

PRIMARY PRODUCTION AND NUTRIENT DYNAMICS
IN SIMPSON LAGOON AND ADJACENT WATERS

by

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INTRODUCTION

The Arctic Ocean has been described-by various authors as the least productive of the world oceans (Ryther, 1963; Appolonio, 1959; Dunbar, 1970) . Even a casual study reveals several abiotic factors which contribute to the low amounts of carbon fixation: (1) the presence of a pack ice cover severely attenuates incoming energy to the water column (2) annual melt in the summer results in stabilization of the watercolumn and this stability, preserved and protected from wind destruction by the ice cover, restricts mixing of deep water nutrients into the euphotic zone; **(3)** for approximately six months of the year the sun is below the horizon and photosynthesis is impossible; and, (4) for the remainder of the year, low solar angles reflect much of the incoming radiation" into space even if open water is available. It is not surprising therefore that productivity is very low and reaches significant proportions only in the coastal regions where the lower latitude, earlier melting, and turbulent mixing from wind and currents allow phytoplankton growth. This productivity along the Arctic Ocean margins is evident in an abundance of larger consumers and their limitation to the marginal waters has been attested by explorers who were reduced to near starvation during their travels in the high arctic oceanic regions (Stefansson, 1921). In recent years, primary productivity data obtained from ice breakers and ice island stations have provided a quantitative base for estimating carbon fixation rates in the Arctic and these have been synthesized into broad scale productivity "zones" by Koblentz-Mishke et al. (1970). They have estimated carbon fixation in the coastal zone of Alaska (less than 200

miles offshore) at approximately $50 \text{ g C/m}^2\text{-yr}$ and further offshore production was shown as less than 50 g C/m^2 .

This section will deal with the primary productivity in the Simpson Lagoon-barrier island ecosystem. The estimates of carbon fixation are compared with other inputs of carbon to the system arising from shoreline erosion and fluvial input from the Kuparuk and Colville Rivers. Finally, the ecological importance of the terrestrial carbon sources is assessed relative to marine phytoplankton production based upon carbon isotope abundances in consumer organisms from Simpson Lagoon. Personnel of LGL-Alaska did not perform any of the primary productivity studies and the principal work was undertaken by the author who cooperated with the LGL-study to provide estimates of energy influx and to determine the role of peat detritus in the lagoon foodweb. Much of the information presented herein has been synthesized from the annual and summary reports of RU 537. We have selected pertinent information from this large-scale study and have expanded the detail to define the role of primary production in the Simpson Lagoon-Harrison Bay area. Readers are encouraged to seek the Cumulative Summary Report of RU 537 and the final reports of RU 359 (R. Homer) for additional information on offshore areas and the Prudhoe Bay area.

NUTRIENT DYNAMICS

Sources and Standing Stocks

In order to estimate the nutrient pools available to phytoplankton at the onset of growth in spring, we have assembled past and current data on nutrient

concentrations in Simpson Lagoon collected by the author in *previous* studies (Schell, 1975) and for NOAA-OCSEAP over the past few years.

Within Simpson Lagoon, circulation beneath the ice becomes severely restricted in late winter as the ice cover approaches maximum annual thickness of 1.6-2.0 m. By ~~May~~, nutrient concentrations reach annual maxima as thermohaline convection of offshore water has replaced lagoon waters during the course of the winter and solute exclusion has contributed to further concentration. Figure 1 and Table 1, from Schell (1975) shows stations sampled in western Simpson Lagoon and the corresponding nutrient and salinity concentrations at these locations. A plot of salinities versus nitrate concentrations yields a linear relationship indicating the solute exclusion during freezing is the primary cause of the wide variations in concentrations. These data have been supplemented by periodic surveys during 1978-1982 which yielded similar concentrations confirming the overall nutrient standing stocks present during the prebreak-up period. The mean nitrate concentration of $6.4 \mu\text{g-atoms N/liter}$ and $0.99 \mu\text{g-atoms/liter}$ phosphate-P yields an N:P ratio of 6.4 and indicates a severe nitrogen limitation relative to phosphorus once plant growth is established. However, the ice algae populations in Simpson Lagoon were found to be very low and the rapid influx of meltwater once break-up commences effectively alters the water column environment to the point that growth by marine species is terminated as sediment-laden freshwater fills the lagoon.

Chronologically, the water-column environment of Simpson Lagoon can be separated into four periods with characteristic nutrient and salinity concentrations:

March - mid-May. Under-ice waters contain uniform vertical salinity and nutrient concentrations with spatial variations reflecting freeze concentration in shallower areas. The areas of less than 1.5 m depth are overlain by bottom-fast ice.

Mid-May - mid-July. An abrupt drop in salinity occurs as break-up flooding from the Kuparuk, Colville, and Sagavanirktok Rivers flush saline waters from the lagoon and inter-island channels with turbid floodwaters containing large quantities of suspended organic and inorganic matter. In spite of the large influx of freshwater, however, areas of the lagoon bottom are overlain with a layer of dense saline water (approximately 40-45 ‰) remnant from winter conditions. This bottom layer persists well into the summer and disappears only after open water allows wind-mixing" to the bottom. Nutrient concentrations during this period are typical of river floodwaters and contain higher inorganic nitrogen concentrations relative to phosphate than the marine waters (Hamilton et al., 1974).

The rapid spreading of the river waters over the lagoon ice deposits a dark layer of sediment onto the ice surface which drastically decreases the albedo and accelerates the melting of the lagoon ice. As the temperature of the river water increases, melting spreads seaward from the deltas and by 15 July, the lagoon is largely ice free.

Mid-July - late September. The open water season in Simpson Lagoon is characterized by a wind-mixed water column that is warmer and less saline than outside of the barrier islands. During calm spells or periods of heavy rainfall, the river water spreads over the surface establishing

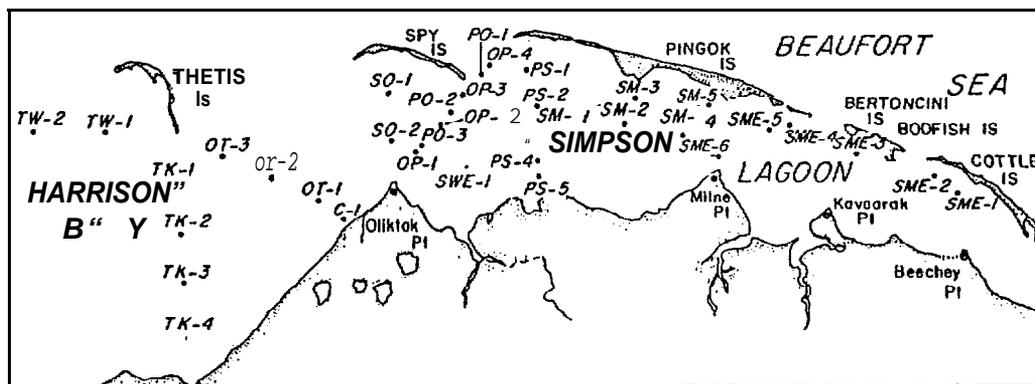


Figure 1. Under-ice nutrient and salinity sample stations, Spring, 1971 (from Schell, 1975).

Table 1. Nutrient and salinity data for stations shown in Figure 1 (from Schell, 1975).

Station Number	Salinity (‰)	Nitrate (µg-at/l)	Phosphate (µg-at/l)	Silicate (µg-at/l)
c-1	33.7	5.1	1.05	19.4
OP-1	37.9	2.7	0.82	17.1
OP-2	36.8	2.2	0.96	20.2
OP-3	34.0	2.2	0.82	17.1
OP-4	41.4	6.9		
OT-1	27.8	3.9	0.94	13.7
OT-2	32.8	4.4	1.01	17.7
OT-3	34.8	5.6	0.93	22.2
PO-1				
PO-2	32.0	3.6		
PO-3	39.1	7.1		
PS-1	40.2	4.6	0.74	28.7
PS-2	45.3	7.3	0.98	33.5
PS-4	57.8	8.4	0.87	26.8
PS-5	51.5	9.4	0.84	40.2
SM-1	45.6	7.8	0.86	35.9
SM-2	45.6	8.5	1.05	42.0
SM-3	57.1	9.7	0.96	48.9
SM-4	56.1	9.3	0.99	47.0
SM-5	58.3	9.4	1.03	49.5
SME-1	45.4	3.8	1.14	22.0
SME-2	42.1	5.4	1.24	28.4
SME-3	55.4	6.7	1.21	50.0
SME-4	65.9	10.5	1.09	53.5
WE-5	49.0	7.5	1.15	38.6
SME-6	59.5	9.4	1.09	48.2
SO-1	35.6	5.5	1.00	22.2
SO-2	34.8	5.4	0.97	21.2
SUE-1	46.5	8.5	0.84	37.8
TK-1	32.3	3.9	1.09	16.7
TK-2	32.6	4.2	0.93	17.8
TK-3	34.1	5.5	1.12	20.2
TK-4	36.5	7.5	0.57	28.2
TW-1	32.0	4.5	0.95	16.7
TW-2	30.4	0.6	1.01	18.1

striking profiles of salinity and temperature with surface values of less than 4 ‰ salinity and 6°C overlying water of 30 */m and 1.3°C at 2.5 m depth. Typically, however, wind mixing produces a homogeneous water column of 20-30 ‰ and temperatures between 0-4°C. Nutrient concentrations are very low during this period due to phytoplankton uptake and only where river water enters the system do nitrate concentrations exceed 0.5µg-atom N/liter.

MidSeptember - February. By late September, freeze-up in the uplands cause a rapid decline in run-off volume and ice cover forms in the embayments. By mid-October most of the lagoon is frozen over unless storms shift the ice cover about. Freeze-up is rapid and ice accretion occurs at around 1 cm/day although areas where slush ice has accumulated through wind stress, the ice may be up to a meter thick. This soft mass of crystals hardens over the course of the winter as congelation ice penetrates the mass.

Nutrient concentrations begin to rise upon cessation of photosynthesis in early winter. Instability of the water column due to brine exclusion and decreasing temperatures causes rapid mixing and thermohaline convection processes replace nearshore waters with offshore inter of lower salinity. Vertical instability extends to the depth of the shelf and mixes nutrients into the upper water column and the nearshore zone. Additional nutrient input occurs via mineralization of dissolved and particulate organic nitrogen and vitrification of the liberated ammonia to nitrite and nitrate. These processes are discussed in a more quantitative sense below. By late February ice accretion rates

begin to decrease (Schell, 1975) and concentrations of nutrients and salinity are again near annual maxima.

In spite of the long season of negligible phytoplankton uptake (mid-September - mid-May), nutrient concentrations in nearshore Beaufort Sea waters prior to the onset of phytoplankton activity are only 10-15 percent of typical pre-bloom concentrations in the Bering Sea or in southeastern Alaskan waters: Thus the initial uptake by phytoplankton is much more constrained and the maximum standing stocks of chlorophyll are always low relative to maxima in more temperate latitudes.

Erosional and Fluvial Inputs of Nitrogen

Our observations that N:P ratios in the inorganic nutrient pools in late winter were always very low relative to the generally accepted value of 15-16:1 (Fleming, 1940) in phytoplankton led us to the premise that nitrogen availability is probably limiting marine plant growth during most of the arctic summer season. Since terrestrial matter contained a much higher N:P ratio of 31:1 (Schell et al., 1982) we felt that nearshore inputs could contribute a high percentage of nutrient requirements during summer. Although terrestrial inputs are small relative to total nitrogen stocks present in the offshore Beaufort Sea, there was sufficient input to Simpson Lagoon to require a quantitative assessment of their importance.

The two primary sources of terrestrial nitrogen are shoreline erosion and the Kuparuk River. The Kuparuk River empties directly into Simpson Lagoon and transported organic matter can accumulate during the period of lagoon ice cover following break-up and must be carried the length of the lagoon for transport out during the open water period.

The inputs from shoreline erosion, in contrast, occur only during the latter part of the summer when erosional processes are active. During late August and September storm surges inundate the 1-2 m peat bluffs and wave action rapidly erodes the permafrost underlying the tundra mat. Once a thermoerosional niche has been cut under the block, a split occurs along ice-wedge polygon boundaries and it collapses into the sea. Wave action continues the erosional processes and very often a "soup" of suspended peat particles fills the water along stretches of shoreline in the lagoon.

Estimation of peat carbon inputs was accomplished using eroded volumes calculated by Cannon and Rawlinson (1978) and from our soil analyses of carbon, nitrogen, and phosphorus on sections obtained from Simpson Lagoon and other locations along the Beaufort coastline.

The estimated volumes from both island and mainland coastal erosion was determined to be $2.5 \times 10^5 \text{ m}^3/\text{yr}$ of which $6.0 \times 10^4 \text{ m}^3$ was peat soils. Based upon an estimated bulk density of $1.1 \text{ kg}/\text{dm}^3$ and a dry:wet ratio of 0.37 (determined from the average of four Simpson Lagoon soil sections), the weight of peat soil is $2.4 \times 10^7 \text{ kg}$. Based upon carbon and nitrogen analyses of soil sections along the coastline (Schell et al., 1982) approximately 16 percent by dry weight is carbon ($3.9 \times 10^6 \text{ kgC}$). The average C:N atom ratio in peat was found to be 16.3 indicating an accompanying $0.3 \times 10^6 \text{ kg N}/\text{yr}$ is eroded into the lagoon.

The Kuparuk River drains directly into Simpson Lagoon and is the only large river to do so. The Colville River, although 12 miles west of Simpson Lagoon, discharges a much larger volume of water (average annual discharge of approximately $12 \times 10^9 \text{ m}^3/\text{yr}$) compared to the Kuparuk ($1.1 \times 10^9 \text{ m}^3/\text{yr}$, Carlson et al., 1977), but the discharge flow which enters the lagoon is estimated at only five percent of the discharge volume. This fraction was determined

during break-up flooding when ice cover prevents wind-driven transport and the plume of the Colville River entering Simpson Lagoon could be estimated from satellite imagery. From the ratio of plume area within the lagoon to the entire plume area the estimate of five percent of total flow contribution to Simpson Lagoon was then made. Since most of the annual flow occurs during and immediately following break-up, it was felt that this estimation technique was reasonable. Once open water season arrives, the relative contributions of Colville River water depends upon wind direction. Under prevailing easterly winds the Colville plume is driven westward in Harrison Bay and does not enter the lagoon. Under westerly winds, however, the plume travels along the coastline and around Oliktok Point and enters the lagoon. This was shown when surface drogues released in the main channel of the Colville River and in eastern Harrison Bay under westerly wind conditions were recovered from the shoreline southwest of Oliktok and the lagoon side of the barrier islands (Kinney et al., 1971).

Calculation of transported organic matter to Simpson Lagoon from the Colville and Kuparuk Rivers used the following data and assumptions.

- 1) Colville River flow = $12 \times 10^9 \text{ m}^3/\text{yr}$ (5% enters the lagoon)
- 2) Kuparuk River flow = $1.1 \times 10^9 \text{ m}^3/\text{yr}$
- 3) Total organic C = 12 mg/liter

The total organic carbon value was based on limited sampling (three intervals) by U.S. Geological Survey personnel (C. Sloan, personal communication). Samples were taken early in break-up, near peak flow and in mid-August. The 12 mg/liter value is a weighted average based upon the discharge data for the sampling period. This concentration was applied to

Table 2. Carbon and Nitrogen Inputs to Simpson Lagoon (kg C/yr)

Primary Production	
Estimated from ^{14}C -uptake	<u>$1.2-1.7 \times 10^6$</u>
Estimated from nitrate-N supply	0.6×10^6
Estimated from regenerated-N (ammonia)	<u>$0.4-0.8 \times 10^6$</u>
Total from inorganic N	<u>$1.0-1.4 \times 10^6$</u>
Estimated faunal food requirements	$0.8-1.6 \times 10^6$
Shoreline erosion	4×10^6
Fluvial input	
Organic carbon	
Kuparuk River (100%)	13×10^6
Colville River (5%)	<u>7×10^6</u>
Total carbon from rivers	<u>20×10^6</u>
Total terrestrial inputs"	<u>24×10^6</u>
Nitrogen inputs (kg N/yr)	
Organic nitrogen	
Shoreline erosion	0.3×10^6
Kuparuk River (100%)	0.9×10^6
Colville River (5%)	<u>0.5×10^6</u>
Total organic N input	<u>1.7×10^6</u>
Inorganic nitrogen	
Shoreline erosion	1×10^3
Kuparuk River (100%)	25×10^3
Colville River (5%)	<u>46×10^3</u>
Total inorganic N input	<u>71×10^3</u>

column during fall storms or the presence of drifted snow can attenuate light penetration to intensities below that required for growth. Other **abiotic** factors such as brine concentration in shallows or the presence of freshwater runoff beneath the ice may stress algal **populations** and retard growth.

As a result, within a few miles of shore, ice algae tends to be patchy and highly variable from year to year. The source of ice **algal** species in the spring bloom is not clear, nor the exact **mechanisms** by which they are incorporated into the ice. Alexander and Horner (1972), Homer (1969), and Horner (1977), note that the dominant ice **algae** are not the same as the algal species observed in fall water samples or post-bloom **phytoplankton**. Hameedi (1978), however, found that ice algae released into the water column of the . Chukchi Sea were a major component of the **phytoplankton** biomass. It is possible that the microhabitat provided by the ice matrix is sufficiently different from the water column that the **algal** speciation is different due to **differing** growth response from a uniform seeding. Algal populations are found in polar ice at all times of the year although growth is rapid only in early fall and late spring (Hoshiai, 1977; Hsiao, 1980; Schell et al., 1982). The seed stock for the spring bloom may, therefore, be already incorporated into the ice and when light and habitat conditions are right, rapid growth occurs. Meguro et al., (1966, 1967) found high concentrations of algae in the Chukchi Sea ice in August and Homer and Schrader (1981) suggested **multiyear** ice as a source of ice algae. The major **sampling** effort in this project has been to cover a broad area with the hope of being able to approximate total carbon inputs rather than describe in **detail** the seasonal progression at one location. This latter aspect was addressed by Research Unit 359 (Homer and Schrader, 1981) and the reader is urged to see this work for a detailed description of the ice algal bloom and speciation. We summarize below the ice

algae data in Schell et al. (1982), and describe the potential importance of this source to the nearshore ecosystem.

Studies of distribution and productivity of ice algae in the Alaskan Beaufort Sea (and the Chukchi Sea at Pt. Barrow) have been conducted by Alexander et al. (1974), Horner et al. (1974), Schell (1980), Homer and Schrader (1981), and Schell et al. (1982).

Our studies have sought to estimate the extent of areal distribution of ice algae and to assess their role as a carbon source in the nearshore ecosystem. Data to date indicate that ice algae make a small contribution to the annual production and that their ecological role is still somewhat uncertain. Although ice algal production occurs during the early spring prior to the phytoplankton bloom and represents a spatially concentrated source of food, there is little indication that a significant fraction of this carbon is grazed during the period of growth. We find that the ice algal layer tends to increase rapidly in density in response to increasing light and to penetrate the ice crystal lattices for several centimeters up from the bottom. Grazing by filter feeders appears very restricted in this crystal matrix. Cores obtained from Simpson Lagoon were occasionally observed to have amphipods in this matrix with a readily evident hole having been made up into the ice. Although the algae were gone from the immediate vicinity of the hole, the area grazed was only a small fraction of the overall population. Access to the algae living in the ice matrix is obviously a major factor retarding the exploitation of this otherwise concentrated food source to herbivores. It should also be noted that the population of herbivores is low in Simpson Lagoon in early spring (Griffiths and Dillinger, 1981) and the larger populations offshore may graze the ice algal resource there more effectively. However, we generally observed higher densities of ice algae

offshore indicating that substantially more effective grazing is unlikely or insufficient to depress algal biomass. (See also A.G. Carey, Research Unit 006.)

Of the potential factors limiting ice algal growth, light intensity appears to predominate. Alexander et al. (1974) found that growth occurred above a light threshold which varied between the two years of the study. In 1972, growth occurred above 0.042 ly/hr (approximately $1.8 \times 10^{-6} \text{ E/m}^2\text{-sec}$) and in 1973, the threshold was at 0.171 ly/hr ($7.25 \times 10^{-6} \text{ E/m}^2\text{-sec}$). This difference in threshold light levels may have been due to differences in species compositions as in 1972 Nitzschia frigida was dominant, while in 1973 Navicula marina was most abundant.

In Schell et al. (1982) we used data from Alexander et al. (1974) and Homer and Schrader (1981) to demonstrate that ice algal growth could best be described by an exponential bimodal growth curve with the first peak occurring near the end of April and the second near the end of May. The magnitude of the first peak is smaller than the second in these data sets although at other locations and years this may not be true. Our own sampling programs showed a wide range in algal biomass in the coastal ice sheet but since our samplings were one-time events in late May, our data offer no substantiation with regard to the phase of the bloom. The data of Appolonio (1965) indicates a bimodal growth curve for ice algae near Devon Island with the first peak being the larger. It should be noted, however, that the 1972 data from Alexander et al. (1974) indicate only one peak in late May.

Ice algae appear to thrive beneath the flat ice pans that typify the winter landfast ice outside of the barrier islands. In early April, pans which had thinner snow cover than the immediate surrounding area of rough pressure field ice due to wind action were found to have visible ice algal

populations on the bottom. It appears that the snow is blown off the smooth pans and is trapped in the rough ice leaving the flat areas with relatively thin snow cover, often less than 10 cm. If the ice beneath is clear, the algae respond to the higher light intensities available in these areas. We do not have data on ice algal densities beneath pressure fields due to the difficulties encountered in coring piled ice. It is reasonable to expect, however, that the increased snow cover and particulate loading usually found in piled ice would effectively prevent light penetration and inhibit algal growth.

Within Simpson Lagoon, the ice cover is usually uniform and overlain with drifted snow. Since the lagoon is shallow, much of the ice is bottomfast and brine exclusion in deeper areas raises the underlying water salinity in excess of 65 ppt in locations with restricted circulation (Schell, 1975). Ice algal populations were small and variable. Although quantitative measurements were obtained at only a few stations, we did not observe visible ice algal bands in bottom ice during inter sampling operations. In western Simpson Lagoon, off Oliktok Point and in the island passes, rough ice was widespread and laden with sediment which may account for the lack of ice algae in that location. Based upon the observed lack of visible ice algae in ice cores and the low standing stocks measured ($<50 \text{ mg C/m}^2$), we estimate that less than 0.1 g C/m^2 is fixed by ice algae within the lagoon system. Since much of the area is overlain with bottomfast ice, the annual variation in average ice algal productivity would probably be small even if the ice cover were unusually free of sediment. The combination of deeper snow depth and limited area available would not allow a major contribution to annual production from this source. In addition, the effective growth season for ice algae is subject to foreshortening due to influx of river water from the Kuparuk and Colville

Rivers. In a typical year, the onset of spring flow occurs around 20-25 May and the stress applied to marine diatom populations by this fresh, turbid water would probably be sufficient to terminate any bloom in progress.

Based upon the conditions described above, we have concluded that the role of ice algae as an energy source to consumers in Simpson Lagoon is minor. Although populations of algae were found to be much denser offshore and in clear-ice areas of Stefansson Sound, the short growing season and inaccessibility to consumers appear to relegate this carbon source to a minor role in nearshore trophic energetic.

Phytoplankton Primary Production

The water column in Simpson Lagoon during the summer season and early fall when phytoplankton carbon fixation is active is characterized by low nutrient concentrations and extremely euryhaline and eurythermal conditions. As a result, carbon fixation rates are low and wind-mixing and turbidity from river plumes also reduce fixation rates. Primary productivity measurements by Alexander et al. (1975) showed a decrease in production from Oliktok to Beechey Point which may be due to the proximity of the Kuparuk River mouth at Beechey Point. Although the productivity data available are from August, the close similarity in rates between the values observed in Simpson Lagoon, Harrison Bay (Schell et al., 1982), and Prudhoe Bay (Coyle, 1974) indicate that extrapolation of observed rates to earlier and later in the season is reasonable. The largest data gap encompasses the period between the decline of ice algae in June and open water in late July. Based upon the nitrate-N available in the water column, we projected a minimum of one gram C/m² fixed by ice algae and phytoplankton prior to open water. This value, although

conservative, is consistent with the very low phytoplankton productivities measured in June and early July off Narwhal Island (Homer and Schrader, 1981; Schell et al., 1982). These production rates are also similar to those measured in Harrison Bay west of Simpson Lagoon and in Prudhoe Bay to the east. Our measurements are listed in Table 3. These data have been composited and used to contour carbon fixation as shown in Figures 3 and 4 and a summary of all data except the icebreaker data of Homer, (1980) are listed in Tables 4 and 5. Offshore, primary production rates increase in response to the stable water column and increased clarity coupled with occasional wind-mixing of nutrients into the euphotic zone during storms. An overall estimate of Alaskan Beaufort Sea productivity has been made by Schell et al. (1982) and these data are consistent with the rates observed in Simpson Lagoon. Figure 2, A-D shows the stations where primary productivity data have been obtained on this project and Figures 3A and 3B show primary production contours for the Simpson Lagoon-Haz-riksen Bay region. For a more detailed description of ice algal production and phytoplankton production in other areas of the Alaskan Beaufort Sea, the reader is urged to see this report.

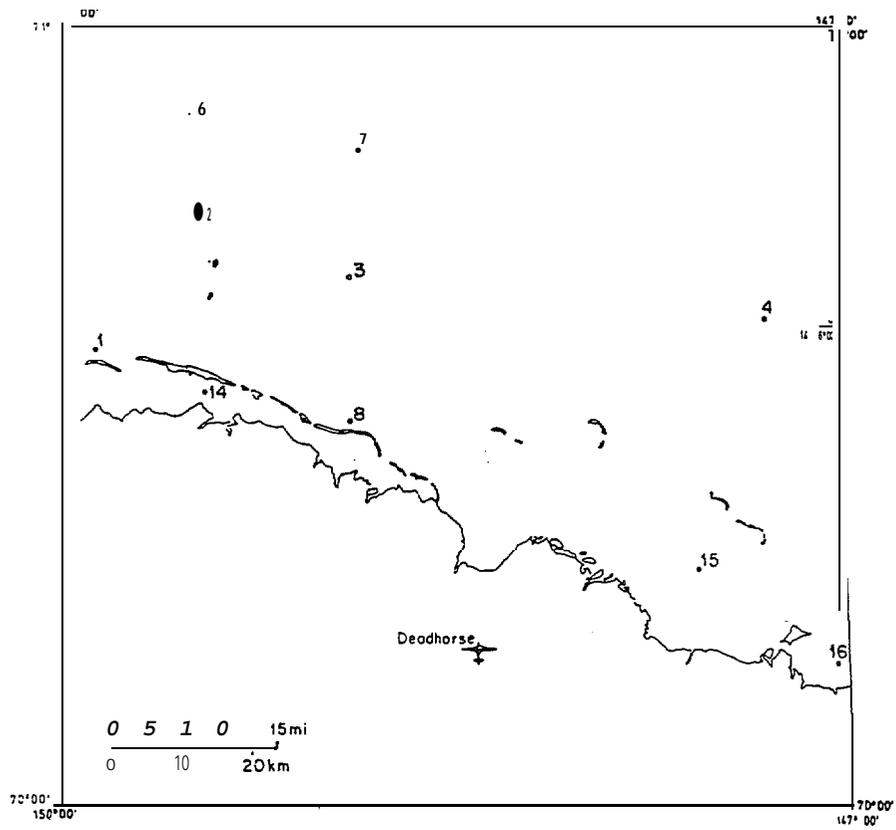


Figure 2, A-D. Station locations and identification numbers for primary productivity measurements listed in Table 3.

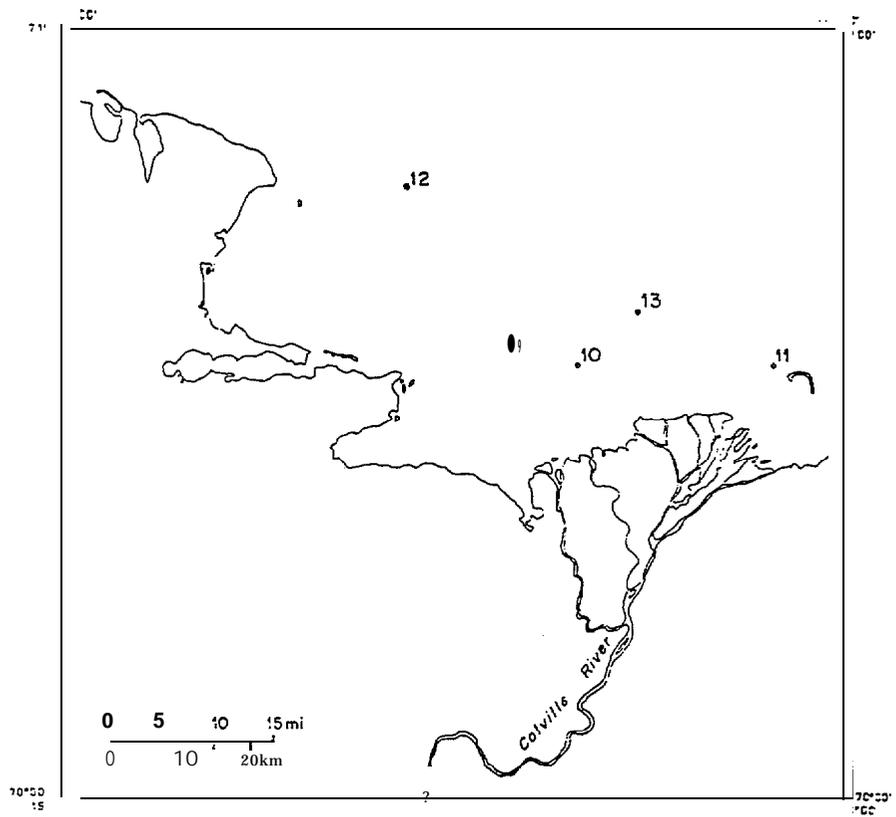


Figure 2B.

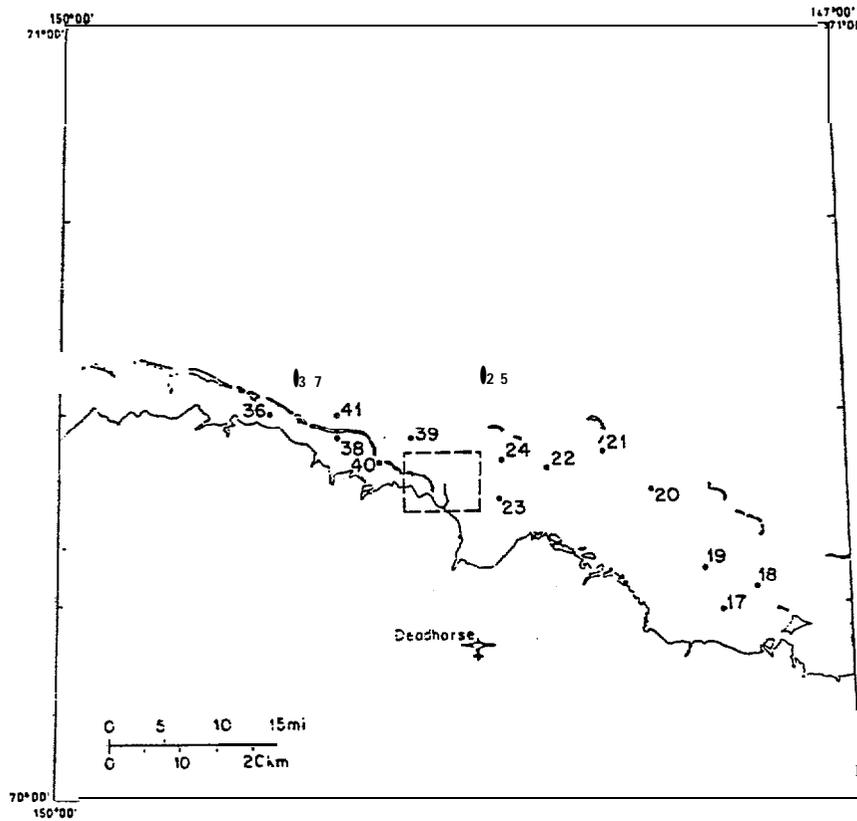


Figure 2C. Inset detail shown in Figure 2D.

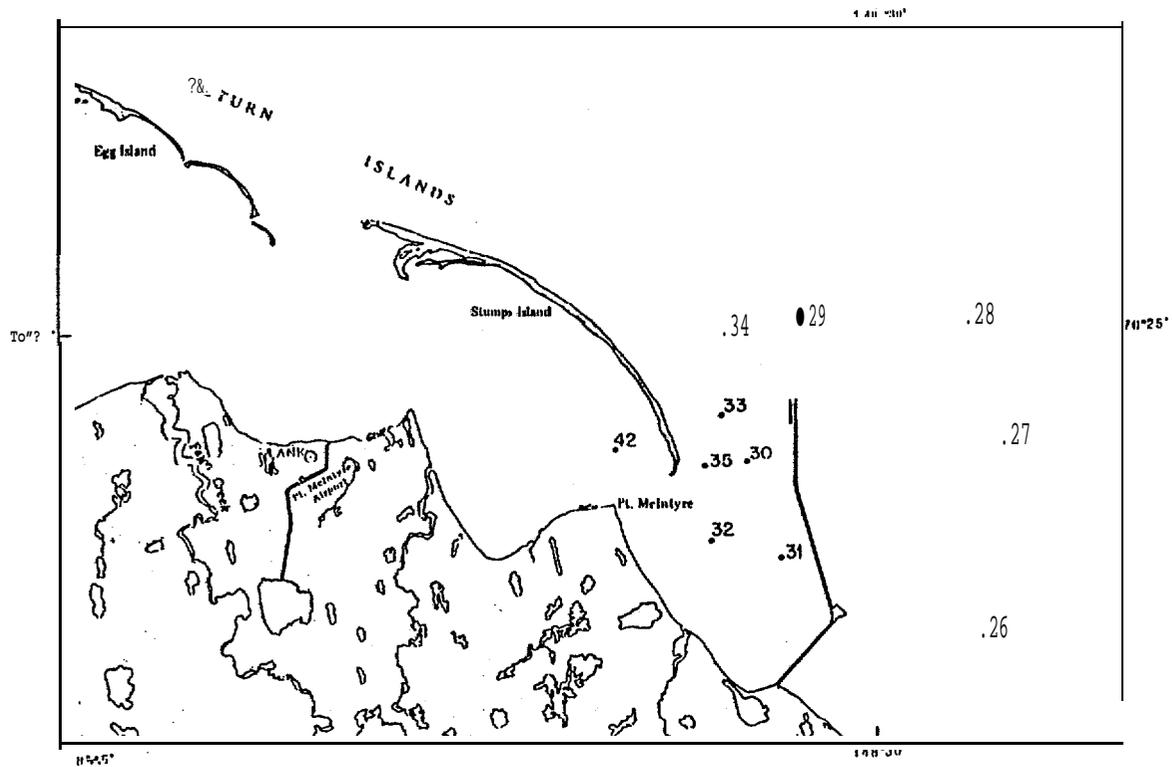


Figure 2D. Primary productivity measurements in the vicinity of the Prudhoe Bay Oilfield Waterflood Causeway.

Table 3. Primary productivity measurements from Simpson Lagoon and adjacent waters, 1978-1981.

Offshore	Station No.	Ident. No.	Location	Depth (m)	Primary Productivity (mgC·m ⁻³ ·hr ⁻¹)
17-18 June 1980	4	1	70°34.6'N 149°50.4'W	9	0.0
	202	2	70°44.8'N 149°27.1'W	12	0.4
	808	3	70°40.7'N 148°53.4'W	0	0.3
				6	0.0
				12	0.2
	Lead	4	70°38.3'N 147°20.3'W	0	0.1
				12	0.0
	Seal Hole	5	70°38.6'N 146°0.20'W	0	0.2
				12	0.0
	2 July 1980	220	6	70°54.8'N 149°27.1'W	0
				12	0.6
880		7	70°50.7'N 148°53.4'W	0	0.8
				6	1.0
8		8	70°30.7'N 148°53.4'W	0	9.7
				6	0.0
			12	0.0	
<u>Harrison Bay</u>					
7-15 August 1980	25	9	70°34.1'N 151°15.6'W	0	0.2
				3	0.2
				6	0.4
	24	10	70°33.5'N 151°00.0'W	0	0.2
				3	0.4
				6	0.5
	34	11	70°33.5'N 151°17.1'W	0	0.1
				3	0.2
				6	0.3
	37	12	70°47.2'N 151°40.0'W	0	0.2
				13	9.9
	38	13	70°37.4'N 150°49.0'W	0	0.2
				7	0.5
			13	0.3	
<u>Simpson Lagoon</u>					
17-18 June 1980	1	14	70°31.8'N 149°25.2'W	0	0.1
				2	0.2
2 July 1980	1	14a	70°31.8'N 149°25.2'W	0	1.7
				2	2.0
8-10 August 1978	1	14b	70°31.8'N 149°25.2'W	0	0.2
				0	0.2
				0	0.4
				0	0.6
				0	0.5

Table 3. Primary productivity measurements from Simpson Lagoon and adjacent waters, 1978-1981. (Continued)

Steffanson Sound Station		Ident.	Location	Depth (m)	Primary Productivity (mgC·m ⁻³ ·hr ⁻¹)
17-18 June 1980	BP	15	70°20.5'N 147°33.8'W	0	0.0
				4	0.1
				7	0.0
	19	16	70°10.5'N 147°07.0'W	0	0.4
				5	0.0
Prudhoe Bay					
22-24 August 1981	1	17	70°14.9'N 147°29.5'W	0	0.0
				4	0.0
				7	0.1
	2	18	70°16.8'N 147°20.6'W	0	1.1
				4	0.0
				8	0.0
	3	19	70°19.7'N 147°34.6'W	0	0.7
				4	0.3
				7	0.5
	4	20	70°23.0'N 147°43.2'W	0	1.8
				4	0.3
				7	0.3
	5	21	70°26.1'N 147°55.9'W	0	1.2
				5	0.4
				10	0.2
	6	22	70°25.8'N 148°07.1'W	0	0.8
				4	0.7
				7	0.0
	7	23	70°23.4'N 148°19.5'W	0	1.0
				2	1.0
				0	0.8
	8	24	70°26.5'N 148°19.4'W	0	0.8
				4	0.4
				8	0.0
	9	25	70°31.1'N 148°20.9'W	0	1.6
				7	0.3
				0	0.7
	10	26	70°22.9'N 148°28.7'W	0	0.7
				0	0.9
				3	0.9
	11	27	70°24.1'N 148°28.6'W	0	0.9
				0	0.9
				5	0.2
12	28	70°25.0'N 148°28.7'W	0	0.2	
			5	0.2	
			0	0.6	
13	29	70°25.0'N 148°31.5'W	0	0.6	
			4	0.5	
			0	0.2	
14	30	70°24.3'N 148°33.1'W	0	0.2	
			2	0.0	
			0	1.5	
15	31	70°23.9'N 148°32.9'W	0	1.5	
			2	0.2	
			0	0.8	
16	32	70°23.9'N 148°33.4'W	0	0.8	
			0	0.4	
			0	0.4	
17	33	70°24.5'N 148°33.5'W	0	0.4	
			0	0.4	
			0	0.4	

Table 3. Primary productivity measurements from Simpson Lagoon and adjacent waters, 1978-1981. (Continued)

Prudhoe Bay	Ident. Station No.	Location	Depth (m)	Primary Productivity ($\text{mgC}\cdot\text{m}^{-3}\cdot\text{hr}^{-1}$)	
	18	34	70°25.0'N 148°33.4'W	3	0.0
	19	35	70°24.2'N 148°34.6'W	0	1.7
	20	36	70°30.0'N 149°08.6'W	0	0.3
				3	0.7
	21	37	70°32.8'N 149°04.7'W	0	0.8
				5	0.1
				10	0.5
	22	38	70°27.9'N 148°55.0'W	0	0.4
				2	0.0
	23	39	70°28.0'N 148°39.5'W	0	0.0
				4	0.0
				9	0.0
	24	40	70°26.1'N 148°45.5'W	0	0.4
				1	0.0
	26	41	70°30.4'N 148°55.0'W	0	1.0
				4	0.0
				11	0.1
	27	42	70°24.3'N 148°31.0'W	0	0.2
				3	0.0

Table 4. Average primary productivity measurements from Harrison Bay, Simpson Lagoon, Prudhoe Bay and offshore of the barrier islands

<u>Sampling Area</u>	<u>Investigators</u>	<u>Sampling Dates</u>	<u>Primary Productivity (mgC·m⁻³·hr⁻¹)</u>
Harrison Bay	Alexander et al., 1975	12-13 August 1971	0.61
	This study	7-15 August 1980	0.28
Simpson Lagoon	This study	17-18 June 1980	0.18
	This study	2 July 1980	1.86
	This study	8-10 August 1978	0.33
	Alexander et al. (1975)	29 July-26 August 1972	2.83
	Alexander et al. (1975)	9-15 August 1971	1.85
Prudhoe Bay	Coyle (1974)	24-29 July 1971	3.46
	Coyle (1974)	11-15 August 1972	0.95
	Coyle (1974)	15-19 August 1971	0.59
	Schell et al. (1982)	22-24 August 1981	0.48
Offshore	Homer and Schrader (1981)	1-31 May 1980	0.07
	Homer and Schrader (1981)	2-11 June 1980	0.21
	This study	17-18 June 1980	0.15
	This study	2 July 1980	1.89
Alexander et al. (1975)	1-29 August 1972	2.39	

Table 5. Monthly averaged primary productivity estimates from ¹⁴C incubations for Harrison Bay, Simpson Lagoon, Prudhoe Bay and offshore.

Study Area	Investigator	Averaged Primary Productivity Values (mg C·m ⁻³ ·hr ⁻¹)*			
		May	June	July	August
Harrison Bay	Alexander et al. (1975)				0.61
	This study				0.28
Simpson Lagoon	This study		0.18	1.86	0.33
	Alexander et al. (1975)				2.27
Prudhoe Bay	Coyle (1974)			3.46	0.77
					0.48
Offshore	Homer and Schrader (1981)	0.07	0.09		
	Schell et al. (1982)		0.15	1.89	
	Alexander et al. 1975				2.39

* No data available for September from nearshore waters. Averaged productivity rates from August (1.0 mg C/m³-hr) were used.

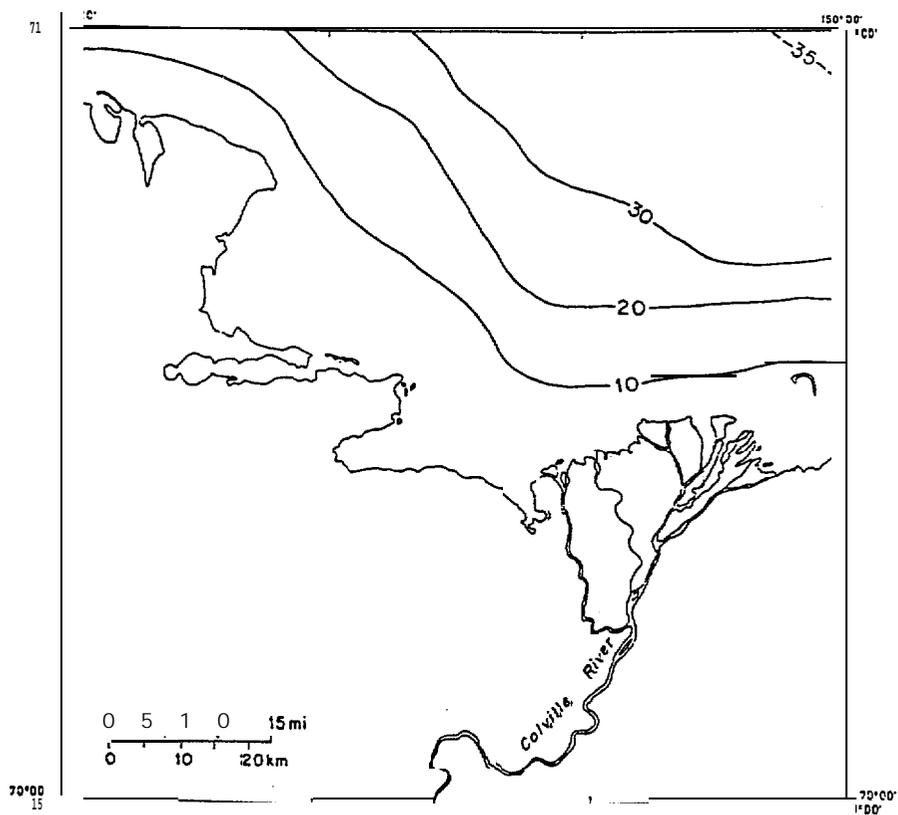
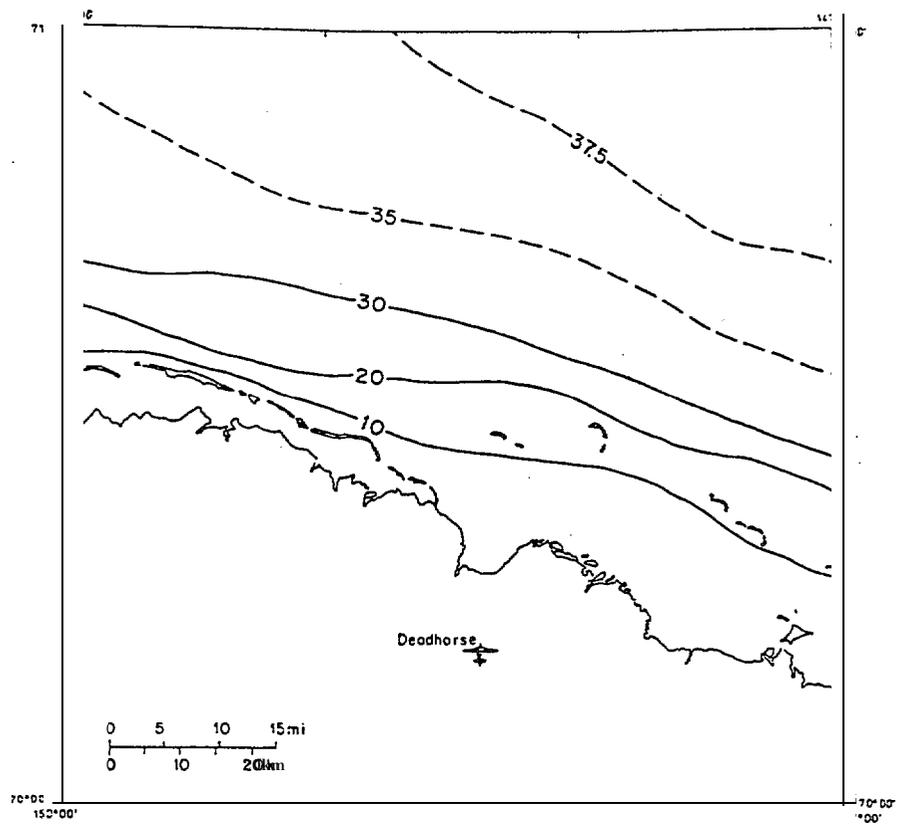


Figure 3B.

Carbon Ingestion

The data available on Simpson Lagoon primary and secondary productivity can be used to compare the food requirements of consumer organisms with the amount of organic matter produced by plants. In our calculations we have included copepods, mysids, amphipods, and infauna as the major organisms utilizing phytoplankton. The calculations and assumptions are described below and the results listed in Table 6.

1) Copepods

- a) Average standing stocks in Simpson Lagoon during the summer are equivalent to 25 mg C/m³ (Griffiths and Dillinger, 1981)
- b) Since limited data are available on winter standing stocks we assume the summer data are representative of the period July-November and that populations decrease to an average value of approximately five percent of summer (Tarbox et al., 1979).
- c) We convert standing stocks to ingestion rates by assuming that copepods ingest 40 percent of their body weight per day (Parsons et al., 1977) and that the same percentage of body carbon is ingested.

2) Mysids and Amphipods

- a) Total population growth is calculated from the seasonal mysid and amphipod densities and the growth equations for first-year class

Mysis litoralis and Onisimus glacialis since these are the dominant species present (Griffiths and Dillinger, 1981).

- b) Growth is related to ingestion using a gross growth efficiency of 10 percent (Parson et al., 1977).

3) Infauna

- a) Infauna biomass is about the same as epifauna (Crane and Cooney, 1974), so we have assumed that infauna ingest the same amount of carbon each year as mysids and amphipods. Food is assumed to be sinking phytoplankton or fecal pellets derived from phytoplankton.
- b) The summer rates are assumed to be twice the winter rates due to temperature and salinity changes.

From the results in Table 6, we calculated the total amount of carbon ingested each year by secondary consumers to be approximately 6.7 g C/m². This was based upon food requirements for amphipods, copepods and infauna derived from average annual densities in Simpson Lagoon. If these organisms have assimilation efficiencies near 60 percent (Parsons et al., 1977), their carbon assimilation is 4.0 g C/m²yr⁻¹. We estimate annual primary productivity in Simpson Lagoon to be 5-7 g C/m²yr⁻¹ from the data of Alexander et al. (1975), and therefore, find ecological efficiencies of 60-80 percent. These values are higher than the usual 20 percent (Parsons et al., 1977) but are certainly within the range one might expect considering the assumptions and data available. It would seem then that the primary and

secondary productivity data appear to balance. Figure 4 presents our findings in a box model illustrating the major carbon fluxes within Simpson Lagoon.

Regeneration of Nitrogenous Nutrients Through Grazing

In determining the amount of nitrogen available for phytoplankton growth we can identify four major sources. These include the inorganic nitrogen (nitrate and ammonia) present in the water column at the onset of growth, the fluvial inputs of nitrate and ammonia from the rivers during runoff season, nitrogen (primarily ammonia) regenerated by secondary consumers, and ammonia released from the large quantities of organic nitrogen in the peat transported to the lagoon by the Colville and Kuparuk Rivers and from shoreline erosion.

The initial quantity of inorganic nitrogen in the Simpson Lagoon water column in late winter is principally nitrate-N and is calculated to be 5.4 mg-atoms N/m^2 , coming from 2 m of melted ice with a concentration of 1.2 mg-atoms N/m^3 and 0.5 m of hypersaline water containing 6 mg-atoms N/m^3 (Schell, 1975; Schell et al., 1982). The nitrate represents the sum of advected nitrate and accumulated vitrification products arising from winter ammonification (regeneration) and further biooxidation.

Regeneration by secondary consumers is determined by assuming that all nitrogen in ingested organic matter which is not used by growth is readily made available to phytoplankton either as excreted ammonia or as fecal pellets which are rapidly mineralized at the sediment-water interface. Loss to sediments (burial) is believed negligible in this context. Since the gross growth efficiency is assumed near 10 percent, 90 percent of the nitrogen ingested by herbivores and detritivores from July through September is regenerated. Using the calculations of carbon ingestion detailed above

Table 6: Carbon ingestion by secondary consumers
in Simpson Lagoon

Group	Ingestion (g C/m ²)			Total
	July - Sept.	Oct - Mid-Feb	Mid-Feb - June	
Copepods	0.9	0.6	0.1	1.5
Mysids	1.1	0.2	0.1	1.3
Amphipods	0.5	0.6	0.2	1.3
Infauna	1.0	0.8	0.8	2.6
Total	3.5	2.2	1.0	6.7

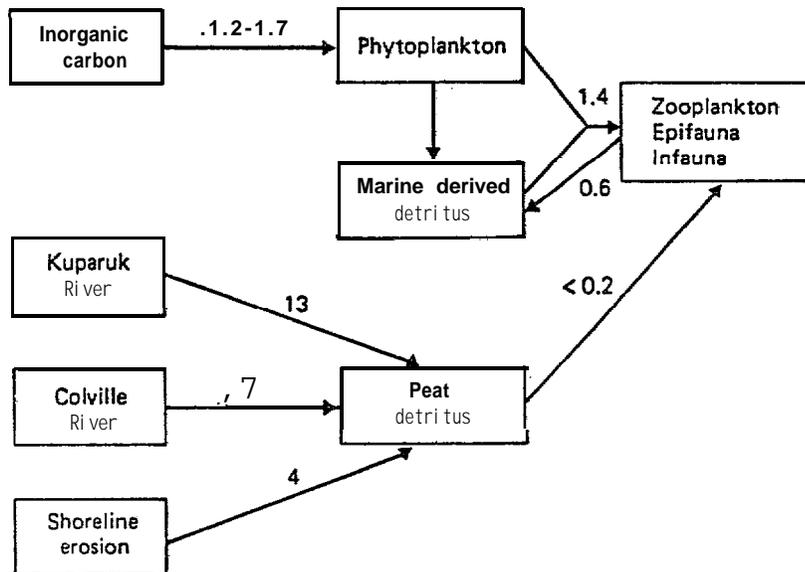


Figure 4. Annual carbon fluxes in Simpson Lagoon ($\times 10^6$ kg). Although organic carbon input from peat is much larger than in situ fixation, isotopic analyses of fauna show very little utilization of terrestrial carbon in the marine environment.

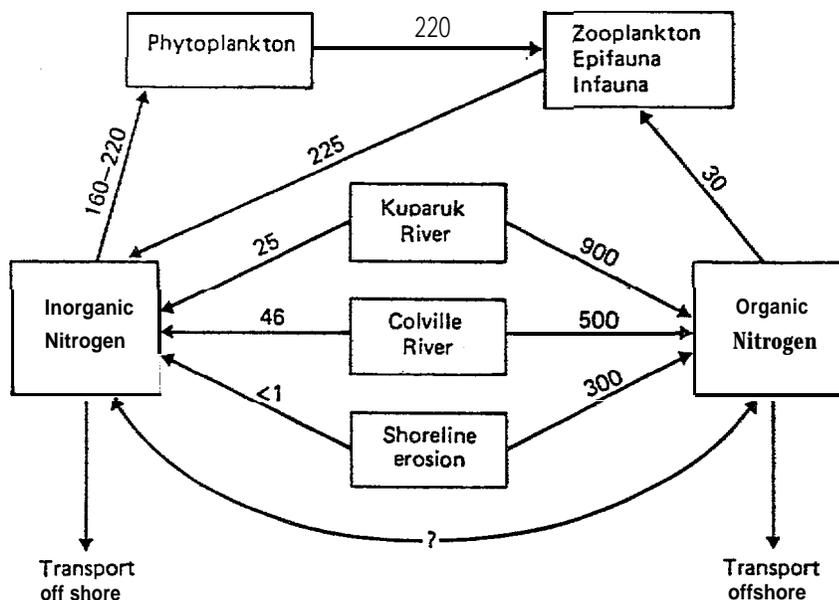


Figure 5. Box model of nitrogen fluxes in Simpson Lagoon. Due to the shallow water depths beneath the ice in Spring, nitrate contributions to the annual budget are small relative to recycled ammonia N ($\times 10^3 \text{ kg}$).

period (Schell, 1974). We are forced to conclude that mineralization of organic nitrogen in peat is too slow to contribute significantly to standing stocks of ammonia and nitrate in Simpson Lagoon during winter months. The reason for the contrastingly high rates observed in the Colville Delta and Dease Inlet are unknown. Similarly, Elson Lagoon near Barrow showed an in situ increase in nitrate nitrogen equivalent to about $0.1 \mu\text{g-atom N/liter-day}$ (Schell, 1974) in waters isolated behind a bar overlain by bottomfast ice. The trivalent nitrogen supporting this vitrification was most likely supplied by eroded terrestrial organic matter as this is the only major input to the system in that area (Lewellen, 1970). Simpson Lagoon, which has relatively unrestricted thermohaline driven circulation until late winter (Matthews, 1980) does not accumulate readily measurable quantities of nitrate.

therefore, much less and we must usually look for either sub-lethal effects or secondary impacts on consumers.

Within a specific area such as Simpson Lagoon, developmental impacts can be ranked with regard to their detrimental effects on production by their denial of a given area for primary producers, usually through alteration of water quality or chemistry.

- 1) Permanent loss of productivity in an area would result from impoundment, filling or causeway construction which would so restrict water movement that species normally tolerant of the nearshore water quality would no longer grow. Similarly, if restriction of circulation prevented access by grazers during the ice-free season, the net effect would be the same.
- 2) Episodic loss of primary producer habitat could occur through accidental oil spills or discharge of phytotoxic chemicals that would render an area unsuitable for growth. Flushing time and dilution of the pollutant determines the recovery rate in this case due to the ubiquitous nature of seed populations and rapid growth characteristics. Since the most severe impacts from this type of event will occur in the consumers present at the time, major concerns are probably elsewhere.
- 3) Chronic discharge of sub-lethal pollutants (e.g., heavy metals, chlorinated hydrocarbons). This type of developmental impact has the most potential for ecosystem stress when evaluating implications associated with primary producers. Since the microalgal populations are dispersed throughout the water column and are effective accumulators of

nutrients and pollutants from low ambient concentrations, they represent the first critical step in biomagnification. As a rearing area of juvenile invertebrates and a preferred habitat for the anadromous fish, Simpson Lagoon appears to be most sensitive to this type of impact. Riverborne pollutants such as persistent pesticides or heavy metals would be quickly scavenged from nearshore waters and passed up the short food chains. Although the organisms of lower trophic levels are characterized by short life spans and may not reveal deleterious effects, the apical organisms such as the anadromous fishes and oldsquaws might achieve serious body burdens. In the case of the anadromous fishes, which are used as food by human populations, a potential health hazard is involved.

It must be emphasized that we are concerned with the relatively warm brackish nearshore waters that characterize Simpson Lagoon and other similar areas to the east and west. The small volume and discrete nature of this water type make it especially sensitive to pollutants since it acquires its nature through the input of runoff in which the potential chronic pollutants are most likely to be transported. Even if coproduced brines are discharged offshore in the future, much larger quantities of pollutant would be required to appreciably change ambient concentrations due to the greater homogeneity and volume of receiving waters. Truett (1981, p. 307) points out that the "Simpson Lagoon" type ecosystem actually extends hundreds of kilometers east and west along the Beaufort Sea coastline but only a few kilometers offshore. Schell et al. (1982) point out that the energy sources supplying the oldsquaws, phalaropes, anadromous fishes and freshwater fishes are closely intertwined through the seasonal dependencies of the organisms on freshwater habitat and that the

demarcation between coastal and pelagic foodwebs occurs a short distance from shore. Only the arctic cod, which enters the brackish water zone in large numbers, is an apparent foodweb linkage to pelagic apical organisms (seals, polar bears). In view of the above, it appears that developmental impacts vary inversely in ease of assessment and potential ecosystem damage.

- 1) Major shoreline alterations or impoundments decrease primary production in area-dependent amounts. Impacts are probably small in view of the size of the coastal ecosystem and the fact that for most cases, the "coastline" is merely moved.
- 2) Episodic events, similarly, can be risk assessed and the impact on primary production will probably be short-lived and limited in scope. A major event (e.g., blow-out) could, however, spread along the coastal ecosystem in patterns analagous to warm water transport and devastate Production for the duration of the event. Nevertheless, the major impacts of such an event would be far more severe on apical organisms. Recovery time would depend upon many factors but primary producers would be among the quickest to recover due to the passive infiltration mechanisms of the population.
- 3) Chronic pollutants present the most difficulty for impact assessment and the most potential for ecosystem perturbation. When considering the limited habitat available and critical dependence of the apical organisms (oldsquaws, phalaropes, fishes) on this habitat, the impact of cumulative pollutants is potentially serious. Discharge permits and construction

designs need **to** be evaluated with cognizance of long-term effects resulting from sub-lethal concentrations of toxic materials.

Peat Detritus

Although peat has been shown to be a substantial energy source to freshwater foodwebs, its role **in** the marine environment is **still** uncertain. Peat supports active microbial populations and since it contains **large** amounts of nitrogen, the respiration and mineralization processes may contribute to the nutrient requirements **of** photosynthetic **microalgae**. The overall significance of these processes is questionable, however, due to the uncertainty regarding relative rates of mineralization and transport offshore. Another potentially very important facet regarding the presence of peat in the nearshore zone is its role as a scavenger and **co-metabolite** of pollutants. The polymeric *and* aromatic nature of **lignin** coupled with a high cation exchange capacity make peat a logical candidate as a sorbant of hydrocarbons, **chlorinated** hydrocarbons, and heavy metal ions. **It** is possible that peat could serve as an accumulator of these pollutants **and**, in **the** case of hydrocarbons and **halogenated** compound, **act** as a co-metabolize in their biodegradation.

Similarly, absorption onto peat **particles would** serve to immobilize heavy metals until transport mechanisms disperse **the** peat offshore. Since peat does not enter the nearshore marine food **chain** to an appreciable extent, sorption onto peat particles would effectively remove a pollutant from the **macrobiota**. This is in direct contrast to the alternative pathway which is accumulation by **phytoplankton** that are grazed by zooplankton and **epibenthic** invertebrates.

DATA GAPS AND RESEARCH NEEDS

The studies conducted over the last few years have produced major insights into the energetic of the Beaufort Sea ecosystem. The process studies have allowed the development of reasonable impact assessment and an approximation of the severity of various potential disturbances. These in turn have led to the following questions for future study in the nearshore Beaufort Sea.

- 1) The role of peat in the nutrient dynamics of nearshore waters is poorly understood. The relative rates of mineralization versus transport offshore are unknown. Since the nitrogen in peat is many times greater than the maximum inorganic standing stocks in Simpson Lagoon., the potential importance is great.

- 2) The rates of advection of water beneath the ice to Simpson Lagoon and the nearshore areas in general are poorly described. In addition to having direct implication in the translocation of peat and nutrients, underice circulation will be a major governing factor in the impacts of pollutants discharged beneath the ice. Although underice circulation is principally a physical oceanographic problem, the bearing on nearshore ecological processes is evident.

- 3) The role of peat as a potential scavenger and co-metabolize in the biodegradation of low-level pollutants needs investigation. Until we know the efficacy of this mundane substance as a sorbant for hydrocarbon and as a complexation agent for heavy metals, it will be difficult to predict the severity of impacts resulting from discharges of drilling muds, sewage effluents and coproduced brines into the marine environment. We will also need to know biodegradation rates of pollutants by peat-associated microflora and the transport velocities of peat particles in the nearshore ecosystem.

- 4) If the experimental studies in 3) reveal that peat is effective as a sorbant of pollutants, further study is indicated on the use of locally mined peat as an ameliorating agent in the case of accidental oil spills or discharges of toxic wastes.

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