8	0.2	
TR2-6	3	163-165	99.0	20.7	
		Total (mg/m ² ; 150-165 cm)	3.6	0.7	180
Station TR3 71°12.0'N 148°20.8'W					
TR3-2	3	140-147	1.5	0.2	
TR3-2	3	147-150	10.4	1.6	
		Total (mg/m ²)	0.4	0.07	20

Chlorophyll concentrations in the ice-water interface varied as widely in 1981 as has been observed in previous years. Average values in the inshore area of Harrison Bay and on a transect seaward of the barrier island were 4.7 and 4.4 mg Chl-a/m² with a range of 0.1-12 mg Chl-a/m². Concentrations often varied within stations in response to snow cover and sediment inclusions in the ice. Translating the chlorophyll concentrations to carbon, as explained below, yields estimates ranging from 5 to 600 mg C/m². Estimates for other areas are included in Table 5.

The carbon to chlorophyll ratio was determined from ice cores collected by this research unit and by RU 359, from their Narwhal Island ice station. A least squares regression applied to the data (Figure 8) gave a slope of 50.0 ± 8.9 ($r = 0.86$). For comparison, Whitaker and Richardson (1980) determined a carbon to chlorophyll-a ratio of 37.1 ± 3.8 for ice algae from a tide crack community of predominantly *Navicula glaciei* in the South Orkney Islands. The larger relative standard deviation of our data (18 percent) compared to Whitaker and Richardson's values (10 percent) is probably due to at least four factors. Our samples were collected over a two-year time period, our stations were spread over a wider area, there is a wide and variable input of terrestrial detritus into the nearshore zone, and species composition probably varied between stations.

An assimilation efficiency (carbon fixation rate/chlorophyll-a concentration) of 0.10 mg C/mg Chl-a-hr was calculated from the primary productivity and chlorophyll-a standing stock measurements of Homer and Schrader (1981). If the seasonal mean Chl-a concentration is multiplied by the assimilation efficiency, the average day length of 21 hours, and the 60 day growing season, the annual productivity can be estimated. Using the mean seasonal Chl-a concentration found at Narwhal Island of 8.2 mg Chl-a/m², the estimated productivity by this method is 1.0 g C/m²-yr, which is slightly higher than the integrated value of 0.7 g C/m²-yr reported by Homer and Schrader (1981).

We also calculated an assimilation efficiency of 0.39 mg C/mg Chl-a-hr from the data collected in 1973 by Alexander et al. (1974). To check this method of estimating primary productivity with the experimentally determined value, the assimilation efficiency was applied

to the average chlorophyll-a concentration off Pt. Barrow of 10.9 mg Chl-a/m². The estimated productivity of 5.4 g C/m²-yr is close to the integrated ¹⁴C-uptake value of 5 g C/m²-yr that they reported.

The estimate of annual primary production of 0.7 g C/m²-yr due to ice algae off Narwhal Island made by Homer and Schrader (1981) may be too low. When the maximum chlorophyll-a standing stock is multiplied by the carbon to chlorophyll-a ratio of 50, which was determined on samples of algae provided by those investigators, the standing stock is 1.3 g C/m². Using their reported chlorophyll-a data, we constructed a best-fit exponential growth curve (Figure 9). The growth was bimodal and from this theoretical curve, total chlorophyll-a production is estimated at 34 mg Chl-a/m² (assuming no grazing or loss due to other factors). Carbon productivity from the exponential growth curve would be 1.7 g C/m²-yr.

The data in Table 5 indicate estimated annual primary productivity is 2 to 9.6 ($\bar{x} = 5$) times higher than the reported maximum standing stock. The data from Homer and Schrader (1981) shows estimated primary productivity that is 0.5 times the estimated standing stock. If we multiply the observed maximum standing stock (1.3 g C/m²) by 5, estimated productivity of 6.5 g C/m²-yr, approximately 10 times their estimated primary productivity, is obtained. Conceivably only about 10 percent of the algae were fixing carbon during the uptake experiments. However, this is inconsistent with data from previous investigators and inconsistent with the fact that the algae were growing exponentially.

When the assimilation efficiency of 0.39 mg C/mg Chl-a-hr calculated from Alexander et al. (1974) is applied to the average chlorophyll-a standing stock (8.2 mg Chl-a/m²), the estimated primary productivity is 4 g C/m²-yr. Ice algae productivity of 4 g C/m²-yr off Narwhal Island is similar to ice algae productivity off Pt. Barrow. Maximum standing stocks were higher at Narwhal Island, but the bloom lasted longer off Pt. Barrow due to the absence of freshwater input from rivers.

Banse (1977) has described in detail the many pitfalls in attempting to use carbon to chlorophyll ratios as a general technique to obtain cell carbon. The principal causes of high variability are 1) changes in carbon to chlorophyll ratios within the cell during various

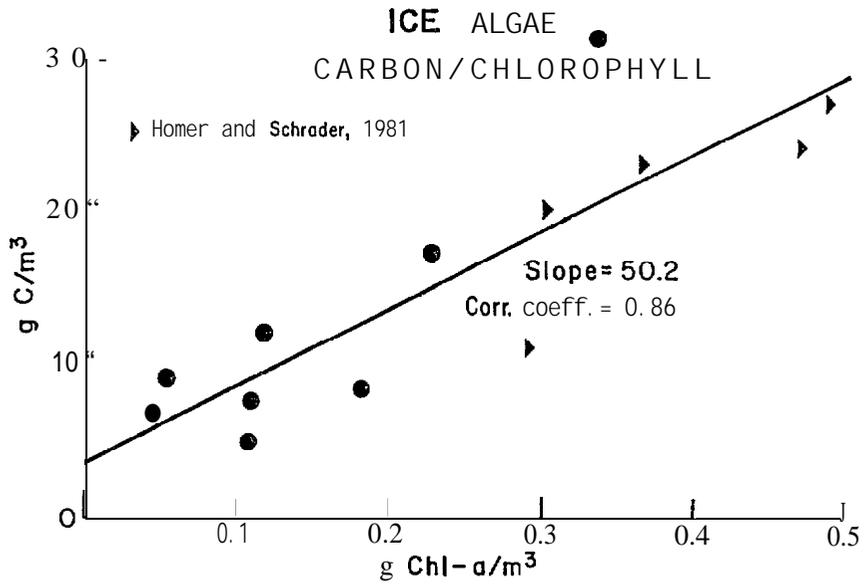


Figure 8. Carbon to chlorophyll relationship in samples of ice algae taken from the Beaufort Sea in the spring of 1980 and in the spring of 1981.

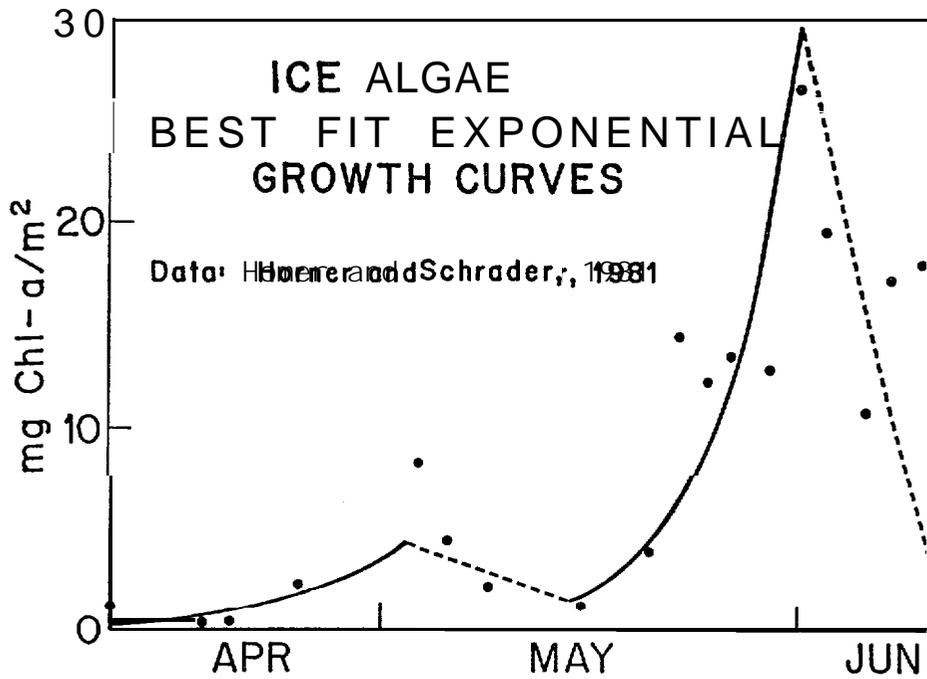


Figure 9. Computer generated best fit growth curve for spring, 1980, ice algae.

growth stages, 2) variation in the C/Chl-a ratio among species of phytoplankton, and 3) varying ratios of grazers to plants. We are fairly confident that the first two sources of error are small with regard to ice algae. Although Homer and Schrader (1981) have shown that a wide variety of species may be present in the algal populations, the heterogeneity does not appear to cause excess scatter in the points used to determine our C/Chl-a ratio. Also, there is no indication that cells are in other than rapid growth phases as shown from the adequate nutrient concentrations and increasing light over the course of the bloom. Although bimodality in the bloom would imply loss of cells and/or chlorophyll at the period of senescence in the first peak, once again our limited samples did not show this. We suspect that if an appreciable error in the C/Chl-a ratio exists, it would most likely arise from an increasing biomass of grazers in response to increasing chlorophyll (plants). We do not have the data yet to test this possibility and can only note that if this were a serious source of error, it should be reflected in a non-linearity of the plot with rapidly increasing C/Chl-a ratios at the higher chlorophyll-a concentrations.

Chukchi Sea Ice Algae Studies, Spring 1981

Ice cores were collected from four locations, designated I (67°59.0'N 167°28.0'W), II (68°22.9'N 167°44.3'W), III (68°22.5'N 167°53.2'W) and IV (68°54.9'N 166°28.0'W) during April and May, 1981 (Table 7). Water samples were also collected at these locations for nutrient and salinity determinations, and at other locations from the ship when ice conditions allowed.

In the cores collected from medium-sized (15-100 m) and small pans (less than 15 m) the chlorophyll-a concentrations were found to be fairly uniform within the different sampling groups. One core collected from a large pan (greater than 100 m diameter) (Station II), contained 78.3 mg Chl-a/m². Cores from medium-sized pans (from Stations I, III and IV) averaged 37.3 mg Chl-a/m², with a range of 24.9 to 56.9. Cores from small pans (Stations III and IV) averaged 3.5 mg Chl-a/m²,

with a range of 3.1 to 4.3 and a core collected from a submerged block contained 5 mg Chl-a/m². Chlorophyll-a in the water column ranged from 0.02 to 0.05 mg Chl-a/m³. Phaenopigment concentrations typically equaled or exceeded the corresponding chlorophyll-a concentrations.

Standing stocks of the ice algae were estimated by multiplying the carbon-chlorophyll-a ratio of 50 to the chlorophyll-a values from the ice cores. The core from the large pan contained 3.9 g C/m². The cores from the medium pans had an average of 1.9 g C/m² with a range of 1.2 to 2.8 g C/m². The small pans had an average of 0.18 g C/m² with a range of 0.1.6 to 0.22 g C/m².

Estimates of annual primary productivity were made by using the 0.39 mg C/mg Chl-a-hr average assimilation efficiency derived from data reported by Alexander et al. (1974). This was multiplied by the averaged chlorophyll-a values to estimate average primary productivity, and then by an average day length of 20 hours and a 60 day growing season. The estimated productivity was calculated to be 18.3 g C/m² for the large ice pan, 8.7 g C/m² for the medium pans, and 0.8 g C/m² for the small pans.

Core III B had a higher chlorophyll-a content than any other core from medium-sized pans and had two distinct bands of algae, located approximately 45 cm from the top of the ice and at the bottom. The upper band accounted for 40 percent of the total 56 mg Chl-a/m². Occasionally during ice breaking operations, ice was observed containing two or sometimes three very distinct bands. If these bands contain large numbers of viable algae, then the carbon produced in these ice pieces could be significantly greater than would be expected from interface production only. Estimating that 80 percent of the ice cover was composed of large and medium-sized pans, an overall productivity for a 60 day season would be 11 g C/m². This estimate of ice algae productivity is approximately twice that of Alexander et al. (1974) for the Chukchi Sea, near Point Barrow.

Ice algae productivity in the Bering Sea has been estimated at 24 x 10⁶ metric tons of carbon for the entire shelf area or 24 g C/m² (McRoy and Goering, 1976). Chlorophyll-a values in cores collected from the Bering Sea in 1972 were typically 5 to 50 mg Chl-a/m², similar to our cores collected from the Chukchi Sea (3 to 78 mg Chl-a/m²). If

the ice cores from the Chukchi Sea and Bering Sea were collected during the height of the spring bloom, and if the rates of primary productivity are comparable, then ice algae productivity in the southern Chukchi Sea may be only slightly less than that of the Bering Sea.

Phytoplankton Production in the Beaufort Sea

Phytoplankton photosynthesis provides the bulk of fixed carbon in the Beaufort Sea. Initial algal production in the spring occurs as ice algae, and phytoplankton production does not become a significant fraction of carbon input until the ice begins to melt, and the ice algae are dispersed into the underlying water column. Although Alexander and Niebauer (1981) and Homer and Schrader (1981) believe that the predominant ice algae species are not the initial phytoplankton species, Hameedi (1978) concludes that the ice algae are a major source of the initial phytoplankton populations. Our work in the Beaufort Sea has been limited to the nearshore zone (usually less than 10 m depth) due to logistic constraints and the emphasis on studying the projected lease areas. Nevertheless, we have attempted to integrate our data into the overall productivity regimes of the coastal Alaska Beaufort Sea. To accomplish this integration, we have relied heavily upon the past work of R. Homer (accomplished from icebreakers and reported in Homer, 1981), the limited data available from Alexander et al. (1975), and our own studies.

Our overall perspective is that phytoplankton primary production is low in the Beaufort Sea and ranges from $10-50 \text{ g C/m}^2\text{-yr}$. The lowest values are found in the nearshore waters less than 2 m deep where turbidity, salinity stress, and the shallow euphotic zone limit productivity and far offshore occur where perennial ice cover limits light, and low nutrient concentrations limit standing stocks and growth rates. In the intermediate area, the retreat of the pack ice northward in summer, nutrients supplied by terrestrial runoff, and the maximum euphotic zone depths lead to the maximum productivities observed. We have no data from the Arctic Ocean far offshore (>200 miles), and the low estimate is projected as a result of ice cover, which is assumed to

TABLE 7. Chukchi Sea ice algae data, 1981

Station I 67°59.0'N 167°22.1'W 27-IV-81

Core I Ice thickness: 1 m Snow: 12 cm

Depth Interval (cm)	Chlorophyll I -g (mg/m ³)	Rhaeopigment (mg/m ³)
75-82	26.2	0.3
82-87	25.6	2.6
87-92	39.5	2.3
92-96	67.9	7.3
96-100	516.7	47.4
Totals mg/m ² (Bottom 8 cm)	30.3	2.2
Totals mg/m ² Whole Core	34.6	2.4

Station II 68°22.9'N 167°44.3'W 3-IV-82

Core 11 A Ice thickness: 1 m Snow: 10 cm

Depth Interval (cm)	Chlorophyll I -q (mg/m ³)	Phaeopigment (mg/m ³)
19.5-26.5	1.4	0.7
26.5-36.5	1.5	0.7
36.5-43.5	1.0	0.5
43.5-49.5	0.8	0.5
49.5-56.5	2.1	0.6
56.5-65.5	11.7	4.0
56.5-65.5	11.7	4.0
65.5-70	7.9	1.9
70-76	10.6	1.7
76-83	12.9	5.1
83-90	3.2	1.1
Totals (mg/m ²)	3.1	1.0

Station III 68°22.5'N167°53.2'W 5-IV-81

Core II B Ice thickness: 2m Snow: 19 cm

Depth Interval (cm)	Chl orophyll I -s (mg/m ³)	Phaeopi gment (mg/m ³)
167-174	23.3	24.4
174-182	12.9	1.4
182-190	3.3	0.8
190-200	11.9	10.4
Totals mg/m ²	3.3	1.1

Core II C Ice thickness: 0.8 m Snow: 20.5 cm

Depth Interval (cm)	Chlorophyll-I (mg/m ³)	Phaeopi gment (mg/m ³)
58-62	10.3	1.6
62-68	19.1	1.9
68-73	16.0	1.7
73-80	1460.9	162.9
Bottom 7 cm (mg/m ²)	76.1	8.5
Total (mg/m ²)	78.3	8.7

Core 111 A Ice thickness: 3 m Core length: 2.9 m Snow: 41 cm

Depth Interval (cm)	Chl orophyll I -g (mg/m ³)	Phaeopi gment (mg/m ³)
0-9.5	1.44	0.57
9.5-17.5	1.26	0.52
17.5-26	1.63	0.39
26-35.5	0.85	0.36
35.5-44	0.53	
44-52	0.40	0.11
52-61	2.86	0.19
61-69	2.30	0.26
69-78	1.12	0.15
78-88	0.67	0.01
88-97	2.17	0.38
97-107	2.86	0.37
107-115	0.16	
115-124	0.46	0.25
124-135	0.11	0.05
135-144	0.58	0.67
144-155	0.34	0.24
155-165	1.42	1.17
165-174	2.03	0.43
174-182	1.22	0.36
182-191	1.79	0.46
191-199	0.48	0.23
199-207.5	1.01	0.31
207.5-215.5	3.06	0.88
215.5-222.5	3.26	0.95
222.5-230	2.50	0.97
230-237.5	5.33	0.95
237.5-244.5	13.93	1.51
244.5-252.5	2.66	
252.5-262	2.00	-
262-271	1.66	0.43
271-285	0.97	0.25
Totals (mg/m ²)	3.96	0.93

Core III B Ice thickness: 1.75 m Snow: 12 cm
Core contained visible layers.

Depth Interval (cm)	Chlorophyll <u>a</u> (mg/m ³)	Phaeopigment (mg/m ³)
18-25	20.0	1.8
25-33	83.0	8.3
33-42	193.4	32.5
42-48	44.0	5.5
48-55	22.8	4.7
102-110	37.3	2.3
110-117.5	26.6	3.2
153.5-162.5	148.6	14.7
162.5-172.5	208.1	15.7
Totals of bottom two sections (mg/m ²)	27.3	2.3
Totals of whole core (mg/m ²)	56.4	6.2

Station IV 68°54.7'N166°28.0'W 8-IV-81

Core IV A Ice thickness: 0.9 m Snow: 10.5 cm

Depth Interval (cm)	Chlorophyll <u>a</u> (mg/m ³)	Phaeopigment (mg/m ³)
77.5-84	15.8	1.8
84-90	557.9	81.0
Totals (mg/m ²)	24.9	3.6

Core IV 8 Ice thickness: 1.0 m Snow: 7 cm
Layer present at 11-22 cm from top of ice.

Depth Interval (cm)	Chlorophyll <u>a</u> (mg/m ³)	Phaeopigment (mg/m ³)
11-22	1.3	0.2
94-97	26.8	
97-100	1595.6	195.6
Totals (mg/m ²)	33.3	4.0

Core IV C Ice thickness: 0.4 m Snow: 0 cm

Depth Interval (cm)	Chlorophyll <u>a</u> (mg/m ³)	Phaeopigment (mg/m ³)
23-30	14.0	
30-40	49.7	
Totals (mg/m ²)	4.3	

Core IV D Ice thickness: 0.8 m Snow: 6-7 cm

Depth Interval (cm)	Chlorophyll <u>a</u> (mg/m ³)	Phaeopigment (mg/m ³)
62.5-70	39.2	8.2
70-77	25.7	3.2
Totals (mg/m ²)	3.4	0.6

reduce light intensities on top of the water column to less than 10 percent of surface irradiance and create a substantially shallower euphotic zone. Data used for areal projections of primary production are listed in Tables 8 and 9.

The area of seasonally open water typically contains 4-10 μg -atoms nitrate N/l at the onset of plant growth, and data from Hufford (1974) show that depletion occurs to at least 50-60 m in much of the nearshore area. If uptake by plants is the primary removal mechanism, minimum annual production can be estimated by assuming unidirectional movement into the particulate fraction and a C:N atom ratio of 7.5. For a mean depth from shore to the 50 m contour of 25 m, and an average of 7 mg-atoms N/m³ nitrogen taken up, fixation equals 175 mg-atoms N/m² which should correspond to 1312 mg-atoms C/m² (= 15.7 g C/m²).

Offshore phytoplankton production is assumed to be limited by ice, and the extent of ice cover therefore governs the areas available for a deep euphotic zone. Satellite imagery provides the most effective means of assessing the temporal and spatial extent of ice-free areas. Research Unit 267 (W. Stringer) has compiled ice extent data for the Harrison Bay-Prudhoe Bay vicinities based on imagery from 1972-1980. These data were used to project probable integrated primary productivity rates and seasonal totals in this area. We then used larger scale satellite imagery (Defense Meteorological Satellite Program) of the entire Beaufort Sea to estimate the extent of ice retreat over the summer and projected the annual productivity at points shown in Figure 10 to reflect these values. The estimated annual primary production values are shown in Figure 11 for the Harrison Bay-Prudhoe Bay area. Figure 12 shows the average seasonal ice retreat for 1978-1980 and Figure 13 shows contoured estimates of primary production in g C/m²-yr for the Beaufort Sea projected through the ice retreat data and average ¹⁴C uptake data.

Problems in extrapolating annual primary productivity rates in the high Arctic arise from two environmental conditions: low solar angles and ice cover. The low solar angles limit the light entering the water column through increased reflectance in water, but no data were obtained on diurnal variability in reflectance of snow and ice surfaces. Melnikov (1980), however, found that snow melt and thinning of the ice

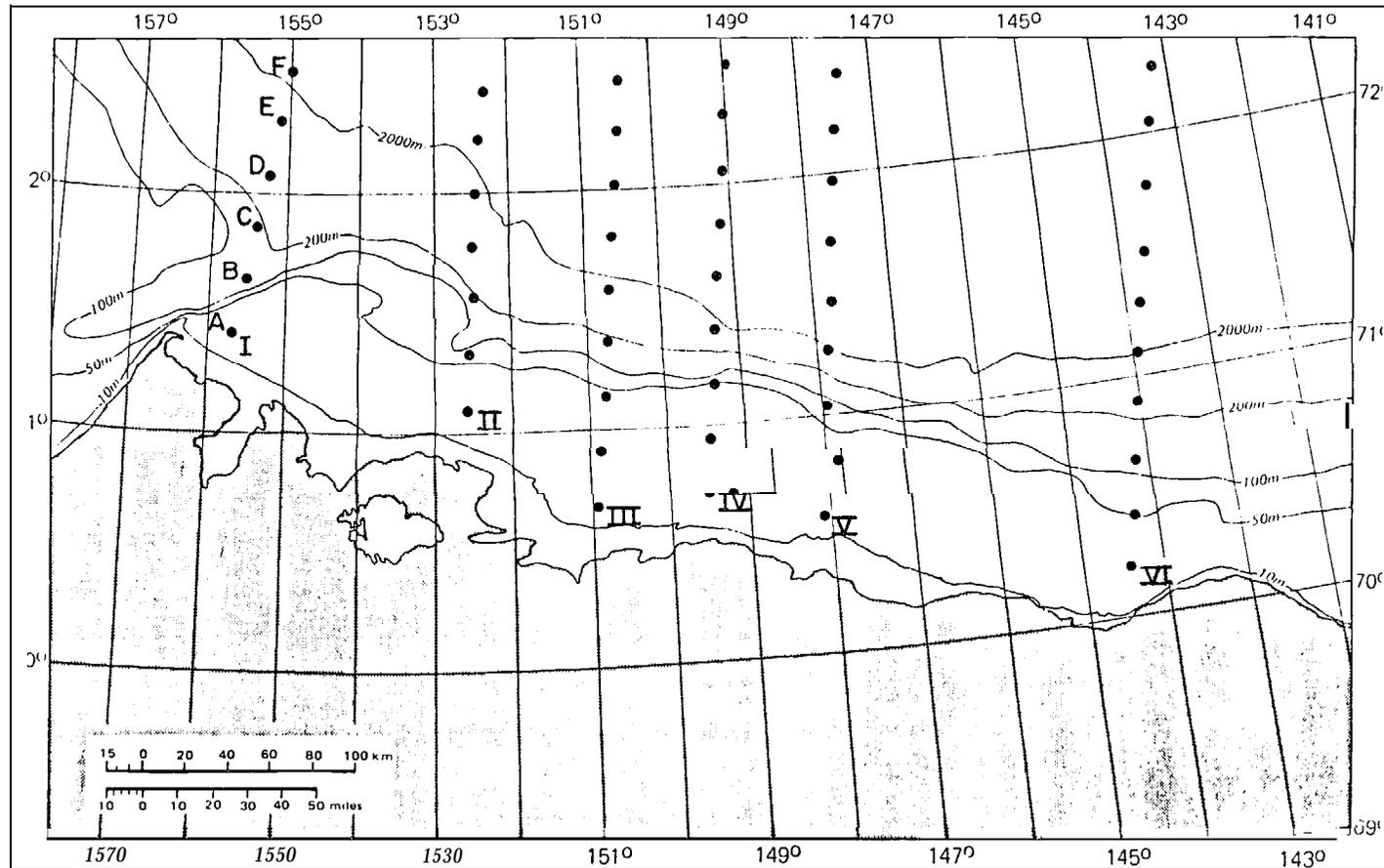


Figure 10. Transect points used for projecting annual primary productivity. Calculated annual productivities are listed in Table 10.

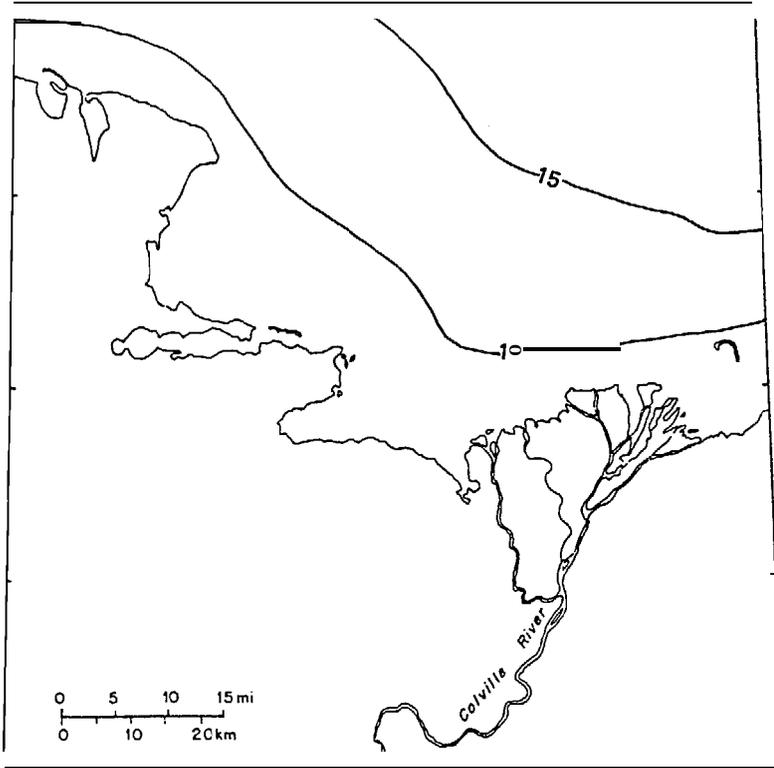


Figure 11A. Phytoplankton annual primary production (g C/m^2) projected from euphotic zone depths, ice retreat data, and ^{14}C uptake measurements. Contours do not match those of Figure 12 because ice data span a longer interval (1972-1980).

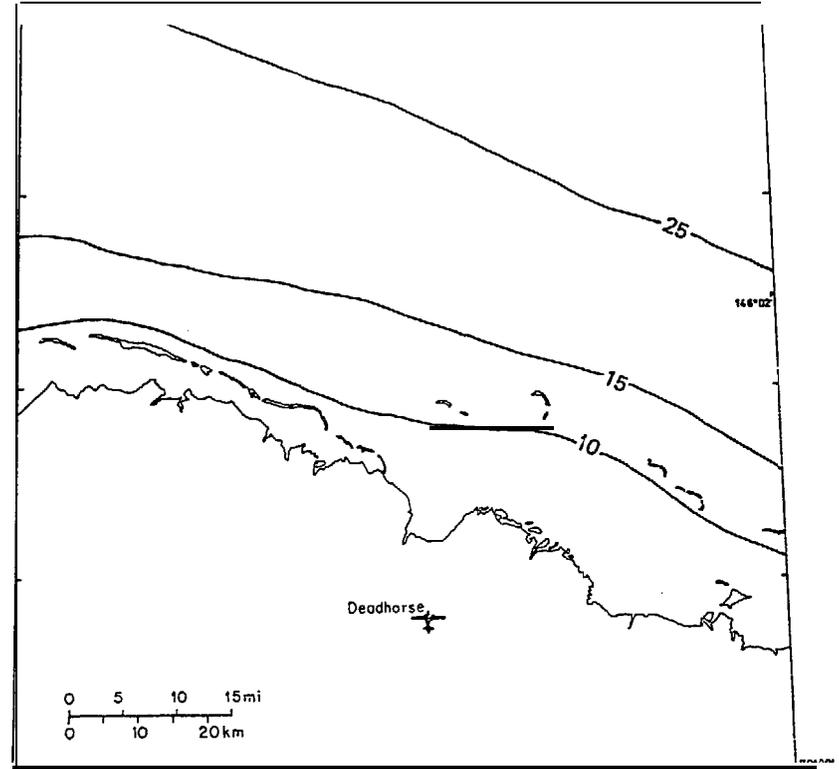


Figure 1B. Phytoplankton annual primary production (g C/m^2) projected from euphotic zone depths, ice retreat data, and ^{14}C uptake measurements. Contours do not match those of Figure 12 because ice data span a longer interval (1972-1980).

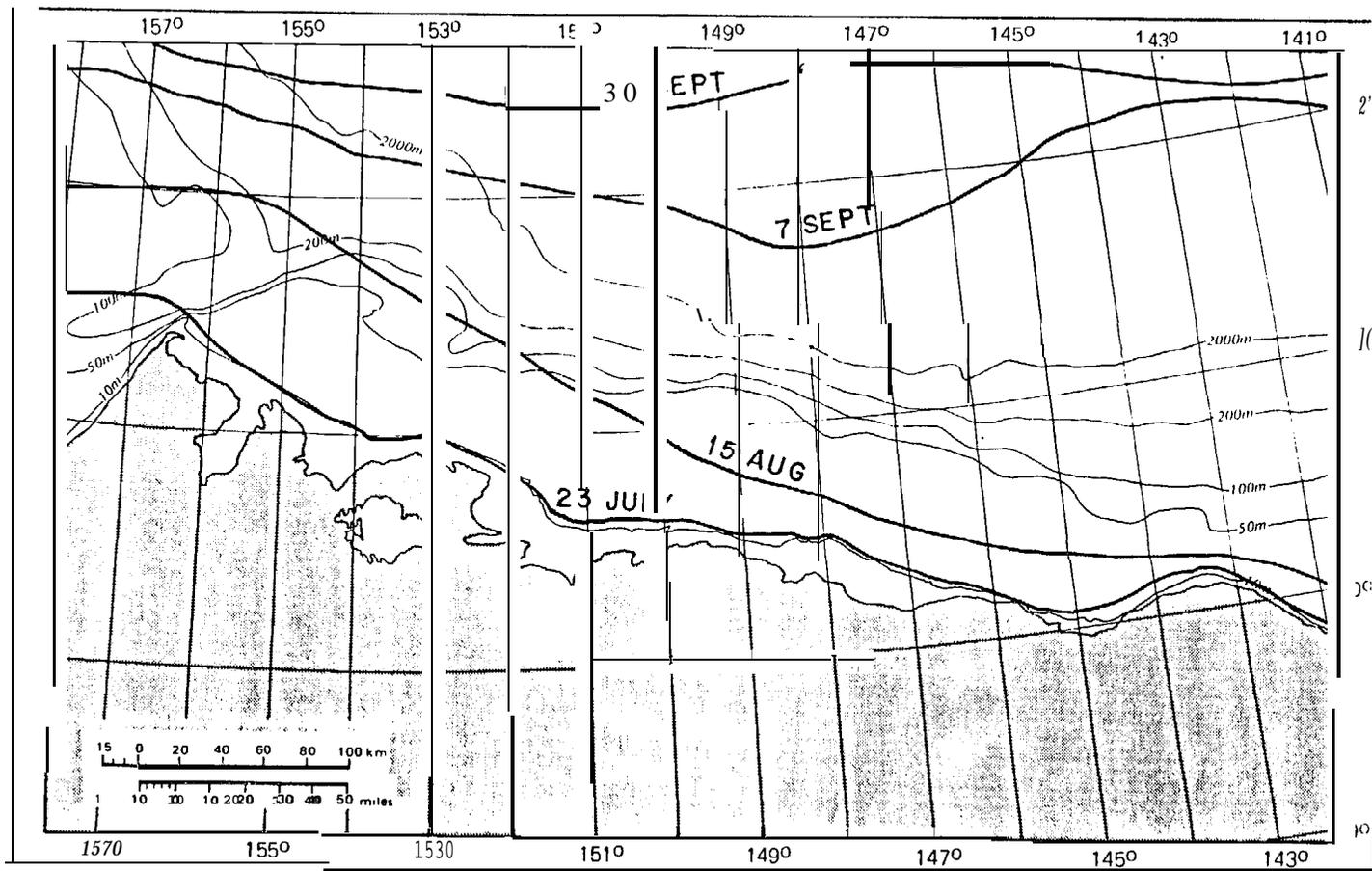


Figure 12. Average seasonal ice retreat 1978-1980, based upon DMSP imagery.

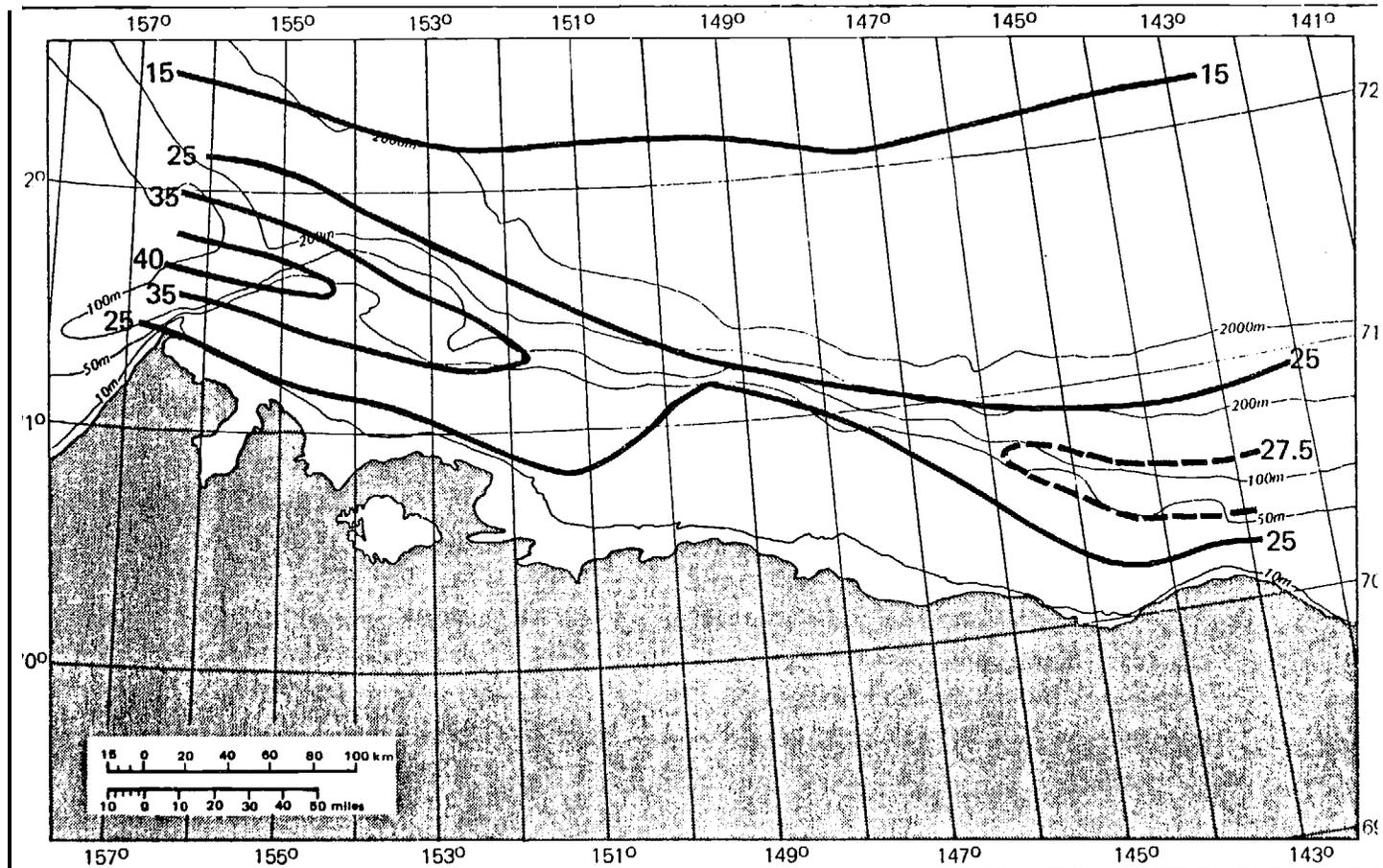


Figure 13. . Average annual primary production ($\text{g C/m}^2\text{-yr}$) in the Alaska Beaufort Sea, 1978-1980. Contours are based upon satellite imagery of ice distribution, ^{14}C uptake measurements and nitrogenous nutrient concentrations.

TABLE 8. Primary production rate data - Beaufort Sea (mg C/m³-hr)

	May	June	July	August	September
Offshore ⁽¹⁾					
SOURCE					
This study	--	0.2	1.2	-- ⁽²⁾	-- ⁽²⁾
Homer (1980)	--	--	0.9*	0.9 ⁽²⁾	0.5 ⁽²⁾
Alexander (1975)	--	--	--	2.4	--
Rates used to estimate productivity	(0.07)	(0.2)	0.9 (0.35)	0.9 (0.35)	0.5 (0.4)
Nearshore ⁽³⁾					
Coyle (1974)	--	--	5.1	1.0	--
Homer and Schrader (1981)	0.07	0.09	--	--	--
Alexander (1975)	--	--	--	1.5	--
This study:					
Prudhoe Bay	--	--	--	0.5	--
Harrison Bay	--	--	--	0.3	--
Foggy Island Bay	--	--	--	0.7	--
Simpson Lagoon	--	--	--	0.5	--
Rates used to estimate productivity	(0.07)	(0.09)	1.1 ⁺ (0.35)	1.0 (0.35)	1.0** ^(0.4)

(1) Data from stations outside the 10 m depth contour. Values in parentheses are for under-ice water.

(2) Average of primary productivity measurements from 1976-77.

(3) Averages of data from stations within the 10 m depth contour.

* Assumed to be the same as the August value.

+ Estimated from nutrient (nitrogen) availability.

** Assumed to be the same as the averaged August value.

TABLE 9. Monthly primary production in the Alaska Beaufort Sea.

	June 30 days x 24 hrs	July 31 days x 24 hrs	August 31 days x 20 hrs	September 15 days x 12 hrs	Totals
Offshore (50 m)					
Euphotic zone depth (m) (1)	50	50	50	50	
Average primary productivity ($\mu\text{gC}/\text{m}^3\text{-hr}$) (2)	0.2	0.9	0.8	0.4	
Monthly production ($\text{g C}/\text{m}^2$)					
a) Beneath ice	3.6	16.7	12.4	1.8	34.5
b) Open water	7.2	33.5	24.8	3.6	69.1
Mid-depth (10-50 m)					
Average euphotic zone depth (m)	30	30	30	30	
Monthly production ($\text{g C}/\text{m}^2$)					
a) Beneath ice	3.2	14.8	11.0	1.6	30.6
b) Open water	4.4	20.1	14.9	2.1	41.5
Nearshore (1-10 m)					
Average euphotic zone depth (m)	4	5	5	5	
Average primary productivity ($\text{mgC}/\text{m}^3\text{-hr}$) (2)	0.1	1.1 (3)	1.0	1.0	
Monthly production ($\text{g C}/\text{m}^2$)					
a) Beneath ice	0.3	4.0	3.1	0.9	8.3
b) Open water	0.3	4.0	3.1	0.9	8.3

(1) Open water euphotic zone; under ice euphotic zone is assigned equivalent to 10 percent surface light intensity; 50 m depth is assigned from observed nutrient depletions (Hufford, 1974).

(2) Values from Table 8.

(3) Values based on nitrate-N availability.

COVER compensates to a large extent for the decreasing solar angles over the course of the summer. The experiment of Steeman Nielsen (1975) which investigated productivity at 55°N during April was felt to be somewhat appropriate for open water conditions since the solar angle at that time approximates that at 70°N in June. He found that during dark, cloudy days, net productivity was reduced by up to 50 percent and the euphotic zone was effectively shallowed by insufficient light.

The assumptions made in the construction of the contours of primary production (Figure 13) require that this map be used as a qualitative guide to regional productivity. We have not included estimates of ranges or errors and do not have sufficient data on offshore productivity to predict accurately the effects of ice cover on nutrient supply, phytoplankton growth or light attenuation. We have employed approximations based on what we believe are reasonable assumptions. The assumptions and data include:

- 1) The ^{14}C uptake rates applied to under-ice areas were taken from Homer (1980) in areas greater than 6 oktas of ice and from our June 1982 measurements. All rates from Homer (1980) were adjusted upward by 25 percent to compensate for assumed loss of photosynthetic products during acid rinsing of filters. Her light intensities used for incubation (ea. 44 $\mu\text{E}/\text{m}^2\text{-sec}$) were similar to under-ice natural intensity.
- 2) Ice cover is assumed to melt at a constant rate over the summer. Although Melnikov (1980) has shown that melt rates vary widely during the season and from year to year, this approximation was used for simplicity. The under-ice euphotic zone is predicted to increase from 9 to 23.5 m during the summer assuming the extinction coefficient of ice remains constant.
- 3) The data of Hufford (1974) show nutrient depletion to over 60 m in nearshore areas of ice-free water. We, therefore, use 50 m as a conservative maximum euphotic zone depth.
- 4) Average ice-free days were calculated from Figure 12.

- 5) Algal growth rates were calculated from ^{14}C -uptake rates and standing stocks estimated from chlorophyll concentration (Table 10). These rates are shown in Figure 14.
- 6) Standing stocks and growth rates were assumed uniform during each month.

Table 11 summarizes the number of ice-free days along each transect of Figure 11. These estimates were derived from the average ice retreat curves shown in Figure 12. Since the cloud cover was often continuous for over a week at a time, there are probably considerable inaccuracies in our estimates of the "ice edge" position at a given date but we had little alternative to using an average rate of retreat. For the purpose of assessing regional productivity, however, we feel this technique presents the best approximation.

We also list in Table 12 our estimates of primary productivity in nearshore waters taking into account ice cover and subsequent open water season.

Offshore nutrient data are available for late summer from Hufford (1974) for the Beaufort Sea and from Kinney et al. (1970) for the Chukchi Sea. Both sources show that nutrient depletion occurs in the upper 35-50 m over most of this area. The deep Chukchi Sea water is richer than the Beaufort Sea due to additions of Bering Sea winter water, and we assumed 12 $\mu\text{g-atoms}$ nitrate $-\text{N}/\text{liter}$ available at the onset of primary production based upon data from Alexander et al. (1975) and Schell (unpublished data). This quantity of inorganic nitrogen would yield (at C:N ratio = 7.5) approximately 54 $\text{g C}/\text{m}^2\text{-yr}$ with a 50 m euphotic zone. If the phytoplankton standing stocks cause a reduction in the euphotic zone, then overall productivity may be less. We feel, however, that the sinking of cells and the earlier open water may result in maximum annual production near 50 $\text{g C}/\text{m}^2$.

Although the above calculations are based upon the uptake of nitrate-N into the particulate fraction, it is certainly true that some regeneration of ammonia and mineralization of organic nitrogen must occur. When considering the Beaufort Sea out to a distance of 200 km from land, the inputs of terrestrial nitrogen shrink to insignificance.

TABLE 10. Estimates of annual production ($\text{g C/m}^2\text{-yr}$) derived from adjusted ^{14}C primary productivity rates and from measured algal growth rates (AGR).

Transect:	I		II		III		IV		V		VI	
Station	^{14}C	AGR										
A	34	34	30	30	21	20	22	24	18	20	26	30
B	44	49	38	44	29	33	23	31	22	30	30	38
c	35	42	29	37	29	37	26	35	26	36	27	36
D	25	35	22	33	26	36	21	32	31	32	25	35
E	17	28	18	29	20	31	18	30	18	30	22	33
F	13	23	14	25	18	30	17	29	17	28	21	32
G			13	23	17	28	16	27	15	27	18	30
H					14	25	13	24	14	25	17	29
I					13	23	13	23	13	24	17	28
J											13	23

TABLE 11. Estimated number of ice free days for stations shown in Figure 11 based on DMSP Imagery, 1978 -1980. *

Transects:	I			II			III			IV			V			VI		
Station	Jul	Aug	Sep															
A	12	31	30	9	31	30	16	31	30	1	31	30	1	31	30	0	25	30
B	1	31	30	0	24	30	0	30	30	0	14	30	0	13	30	0	14	30
C	0	21	30	0	13	30	0	16	30	0	9	30	0	10	30	0	11	30
D	0	9	30	0	5	30	0	10	30	0	3	30	0	4	30	0	8	30
E	0	7	30	0	2	30	0	2	30	0	0	30	0	0	30	0	5	30
F	0	0	30	0	0	10	0	0	29	0	0	24	0	0	23	0	3	30
G				0	0	0	0	0	22	0	0	16	0	0	15	0	0	30
H							0	0	7	0	0	5	0	0	7	0	0	26
I							0	0	0	0	0	0	0	0	2	0	0	24
J																0	0	0

* June was ice covered for all stations and is not included in the table.

TABLE 12. Phytoplankton production estimates ($\text{g C/m}^2\text{-yr}$) from ^{14}C uptake rates and algal growth rates (AGR) for depth intervals in the nearshore Beaufort Sea (<20 m).

Depth interval (m)	June		July		August		September	
	^{14}C	AGR	^{14}C	AGR	^{14}C	AGR	^{14}C	AGR
0-5	0.3	1.4	3.1	3.4	3.1	2.3	1.8	1.4
5-10	0.2	1.8	2.0	3.4	3.1	2.2	1.8	1.3
10-15	0.0	1.8	0.4	3.3	3.1	2.3	1.8	1.4
15-20	0.0	1.8	0.0	3.4	3.1	2.2	1.8	1.3
Total	0.5	6.8	5.5	13.5	12.4	9.0	7.2	5.4

However, the regeneration of nitrogen assimilated by phytoplankton through grazing and excretion by zooplankton becomes the variable which could alter annual production estimates by a large fraction. If, for example, phytoplankton populations were capable of using the very low light levels efficiently and the particulate nitrogen pool was turned over just one time during the summer, our estimates of primary production based upon N uptake would be low by a factor of 2. As pointed out earlier in discussing terrestrial inputs, this almost certainly occurs in the shallow brackish warm waters next to the coastline.

Another approach toward estimating annual production was the application of the equation of Eppley and Peterson (1979). In seeking to relate the productivity arising from "new" nitrogen advected or diffused into the euphotic zone (Dugdale and Goering, 1967) with the productivity resulting from nitrogen (primarily ammonia) regenerated in situ, they established the relationship.

New production/total production = 0.0025 (total production). Harrison, et al. (1982) applied this equation to Baffin Bay waters and calculated total annual production of $188 \text{ g C/m}^2\text{-yr}$, about double previous estimates from the same area. They derived their estimate from measured nitrate and ammonia uptake rates. They did not, however, adjust this estimate downward to compensate for the period of winter darkness when growth would be solely light limited.

When we assume an assimilation of $4 \text{ } \mu\text{g-atoms NO}_3\text{-N/liter}$ and a 35-50 m euphotic zone we obtain a "new carbon" production between 12.6 and 18 g/m^2 . Inserting these values into the equation, our total annual production would equal $71\text{-}85 \text{ g C/m}^2\text{-yr}$. If we apply a reduction factor based on the fact that light is severely limiting between mid-October and mid-April, the range of annual production is $35\text{-}42 \text{ g C/m}^2\text{-yr}$. These values are in good agreement with the annual productivities we predict from ^{14}C -uptake data alone. It should be noted the Eppley-Peterson equation was intended for offshore, oligotrophic waters. The pronounced stratification, ice cover and low nutrient concentrations in the Beaufort Sea produce conditions very similar to offshore oceanic waters of lower latitudes.

Truett (1981), in his synthesis of the Simpson Lagoon ecosystem study notes the importance of the wind-driven longshore transport in

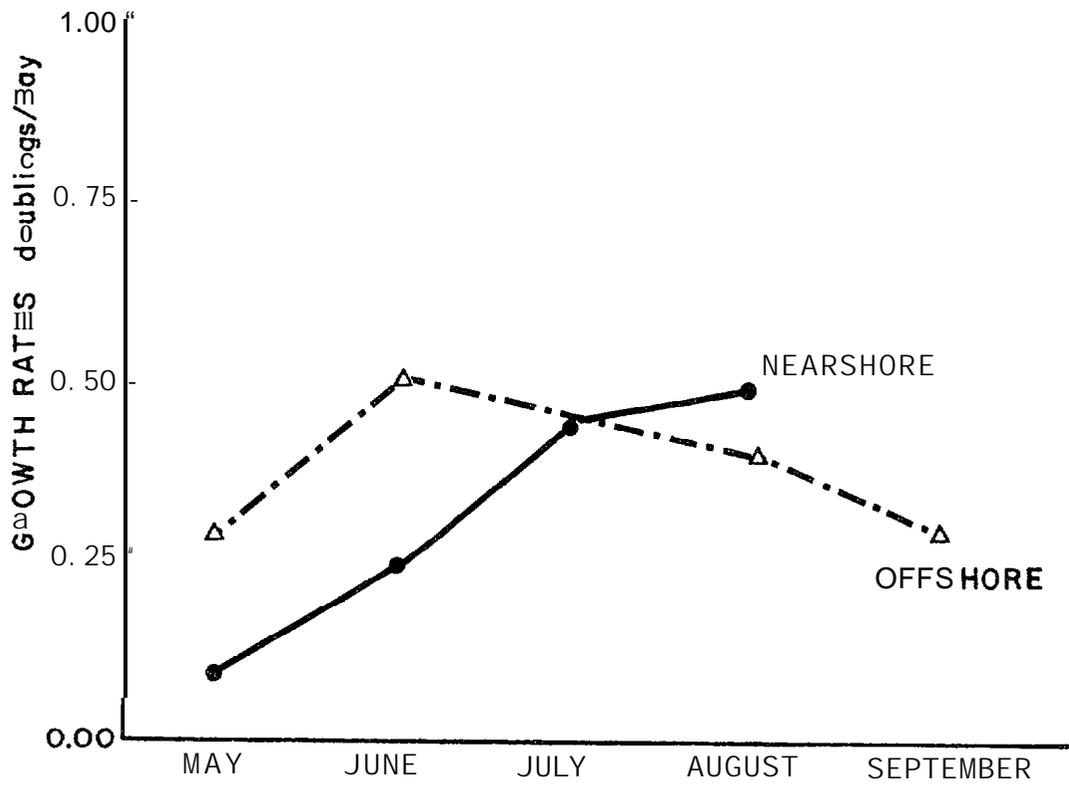


Figure 14. Phytoplankton growth rates in offshore and nearshore Beaufort Sea waters.

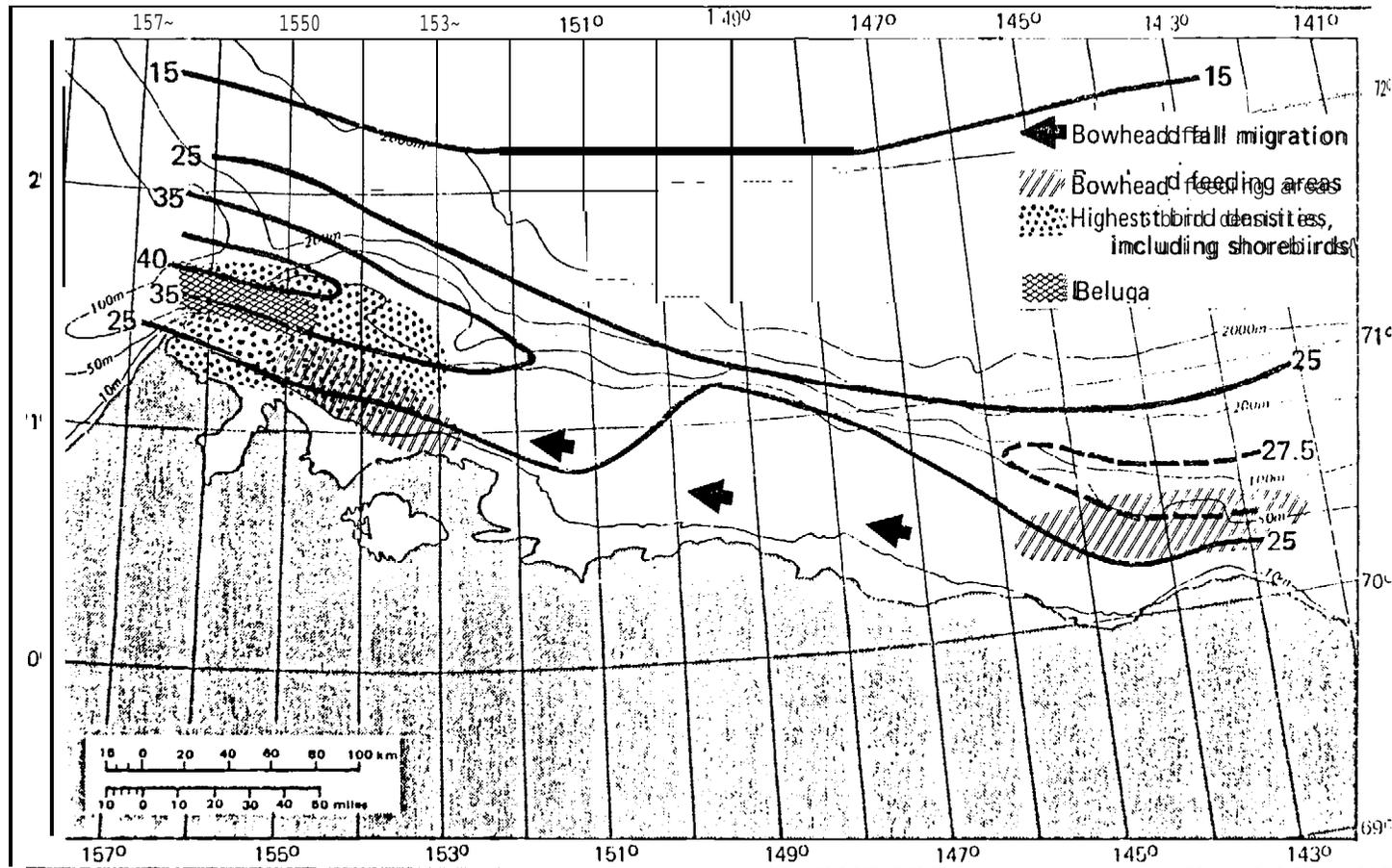


Figure 15. Observed concentrations of marine mammals and birds in relation to areas of projected primary production.

determining the water characteristics along the shoreline. This brackish warm water is a mix of river water and marine water which is transported by prevailing easterly winds to the west. Satellite imagery shows evidence of this transport along the entire shoreline. We hypothesize that the continual addition of freshwater laden with inorganic and organic nitrogen should result in a progressive nutrient enrichment in coastal waters as the longshore transport approaches Point Barrow. At Point Barrow, the Bering-Chukchi water moving northward intersects this flow and induces eddy formation in the area northeast of the Plover islands. The enhanced production anticipated from mixing the more nutrient-rich Bering-Chukchi waters and the enriched brackish coastal water should be evident as increased primary and secondary production in this area.

Chlorophyll concentration data from Homer (1981) support this premise and we estimate that annual production may approach 50 g C/m² which makes this area one of the most productive of the Alaskan Beaufort Sea. Braham and Krogman (1977) identify this area as a fall concentration locality for bowhead whales during the westward migration which may be a result of increased concentrations of prey organisms.

Other investigators have identified areas near Barrow and Barter Island as being important habitat for mammals and birds. Figure 15 shows composite information from Braham and Krogman (1977), Divoky (personal communication), Frost and Lowry (1981), and Burns et al. (in preparation) regarding observed concentrations of birds and marine mammals in the Beaufort Sea. The short food webs with vertebrate consumers relying on herbivorous mysids, amphipods, euphausiids and copepods lends credence to the apparent correlation between areas of high primary production and faunal density.

Cellulose Biodegradation in Marine Waters

Oxidation of cellulose in the waters of Elson Lagoon by microbial populations was demonstrated in 1978 in a series of laboratory experiments performed at the Naval Arctic Research Laboratory at Barrow. During 1979, in cooperation with D. Schneider (RU 356), these experiments were expanded to test the ability of the amphipods *Gammarus*

setosus and *Onisimus* sp. to utilize peat detritus as a food source and to acquire additional data on microbial oxidation by in situ populations at temperatures typical of summer and winter environments. The 1978 experiments had revealed active microbial oxidation in peat exposed to seawater and in the water column. Figure 16 shows the temperature effects on cellulose oxidation using water from two stations in Elson Lagoon. The cellulose was suspended in the seawater, and subsamples were stripped for radiolabeled carbon dioxide to yield the plot shown. The active degradation of cellulose at 0°C indicates that the microbial populations have adapted to the cold environment. It is reasonable to assume that the influx of eroded peat contributes to the active populations of microorganisms in the water column.

The ability of amphipods to feed upon and digest detrital material directly would be an obvious adaptive advantage in arctic waters where photosynthesis is highly seasonal. Work by RU 356 on feeding preferences of the common amphipods of Elson Lagoon has shown that some amphipods ingest and appear to assimilate peat detritus. The amphipod *Gammarus setosus* was the most active peat consumer, but unfortunately this species was not present among the animals trapped during the December 1978 experiments. Instead, a mix of small amphipods, primarily the predatory amphipods *Boeckosimus* sp. and *Onisimus* sp. were tested for peat ingestion and cellulose biodegradation. Neither species was found to release radiolabeled carbon dioxide into solution, indicating there was no assimilation of the cellulose. The presence of amphipods in samples of seawater and peat yielded lower oxidation rates than peat plus seawater alone. Possible grazing of meiofauna and bacteria may have caused this depression in the rate of carbon dioxide evolution, but the lack of label appearing in the amphipods did not lend support to this concept.

Although these initial experiments did not support the hypothesis that amphipods were directly utilizing detrital peat, the high rates of microbial biooxidation in the water column and associated with the peat detritus were felt to warrant further investigation to help establish mean lifetimes for peat particles in the nearshore waters. During July 18-20, 1979, the microbial oxidation rates of peat were again measured and compared with the oxidation rates due to the ingestion of the peat by the amphipods *Onisimus* sp. and *Gammarus setosus* at typical summer

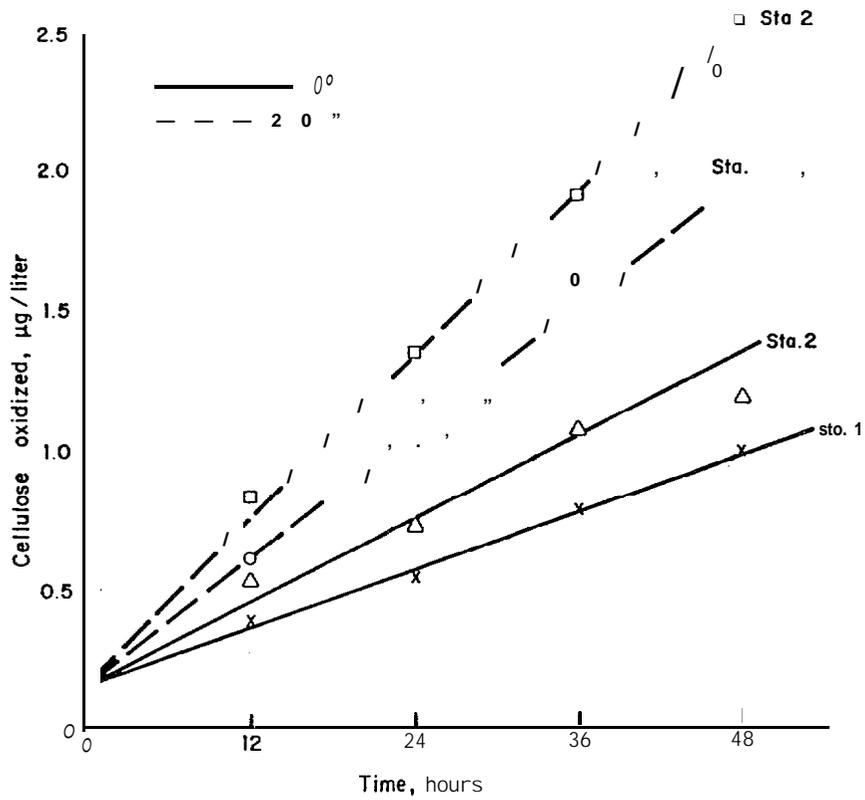


Figure 16. Carbon dioxide evolution from ^{14}C -labeled cellulose in Elson Lagoon water.

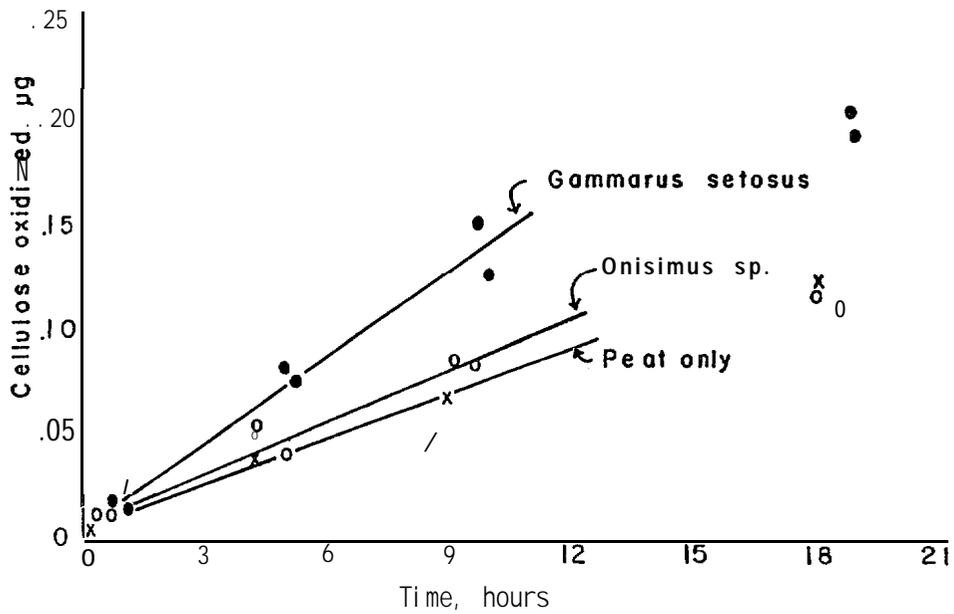


Figure 17. Carbon dioxide evolution from ^{14}C -labeled cellulose mixed with seawater-wet peat and fed to amphipods.

lagoon temperatures. The results of these experiments, which are summarized in Figure 17, show a remarkable contrast between the two amphipods in cellulose oxidation rates. The sample with *Onisimus* amphipods showed a carbon dioxide evolution rate that closely approximated the background rate due to microflora in the detritus and water, confirming the apparent inability of this genus to assimilate peat detritus. In contrast, the sample with *G. setosus* yielded a much higher rate of oxidation. Dissection of the animals showed that radioactivity from the cellulose had been incorporated into body tissue, although considerable variability occurred among animals, preventing a meaningful estimate of assimilation efficiency. Nevertheless, after mixing with 9 mg peat (dry weight), an average of 0.3 percent of the radiolabeled cellulose had been oxidized to carbon dioxide over the 18 hour experiment. Dividing this oxidation rate into the total weight of peat, a mean assimilation rate of 1.5 μg peat/amphipod-hr is obtained, assuming the peat is assimilated at rates near those of the labeled cellulose. Incorporation of metabolized ^{14}C -cellulose into body tissue, as measured in the dissected animals, was approximately as great as oxidation to carbon dioxide, indicating utilization of the cellulose for growth. These invertebrates represent the most efficient pathway we have found by which peat carbon can be transferred to higher organisms in marine foodwebs.

The rate of peat oxidation by microfloral and meiofaunal populations was estimated in a similar fashion. During the 18 hour experiment, at 8°C, 0.13 percent of the label was released as carbon dioxide which translates to a turnover time of 6×10^2 days. At 0°C, the turnover time was 4×10^2 days. This is somewhat surprising, but it may only reflect increased populations of microorganisms in the sample of peat which had been held for a day in the laboratory prior to the experiment. These data compare well with data from the 1978 experiments on peat oxidation, which gave a turnover time of 6×10^2 days at 0°C using a sample of seawater-saturated peat from Milne Point. We suspect the agreement is more coincidental than indicative of similarity in oxidation rates, since it would be more reasonable to expect wide variations due to differing populations of bacteria, nutrient concentrations, temperature, oxygen concentrations and response

to fresh versus degraded peat materials. The turnover times do indicate, however, that the peat is readily oxidized by microorganisms and contributes to ecosystem energetic in the nearshore zone.

Nutrient Dynamics and Under-ice Circulation

Nutrient concentrations rise steadily in the under-ice waters of the nearshore Beaufort Sea following the cessation of plant uptake in the fall. The increase is due to three additive factors -- regeneration in situ by microbial activity, advective transport, and freeze concentration of the solutes in underlying water as the ice thickens. By November, samples taken in the nearshore area showed nitrate concentrations of approximately 1-2 $\mu\text{g-atoms NO}_3\text{-N/liter}$, although the phosphate concentrations remained very low in Simpson Lagoon. The low phosphate concentrations in the presence of nitrate may indicate that bacterial vitrification is active in these waters following mineralization of organic N in eroded peat. Microbial uptake of phosphate has been demonstrated in eroded peat samples from Simpson Lagoon, and high vitrification rates were evident in the Colville Delta channels in earlier studies (Schell, 1974).

By spring, tidal and surge-pumped currents and thermohaline convection have replaced nearshore waters from all areas where offshore exchange is possible. The generalized movement of the under-ice water as shown in Figure 17 was hypothesized as a possible supply of nutrients to ice algae by this research unit in 1977. The combination of nutrient data, ice algal biomass in Stefansson Sound, and the current data obtained by Brian Matthews (RU526) now strongly support this concept.

In order to determine the residence time of water in Stefansson Sound during the winter we have developed a two-layer model based on conservation of salt and volume. It describes the under-ice salinity changes inside the barrier islands as a function of brine exclusion during ice formation and flushing by less saline offshore water. Figure 18 shows the model in box form with all the necessary parameters. The mathematics of the model are as follows:

$$\frac{dS}{dt} = (V \frac{ds}{dt} - s \frac{dV}{dt}) / V^2$$

where

$\frac{dS}{dt}$ = change in salinity inside Stefansson Sound with time

$\frac{ds}{dt}$ = change in total salt content of Stefansson Sound with time

$$= RF(S-a)A_s + US_i A_p - USA_p$$

$\frac{dV}{dt}$ = change in volume of water in Stefansson Sound with time

$$= -RA_s$$

V = volume of Stefansson Sound at any time (t)

$$= (Z_0 - Rt) A_s$$

s = Total salt content of Stefansson Sound at any time (t)

$$= (Z_0 - Rt)(S - ab) A_s$$

This yields the equation:

$$\frac{dS}{dt} = \frac{S(A_s R(F + 1) - AU) + A S_i U - A_s Ra(F+b)}{A_s(Z_0 - Rt)}$$

which can be solved for U:

$$U = \frac{A_s R[Rta(F + b) - Z_0(F + 1) (S_0 - (1 - \frac{Rt}{Z_0}) S_t)]}{A_p Z_0 [S_0 - S_t + \frac{Rt}{Z_0} (S_0 - S_i)]}$$

where:

S_i = offshore salinity

S_t = Stefansson Sound salinity at any time (t)

S_0 = Stefansson Sound salinity at time (t=0)

F = fraction of salt excluded during ice formation

R = rate of ice formation

Z = depth of Stefansson Sound at any time (t)

Z_0 = depth of Stefansson Sound at time (t=0)

a = salinity of lower layer minus salinity of upper layer
 b = fraction of water column which is the upper layer
 A_S = area of Stefansson Sound
 A_p = Mean cross-sectional area of passes between barrier islands
 which define Stefansson Sound for the time period considered
 U = velocity of currents through passes of cross-sectional area
 equal to A_p

The velocity in the upper layer (U_u) = U/b , while the velocity in the lower layer (U_l) = $U/1-b$.

Table 13 lists the salinity data for three winter seasons accumulated from Matthews (1981), Toimil and England (1982), and this report, and the current velocities and residence times calculated from the model. In order to compare our velocities with those measured by Matthews (1981), we have also considered the upper layer thickness to be equal to one-third of the water column.

Our calculated currents are quite consistent from one year to the next, but for the same 49 day period in 1978, Matthews (1981) measured currents about three times higher than our values. Given the frequent surges induced by barometric changes during the winter, periodic high current velocities are to be expected. It seems most reasonable to conclude then, that the residence time for water in Stefansson Sound during the winter is about 20-60 days, with an average of near 40 days in the spring season. From nutrient data acquired offshore, we can calculate the uptake efficiency of the epontic algae as the water moves shoreward at the ice-water interface. Table 14 lists the environmental conditions in Stefansson Sound at the peak of the ice algal bloom in late May. Note that there is no indication of nutrient limitation at this late stage in the development of the epontic algal community. Instead, as described above, light is the predominant factor restraining primary production. Limited data are available on the rate of nutrient utilization in June, but this may be the time of increasing productivity beneath areas of leads or clear ice. Melting and sloughing off of the ice algal layer should result in greatly increased light penetration which, when coupled with 24 hour sunlight, should provide favorable conditions for phytoplankton photosynthesis.

WATER COLUMN SALINITY

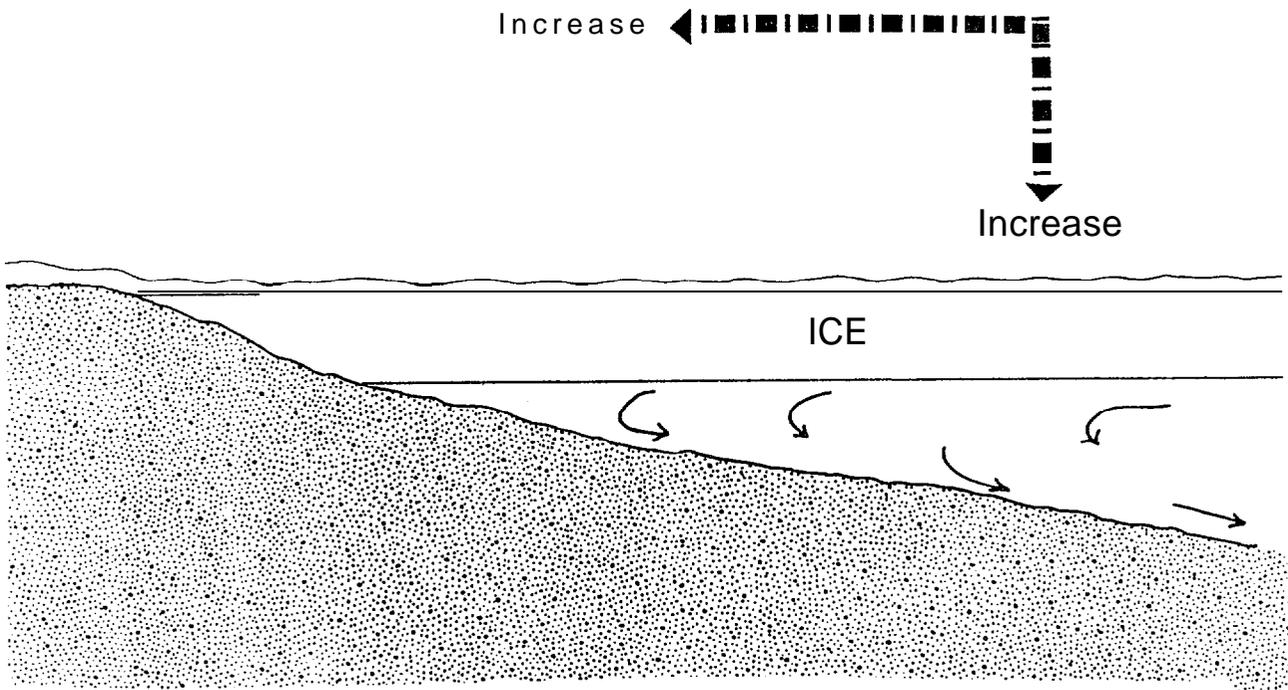


Figure 18. Generalized thermohaline convection pattern induced by brine exclusion during ice formation.

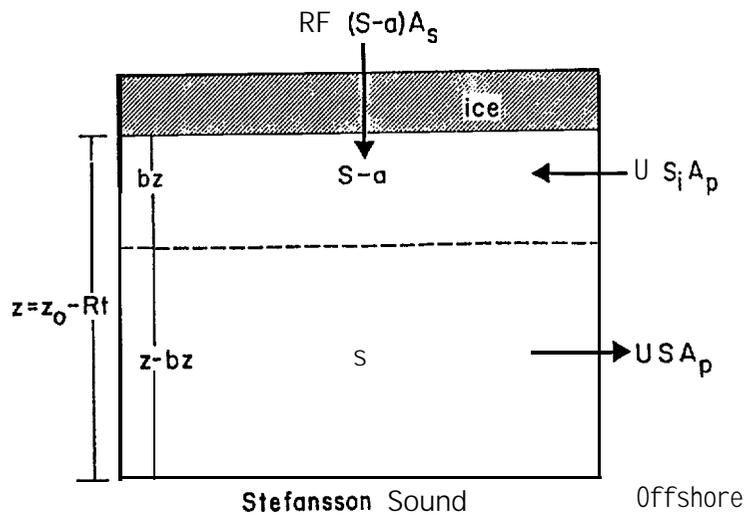


Figure 19. Water exchange model for Stefansson Sound. (See text for explanation of terms.)

TABLE 13. Water exchange model data and results.

Year	Period	t (days)	Z (m ⁰)	S ₀ (ppt)	S _t (ppt)	U _U (cm/Sec)	U ₁ (cm/sec)	Residence Time (days)
197B - 79	12 Nov - 31 Dec	49	3.6	32.5	34.3	1.1	0.5	50
	12 Nov - 12 Feb	92	3.6	32.5	34.8	1.5	0.7	36
	24 Jan - 31 March	66	2.9	33.4	34.0	0.7	0.3	49
	12 Nov - 31 March	139	3.6	32.5	38.0	0.8	0.4	46
1980 - 81	9 Nov - 7 May	180	3.6	28.8	33.1	0.8	0.4	45
1981 - 82	1 Ott - 25 May	237	4.0	27.8	34.4	0.6	0.3	60

a = 1.0 ppt
 b = 0.33
 F = 0.83 (Schell 1975)
 S₀ = 31.5 ppt
 R¹ = 0.01 m/day (Schell 1975)
 A = 8.8 x 10⁸ m²
 A_p^{s*} = (252 - 0.5t) x 10³ m²

* In this equation, t is the time since the start of freeze-up.

Table 14. Under-ice conditions in late spring, Stefansson Sound Beaufort Sea.

ENVIRONMENTAL CONDITIONS	
STEFANSSON SOUND - MAY 1979	
SALINITY	32 - 50% . ICE 1.6 - 2.0m
WATER TEMP.	-1.8 to -2.9° AIR TEMP. -30 to 0°
SNOW COVER	10 - 50 cm DAYLIGHT > 20 hrs
LIGHT PENETRATION, UNDER-ICE - 0.0-0.90 % surface	
MAXIMUM LIGHT INTENSITY, UNDER-ICE ~1000 lux	
~20 μE m ⁻² s ⁻¹	
NUTRIENT CONCENTRATIONS	
NITRATE + AMMONIA - N	4 - 10 μg - at/l
PHOSPHATE - P	0.5-1.1 "
SILICATE - Si	20-50 "

Since nutrient concentrations provide little insight into the dynamics of nitrogen and phosphorus cycling and limiting elements, we have attempted to assess the relative magnitudes of the major factors governing the availability of nutrients in nearshore waters.

Allochthonous inputs of terrestrial nitrogen occur during the summer months and offer several reasons for probable importance to the marine ecosystem:

1. Peak input occurs during breakup flooding and injects both inorganic and organic nitrogen into the nearshore marine waters early in the primary production season.
2. Water temperatures of the river water are usually much higher than the marine waters, and microbial processes should be accelerated.
3. River water contains several times greater concentrations of dissolved and particulate organic nitrogen than marine waters. Marine water, however, is relatively rich in phosphate and may accelerate microbial growth through synergistic effects. High nitrification rates observed in delta channels with mixed marine and freshwater (Schell, 1975) tend to support this hypothesis.

To assess the role of terrestrial nutrients in marine phytoplankton production, a mass balance calculation made on nitrogen inputs can be compared to nitrogen requirements by phytoplankton in the nearshore zone. Assumptions and determinations include:

1. Late winter inorganic nitrogen concentrations in marine waters averaged $4 \mu\text{g-atoms/liter}$ in the 1.8 m ice cover (this study; Schell and Hall, 1972).
2. Planimetry of the nearshore zone of the Alaskan Beaufort Sea out to the 10 m contour defines an area of $8.7 \times 10^9 \text{ m}^2$. For estimation of water volume in this area, a uniform slope offshore

is assumed and an average distance offshore of 10 km to the 10 m depth contour.

3. Annual ice thickness is 1.8 m, and 20 percent of solutes in the water is included in the ice during freezing.
4. Total river runoff into the Beaufort Sea from commencement of spring flow until July 1 is $16.8 \times 10^9 \text{ m}^3$. Average nitrate-N concentration in the river water is $4 \text{ } \mu\text{g-atoms/liter}$.
5. Organic nitrogen input from the rivers is $840 \times 10^3 \text{ kg-atoms}$. Inorganic nitrogen input is $70 \times 10^3 \text{ kg-atoms}$.

The formation of the winter ice cover reduces the underlying water volume from $44 \times 10^9 \text{ m}^3$ to about $30 \times 10^9 \text{ m}^3$. At 4 mg-atoms N/m^3 , a total standing stock of $120 \times 10^3 \text{ kg-atoms}$ of inorganic nitrogen is present in the water at the onset of algal growth in spring. Another $11 \times 10^3 \text{ kg-atoms}$ are present in the ice cover and are released during brine drainage and melting, yielding a total in situ standing stock of $131 \times 10^3 \text{ kg-atoms}$ of inorganic nitrogen (mostly nitrate-N).

As breakup progresses, river runoff adds an additional $70 \times 10^3 \text{ kg-atoms}$ inorganic nitrogen and $840 \times 10^3 \text{ kg-atoms}$ dissolved and particulate organic nitrogen. Data from the Colville Delta saline waters indicate in situ nitrification rates of $0.23 \text{ } \mu\text{g-atoms N/liter-day}$. Mineralization rates of dissolved organic nitrogen in Elson Lagoon during late spring occurred at $0.13 \text{ } \mu\text{g-atoms N/liter-day}$ (Schell, 1974). Since these rates were observed at temperatures near -2°C , the warmer runoff water of Colville River flow in June may result in faster rates of mineralization.

It is interesting to compare the primary productivity rates measured in the Beaufort Sea with the nitrogen available for growth. Using a carbon:nitrogen atom ratio of 7.5, the inorganic nitrogen entering the nearshore zone is sufficient for the fixation of $1.5 \times 10^6 \text{ kg-atoms carbon}$. If mineralization were sufficiently fast to make available most of the dissolved organic nitrogen, the total nitrogen

standing stock would be sufficient to produce 7.8×10^6 kg-atoms C on a once-through uptake. Our estimate of annual carbon fixation for this same area (via ^{14}C -uptake data) is about $10\text{-}15 \times 10^6$ kg-atoms for the May-July period. Since grazing and regeneration would turn over much of the nitrogen in situ, the amounts present at the start of the season and transported into the coastal zone must account for the observed productivity. Since nitrogen is the limiting nutrient for marine primary production, we can also estimate that turnover of the nitrogen pool must occur 7-10 times during this period if the terrestrial organic nitrogen does not mineralize at an appreciable rate. If, however, the major fraction of the organic nitrogen is mineralized and enters the marine nitrogen cycle, then the necessary turnovers drop to only two or three times during the fixation of the $10\text{-}15 \times 10^6$ kg c. The data from Hufford (1974) indicate that deeper (75 m) offshore concentrations of nitrate are higher ($10\text{-}15 \mu\text{g-atoms N/liter}$), and it is possible that wind mixing in summer may advect larger quantities of nitrogen to the euphotic zone. This source is probably much more important further offshore.

These estimates are not intended to represent the quantitative movements among compartments of the coastal nitrogen cycle, 'out to describe the probable major role of allochthonous nitrogen to coastal productivity. The observed rates of carbon fixation coincide well with the conceptual model of nitrogen supply. Although loss from the nearshore zone through sedimentation and transport offshore beyond the 10 m contour must account for a fraction of the inputs, uptake rates are rapid, as evidenced by the depletion of nitrate concentrations in Harrison Bay off the mouth of the Colville River.

The uptake of dissolved nitrogen into the particulate fraction progresses until the cessation of primary productivity in the fall. Soon thereafter, decomposition and regeneration of inorganic nitrogen result in the accumulation of nitrate and ammonia in the water column. The large quantities of organic nitrogen accumulated through uptake and fluvial transport over the summer should be reflected in high standing stocks of nitrate and ammonia, but this condition is not observed except in localized areas of restricted circulation. Instead, tidal and surge-pumped currents coupled with thermohaline convection transport

more saline, denser waters containing the regenerated nutrients offshore. As mentioned above, the currents measured by Matthews (1981) and calculated from our water exchange model yield residence times for Stefansson Sound water during winter of 20-60 days. Schell (1975) has made a similar estimation for Dease Inlet and concluded that thermohaline convection and surge and tidal flushing could replace the under-ice waters as often as every 7-10 days. The significance these currents add to nutrient budgets is pronounced.

Data obtained from a transect offshore in spring 1982 support our model. Figures 20 and 21 show the salinity and nutrient concentrations northward across Stefansson Sound and approximately 50 km beyond Narwhal Island. Salinities within the lagoon system and in downslope bottom water offshore are higher than in the overlying water column by 3-10 percent. Nitrate concentrations are about doubled, however, indicating that the mineralization of organic nitrogen and nitrification processes continue throughout the winter. By dividing the increase of $3 \mu\text{g-atoms NO}_3 - \text{N/liter}$ by the calculated residence times of 20-60 days in the lagoon, we estimate the input rate due to in situ regeneration of nitrate at 0.05-0.15 $\mu\text{g-atom N/liter-day}$. This estimate compares favorably with previous estimates of 0.13 $\mu\text{g-atom N/liter-day}$ in Elson Lagoon near Barrow and 0.07 $\mu\text{g-atoms N/liter-day}$ in saline channels of the Colville delta (Schell, 1974).

Instead of accumulating high concentrations of inorganic nitrogenous nutrients in the nearshore under-ice waters over the winter season, this nitrogen is largely transported to offshore deep water. The ambient concentrations in early spring are derived from the offshore surface water advected toward the coast. Since these waters are relatively low in nitrogenous nutrients, the role of allochthonous inputs during breakup and river flow over the summer season are accentuated.

Phosphate Uptake Experiments -- August 1978

The results in Table 15 show the concentrations of dissolved inorganic phosphate (DIP) and total organic phosphorus (TOP) in Milne

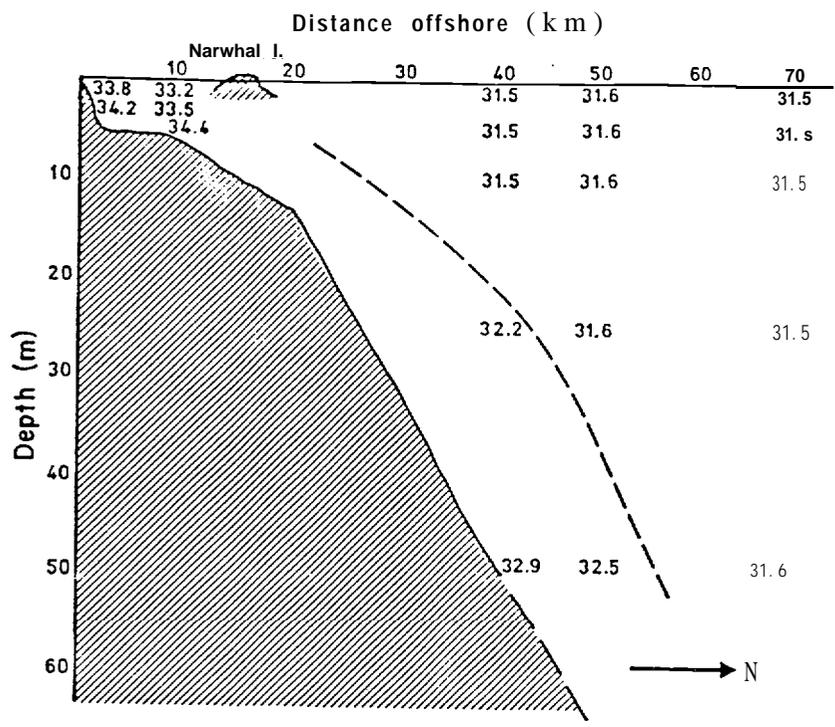


Figure 20. Salinities (ppt) north of Prudhoe Bay, Alaska, 28 May 1982.

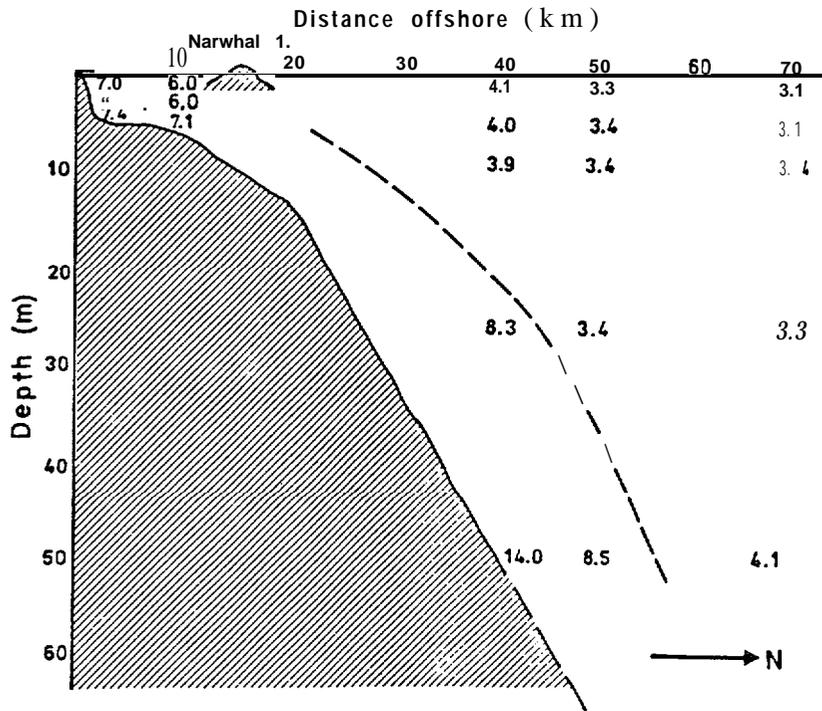


Figure 21. Nitrate concentrations ($\mu\text{g-atoms N/liter}$) north of Prudhoe Bay, Alaska, 28 May 1982.

Point seawater. The phosphate uptake rates of Milne Point seawater samples and peat-amended Milne Point seawater samples are shown in Tables 16 and 17. The peat-amended seawater took up phosphate at a significantly higher rate than the HgCl_2 poisoned control and the autoclave control, indicating that the uptake was predominantly biological in nature versus a nonbiological sorption (Table 17). Since the phosphate uptake rates in seawater did not increase significantly with concentration up to additions of $0.50 \mu\text{g atom P/liter}$, and the indigenous concentration was $0.20 \mu\text{g atom P/liter}$, the mechanisms responsible for uptake and release of phosphorus at these lower concentrations were most likely in steady state (Table 16). The increased uptake response to additions of higher concentrations of phosphate (1.0 and $2.0 \mu\text{g atom P/liter}$) probably indicates a stimulation of biological phosphate incorporation above steady state levels. A physical sorption study might test this interpretation.

Carbon Isotope Studies of Nearshore Foodwebs

The intricacies of nearshore and estuarine marine foodwebs present formidable obstacles to assigning significance to various energy source materials supporting resident fauna. Primary production from phytoplankton, benthic microalgae, macrophytes, and allochthonous terrigenous vegetation can all contribute with varying efficacy, and the quantification of inputs is often difficult or impossible. Recent studies have sought to bypass the various foodweb steps between source and consumer of interest by making use of natural $^{13}\text{C}/^{12}\text{C}$ isotope ratios to estimate source allocations. If a moderately large difference in the $^{13}\text{C}/^{12}\text{C}$ isotope ratios of the source materials occurs, then relative significance can be ascribed to these sources upon determination of carbon isotopic abundances in the organisms of interest. The marked difference in $\delta^{13}\text{C}$ resulting from C-3 and C-4 photosynthetic pathways yields a natural signal easily traced in herbivores grazing on these plants (DeNiro and Epstein, 1978). As long as the source materials and dietary preferences have a relatively large separation in isotopic signature and are limited to two or three in

TABLE 15. Phosphorus analyses - **Milne** Point water.

Station	Date	DIP* μg-atom P/liter	TOP** μg-atom P/liter
1 (surface)	27 Jul 78	0.36	0.72
4 (bottom)	27 Jul 78	2.07	1.55
1 (surface)	7 Aug 78	0.20	0.49
4 (bottom)	7 Aug 78	0.15	0.24
1 & 4 (pooled)	8 Aug 78	0.12	

*DIP = dissolved inorganic phosphate
 **TOP = total organic phosphorus

TABLE 16. Phosphate uptake by **Milne** Point seawater,

Phosphate Added* (μg-atom P/liter-hr)	Uptake Rate (μg-atom P/liter-hr)
Carrier free ³² Pi	5.6
0.05	5.5
0.10	4.8
0.50	6.9
1.0	18.0
2.0	52.0

*Ambient dissolved inorganic phosphate - 0.20 μg-atom P/liter.

TABLE 17. Phosphate uptake by peat amended seawater.

Sample	Total Inorganic Phosphate (μg-atoms P/g peat)	Uptake Rate (μg-atoms P/g peat-hr)
Peat and filtered Milne Point water	3.12	1.08
HgCl₂ poisoned	3.12	0.17
Autoclave	3.12	0.03

number, the allocation of the source material can often be accomplished. Nature is rarely so cooperative. In estuarine situations where several of these studies have been performed, flora are varied in species and isotopic composition. Studies by Haines and colleagues (Haines, 1976a, b; Haines and Montague, 1979; Hackney and Haines, 1980) using the ^{13}C differences between C-3 and C-4 plants in Georgia and Mississippi estuaries, attempted to quantitate the dependencies of marsh fauna on the marsh grasses *Spartina* spp. and *Juncus* spp. with moderate success. Major difficulties arose however, due to natural variability in the $\delta^{13}\text{C}$ within a given species and due to contributions of heterogeneous populations of epiphytic algae, photosynthetic bacteria, and numerically minor species of vascular plants occurring within the environment with overlapping $^{13}\text{C}/^{12}\text{C}$ abundances. The possibility of chemosynthetic fixation as a major pathway of carbon input has been proposed by Peterson et al. (1980) to alternatively account for some of the conclusions reached by Haines (1977) regarding the role of *Spartina*-derived detritus in supporting Georgia estuarine ecosystems. The ambiguous conclusions arise from the overlap in the $\delta^{13}\text{C}$ signal and the use of a single isotopic label to trace foodweb pathways.

We present here a study on arctic Alaska estuarine foodwebs using both ^{13}C and ^{14}C natural abundances, and describe an ecosystem having a large dependency on allochthonous carbon with a delay of up to several thousand years occurring between primary production and its utilization by consumer organisms. Nearshore carbon inputs consist of primary production by ice algae and phytoplankton, supplemented by peat and vegetative detritus transported by the rivers or added directly by shoreline erosion. Within the shallow nearshore zone (out to the 10 m depth contour, approximately 10 km), allochthonous carbon inputs are about equal to annual primary production (see Figure 22). Since radiocarbon dating of soil sections showed that the peat has been accumulating for 8,000-12,000 years B.P., large depletions in ^{14}C abundances would be found in a foodweb based on peat carbon. $^{13}\text{C}/^{12}\text{C}$ abundances typical of coldwater marine algae were anticipated in pelagic organisms offshore (McConnaughey and McRoy, 1979a) and a uniform C-3 isotopic signature typical of peat and tundra vegetation represent the terrigenous organic matter. The typically

BEAUFORT SEA COASTAL ZONE
ENERGY INPUT
10⁶ kg C/year

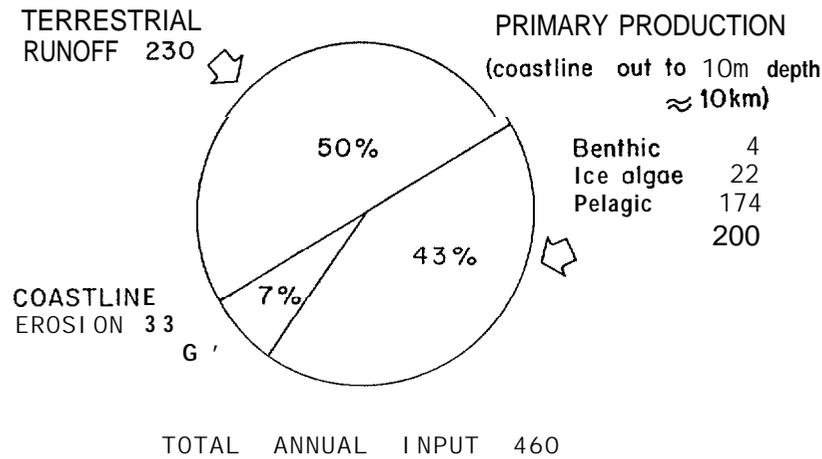


Figure 22. Annual inputs of carbon to the nearshore waters of the Beaufort Sea.

short food chains of the Arctic also indicated minimal problems with biochemical fractionation effects (DeNiro and Epstein, 1978). Organisms consuming these sources either directly or indirectly should yield an isotopic distribution based on source materials as shown in Figure 23.

Preliminary sampling of the particulate organic matter transported by the Colville River over the breakup flood season indicated that the bulk of the fluvial particulate carbon was peat and not modern vegetative detritus carried by surficial runoff. In contrast, the large mysid and gammarid amphipod populations in the receiving marine waters showed only minor depressions in ¹⁴C content and had δ¹³C values indicative of predominantly marine carbon. Radiotracer experiments with ¹⁴C-labeled cellulose indicated active microbial degradation of the peat when exposed to marine waters but the foodweb linkages necessary for efficient transfer to higher trophic levels are apparently lacking. Apical marine organisms from Simpson Lagoon such as four-horn sculpins (*Myoxocephalus quadricornus*) and arctic cod (*Boreogadus saida*) also contained carbon isotope abundances typical of pelagic primary producers, confirming their dependency upon marine carbon fixation.

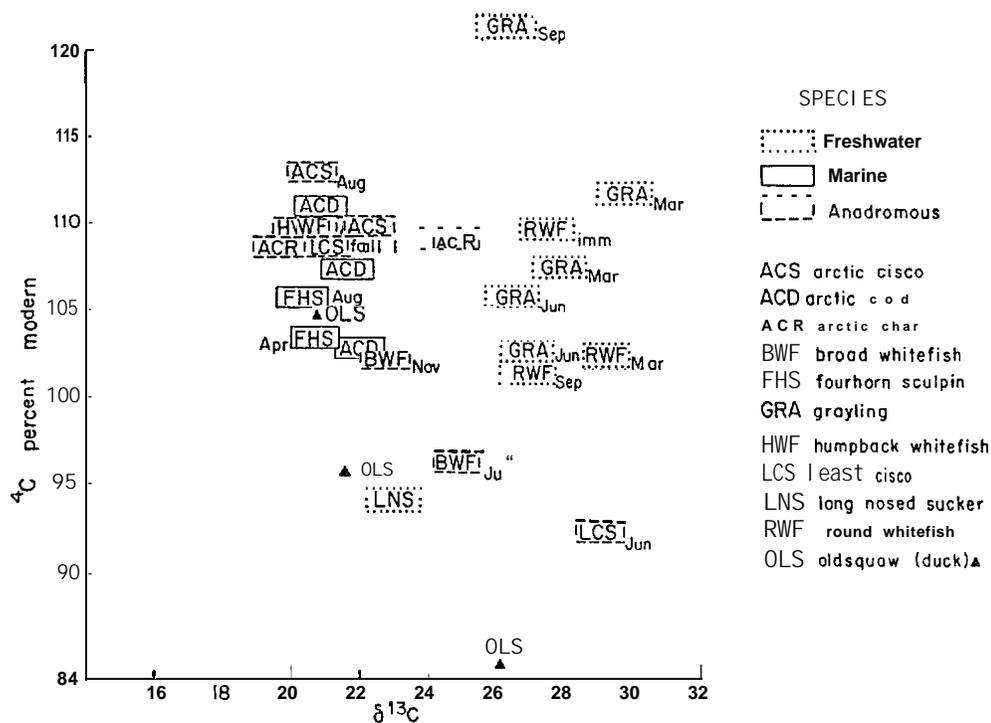


Figure 23. Carbon isotope distribution in coastal Beaufort Sea organisms.

Seasonal residents of the nearshore Beaufort Sea marine waters are typified by avifauna such as migratory oldsquaw ducks (*Clangula hyemalis*) and several species of anadromous fishes, principally ciscoes (whitefish), which enter the marine environment after overwintering in the rivers. The oldsquaw ducks of breeding age migrate north to the tundra lakes and ponds where they nest, molt, and feed upon freshwater invertebrates. Non-breeders and some of the pre-molting birds (males), however, summer on the nearshore lagoons and feed upon the marine invertebrates, thereby splitting the species into segments dependent upon freshwater or marine foodwebs. A detailed description of avifauna is given by Johnson and Richardson (1981). Similarly, the whitefish do not re-enter the rivers until freeze-up and ascend the rivers to overwinter in deep pools. Since Alaskan north slope rivers freeze to the bottom in shallow areas, and essentially cease flowing for most of the late winter (Arnborg et al., 1966), movement within the river system is very restricted for the obligate freshwater fish species and the overwintering anadromous fish. Samples of fish were collected prior to entering the Colville River, beneath the ice in March, and in the Colville Delta as they were recentering the marine waters in June.

Figure 23 shows the isotopic composition of a cross-section of the fishes and oldsquaw ducks from freshwater and marine environments and a complete list of isotopic data is presented in Table 18. The marine fish are tightly grouped near $\delta^{13}\text{C}$ of -21 ppt and a ^{14}C content of 104-110 percent modern.¹ The anadromous species captured after feeding in the marine environment for the summer are isotopically indistinguishable from obligate marine species, indicating that peat is not a significant source of carbon to nearshore marine foodwebs. The principal prey species found in stomach contents were mysids (^{14}C = 106 percent modern) and gammarid amphipods (^{14}C = 104 percent modern), indicating that very little of the peat carbon is passed up the food chains to the larger marine invertebrate populations. One species of amphipod, *Gammarus setosus* was anomalously low in ^{14}C abundance (96.6 percent modern) and has been shown by Schneider (1980) to be an avid consumer of peat detritus, and Schell (1980) has shown that ^{14}C -labeled cellulose is readily consumed and respired by the

¹ Carbon-13/12 ratios are expressed as $\delta^{13}\text{C}_{\text{PDB}}$, where $\delta^{13}\text{C}_{\text{PDB}} = [(R_{\text{sample}} - R_{\text{std}})/R_{\text{std}}] \times 1,000$, where R is the ratio $^{13}\text{C}/^{12}\text{C}$ and $\delta^{13}\text{C}$ is reported in parts per thousand relative to the PDB standard. The carbon-14 activity of a 1950 AD sample is expressed as 100 percent modern, normalized to $\delta^{13}\text{C}$ of -25 ppt to correct for fractionation effects. Modern tundra vegetation is 122-140 percent with lower values in annual grasses, leaves and aquatic algae. Higher values are found in woody plants, standing dead grasses, and sedges. Marine macroalgae samples (*Laminaria* spp.) are 103-107 percent (n = 4). "Average peat" was taken to be the mean activity of a uniform layer of peat accumulating at constant rate for 8,142 years. Actual basal peats along shorelines and rivers ranged from 3,400 to 12,600 years B.P. The mean was 36.3 percent modern (n = 6, S.D. = ± 15.3 percent modern), yielding an average activity of 62.9 ± 10.2 , -11.3 percent modern. This average peat activity is probably lower than the overall activity of peat entering the aquatic systems. An actual particulate sample from the Colville River was 74.4 percent modern. Since no quantitation of modern material in these samples was attempted, the more conservative value of 62.9 percent was used to determine peat carbon content in organisms. Isotopic analyses were performed by Beta Analytic, Inc., Geochron Division of Krueger Industries, and Teledyne Isotopes. Precision in ^{14}C analyses was typically ± 1 percent and $\delta^{13}\text{C}$ analyses were ± 0.05 -0.1 ppt. Analyses costs limited replication of samples. *Laminaria* from one collection site were sent to each laboratory and yielded the following activities: 105.7 (GD, KI); 105.0, 107.1 (BAI); and 102.8 (Teledyne).

organism. It does not, however, comprise a large fraction of the prey invertebrates consumed by the **anadromous** fishes and oldsquaws (Griffiths and Dillinger, 1981). Apparently the **microbial-meiofaunal-invertebrate** foodweb pathways in the marine waters are inefficient to the point that apical foodweb organisms receive very little direct benefit from **detrital** inputs.

Arctic freshwater organisms contrast markedly with marine organisms in their variability in ^{14}C content. Although modern aquatic primary production centers at about 123 percent modern, as evidenced by both submerged algal mats (122.2) and emergent macrophytes (123.9, $n = 3$), the ^{14}C content of the fauna varies from 120.9 to 93.5 percent modern. The seasonal variation of ^{14}C content in Colville River grayling (*Thymallus arcticus*) suggests a major alteration of food dependencies over the hydrologic year (Figure 24). Grayling are known to feed heavily upon surface drift insects (Morrow, 1980) in headwaters during summer when benthic primary production is rapid, and the ^{14}C content of fish taken in September is in agreement. With the appearance of ice cover in September, the available food becomes the benthic and epibenthic insect larvae in the rivers in overwintering areas. Two fish sampled in March had ^{14}C contents of 108 and 111 percent modern, and by June, when breakup of the nearly 2 m thick ice cover occurred, two fish yielded values of 102 and 106 percent modern. Since under-ice primary production is nil during the arctic winter darkness, this shift in ^{14}C content must represent an increasing reliance on peat carbon to replace recent primary production. By using the value of 123 percent modern as that of modern freshwater energy sources and 63 percent modern as average peat activity, the peat carbon content in grayling can be estimated to range from less than 4 percent in summer to a maximum of near 37 percent by the end of the winter season.

Some of the **anadromous** fish sampled follow a similar pattern. Least ciscoes (*Coregonus sardinella*) and arctic ciscoes (*Coregonus autumnalis*) caught in October and November entering the Colville River Delta were isotonically marine modern fish ($\delta^{13}\text{C} = -17.5$ to -22.9 , 102.9 to 109.2 percent modern). In June, a least cisco netted during breakup flooding and out-migration contained stable carbon isotope ratios typical of freshwater fish ($\delta^{13}\text{C} = -29.1$) and a large

TABLE 18. Summary of Carbon Isotope Data - Beaufort Sea - November, 1981

Sample Identification	$\delta^{13}\text{C}$	^{14}C activity, % Modern (corr. to $\delta^{13}\text{C} = -25^{\circ}/\text{oo}$)	Years B.P.
VEGETATIVE			
MIL 78-3; GX5822, Sagavanirktok River basal peat	-28.5		3,400 65.5
MIL 78-2; GX5821, Pingok Is. basal peat	-28.3		8,432 35.0
NIL 78-4; GX5824, Tundra plants, modern	-28.2		141.1 \pm .5
MIL 78-1; GX 5820, Milne basal peat	-28.7		9,052 32.4
I-6838 Oliktok basal peat	--		8,550 34.5
I-6839 Kavearak Pt. basal peat	--		12,660 20.8
81-8; Beta 2918, <i>Nostoc</i> mats, 27 Jun 81	-20.24		122.2 \pm 0.9
81-9; Beta 2919, <i>Arctophila fulva</i>	-19.51		123.6 \pm 0.6
81-12; Beta 3530, <i>Arctophila fulva</i>	-26.85		121.1 \pm 0.8
81-13; Beta 3531, <i>Carex aquatilis</i>	-30.49		127.1 \pm 0.6
81-15; Beta 3533, Basal peat, Lake 3, USFWS camp	-27.24	9,805	29.5 \pm 1.3
81-19; Beta 3537, <i>Salix</i> spp.	-28.14		138.1 \pm 0.6
79-5; GX 6274, <i>Laminaria</i> , whole plants	-15.4		105.7
79-7; UM-1738, <i>Laminaria</i> sti pes	-17.47		105.0 \pm .8
79-8; UM-1739, <i>Laminaria</i> blades	-15.04		107.1 \pm 1.4
79-23; I-II, 354, <i>Laminaria</i> blades	-18.2 \pm .2		102.8 \pm 0.8
79-12; UM-1803, Colville R. particulate C., 2 Jun 79	-26.39	900	89.4 \pm 1.6
79-14; UM-1804, Kuparuk R. particulate C., 31 May 79	-26.89	2,683	71.6 \pm 1.1
79-11; Beta 1027, Colville R. particulate C., 12-14 Jun 79	-27.01	2,375	74.4 \pm .9
81-6; Beta 2650, Lake C-2, 0-7.5 cm Seals.	-30.71	3,840	62.0 \pm 0.9
81-7; Beta 2651, Lake C-2, 7.5-18 cm Seals.	-29.61	4,400	57.8 \pm 0.7
81-16; Beta 3534, Gooseneck Lake sediments	-27.09	2,068	77.3 \pm 0.7
INVERTEBRATES			
MIL 78-6; GX5825, Mysids Aug 78	-23.6		105.9
MIL 78-8; GX5827, <i>Saduria</i> , Aug 78	-18.5		103.1
MIL 78-9; GX5828, <i>Onisimus</i> amphipods, Aug 78	-18.3		103.7
79-18; Beta 1030, <i>Saduria</i> , S.L., Nov 79	-20.43		102.9 \pm .9
79-19; Beta 1031, <i>Gammaracanthus</i> amphipods, Nov 79	-20.91		99.8 \pm .8
79-20; Beta 1032, <i>Weyprechtia</i> amphipods, Nov 79	-20.71 \pm .05		98.4 \pm 1.5
79-21; Beta 1033, Arctic cisco <i>Coregonus autumnalis</i> , stomach contents, Nov 79	-22.70 \pm .02		97.4 \pm 0.6

TABLE 18. (Continued)

Sample	Identification	$\delta^{13}\text{C}$	^{14}C activity % Modern (corr. to $\delta^{13}\text{C} = -25\text{‰}$)	Years B.P.
82-12;	Beta 5015, Arctic cisco stomach contents (amphipods), fall 81	-23.43		103.6 ± 0.9
80-10;	Beta 1742, <i>Gammarus setosus</i> , Barrow, Jul 80	-19.92		96.6 ± 0.8
81-11;	Beta 3529, <i>Daphnia</i> , cyclops, Helm. pond, 29 Aug 81	-16.41		119.8 ± 0.8
FISH Marine				
MIL 78-5;	GX 5824, Four Horn sculpin, <i>Myoxocephalus</i> <i>quadricornis</i> (Aug 78)	-20.5		105.3
79-9;	UM-1740, Four horn sculpin (Apr 79)	-20.82		104.4
79-2;	GX 6271, Arctic cod, <i>Boreogadus saida</i> , (Aug 78).	-21.5		107.3
79-10;	UM-1741, Arctic cod (Aug 78)	-21.6		103.7
80-13;	Beta 1745, Arctic cod, offshore (May 80)	-20.89		109.8 ± 0.8
Anadromous				
MIL 78-7;	GX5826, Humpback whetfish, <i>C. pidschian</i> , Colv. delta, fall 77	-20.4		109.5
MIL 78-10;	GX5829, Least cisco, <i>C. sardinella</i> , Colv. delta, fall 77	-21.2		109.2
80-8;	Beta 1741, Least cisco, Jun 80	-29.10	687	91.8 ± 0.8
80-21;	Beta 1987, Least cisco, Colv. delta, Nov 80	-22.90		103.1 ± 1.2
81-18;	Beta 3536, Least cisco, imm., Helm. pond, 29 Aug 81	-28.8		114.3 ± 0.8
82-1;	Beta 5004, Least cisco, Colv. delta, 10 Oct 81	-20.58		105.6 ± 0.8
82-2;	Beta 5005, Least cisco, Colv. delta, 17 Oct 81	-20.58		107.3 ± 0.8
82-3;	Beta 5006, Least cisco, Colv. delta, 26 Oct 81	-21.33		108.3 ± 0.7
82-4;	Beta 5007, Least cisco, Colv. delta, 4 Nov 81	-22.06		106.5 ± 0.7
82-5;	Beta 5008, Least cisco, Colv. delta, 20 Jun 82	-21.22		106.8 ± 0.8
82-6;	Beta 5009, Least cisco, Colv. delta, 20 Jun 82	-23.23		110.9 ± 0.8
GX5388;	Arctic cisco, <i>C. autumnalis</i> , Colv. delta, fall 77	-21.8		109.6
79-6;	GX6275, Arctic cisco, Aug 78	-20.7		112.7
82-7;	Beta 5010, Arctic cisco, Colv. delta, 10 Oct 81	-17.50		106.4 ± 1.0
82-8;	Beta 5011, Arctic cisco, Colv. delta, 4 Nov 81	-19.07		103.2 ± 0.7
82-9;	Beta 5012, Arctic cisco, Colv. delta, 13 Nov 81	-20.50		102.9 ± 0.8
82-10;	Beta 5013, Arctic cisco, Colv. delta, 20 Jun 82	-21.84		102.4 ± 0.9
82-11;	Beta 5014, Arctic cisco, Colv. delta, 20 Jun 82	-21.33		104.3 ± 0.9

TABLE 18, (Continued)

Sample Identification	$\delta^{13}\text{C}$	^{14}C activity, % Modern (corr. to $\delta^{13}\text{C} = -25\text{‰}$)	Years B.P.
80-7; Beta 1740, Broad whitefish, <i>C. nasus</i> , 16 Jun 80	-24.86		94.8 ± 0.6
80-23; Beta 1989, Broad whitefish, 5 Nov 80	-22.26		102.0 ± 0.8
82-13; Beta 5016, Broad whitefish, Colv. delta, 20 Jun 82	-20.53		104.8 ± 1.0
79-15; Beta 1028, Round whitefish, <i>Prosopium cylindraceum</i> , Sep 79	-26.9 ± 0.9		101.4 ± 0.8
80-2; Beta 1267, Round whitefish, adult, Mar 80	-29.32 ± 0.1		101.8 ± 0.7
80-1; Beta 1075, Round whitefish, imm., Mar 80	-27.50 ± 0.5		109.0 ± 0.7
80-17; Beta 2005, Round whitefish, 22 Mar 80	-24.68		110.4 ± 0.8
80-19; Beta 1985, Arctic char., Ott 80	-24.56		106.8* ± 1.0
81-2; Beta 2375, Arctic char., Colv. delta, Nov 80	-20.04		107.6 ± 0.8
80-20; Beta 1986, Boreal smelt, <i>Osmerus mordax</i> , fall 80	-21.72		108.4 ± 1.1
Freshwater			
79-17; Beta 1029, Grayling, <i>Thymallus arcticus</i> , Colv. R., Sep 79	-26.4 ± .02		120.9 ± .7
80-3; Beta 1268, Grayling, 22 Mar 80 (21 cm)	-29.82 ± .03		111.1 ± 0.6
80-24; Beta 1990, Grayling, 22 Mar 80	-28.18		107.5 ± 0.9
80-4; Beta 1738, Grayling, Jun 80 (35 cm)	-26.68		105.5 ± 1.1
80-5; Beta 1739, Grayling, Jun 80	-26.92		102.1 ± 1.0
80-11; Beta 1743, Long-nosed sucker, <i>Catostomus catostomus</i> , Colv. R., Aug 80	-23.01		93.5 ± 0.8
81-1; Beta 2374, Burbot, Colv. R., Nov 80	-23.39		107.1 ± 0.8
BIRDS			
79-1; GX6270, Olsdquaw, <i>Clangula hyemalis</i> , adult female, Simpson Lagoon	-20.7		104.9
80-14; Beta 1746, Olsdquaw, adult female, Thetis Is., 2 Aug 80	-21.55		95.8 ± 2.0
80-15; Beta 1747, Olsdquaw, male, 2 Aug, Thetis Is.	-26.06	1,305	85.0 ± 0.8
81-3; Beta 2555, Olsdquaw, male, 26 Jun 80 (#33-80)	-21.02		114.7 ± 0.7
81-4; Beta 2556, Olsdquaw, juv., 28 Aug 80 (124, 125-80)	-27.77		109.6 ± 0.7
81-5; Beta 2557, Olsdquaw, male, post-molt (#123-80)	-28.51		104.6 ± 0.7

TABLE 18. (Continued)

Sample Identification	$\delta^{13}\text{C}$	^{14}C activity % Modern (corr. to $\delta^{13}\text{C}$)	Years B.P.
MAMMALS			
Terrestrial			
81-10; Beta 2920, Lemming, <i>Lemmus sibericus</i> , female, 27 June 81	-26.09		127.4 ± 0.5
81-14; Beta 3532, Lemming, <i>L. sibericus</i> , 4 imm., ?9 Aug 81	-26.75		126.1 ± 0.8
81-17; Beta 3535, Caribou, Aug 81	-28.68		130.6 ± 0.6
Marine			
81-B4-Mus; Beta 2921, Bowhead, male, 28.5 ft., Barrow, 30 May 81	-18.92		101.8 ± 0.9
81-B4-Oil; Beta 2922, Bowhead, <i>Balaenamysticetus</i> , male, 28.5 ft., Barrow, 30 May 81	-21.00		102.8 ± 1.0
81-WW2-Oil; Beta 2924, Bowhead, female, 58 ft., Wainwright, 18 May 81	-25.53		93.1 ± 0.8
81-WW3-Mus; Beta 2923, Bowhead, female, 54 ft., Wainwright, 27 May 81	-17.95		102.2 ± 0.8
81-WW3-Oil; Beta 2925, Bowhead, female, 54 ft.	-24.90		105.3 ± 0.7
81KK2-1-Oil; Beta 3538, Bowhead, male, 46 ft., 8 Sep 81	-25.20		104.9 ± 0.7
81KK2-2M-Mus; Beta 3545, Bowhead, male, 46 ft., 8 Sep 81	-18.65		102.7 ± 0.9
81KK3-1-Oil; Beta 3539, Bowhead, female, 53 ft., 22 Sep 81	-21.37		98.2 ± 0.8
81KK3-2M-Mus; Beta 3544, Bowhead, female, 53 ft., 22 Sep 81	-19.01		103.5 ± 0.9
81-21-Oil; Beta 3541, Ring seal, <i>Phoca hispida</i> , PPUP-11-81, female	-22.69		97.8 ± 0.8
81-22-Mus; Beta 3542, Ring seal, PPUP-11-81, female	-16.97		113.1 ± 0.7
81-23-Mus; Beta 3543, Bearded seal, <i>Erignathus barbatus</i> , PPUE-2-81	-18.10		104.8 ± 0.8

depression in ^{14}C (91.8 percent modern) equivalent to 55 percent peat carbon. The other least ciscoes and all arctic ciscoes caught in June were isotopically marine fish ($^{13}\text{C} = -21.2$ to -23.2 , 102.4 to 110.9 percent modern). It is not known whether these fish overwintered in saline delta channels or offshore. The only other anadromous fish sampled in both fall and spring was the broad whitefish *C. nasus*, which showed an isotopic shift but did not lose its entire marine carbon content over the winter as indicated by $\delta^{13}\text{C}$ values. This may reflect wintering on the high fat content in the fish following summer feeding in the marine environment.

Some of freshwater fish sampled varied widely in ^{14}C content but did not show a seasonal trend. Round whitefish, *Prosopium cylindraceum*, a freshwater fish widely distributed in the Colville River system, showed a range in isotopic composition that is difficult to define given the lack of knowledge on the past life history of the fish sampled. Two of the four fish sampled, however, were depleted in ^{14}C to 101 and 102 percent modern which corresponds to approximately 35 percent peat carbon, whereas the other two fish at 110 percent modern were 21 percent peat carbon. One specimen of long-nosed sucker, *Catostomus catostomus* collected in the summer from the Colville River was 93.5 percent modern or equivalent to 49 percent peat, but had a $\delta^{13}\text{C}$ of -23.0 which is relatively enriched in ^{13}C for a freshwater fish. Although this fish is a detritivore and the apical organism in detrital foodwebs, this difference in $\delta^{13}\text{C}$ is difficult to ascribe solely to biochemical fractionation effects which occur between trophic levels and are typically less than one δ unit (DeNiro and Epstein, 1978).

The three samples of oldsquaw ducks shown in Figure 23 represent close to the full spectrum of foodweb dependencies and isotopic variation found in resident fauna. Sample 79-1 (Table 18) was a non-breeding female taken from Simpson Lagoon after summering in marine waters. It is isotopically similar to obligate marine fish and reflects a diet of marine invertebrates. Sample 80-14 is a female that had recently returned to marine waters after nesting on the tundra and had been feeding in the marine habitat for several days. Sample 80-15 is a post-molt male which was taken very shortly after leaving the tundra lakes and reaching Harrison Bay. This bird has a $\delta^{13}\text{C}$ value near

typical of freshwater organisms and shows a ^{14}C depression equivalent to 60 percent peat carbon. At 85 percent modern, this bird shows the lowest ^{14}C content of any organism we have sampled to date, and implies that the insect larvae and other prey organisms it had consumed must also have had the same cumulative ^{14}C depression. We have not yet been able to acquire enough insect larvae (especially chironomids, the favored prey organism) to perform precise radiocarbon content determinations but the availability of accelerator carbon dating instruments in the near future will enable us to analyze these small samples.

Three documented oldsquaw samples were acquired in 1980 from lakes (70°42'N, 152°40'W) near Cape Halkett west of Harrison Bay (E. Taylor, personal communication). These birds included a migrant newly arrived to the tundra in June (81-3), a juvenile taken in August (81-4), and a post-molt male (81-5). They clearly reflected the isotopic composition of their food. Bird 81-3 was marine-modern and the two birds from the tundra were isotopically terrestrial and ^{14}C depressed although only to a maximum peat equivalent of 31 percent peat carbon in the male. The higher ^{14}C content of the juvenile (81-4), which favored shallow areas for feeding, reflects a higher percentage of modern primary production supporting prey organisms. The considerable difference in peat content between bird 80-15 (60 percent) and 81-5 (30 percent) may indicate that considerable variation occurs in energy source dependencies among the lakes on the coastal plain.

The changes which occur in the carbon isotopic composition of birds and fishes upon changing their food source makes these organisms particularly amenable to in situ determinations of carbon metabolic rates. Until now, the use of isotopic tracers in measuring transfer rates of carbon in foodwebs has been limited to experiments performed in the laboratory. Whereas these experiments can yield useful information, their artificial nature and the problems associated with closed system tracer experiments (Conover and Francis, 1973) detract from their utility.

The model in Figure 25 allows a first attempt to be made at determining carbon turnover rates for organisms living in their natural environment. This technique eliminates container effects since the

system is necessarily an open one. The model assumes a steady state condition for the predator (i.e., no growth), which should hold quite well for the adult specimens we have used in the calculations. The other assumption is that the carbon in the organism is instantaneously mixed so that respired carbon has the same isotopic composition as the organism. This assumption should also be reasonable since the rates are measured over long periods of time.

The model essentially results in an equation describing the exponential change in isotopic composition of the predator ($\delta^{13}\text{C}_t$, $^{14}\text{C}_t$) from its value at the time it changed its food source ($\delta^{13}\text{C}_{t=0}$, $^{14}\text{C}_{t=0}$) to that found after feeding for some period (t) on different food ($\delta^{13}\text{C}_F$, $^{14}\text{C}_F$). Table 18 provides the necessary information on the isotopic composition of predators at various times as well as that of their food sources. For all turnover rate calculations we have used the following values for food: $\delta^{13}\text{C}$ marine = -21.0, $\delta^{13}\text{C}$ terr = -28.5, ^{14}C marine = 110.0, ^{14}C terr. modern = 125.0, ^{14}C river = 92.0.

Least cisco $\delta^{13}\text{C}$ values (Figure 26) indicate that a ^{13}C isotopic equilibrium had been reached between fish and food by the end of the spring. Therefore, we expect that equilibrium has also been reached with respect to the ^{14}C isotope. This reasoning leads us to believe that until more data is available on the ^{14}C content of prey organisms, a ^{14}C activity of 92 percent modern should be used for the food of fish overwintering in the river. Sampling of the river for benthic invertebrates is planned and should allow us to refine this estimate.

The calculated turnover rate constants and turnover times ($1/K$) for least ciscoes are given in Table 19. Because the June and September fish have an isotopic composition which is essentially the same as their food, we have estimated the turnover rate to be at least as great as that necessary for the fish to be within one ^{13}C unit or two ^{14}C percent modern units of its food.

The results show that during the summer a least cisco assimilates an amount of carbon greater than 1.5 percent of its body carbon each day. This rate is comparable to that of 2.3 percent calculated from the results of a feeding experiment performed by Craig and Haldorson (1981)

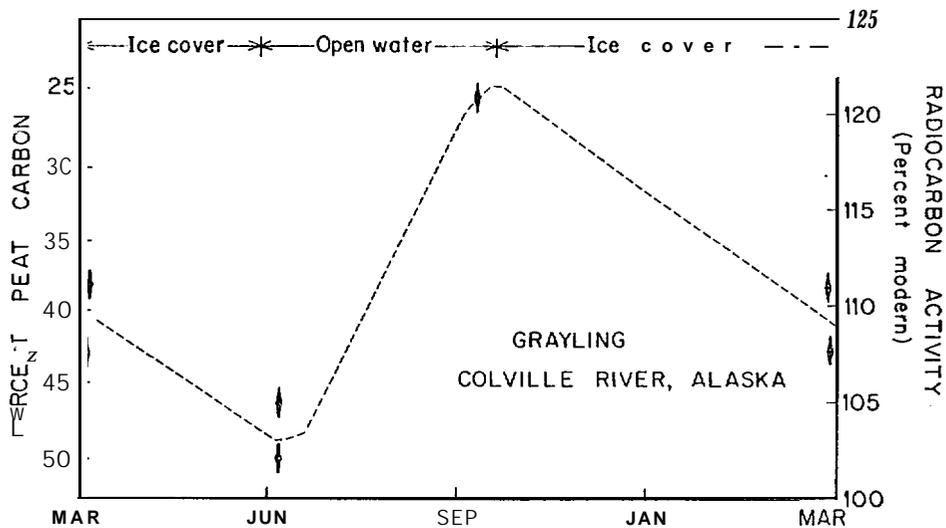


Figure 24. Seasonal variation in radiocarbon activity of Colville River grayling (*Thymallus arcticus*).

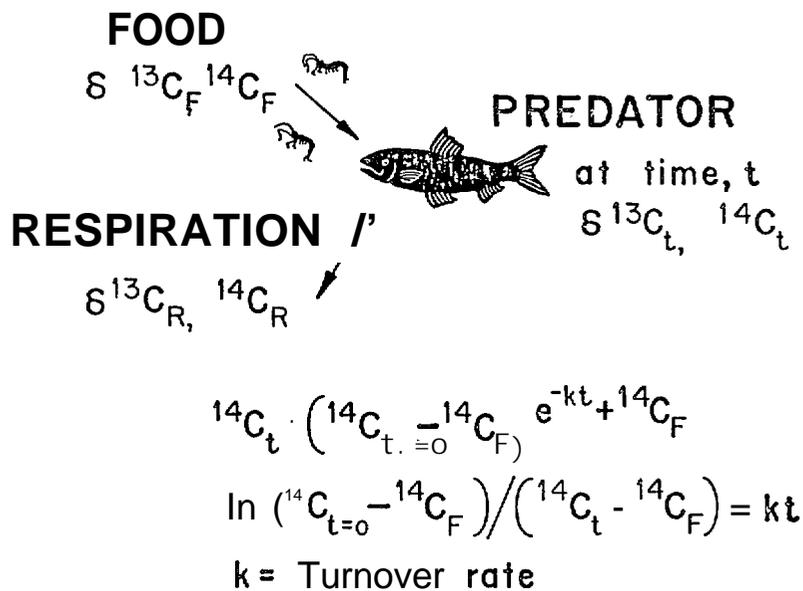


Figure 25. Model of carbon isotope turnover in consumer organisms.

TABLE 19. Turnover rate determination.

	Season interval	Isotope used	Turnover rate (‰ day^{-1})	Turnover time (days)
Least cisco	SEP-JUN	Both	>0.7	<140
	JUN-SEP	Both	>1.5	<70
Arctic cod	JUN-SEP	Lit.	2.3	45
Grayling	SEP-JUN	^{14}C	0.3-0.4	250-330
	JUN-SEP	^{14}C	>1.2	<85
Broad Whiti fish	NOV-JUN	^{13}C	0.2	500
		^{14}C	0.5	200
Oldsquaw	JUN-AUG	^{13}C	2.8	35
	JUN-SEP	^{13}C	2.7	35
	JUN-SEP	Lit.	10.0	10

on an arctic cod, using a carbon/wet weight conversion of 0.06 for food and 0.11 for fish, and an assimilation efficiency of 0.7. During the winter, however, we estimate that these fish reduce their turnover rates to about 25-50 percent of the summer rates.

The arctic grayling, an obligate freshwater fish, also switches its energy source from summer to winter (Figure 24). Since more data are available for the grayling, it was possible to perform a least squares linear regression on a plot of $\ln \left(\frac{^{14}\text{C}_{t=0} - ^{14}\text{C}_{\text{food}}}{^{14}\text{C}_t - ^{14}\text{C}_{\text{food}}} \right)$ vs. time to determine the value of K (slope). The plot is shown in Figure 27 and is a good fit for field data ($r = 0.94$). Carbon turnover rates in grayling are slightly slower than those of the least cisco (Table 19), but are similarly reduced from summer to winter. These reductions in carbon metabolism by overwintering fishes may well be a response to colder water temperatures and a decreased availability of food in the overwintering areas of the river.

We have also compared seasonal isotopic shifts in samples of migratory birds. When oldsquaw ducks arrive at the tundra lakes and ponds after overwintering in a marine environment, their $\delta^{13}\text{C}$ values reflect their marine carbon composition. Through the course of the summer, however, their ^{13}C content decreases in response to the freshwater food (Figure 28). This change has been used to calculate the turnover rates for oldsquaw ducks (Table 19). **It is not known when our**

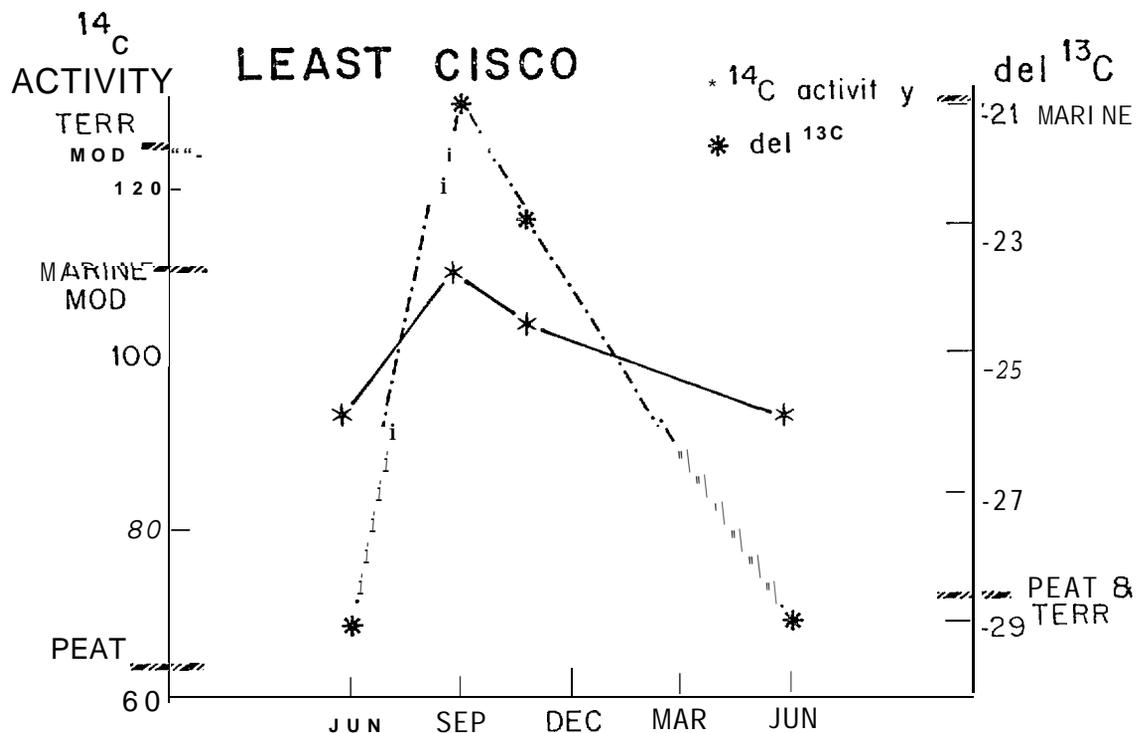


Figure 26. Seasonal variation in carbon isotopic composition of least cisco (*Coregonus sardinella*).

specimens arrived on the tundra, but by assuming that they arrived no earlier than mid-June (E. Taylor, personal communication) we can say that these birds turn over at least 2.7 percent of their body carbon each day. This rate is much slower than that of 10 percent calculated from the equation of Kendeigh et al. (1977) for bird energy requirements during the molting period, using a kcal/wet weight conversion of 1.9 and an oldsquaw wet weight of 895 g. This may imply that these oldsquaws began feeding in freshwater much later than mid-June, either because they arrived later in the season, did not feed extensively during breeding activities and while setting up their territories or had a low availability of food in the early summer before the sediments thawed.

We believe that as more samples of predators and their food items are obtained, this method will allow us to gain valuable information on the energetic of consumer organisms and the ways in which they may alter their metabolism under changing environmental conditions.

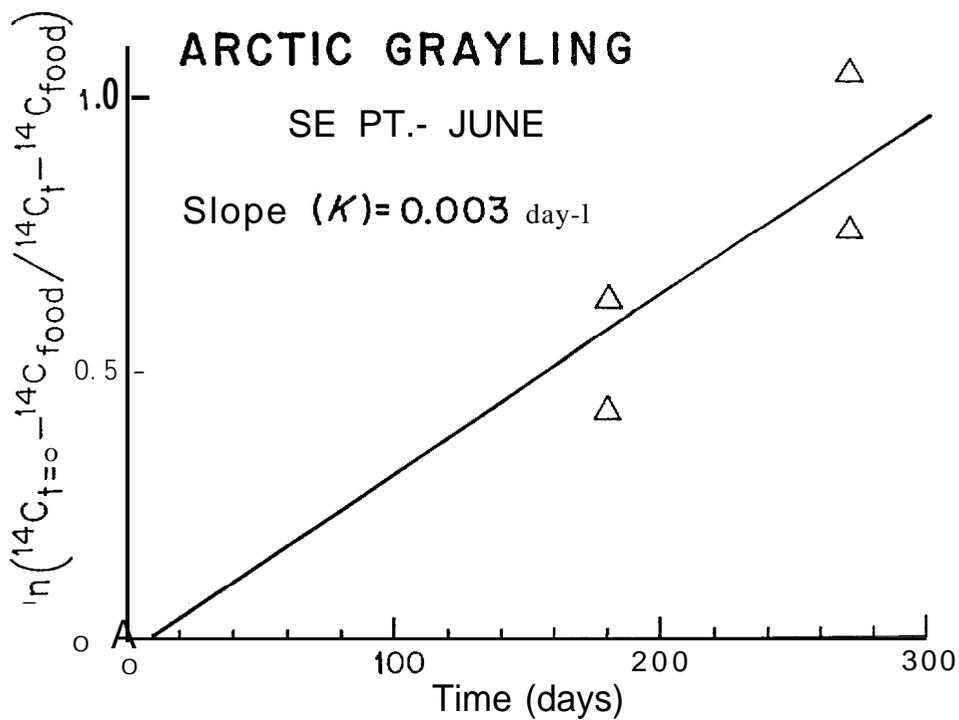


Figure 27. Least squares regression determination of carbon turnover rate constant in grayling (*Thymallus arcticus*).

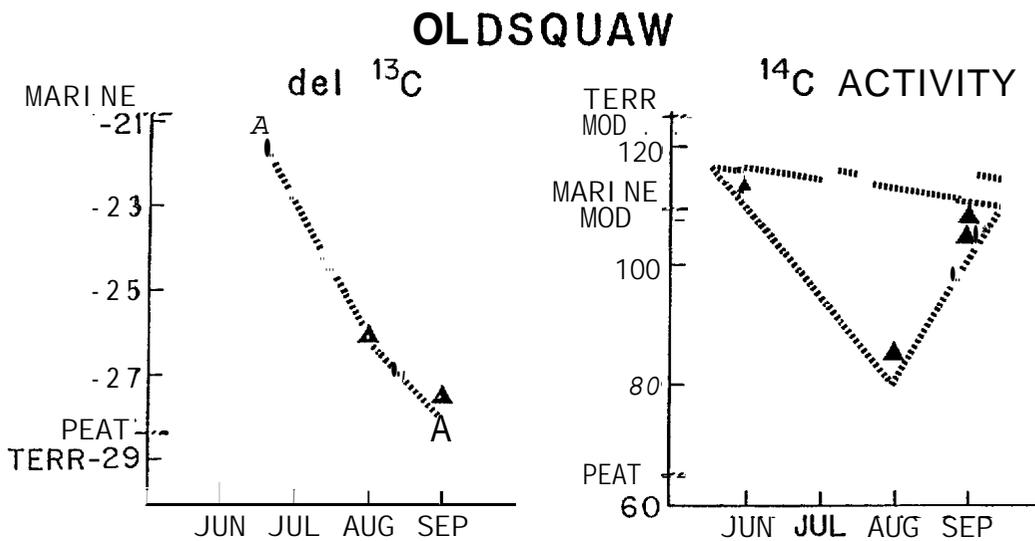


Figure 28. Seasonal variation in carbon isotopic composition of **oldsquaw** ducks.

The foodweb linkages represented in the utilization of peat carbon and transfer to higher organisms constitute a remarkable adaptation to a temporally independent carbon source in an area which is characterized by extremes in seasonal primary production. The success of the freshwater fishes and waterfowl in turn depends upon the prey organisms which use the peat carbon efficiently. To date, because of sampling difficulties and the unavailability of instrumentation capable of radiocarbon determination on small samples, we have been unable to directly measure the peat carbon content of the various insect larvae which constitute the prey organisms.

Of the most common freshwater prey organisms found in fish and bird stomachs, chironomid larvae constitute the most logical link between peat and higher trophic levels. Their abundance and ubiquity, coupled with a known ability to subsist in anaerobic organic sediments, makes these organisms the likely major efficient link in detrital foodwebs based on peat. We have collected several samples of these organisms and as accelerator ^{14}C -dating service becomes available at the University of Arizona, we will test this hypothesis. In addition, through a series of laboratory feeding experiments we hope to obtain peat assimilation efficiencies by chironomids at temperatures typical of arctic aquatic environments. This work is currently in progress.

Foodwebs in the arctic coastal zone interact strongly through the anadromous fish and waterfowl. The data presented herein show that the marine foodwebs can be significantly affected by terrestrial detritus only through indirect effects arising from nutrient additions to the phytoplankton nutritional requirements derived from mineralization of peat organic nitrogen. Developmental impacts on seals, polar bears, and arctic cod can be predicted to be minimal if the impacts affect only the input of allochthonous carbon.

In contrast, we have shown that onshore impacts which could alter food chain structure (e.g., indiscriminate use of insecticides, stream bed alternation, stripping of peat from shorelines) could in turn impact apical marine organisms such as anadromous fish and waterfowl populations which have aesthetic and subsistence value to humans. The same applies to the obligate freshwater organisms of high trophic levels.

Marine Mammal Feeding Studies

Preliminary work was begun in 1981 on attempting to determine feeding area dependencies in bowhead whales. The study is based on the premise that the phytoplankton production which occurred in areas of upwelling could be expected to show a depression in ^{14}C content if deep water were brought to the euphotic zone. Once the isotopic signature was in the phytoplankton, it would be transmitted up the food chain to zooplankton and to the bowhead whales feeding in the area. Furthermore, since feeding in excess of metabolic requirements would result in fat and oil accumulation in the marine mammals, a semiquantitative assessment as to the relative importance of various feeding areas might be possible. Table 14 lists the $^{13}\text{C}/^{12}\text{C}$ ratios and ^{14}C abundances in muscle and blubber tissue of bowhead whales taken by native whaling crews during their spring migration into the Beaufort Sea, and during the fall migration westward toward Barrow and south. Figure 29 shows these samples plotted. Immediately apparent is the close grouping in isotopic composition between fall and spring muscle tissue samples, and a wide scatter in both ^{13}C and ^{14}C content in the oil. Although the paucity of samples does not allow much room for interpretation at this point, we can infer the following:

1. The close grouping of both fall and spring muscle tissue samples intermediate to the ^{14}C range of values obtained for blubber oil implies that the fate of most food assimilated by the whale is storage in blubber. The muscle tissue is replenished from the blubber at a relatively constant rate and smooths out the isotopic shifts in the blubber over the year.
2. The two samples of oil with ^{14}C activities below 100 percent modern give evidence of primary production derived from upwelled or deep mixed water. Interestingly, the lowest ^{14}C activity and most depleted ^{13}C sample are from a large (18 m) female whale taken from the spring migration northward. Although it is conceivable that this isotopic composition could have been retained overwinter, we feel a more likely source would have been feeding in the Bering Sea during the winter months.

BOWHEAD WHALE

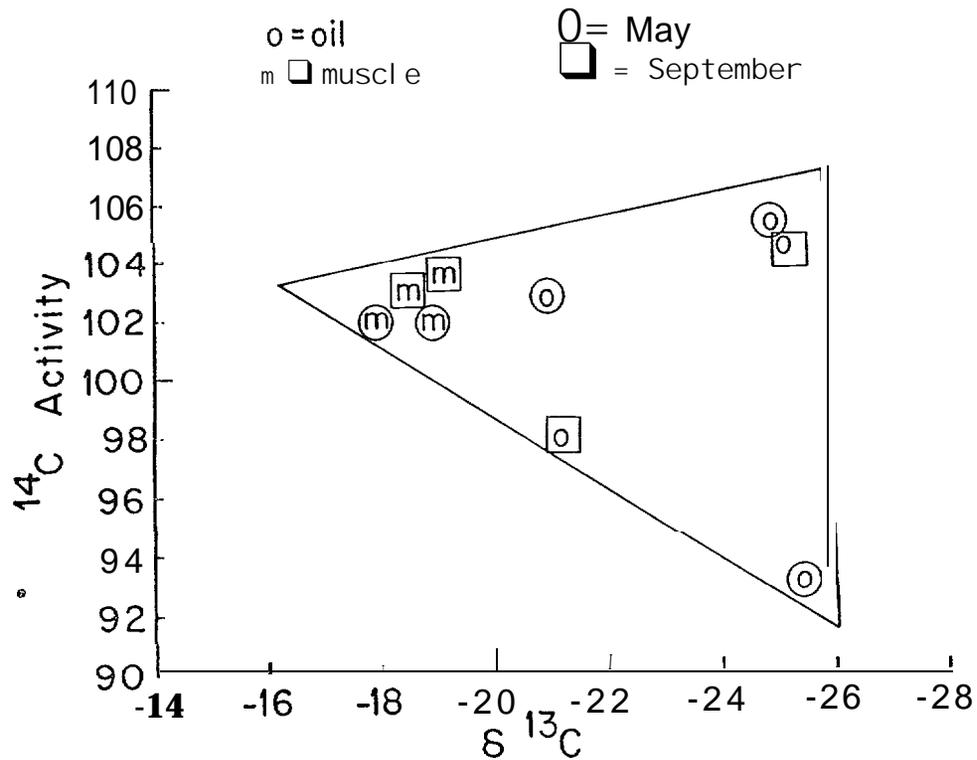


Figure 29. Carbon isotope distribution in bowhead whale tissue. ^{14}C activity units are percent modern; ^{13}C is expressed as parts per thousand relative to PDB standard.

3. The samples of oil showing high ^{14}C activities must reflect feeding on prey organisms supported by primary producers growing in stable open surface waters or in coastal area. Seasonal effects could also account for the higher ^{14}C content as the water above the pycnocline progressively exchanged older carbon dioxide from winter deep mixing with the atmospheric pool. This would imply, however, that the two whales taken during the fall migration (81KK2, 81KK3) had accumulated the major fraction of their blubber at two differing seasons anti/or locations in the Beaufort Sea.

The initial samples run on whale tissue are remarkable in their variety of isotopic composition. Evidence for upwelling-supported primary production in the Beaufort Sea is also apparent in ring seal oil

(*Phoca hispida*) taken off Pingok Island. This sample, kindly supplied by K. Frost of Alaska Department of Fish and Game, also yielded a ^{14}C activity below 100 percent modern and is close to the activity shown by a fall whale taken at Barter Island (81KK3).

The initial samples of marine mammal tissues analyzed in 1981 show a wide variation in isotopic composition. Although we do not have sufficient samples to make any definitive statements about primary feeding and energy accumulation areas, we are looking forward to acquiring more data from the marine mammals and their prey from the Bering and Beaufort seas.

Linear Growth in *Laminaria solidungula* and *L. saccharina*

Figure 30 shows the results of growth measurements taken from November 1979 to July 1981. In *L. solidungula* in 1980 the lowest rate of linear growth (0.25 mm/day) occurred during the ice-free period, from July to November. Maximum growth rates in 1980 were recorded between February and April (1.41 mm/day). In *L. saccharina*, the lowest rate of linear growth occurred between November 1979 and February 1980 (0.12 mm/day) and the highest between late April and late July 1980 (4.69 mm/day). Similar results were obtained for 1981 but the periods of maximum and minimum growth are not as well defined because of one less visit to the study site. Since the turbid ice canopy in Stefansson Sound prevented penetration of light between October and early July, *L. solidungula* completed most of its annual linear growth in absolute darkness. In contrast, *L. saccharina* may have completed much of its growth during and immediately following breakup in late June and July when light penetration of the ice canopy is more likely to occur.

Concentrations of inorganic nitrogen in the form of NO_2^- and NO_3^- in the seawater are shown beneath the growth curves for both species of *Laminaria* in Figure 30. The concentrations of inorganic nitrogen follow an annual cycle typical of Arctic (Chapman and Lindley, 1980) and temperate waters (Chapman and Craigie, 1977; Wheeler and North, 1981) and are shown here for the period between November 1979 and

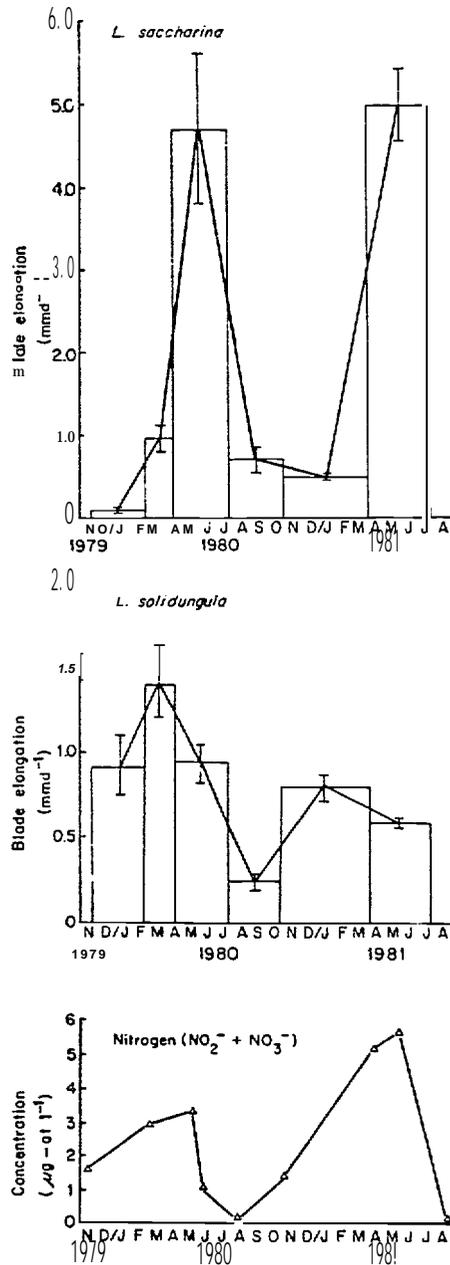


Figure 30. The pattern of blade growth (means $\pm 95\%$ confidence limits) in *Laminaria saccharina* and *L. solidungula* in relation to seasonal variations in inorganic nitrogen concentrations.

August 1981. Levels of inorganic-N are lowest in summer (less than 0.1 $\mu\text{g-at N/l}$), increase through the fall and winter months, and peak in late May (3.3 to 5.7 $\mu\text{g-at N/l}$). Periods of highest linear growth in both *L. solidungula* and *L. saccharina* occur during higher concentrations of inorganic nitrogen. A similar pattern between growth and nitrogen availability has also been documented for *L. solidungula* in the Canadian High Arctic by Chapman and Lindley (1980).

Growth in *L. solidungula* in the Boulder Patch is both energy and nitrogen limited, since neither resource is available in sufficient quantities simultaneously. During the summer open-water period when light is available, the plants must fix all the carbon necessary for their annual growth, reproduction, and metabolism. Little growth occurs during this period due to insufficient concentrations of inorganic-N needed for the synthesis of new tissue. Instead, the products of photosynthesis are stored and used during the winter when inorganic-N is available for the production of a new blade. Inorganic-n is depleted as a result of the annual spring bloom of microalgae and is slowly replenished through regeneration and exchange with ocean water. Our in situ growth studies of *L. solidungula* show that these plants can produce 95% of their original biomass as new plant tissue annually. Based on this, the net carbon contribution made by these plants to the ecosystem can be calculated from data on standing crop and carbon content.

An Annual Carbon Budget for the Boulder Patch

Figure 31 shows the annual net increase in biomass of 17 plants as a function of their initial weight. The average annual production-to-biomass ratio (P:B) was 0.95 ± 0.14 (mean \pm 95% confidence limit), and the annual mean growth was 0.0022 g/g-day (grams of wet weight added per gram of plant per day). The standing crop of all three species of kelp (of which *L. solidungula* constituted over 95%) ranged from 67 g/m² in areas of 10 to 25% rock cover to 262 g/m² where rock cover exceeds 25%. Using the results of the geophysical surveys conducted by Toimil (1980), the area of 10 to 25% rock cover is about $13 \times 10^6 \text{ m}^2$, and the area with cover greater than 25% is $7.3 \times 10^6 \text{ m}^2$. Integrated over these areas, the standing crop of the kelp is estimated to be $2.8 \times 10^9 \text{ g}$.

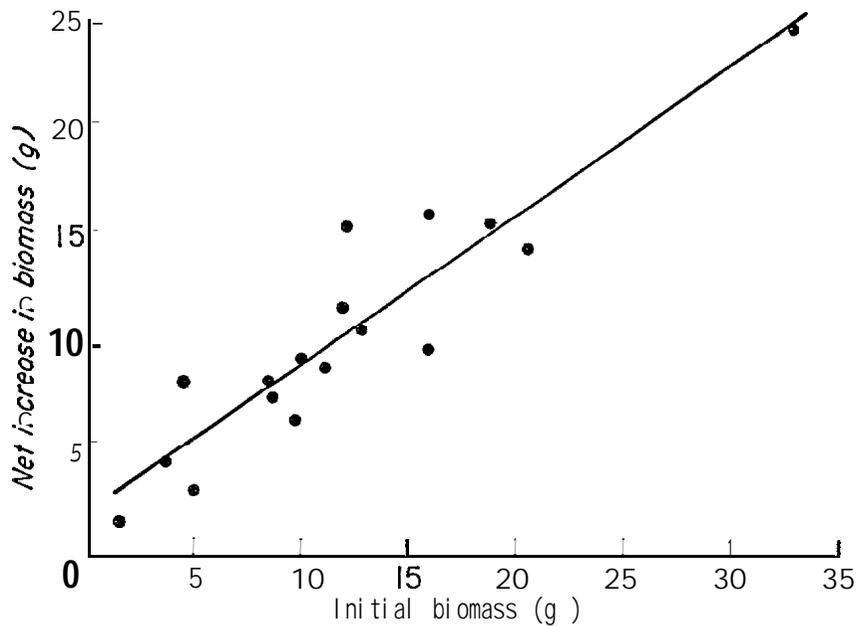


Figure 31. Annual net increase in biomass as a function of initial biomass in *L. solidungula* plants living under a turbid ice canopy.

The standing crop of kelp in Stefansson Sound is 0.48×10^9 g dry weight assuming that the standing crop is about 17% dry matter. Over 90% of the standing crop is *L. solidungula*. The carbon content of the dry matter in *L. solidungula* is approximately 32% (Chapman and Lindley, 1981) and varies little seasonally. On this basis, the annual energetic contribution made by the kelp in Stefansson Sound is 146×10^6 g C or about 7.2 g C/m^2 based on a P:B ratio of 0.95. This estimate does not take into account any patchiness in the turbid ice canopy or its complete absence in some years.

In years characterized by the presence of a turbid ice canopy, only three sources of marine carbon are available to consumers in the Boulder Patch - kelp, phytoplankton, and benthic microalgae. The spring bloom of ice microalgae, which is common in most arctic coastal areas (Alexander, 1975; Hsiao, 1980) does not occur in this area because of the lack of light caused by the presence of turbid ice. Assuming an annual P:B ratio of 7 for benthic microalgae (mean biomass 3.3 g/m^2), the net carbon production is $0.39 \text{ g/m}^2\text{-yr}$ or $8 \times 10^6 \text{ g/m}^2\text{-yr}$.

Phytoplankton productivity is estimated at 102×10^6 g C/yr, based on C-14 labeled uptake experiments at this site. The contribution made by the kelp is 146×10^6 g C/yr. Kelp thus contributes a major source of carbon to consumers in the Boulder Patch (Figure 32).

Carbon Isotope Studies in the Boulder Patch

In the Boulder Patch in Stefansson Sound, $^{13}\text{C}/^{12}\text{C}$ ratios indicate that kelp carbon is utilized and important to several organisms in the kelp bed itself (Table 20). Organisms observed directly feeding on or in contact with the kelp (chitons and snails, $\delta^{13}\text{C}$ from -17 to -17.5) exhibited ratios closest to that of kelp ($\delta^{13}\text{C} = -14.6$). Mysids, which are known to be filter feeders, presented the greatest surprise. Mysids collected by Schell near the Colville River (80 km west of the Boulder Patch) had $\delta^{13}\text{C}$ values of -23.6, which indicates a microalgal food source as predicted by its feeding habit. In the kelp bed, mysids had $\delta^{13}\text{C}$ values of -18.9 and -19.4, indicating a dependence on macroalgal carbon. It is not apparent at this time how these animals incorporate macroalgal carbon into their tissue.

The $^{13}\text{C}/^{12}\text{C}$ ratio obtained thus far are also highly encouraging in that the carbon content of the organisms reflect their predicted food source. Obligate filter feeders (hydroids, $\delta^{13}\text{C} = -23.5$) had ratios similar to that of phytoplankton ($\delta^{13}\text{C} = -23$ to -25). The amphipod *Atylus* consumes a variety of food which was reflected in widely different $\delta^{13}\text{C}$ values between organisms (-19.5 and -22.3). In general, $^{13}\text{C}/^{12}\text{C}$ ratios reflect known diets of these organisms thus adding credibility to the use of stable carbon isotope ratios in this study.

The importance of kelp as a winter food source may be seen in the shift of the carbon-isotope composition of mysids from summer to winter (Figure 33). The $^{13}\text{C}/^{12}\text{C}$ ratio in mysids is lowest in the summer (most negative ^{13}C values) when phytoplankton productivity is greatest, but this ratio increases during the winter as phytoplankton production ceases and the available food contains a greater proportion of kelp carbon relative to phytoplankton carbon.

TABLE 20. Summary of Carbon Isotope Ratios of Biota Collected in the Boulder Patch.

Sample Number	Description	$\delta^{13}\text{C}$
BOULDER PATCH		
PORIFERA		
41-04	<i>Choanites lutkeni</i>	-20.0
CNIDARIA		
41-59	<i>Sertularia cupressoides</i>	-23.5
41-20	<i>Gersemia rubiformis</i>	-22.0
ANNELIDA		
41-52	<i>Spinthera alaskensis</i>	-21.8
MOLLUSCA		
41-11	<i>Polinices</i> spp. (several)	-17.0
41-03	<i>Amicula vestita</i>	-17.5
ARTHROPODS		
Amphipoda		
41-01A	<i>Atylus carinatus</i>	-19.5
41-01B	<i>Atylus carinatus</i>	-22.3
41-76	<i>Weyprechtia heuglini</i>	-21.0
41-77	<i>Gammarus setosus</i>	-20.5
41-42	<i>Gammarocanthus loricatus</i>	-20.2
Crustacea		
41-44A	<i>Mysis litoralis</i> (3)	-19.4
41-44B	<i>Mysis litoralis</i> (3)	-18.9
111-01	<i>Mysis litoralis</i> (4) (formally 11-81-01)	-20.0
41-43J	<i>Mysis litoralis</i> (8)	-20.9
81-02	<i>Mysis litoralis</i> (3) (formally 8-18-02?)	-21.2

TABLE 20. (Continued)

ECHINODERMATA		
41-07	<i>Leptasterias graenlandica</i>	-21.7
CHORDATA		
41-21	<i>Boreogadus saida</i>	-21.2
41-38A	<i>Liparis herschelini</i>	-21.3
41-38B	<i>Liparis herschelini</i>	-20.1
41-75	<i>Myoxocephalus quadricornis</i>	-18.8
ALGAE		
41-26B2	<i>Laminaria solidungula</i>	-14.6
41-58	<i>Neodilsea integra</i>	-18.8
EASTERN BEAUFORT SEA		
18-BDR-1	<i>Mysis litoralis</i> (3) (formally 8-81-BDR)	-21.0
81-SC-1A	Copepods (12) (formally 8-81-SC1)	-24.6
81-SC-1B	Copepods (14) [formally 8-81-SC2)	-23. ?
81-SC-3	<i>Mysis litoralis</i> (formally 8-81-SC3)	-20.8
FEEDING EXPERIMENTS		
32-TK-1	<i>Mysis relicta</i> (6)	-19.8
32-TP-2	<i>Mysis relicta</i> (2)	-20.2

BOULDER PATCH PRIMARY PRODUCTION ENERGY INPUT

10^3 Kg Carbon / Yr

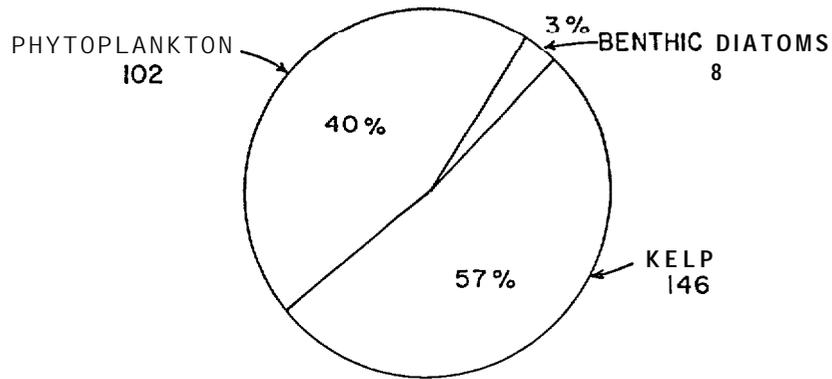


Figure 32. Carbon inputs to the Stefansson Sound Boulder Patch.

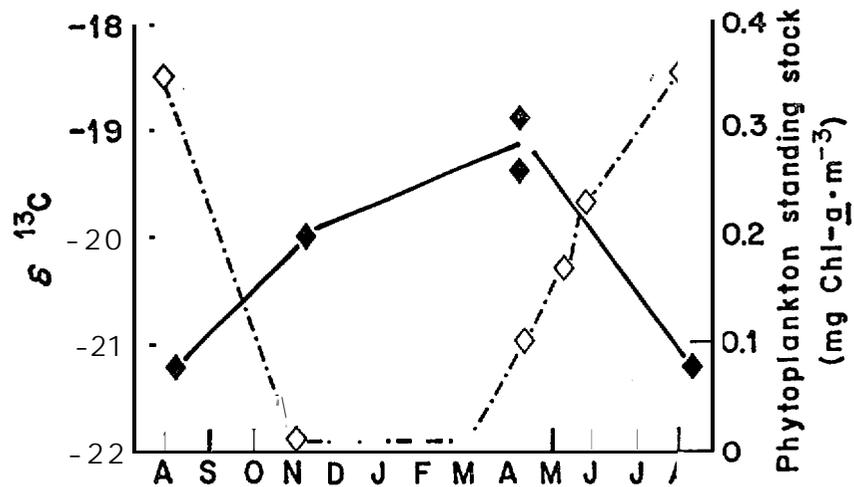


Figure 33. The relationship between mysid (*Mysis litoralis*) carbon isotope composition and phytoplankton standing stock in the Boulder Patch.

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Appendix 1. Nutrient and Salinity Data, 1980.

Date	Station	Location	Depth (m)		Salinity /‰	Nitrate + Nitrite -N	Phosphate -P	Silicate -Si
			Bottom	Sample				
5 Mar	Boulder Patch	70°19.6'N 147°34.5'W	5	0.0	35.88	2.93	0.55	18.0
				3.0	35.89	2.87	0.57	17.6
				5.0	35.93	2.87	0.51	17.6
6 Mar	Boulder Patch	70°19.6'N 147°34.5'W	5	0.0	35.95	2.88	0.48	18.3
				3.0	35.96	3.00	0.49	18.9
				5.0	36.01	2.98	0.58	18.1
3 Apr	15	70°26.5'N 148°19.7'W	4	0.0	36.20	3.43	0.57	18.2
				3.0	36.30	3.00	0.49	18.9
				4.0	35.80	2.98	0.58	18.1
3 Apr	16	70°26.1'N 147°55.9'W	6	0.0	36.30	2.82	0.65	14.2"
				6.0	36.10	2.91	0.30	14.5
3 Apr	17	70°22.6'N 147°43.4'W	5	0.0	36.50	3.40	0.72	18.2
				5.0	36.80	3.52	1.34	17.7
3 Apr	18	70°16.7'N 147°17.3'W	6	0.0	36.40	3.68	0.90	20.6
				6.0	---	4.19	0.86	21.0
3 Apr	19	70°11.0'N 147°03.5'W	5	0.0	37.30	3.64	1.05	19.7
				4.5	---	3.64	0.77	19.6
3 Apr	20	70°14.2'N 147°29.8'W	3	0.0	37.80	3.60	0.56	19.6
				3.0	37.70	3.61	0.56	19.6
3 Apr	22	70°23.8'N 148°19.0'W	1	1.0	---	4.97	0.76	19.7
4 Apr	12	70°33.3'N 150°21.6'W	7	0.0	35.70	2.92	0.63	8.2
				3.0	35.80	2.99	0.63	13.2
				7.0	36.00	3.16	0.65	17.1

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Appendix 1. (Continued)

Date	Station	Location		Depth (m)		Salinity ‰	Nitrate + Nitrite -N (-----microgram-atoms/liter-----)	Phosphate -P	Silicate -Si
				Bottom	Sample				
4 Apr	13	70°34.9'N	150°41.5'W	8	0.0	35.30	2.85	0.63	12.9
					4.0	35.45	2.96	--	
					7.5	---	2.91	0.63	13.6
4 Apr	3	70°32.1'N	149°51.7'W	2	2.0	---	2.95	0.55	17.3
4 Apr	11	70°27.5'N	150°04.7'W	2	2.0	---	4.85	0.50	40.7
4 Apr	4	70°35.4'N	149°51.7'W	12	0.0	35.20	2.70	0.68	12.8
					5.0	34.90	2.85	0.61	14.6
					8.0	29.60	2.67	0.68	13.1
					11.5	36.90	3.01	0.59	15.6
5 Apr	9	70°32.8'N	149°42.9'W	2	2.0	---	3.73	0.62	25.1
5 Apr	10	70°35.6'N	149°42.9'W	14	0.0	34.90	2.65	0.71	13.1
					4.0	34.90	2.60	0.67	13.2
					9.0	34.81	2.53	0.69	12.5
					13.8	36.40	2.78	0.67	14.2
5 Apr	Colville River (Helmericks)	70°26.0'N	150°23.0'W	5	0.0	23.71	4.60	0.19	32.2
					5.0	31.00	5.84	0.27	45.7
6 Apr	1	70°33.6'N	149°25.2'W	2	2.0	61.49	3.30	--	26.5
6 Apr	2	70°35.3'N	149°27.0'W	11	0.0	35.29	3.26	0.54	17.0
					6.0	35.24	3.43	0.57	16.9
					10.5	35.60	3.29	0.55	17.1
6 Apr	6	70°32.3'N	149°02.6'W	8	0.0	35.17	3.15	--	17.4
					5.0	35.50	--	0.44	15.9
					8.0	32.60	3.72	0.61	20.3

Appendix 1. (Continued)

Date	Station	Location		Depth (m)		Salinity ‰	Nitrate + Nitrite -N (-----microgram-atoms/liter-----)	Phosphate -P	Silicate -Si
				Bottom	Sample				
6 Apr	8	70°31.1'N	148°54.0'W	7	4.0	35.55	3.32	0.49	17.2
					6.9	35.50	3.26	0.50	18.1
6 Apr	14	70°20.2'N	148°20.3'W	2	2.0	---	4.44	0.41	33.1
					2.5	---	4.39	0.35	33.1
6 Apr	17	70°29.2'N	148°50.1'W	2	2.0	59.02	4.47	0.59	26.5
6 Apr	21	70°28.7'N	148°33.0'W	7	0.0	35.70	3.33	0.56	17.2
					4.0	34.20	3.23	0.55	17.4
					6.5	36.00	3.28	0.57	17.3
25 May	4	70°34.6'N	149°50.4'W	9	0.0	35.1	3.31	0.67	16.5
					9.0	35.8	3.44	().67	17.4
25 May	75	71°49.8'N	149°46.6'W	13	0.0	32.4	1.58	0.62	10.7
					5.0	32.4	1.54	0.51	10.5
					13.0	32.4	1.40	0.54	10.5
24 May	50	71°22.9'N	149°49.6'W	12	0.0	32.9	2.67	0.62	16.5
					7.0	32.8	2.78	0.60	19.4
					12.0	32.8	2.83	0.61	17.6
25 May	25	70°51.7'N	149°40.6'W	13	0.0	32.5	1.41	0.61	9.7
					7.0	32.5	1.42	0.61	9.3
					13.0	32.5	1.40	0.50	9.3
28 May	19	70°11.1'N	147°03.2'W	5	0.0	35.8	2.79	0.58	17.5
					5.0	37.6	3.36	0.47	19.4
28 May	18	70°16.4'N	147°12.2'W	5	0.0	35.9	3.11	0.57	18.1
					5.0	---	3.18	0.53	19.0

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Appendix 1. (Continued)

Date	Station	Location		Depth (m) Bottom	Sample	Salinity ‰	Nitrate + Nitrite -N (-----microgram-atoms/liter-----)	Phosphate -P	Silicate -Si
28 May	20	70°14.2'N	147°29.3'W	5	0.0	9.3	1.85	0.15	27.6
					5.0	30.0	3.22	0.53	19.7
28 May	Boulder Patch	70°17.7'N	147°32.4'W	6	0.0	35.3	3.00	0.65	17.8
					6.0	35.9	3.31	0.55	20.2
28 May	17	70°22.4'N	147°33.8'W	7	0.0	33.8	2.84	0.55	18.1
					7.0	38.1	3.40	0.51	22.7
29 May	14	70°20.0'N	148°20.5'W	2	0.0	---	2.46	0.55	14.4
29 May	16	70°26.1'N	147°55.9'W	7	0.0	---	2.92	0.58	16.0
					7.0	35.0	3.07	0.56	17.6
29 May	22	70°23.8'N	148°19.0'W	2	0.0	35.3	3.05	0.61	16.9
29 May	15	70°26.5'N	148°19.7'W	7	0.0	---	3.94	0.53	20.6
					6.5	--	3.90	0.52	16.5
29 May	7	70°27.9'N	148°54.7'W	2	0.0	---	3.00	0.54	16.1
29 May	8	70°30.7'N	148°53.4'W	7	0.0		2.95	0.56	16.1
					7.1	34.9	3.11	0.40	24.9
29 May	6	70°31.5'N	149°01.2'W	10	0.0	---	2.95	0.55	15.4
					5.0	---	3.07	0.58	17.4
					10.0	35.3	2.90	0.53	16.6
29 May	2	70°34.8'N	149°27.1'W	12	0.0	35.3	3.48	0.57	17.9
					7.0	35.6	3.17	0.58	17.1
					12.0	35.6	3.18	0.53	17.5

Appendix 1. (Continued)

Date	Station	Location		Depth (m) Bottom	Sample	Salinity ‰	Nitrate + Nitrite -N	Phosphate -P	Silicate -Si
							(-----microgram-atoms/liter-----)		
29 May	10	70°35.5'N	149°37.0'W	10	0.0	35.3	3.48	0.57	16.8
					2.0	---	--	--	--
					5.0	35.5	3.21	0.53	17.6
					10.0	35.9	3.03	0.56	17.5
30 May	5	70°30.0'N	149°09.5'W	2	0.0	---	3.66	0.51	29.5
30 May	Harrison Bay	70°34.7'N	151°19.6'W	5	0.0	1.7	--	--	--
					5.0	34.9	--	--	--
30 May	Harrison Bay	70°33.7'N	150°57.0'W	7	0.0	34.8	--	--	--
					7.0	35.3	--	--	--
30 May	13	70°34.2'N	150°41.0'W	7	0.0	35.6	--	--	--
					7.0	35.8	--	--	--
30 May	12	70°33.1'N	150°21.0'W	8	0.0	36.4	3.57	0.53	18.1
					5.0	36.3	--	--	--
					8.0	36.2	3.31	0.48	17.6
30 May	11	70°29.3'N	150°07.3'W	--	0.0	2.3	--	--	--
30 May	3	70°31.7'N	149°50.4'W	--	0.0	15.7	3.12	0.18	23.9
17 Jun	4	70°35.4'N	149°51.7'W	9	0.0	1.10	0.34	0.29	8.2
					5.0	0.80	0.50	0.34	9.7
					9.0	33.00	2.34	0.71	14.1
17 Jun	1	70°33.6'N	149°25.2'W	2	0.0	0.80	0.23	0.20	5.8
					2.0	9.30	0.96	0.25	13.2

Appendix 1. (Continued)

Date	Station	Location		Depth (m) Bottom	Sample	Salinity /100	Nitrate + Nitrite -N (-----microgram-atoms/liter-----)	Phosphate -P	Silicate -Si
17 Jun	202	70°44.8'N	149°27.1'W	12	0.0	32.80	1.42	0.59	9.7
					6.0	33.20	1.52	0.72	9.9
					12.0	33.45	1.03	0.72	11.0
17 Jun	808	70°40.7'N	148°53.4'W	12	6.0	34.40	2.06	0.74	13.1
					12.0	33.80	2.05	0.71	12.1
18 Jun	Boulder Patch	70°20.5'N	147°33.8'W	7	0.0	0.20	0.61	0.16	13.1
					4.0	4.60	0.58	0.16	17.1
					7.0	---	1.14	0.35	16.3
18 Jun	Lead	70°38.3'N	147°20.3'W	12	0.0	31.6	1.15	0.68	10.0
					12.0	32.9	1.71	0.64	11.5
18 Jun	Seal hole	70°38.6'N	146°02.0'W	12	0.0	5.2	--	0.25	2.4
					12.0	31.6	2.11	0.92	13.5
18 Jun	19	70°10.5'N	147°07.0'W	5	0.0	27.3	0.23	0.21	3.4
					5.0	---	--	--	--
2 Jul	1	70°33.6'N	149°25.2'W	2	0.0	35.4	0.18	0.09	9.2
					2.0	39.9	0.10	0.23	7.0
2 Jul	220	70°54.8'N	149°27.1'W	12	0.0	0.8	--	0.03	0.4
					6.0	33.5	1.49	0.46	10.2
					12.0	33.5	1.84	0.51	12.4
2 Jul	880	70°50.7'N	148°53.4'W	12	0.0	0.8	--	0.21	0.6
					6.0	32.2	1.34	0.53	11.0
					12.0	---	--	--	--

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Appendix 1. (Continued)

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Date	Station	Location		Depth (m) Bottom	Sample	Salinity ‰	Nitrate + Nitrite -N (-----microgram-atoms/l)	Phosphate -P -atoms/l	Silicate -Si -microgram-atoms/l
2 Jul	8	70°30.7'N	148°53.4'W	12	0.0	1.6	0.10	0.37	32.9
					6.0	33.0	2.06	0.57	13.0
					12.0	34.5	2.61	0.56	15.5
2 Jul	Beach	70°30.4'N	148°55.0'W	0	0.0	2.9	0.20	0.05	9.0
8 Aug	28	70°44.0'N	151°53.0'W	6	0.0	21.11	0.10	0.00	6.9
					3.0	21.43	0.10	0.00	5.7
					6.0	27.00	0.50	0.35	8.7
8 Aug	27	70°40.0'N	151°46.0'W	6	0.0	22.74	0.10	0.14	8.5
					3.0	22.84	0.10	0.26	10.0
					6.0	25.95	0.10	0.28	9.0
8 Aug	26	70°37.3'N	151°28.7'W	7	0.0	24.57	0.10	0.21	16.7
					3.0	24.54	0.20	0.25	16.9
					6.0	26.82	0.50	0.30	17.3
13 Aug	25	70°34.1'N	151°15.6'W	7	0.0	27.49	0.50	0.50	13.8
					3.0	28.05	0.50	0.45	12.4
					6.0	30.26	0.20	0.44	9.1
13 Aug	24	70°33.5'N	151°00.0'W	7	0.0	20.30	2.33	0.22	30.3
					3.0	29.92	0.50	0.49	9.7
					6.0	30.76	0.50	0.60	9.4
13 Aug	23	70°35.0'N	150°42.6'W	7	0.0	29.25	0.10	0.25	9.1
					3.0	29.72	0.10	0.49	8.6
					6.0	31.89	0.50	0.55	8.3
13 Aug	34	70°33.5'N	150°17.1'W	6	0.0	28.70	0.10	0.16	9.9
					3.0	28.70	0.50	0.50	9.7
					6.0	31.22	0.50	0.54	7.0

Appendix 1. (Continued)

Date	Station	Location		Depth (m) Bottom	Sample	Salinity ‰	Nitrate + Nitrite -N Phosphate -P Silicate -Si (-----microgram-atoms/liter-----)		
9 Aug	33	70°35.0'N	150°15.0'W	9	0.0	22.80	0.10	0.16	22.1
					5.0	28.27	0.10	0.50	10.2
					9.0	30.73	0.50	0.54	8.2
9 Aug	32	70°35.0'N	151°03.0'W	9	0.0	20.29	0.50	0.11	25.8
					9.0	21.57	1.00	0.12	19.8
9 Aug	31	70°36.3'N	151°13.9'W	9	0.0	19.50	0.10	0.14	16.4
					5.0	23.47	0.10	0.16	11.3
					9.0	30.87	0.50	0.51	7.6
9 Aug	30	70°36.3'N	151°17.5'W	9	0.0	24.37	0.10	0.20	8.3
					5.0	24.34	0.10	0.20	9.1
					9.0	30.59	0.20	0.40	6.0
9 Aug	29	70°43.0'N	151°47.0'W	9	0.0	23.19	0.10	0.08	7.0
					5.0	29.44	0.10	0.22	7.0
					9.0	27.36	0.10	0.31	6.3
14 Aug	37	70°47.2'N	151°40.0'W	13	0.0	23.73	0.10	0.26	10.5
					7.0	30.89	0.10	0.00	2.1
					13.0	31.77	0.20	0.80	4.0
14 Aug	38	70°37.4'N	150°49.0'W	13	0.0	26.13	0.10	0.61	9.0
					7.0	29.97	0.10	0.62	7.9
					13.0	32.10	0.10	0.66	9.1
7 Aug	35	70°32.8'N	150°09.5'W	3	0.0	25.19	0.10	0.28	8.8
					2.5	26.30	0.10	0.32	11.7
9 Aug	36	70°33.8'N	152°02.7'W	1	0.0	13.84	0.10	0.00	7.6
					1.0	13.90	0.50	0.11	8.3

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Appendix 1. (Continued)

Date	Station	Location		Depth (m)		Sample	Salinity ‰	Nitrate + Nitrite -N Phosphate -P Silicate -Si (-----microgram-atoms/liter-----)		
				Bottom						
4 Sep	Kuparuk River	70°15.0'N	148 °59.5'W	--	0.0	---	0.50	0.00	60.5	
4 Sep	Reindeer Island	70°28.9'N	148 °20.9'W	--	0.0	23.46	0.10	0.31	13.2	
4 Sep	Peat Island			--	0.0	---	1.00	0.12	26.2	
9 Nov	Narwhal	70°25.3'N	147°29.6'W	10	0.0	28.20	1.25	0.54	19.5	
					5.0	30.04	4.50	0.84	25.8	
					10.0	31.07	4.59	0.91	30.8	
9 Nov	Boulder Patch	70°19.3'N	147°35.1'W	5	0.0	28.16	1.17	0.14	20.8	
					5.0	28.76	0.10	0.32	19.0	

Appendix 2. Nutrient and Salinity Data, 1981.

Date	Station	Location		Depth (m)		Salinity ‰	Nitrate + Nitrite -N		
				Bottom	Sample		Ammonia -N		
							-----microgram-atoms/liter-----		
17 Apr	Harrison Bay 1	70°36.0'N	151°38.0'W	5	1.7	32.82	6.9	0.5	1.19
					5.0	34.41	6.1	0.5	1.15
2 Apr	Harrison Bay 2	70°33.9'N	151°08.0'W	7	1.5	31.78	5.0	0.3	1.25
					3.0	32.79	4.7	0.7	1.17
					6.5	32.92	5.3	0.2	1.19
12 Apr	3	70°34.8'N	147°04.4'W	7	1.7	33.03	5.5	0.0	1.27
					3.5	32.83	5.7	0.0	1.29
					7.0	32.67	5.7	0.2	1.29
12 Apr	Colville River	70°24.5'N	147°28.1'W	2	3	29	3	2.1	0.2
13 Apr	2°	70°44.2'N	147°28.2'W	5	1.5	32.88	8.5	0.0	1.3
					5.0	33.98	5.4	0.1	1.29
13 Apr	19	70°01.0'N	147°03.5'W	4	1.5	33.45	6.0	0.1	1.27
					4.0	33.59	5.5	0.2	1.32
13 Apr	8	70°16.7'N	147°17.3'W	5	1.6	28.33	4.0	0.0	1.20
					5.0	32.98	5.8	0.1	1.22
3 Apr	Boulder Patch	70°18.0'N	147°32.3'W	7	1.6	32.92	4.6	1.1	1.15
					3.0	32.80	4.1	0.1	1.20
					6.5	31.52	5.3	0.2	1.30
14 Apr	2	70°33.3'N	150°21.6'W	7	1.6	32.88	5.6	2.2	1.44
					3.0	32.16	5.4	2.7	1.24
					6.5	32.71	7.2	0.1	1.28
14 Apr	3	70°32.0'N	149°51.7'W	2	1.3	39.76	6.6	0.7	0.83

Appendix 2. (Continued)

Date	Station	Location		Depth (m) Bottom	Sample	Salinity ‰	Nitrate + Nitrite -N Ammonia -N Phosphate -P (-----microgram-atoms/liter-----)		
14 Apr	2	70°35.1'N	149°28.6'W	12	1.6	32.53	4.6	0.5	1.28
					6.0	32.45	4.8	0.2	1.32
					12.0	32.47	5.6	0.2	1.29
14 Apr	8	70°31.0'N	148°55.0'W	12	1.6	33.07	4.8	0.3	1.32
					6.0	32.93	4.7	0.0	1.32
					12.0	32.94	4.6	0.1	1.27
14 Apr	15	70°26.4'N	148°19.0'W	a	1.6	33.06	4.8	0.0	1.33
					4.0	32.15	4.2	0.0	1.27
					8.0	33.92	4.9	0.0	1.27

Appendix 3. Chlorophyll I, Phaeopigments, ¹⁴C Primary Productivity Rates and Light Data from 1982 Stations.

Date	Station	Location	Depth (m)	Chlorophyll I	Phaeopigments	Primary	Light	% Surface
				(mg/m ³ for phytoplankton; mg/m ² for ice algae)		(mg/m ³ hr)	(ft candles)	
25 May	HB 1A	70°38.2'N 150°28.2'W	ice core	76.1	3.5	N.D.	N.D.	N.D.
			1.5	0.07	0.08	N.D.	N.D.	No.
			6	0.05	0.04	N.D.	N.D.	N.D.
			12	0.01	0.03	N.D.	N.D.	N.D.
25 May	HB 2A 8	70°40.5'N 150°36.4'W	ice core	0.1	<0.01	N.D.	N.D.	N.D.
			ice core	0.1	0.01	N.D.	N.D.	N.D.
			1.5	0.01	0.02	N.D.	N.D.	N.D.
			5	0.01	0.02	N.D.	N.D.	N.D.
			10	0.02	0.03	No.	N.D.	N.D.
25 May	HB 3	70°41.9'N 150°40.9'W	1.5	<0.01	0.02	N.D.	N.D.	N.D.
			6	0.02	0.03	N.D.	N.D.	N.D.
			12	<0.01	0.01	N.D.	N.D.	N.D.
25 May	HB 4A 8	70°38.0'N 150°52.0'W	ice core	27.3	2.9	N.D.	N.D.	N.D.
			ice core	7.9	0.7	N.D.	N.D.	No.
			1.5	0.15	0.12	N.D.	N.D.	N.D.
25 May	2D A 8 c	70°14.2'N 147°29.8'W	ice core	2.9	0.2	N.D.	N.D.	N.D.
			ice core	2.7	0.3	N.D.	N.D.	N.D.
			ice core	7.4	0.5	N.D.	N.D.	N.D.
			12	0.08	0.06	0.02	3.0	0.05
25 May	8P A B c	70°19.6'N 147°34.5'W	ice core	19.9	0.9	N.D.	N.D.	N.D.
			ice core	22.0	1.0	N.D.	N.D.	N.D.
			ice core	20.0	0.2	N.D.	N.D.	N.D.
			2	0.49	0.04	0.03	5.0	0.1
			4	0.05	0.04	N.D.	N.D.	N.D.

Appendix 3. (Continued)

Date	Station	Location	Depth (m)	Chlorophyll	Phaeopigments	Primary	Light	Surface
				(mg/m ³ for phytoplankton; ng/m ² for ice algae)		Productivity (mg/m ³ hr)	(ft candles)	
26 May	8 A B c	70°30.4'N 148°55.0'W	ice core	<0.1	<0.1	N.D.	N.D.	N.D.
			ice core	<0.1	<0.1	N.D.	No.	N.D.
			ice core	<0.1	<0.1	N.D.	N.D.	N.D.
			2	0.03	0.05	0.00	N.D.	N.D.
			5.5	0.03	0.03	N.D.	N.D.	N.D.
			11	0.06	0.08	N.D.	N.D.	N.D.
26 May	2 A B c	70°34.9'N 149°27.5'W	ice core	8.5	1.2	N.D.	N.D.	N.D.
			ice core	3.4	0.1	N.D.	No.	N.D.
			ice core	11.5	0.4	N.D.	N.D.	N.D.
			2	0.35	0.30	0.00	N.D.	N.D.
			4	0.16	0.1?	N.D.	N.D.	No.
26 May	3 A B c	70°32.1'N 149°51.7'W	ice core	0.3	<0.1	N.D.	N.D.	N.D.
			ice core	2.6	<0.1	N.D.	N.D.	N.D.
			ice core	0.1	<0.1	N.D.	N.D.	N.D.
			1.5	0.29	0.35	0.00	N.D.	N.D.
28 May	P. Bay A B c	70°20.0'N 148°20.5'W	ice core	7.3	0.3	N.D.	N.D.	N.D.
			ice core	7.4	0.9	N.D.	No.	N.D.
			ice core	0.9	<0.1	N.D.	N.D.	N.D.
			1.7	5.62	1.03	0.33	N.D.	N.D.
28 May	18 A B c	70°16.7'N 147°17.3'W	ice core	1.4	0.?	N.D.	N.D.	N.D.
			ice core	0.1	<0.1	N.D.	N.D.	N.D.
			ice core	0.3	0.0	N.D.	N.D.	N.D.
			1.7	0.08	0.06	0.03	N.D.	N.D.
			3.5	0.07	0.06	N.D.	N.D.	N.D.
			6.5	0.04	0.05	N.D.	N.D.	N.D.

Appendix 3. (Continued)

Date	Station	Location	Depth (m)	Chlorophyll	Phaeopigments	Primary	Light	% Surface	
				(mg/m ³ for phytoplankton; mg/m ² for ice algae)		(mg/m ³ hr)	(ft candles)		
28 May	19 A B	70°11.0'N 147°03'W	ice core	1.5	0.4	N.D.	N.D.	N.D.	
			ice core	2.0	0.1	N.D.	N.D.	N.D.	
				1.1	<0.1	N.D.	N.D.	N.D.	
			1.7	0.19	0.11	0.13	N.D.	N.D.	
			4.5	0.42	0.31	N.D.	N.D.	N.D.	
28 May	NT 2 A B c c'	70°40.4'N 147°24.4'W	ice core	6.2	0.6	N.D.	N.D.	N.D.	
			ice core	6.5	0.5	N.D.	N.D.	N.D.	
			ice core	6.3	3.1	N.D.	N.D.	N.D.	
			ice core	15.7	1.8	N.D.	N.D.	N.D.	
28 May	NT 2 (under ice)		1.5	0.04	0.02	0.09	110	1.2	
			5	0.03	0.02	0.14	60	0.6	
			10	0.42	0.01	N.D.	N.D.	N.D.	
			25	<0.01	<0.01	N.D.	N.D.	N.D.	
			50	0.24	0.02	N.D.	N.D.	No.	
	NT 2 (lead)			0	0.07	0.03	0.05	2,800	62.2
				5	0.06	0.02	0.06	1,000	22.2
				10	0.05	0.06	0.03	500	11.1
				25	0.01	0.01	0.01	130	2.9
				50	0.31	0.64	N.D.	N.D.	N.D.
	28 May	NT 3 A (under ice)	70°52.9'N 147°20.2'W		0.4	<0.1	N.D.	N.D.	N.D.
				1.5	0.07	0.04	0.04	10	0.1
				5	0.08	0.04	N.D.	N.D.	N.D.
				10	0.08	0.05	N.D.	N.D.	N.D.
25				0.06	0.03	N.D.	N.D.	N.D.	
50					0.02	N.D.	N.D.	N.D.	

Appendix 3. (Continued)

Date	Station	Location	Depth (m)	Chlorophyll I (mg/m ³ for phytoplankton; mg/m ² for ice algae)	Phaeopigments	Primary Productivity (mg/m ³ hr)	Light (ft candles)	% Surface
			2	0.19	0.10	0.05	1,200	17.1
			6	0.12	0.08	0.04	500	7.1
28 May	NT 4 A	71°12'N 147°20.2'W		2.6	<0.1	N.D.	N.D.	N.D.
	(under ice)		1.5	4.3	0.2	N.D.	N.D.	N.D.
			5	0.65	0.09	0.25	190	2.6
			5	0.14	0.08	0.09	71	1.0
			10	0.17	0.10	N.D.	N.D.	N.D.
			25	0.13	0.08	No.	N.D.	N.D.
			50	0.07	0.05	N.D.	N.D.	N.D.
21 June	PBT 2	70°52'N 148°20.5'W	0	0.65	0.92	0.53	3,500	38.9
			5	0.20	0.05	0.47	700	7.8
			10	0.20	0.13		N.D.	N.D.
			15	0.19	0.05	0.28	N.D.	N.D.
			20	0.21	0.07	0.28	N.D.	N.D.
			25	0.12	0.05	0.10	87	1.0
			30	0.05	0.02	0.04	N.D.	N.D.
			35	0.04	0.02	<0.01	N.D.	N.D.
			40	0.04	0.02	0.01	N.D.	N.D.
			50	0.02	0.02	N.D.	N.D.	N.D.
			60	0.11	0.20	N.D.	N.D.	N.D.
23 June	PBT 1	70°35.5'N 148°20.5'W	1	0.16	0.03	0.86	600	7.1
			5	0.14	0.03	0.17	130	1.5
			10	0.16	0.02	0.06	31	0.4
			15	0.19	0.03	0.04	12	0.1
			20	0.19	0.02	<0.01	11	0.1
			23	1.22	0.99	N.D.	N.D.	N.D.