

CHAPTER 5

Primary Production, Nutrient Dynamics, and
Trophic Energetic

by

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SUMMARY AND CONCLUSIONS

A limited ecological sampling effort was undertaken in summer 1982 in Angun and Beaufort lagoons near the U.S.-Canadian border in arctic Alaska. The objective of this study was to compare the nutrient dynamics, primary productivities, and trophic energetic of these lagoons with the intensively studied Simpson Lagoon-Prudhoe Bay area to the west. The findings were assessed with respect to potential impacts arising from potential oil and gas development. An overview of our findings follows:

1. Annual primary production is lower in the Beaufort Lagoon area, approximately 25 percent of the Simpson Lagoon area (**2.0 vs 6 g C.m⁻².yr⁻¹**).
2. Terrestrial inputs of energy are important to food webs in the Beaufort Lagoon area and were responsible for 50-80 percent of the carbon in samples of arctic cisco and a flounder. This is in contrast to Simpson Lagoon where terrestrial carbon was unimportant to marine trophic energetic. This difference may be due to the **lower in situ** primary production relative to terrestrial. carbon inputs or may be due to recent immigration (by the arctic cisco) from overwintering areas where freshwater and terrestrial food sources dominate (see Truett, this volume). The arctic flounder, as a predator of benthic invertebrates, is probably reflecting the energy sources supporting polychaetes and other infauna of the lagoon sediments.
- 3* Pelagic primary production supports offshore food webs. The relatively high productivity along the Beaufort Sea coastline may be due to periodic upwelling and a recycling of terrestrially-derived nutrients. Nutrient regeneration and vitrification processes are evident beneath winter ice cover. A model describing these processes has been constructed.
4. The lagoons in the eastern Alaskan Beaufort may be more sensitive to pollutant inputs and development than Simpson Lagoon because of (a) longer water exchange times, (b)

trophic dependencies on terrestrial carbon, and (c) biomagnification if pollutants are adsorbed on peat particles.

INTRODUCTION

This study is part of a coordinated effort to compare the physical oceanography, chemistry, and biology of lagoons in the eastern Alaskan Beaufort Sea with those farther west, along the central Alaskan Beaufort coast (e.g. Simpson Lagoon). These data were obtained with an awareness toward the potential impacts of oil and gas development in the area. The specific objectives of this study were to:

1. Compare the primary productivity of the eastern Beaufort with more western areas.
2. Describe the nutrient dynamics of the region and the possible effects of the freshwater inputs.
- 3* Use natural abundances of carbon isotopes to describe the trophic interactions and to determine the role of allochthonous carbon from tundra sources in supporting the fishes and birds of the lagoons and their prey species.

The Beaufort and Chukchi seas present a paradox in that they are characterized by areas of high productivity in close proximity to areas of extremely low primary production. The coastal zone of the Beaufort Sea and the southern Chukchi Sea are inhabited by large numbers of fishes, birds, and marine mammals, whereas in the perennial ice zone a few hundred km to the north, there exists a biological desert with a very sparse fauna sustained by the lowest primary production of the world oceans (Melnikov 1980). Nevertheless, the observed rates of primary productivity and the high densities of herbivorous invertebrates in the nearshore lagoons imply that offshore production is very important in the trophic energetic of the ecosystem. Griffiths and Dillinger (1981) describe the distribution of invertebrates, primarily mysids and amphipods, and state that onshore migration during summer is essential in maintaining the prey availability for anadromous fishes and birds in the lagoons and embayments along the

coastline. In addition, Frost and Lowry (1983), in discussing the energy requirements of vertebrate consumers of the coastal zone outside of the lagoon systems, emphasize the close coupling of consumers to primary production wherein copepods and euphausiids are the principal prey items of arctic cod and bowhead whales. All other carnivores are in *turn* linked closely to the cod or the invertebrates.

This investigation, although focused in part on the in situ processes of the eastern Beaufort Sea lagoons of Alaska, has also considered the ecosystem as a whole and addresses the problem of describing the processes governing offshore primary production. Truett (1981) in his synthesis of the Simpson Lagoon ecosystem described the mechanisms by which offshore production is transported shoreward from deep water and contributes to the secondary production in the nearshore zone. We discuss the reasons for extending his findings to the more eastern lagoons and the Alaskan Beaufort Sea coastline as a whole.

This report consists, therefore, of two sections. The first reports our data obtained during the summer 1982 and includes estimates of primary productivity with related nutrient chemistry parameters. The second part synthesizes these data, the information available from previous work by the authors, and the literature. This synthesis attempts to consider the factors governing primary production in the Beaufort Sea. In addition, we present a hypothesis describing the physico-chemical processes governing nutrient supply to nearshore phytoplankton with supporting data and theoretical considerations. The resulting model of nutrient dynamics and phytoplankton productivity may account for the observed distribution of consumers in coastal waters.

STUDY AREA

A description of the general study area is given in the "PREFACE" to this volume. However, more detailed descriptions of specific sampling stations are given in Figure 5-1 of this Chapter.

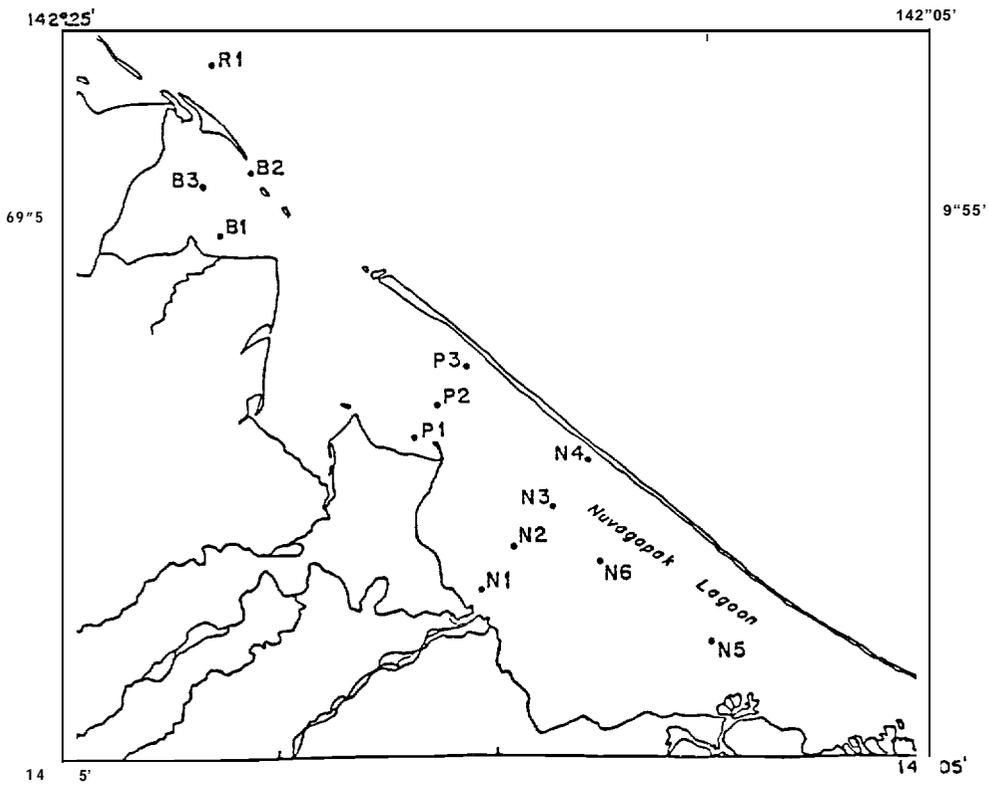
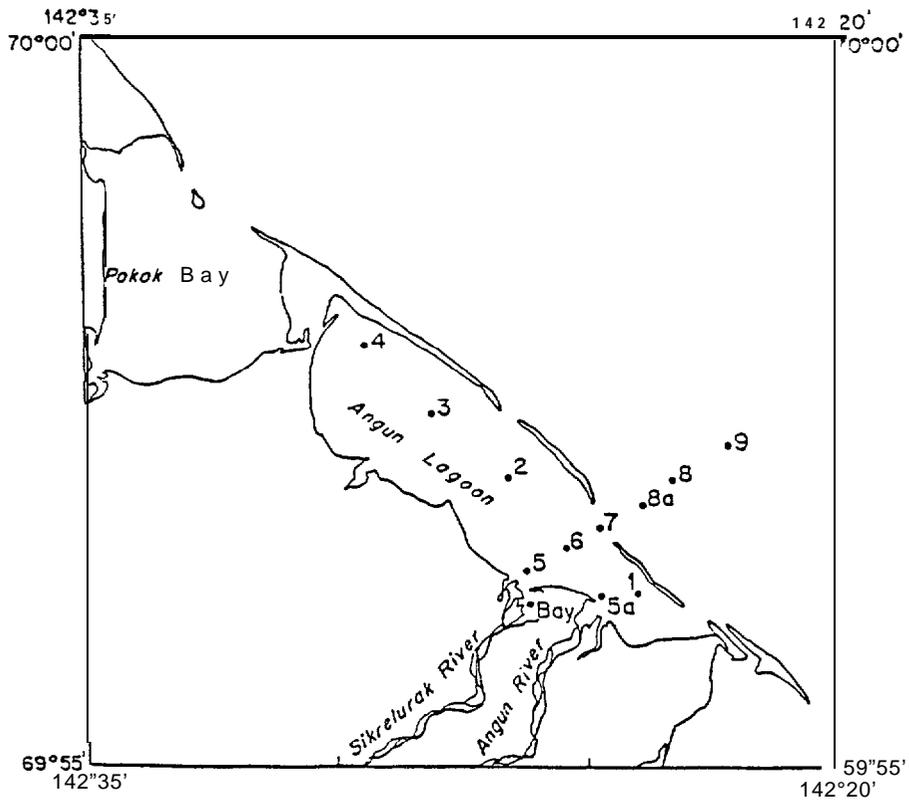


Figure 5-1. Station locations, summer 1982.

METHODS

Field Trips

We collected samples during two field trips to the Beaufort Lagoon area during summer 1982. The first trip was during **the** period 24 July to 7 August when nutrient sampling and primary productivity measurements were conducted at stations **in** Angun and Beaufort lagoons (Figure **5-1**). Ancillary data on chlorophyll concentrations, light penetration, and salinities also were obtained at each station. Dense ice cover prevented any sampling of offshore waters.

During the same period food web studies were carried out in freshwater and lagoon environments. Samples of arctic **cisco**, char, and flounder were obtained from LGL personnel. We collected basal peats from lagoon shorelines and particulate carbon and drift insects from the three major streams entering Angun **Lagoon**. Water samples from streams emptying into lagoons **also** were collected in order to determine stream nutrient concentrations. Prey organisms were collected from the lagoon waters by towing plankton nets from small boats, and sediment samples from the lagoon bottom were taken with an Ekman dredge.

A fall trip (18-23 September) was made to obtain information on September primary productivity rates in the lagoon. Again, very bad weather limited **sampling**, but rates were obtained from four stations **in** Beaufort (**Nuvagapak**) Lagoon. Nutrient **samples**, chlorophyll concentrations, salinities and *water* column light intensities also were obtained from each station.

Methods of measuring primary production, nutrient concentrations and **for** determining the amounts of various isotopes **of** carbon are identical to those described in **Schell** (1981) for very similar studies conducted in the Simpson Lagoon area.

RESULTS

Physical Characteristics of Eastern Beaufort Sea Lagoons

Since the field work did not begin until after the ice had cleared from the lagoons, we attempted a reconstruction of the summer chronology and its effects on the hydrography of the lagoons based on satellite imagery of the area acquired over the past few years. It is assumed that the winter under-ice conditions **in** the eastern Beaufort Sea lagoons are similar to more westerly areas in the following ways.

1. Temperatures, snowfall, and prevailing wind directions and velocities are similar to the Simpson Lagoon area over the **climatological** year.
2. River influx to the region ceases after freeze-up in the **fall** and is negligible during the winter months.
- 3* Spring runoff contributes the bulk of annual runoff and carries the major fraction of freshwater, heat, nutrients, and organic matter contributed to the lagoons by **fluvial** transport.
4. Ice melt and breakup occurs in the *lagoons* before it does in offshore areas due to lowered **albedo** from stream overflow and the influx of warm river water.
- 5* Spring runoff provides the impetus for the initial flushing from lagoons of hypersaline waters accumulated in late winter and sets the initial hydrographic conditions of "summer." As runoff volume dwindles rapidly at the end of **snowmelt** and the area of open water increases during the summer, exchange with offshore waters becomes the dominant process governing the salinity and temperature structure in the lagoons.

Breakup chronology based upon satellite imagery was compiled from Landsat imagery obtained over the period 1978-1980. For the study area the sequence was as follows:

10-14 June. Eastern end of Beaufort (**Nuvagapak**) Lagoon **opens** in response to **Aichilik** River influx. Angun Lagoon begins to open near mouths of **Sikrelurak** and Angun rivers. Pokok Bay is solidly frozen.

15-?? June. Open water expands to approximately the eastern half of Beaufort (**Nuvagapak**) Lagoon. The eastern half of Angun Lagoon opens, and the rest is broken ice depending upon wind conditions. Pokok Bay ice breaks up. **By** 30 June, Beaufort (**Nuvagapak**) Lagoon is essentially ice free except for ice remnants in the extreme eastern end.

1-10 July. Remnants of scattered ice in Angun and Beaufort (**Nuvagapak**) lagoons have melted, and in Pokok Bay there are considerable ice remnants. Ice cover is **still** tight outside of the barrier islands except in the vicinity of the entrances.

10-18 July. All lagoons are ice free. Pack ice is in motion beyond the barrier islands. An influx of **floes** from offshore, apparently through tidal exchange, represent the **only** ice inside the lagoons.

Hydrographic Structure of Lagoon Waters

Our arrival at Beaufort (**Nuvagapak**) Lagoon coincided with the loosening of offshore fast ice from the barrier islands and maximum sea ice melting. **The first** sampling of Angun Lagoon (26 July) showed no evidence of residual **hypersaline** bottom water from the previous winter. Based on spring salinities **in** Simpson Lagoon, we would anticipate salinities of greater than 35 ppt **if** freeze concentration processes are similar. However, if there are no shallow sills in the major entrance channels of the lagoon (and our observations and Coast Guard charts indicate that this is so), water exchange during the winter may be rapid enough to prevent brine accumulations. Although we have found high

salinity bottom waters that persist well into the summer in **Elson** and Simpson lagoons, there were none evident in our 26 July sampling of Angun Lagoon.

Circulation and Water Exchange

The **salinity**, nutrient, and primary productivity data obtained from stations shown on Figure 5-1 are listed in Tables 5-1 and 5-2. Immediately apparent in the 26 July data are the low surface salinities which result from ice melt and runoff, and contribute to the stability of the water column. Nevertheless, wind mixing can destroy *the pycnocline* as is evident in data from later dates. A summary of our observations and inferences regarding water exchange follows.

26 July - Angun Lagoon. Surface salinities increase from the western end of the lagoon toward the entrance, whereas bottom salinities decrease in the same direction. The tidal exchange with offshore water is believed responsible for the higher salinity deep water. We estimated the **pycnocline** to be at 2.25-3.5 m and an average water column **salinity** of **19.0 ppt**.

29 July - Angun Lagoon. Wind mixing has turned over **the** water column, and the average salinity of **18.2** ppt agrees well with our estimated average value of **19.0 for three previous days**. The slightly lower salinity observed on 29 July may also reflect an **influx** of low salinity (16.8 ppt) water from offshore. Observed currents were weak at the time of sampling, and horizontal gradients were not pronounced.

31 July - Angun Lagoon. Surface and bottom salinities reflect strong wind mixing coupled with an exchange between high salinity lagoon water and offshore surface waters which have been diluted by melting pack ice.

Table 5-1. Chlorophyll, phaeopigment and light data from Angun Lagoon and Beaufort Lagoon stations collected in July, August and September 1982.

Date	Station	Sample depth (m)	Chlorophyll (mg/m ³)	Phaeopigments	Light Intensity (uE/m ² -see)	Percent of surface (underwater)
26 July	AL 1	0.0	N.D.	N.D.	1,330	100.0
		1.0	N.D.	N.D.	900	69.0
	AL 2	0.5	N.D.	N.D.	1,100	80.3
		4.0	N.D.	N.D.	240	17.5
	AL 3	0.5	N. o.	N.D.	1,180	78.7
		4.0	N. D.	N.D.	350	23.3
	AL 4	0.5	N.D.	N.D.	880	64.7
	AL 5A	0.0	N. D.	Ho.	1,700	100.0
	AL 6	0.5	N.D.	N.D.	1,300	74.4
		4.5	N.D.	N.D.	565	32.5
AL 7	0.5	N.D.	N.D.	940	73.3	
	2.5	il. c.	N.D.	400	33.3	
29 July	AL 1	0.5	0.04	0.06	155	84.2
		1.2	0.10	0.08	136	27. ?
	AL 2	3.0	0.11	0.10	82	52.9
		0.5	0.12	0.07	228	84.4
	AL 3	3.5	0.19	0.17	67	24.8
		0.5	0.12	0.07	222	69.5
	AL 4	0.0	0.20	0.10	1.6	100.0
	AL 5	1.0	0.10	0.07	111	68.1
AL 6	0.5	0.16	0.10	102	91.9	
	3.0	0.13	0.10	44	39.6	
31 July	AL 1	0.5	N. o.	No.	74	71.2
		1.0	0.18	0.14	110	55.0
	AL 2	2.5	0.18	0.10	48	24.0
		1.0	0.18	0.11	77	54.2
	AL 3	3.0	0.19	0.10	23	19.2
		0.5	0.20	0.13	90	87.4
	Bay	1.0	N.D.	N.D.	152	44.7
	AL 6	0.0	0.15	0.09	79	100.0
		2.0	No.	N.D.	30	38.0
	AL 7	1.0	0.08	0.06	33	54.3
4.0		0.11	0.05	7	12.0	
4 Aug	AL 1	0.5	0.30	0.19	N.D.	N.D.
		1.0	0.22	0.26	N.D.	N.D.
	AL 2	3.0	N.D.	No.	No.	N.D.
		1.0	0.20	0.14	N.D.	N.D.
	AL 3	3.0	0.24	0.21	N.D.	N.D.
		1.0	No.	N. D.	N. D.	N. D.
	AL 4	1.0	No.	N. D.	N. D.	N. D.
	AL 5	0.5	0.24	0.10	N. D.	N. o.
Bay	0.0	0.41	0.24	N. D.	N. D.	
	1.0	0.42	0.22	N. D.	N. D.	

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Table 5-1 (cont'd)

Date	Station	Sample depth (m)	Chlorophyll (mg/m ³)	Phaeopigments	Light Intensity ($\mu\text{E}/\text{m}^2\text{-sec}$)	Percent of surface (underwater)
4 Aug	AL 6	1.0	0.17	--	N.D.	N.D.
		0.0	N.D.	N.D.	N.D.	N.D.
	AL 7	2.0	0.23	0.17	N.D.	N.D.
		4.0	0.24	0.20	N.D.	N.D.
	AL 8A	1.0	0.14	0.05	N.D.	N.D.
		3.0	0.28	0.09	N.D.	N.D.
	AL 8	1.0	0.15	0.05	N.D.	N.D.
		4.0	0.42	0.12	N.D.	N.D.
5 Aug	AL 8	0.0	0.70	0.22	N.D.	N.D.
		2.0	0.41	0.14	N.D.	N.D.
		4.0	0.30	0.13	N.D.	N.D.
	AL S	0.0	0.41	0.12	N.D.	N.D.
		1.0	0.51	0.17	N.D.	No.
		3.0	0.34	0.15	N.D.	N.D.
		5.0	0.31	0.16	N.D.	N.D.
		7.0	0.16	--	N.D.	No.
6 Aug	N 1	0.5	0.31	0.24	602	73.7
		2.0	0.56	0.30	140	17.1
	N 2	0.5	0.29	0.18	250	33.0
		2.7	0.29	0.16	50	16.6
	N 3	0.5	0.32	0.22	310	71.9
		2.5	0.33	0.25	51	11.7
	N 4	0.0	0.32	0.21	430	100.0
	P 1	1.0	0.18	0.0%	474	57.4
		0.5	0.27	0.10	650	84.5
	P 2	3.0	0.64	0.24	147	19.1
		0.5	0.27	0.15	345	81.5
		3.0	0.28	0.20	89	21.0
	B 1	0.5	0.24	0.11	780	81.0
		2.0	N.D.	N.D.	393	40.8
	B 2	0.5	0.27	0.13	770	81.9
		2.0	0.23	0.16	300	31.9
21 Sep	R 1	0.5	0.54	0.21	280	81.1
		2.0	0.57	0.11	155	44.9
	B 3	0.5	0.57	0.26	200	57.1
		1.5	0.56	0.30	119	34.0
	N 5	0.5	0.59	0.24	420	65.6
		1.5	0.61	0.24	80	12.5
	N 6	0.5	0.57	0.28	110	73.3
		1.5	0.69	0.30	44	29.2
		2.5	0.60	0.30	8	5.5

No. - Not determined.

Table 5-2. Salinity and nutrient data, 1982.

Date	Station No.	Depth (m)		Salinity /100	Nitrate-N	Nutrients ($\mu\text{g-atoms/liter}$)		
		Bottom	Sample			Ammonia-N	Phosphate-P	Silicate-Si
26 Jul 82	Angun Lagoon 1	1.4	1.0	17.10	0.1	0.9	0.65	6.40
	AL 2	4.0	0.5	15.83	<0.1	0.8	1.40	4.72
			4.0	27.54	<0.1	0.8	1.33	6.16
	AL 3	4.0	0.5	15.67	<0.1	0.8	0.76	5.68
			4.0	27.35	<0.1	0.9	1.32	2.36
	AL 4	2.0	0.5	15.57	<0.1	1.3	1.11	3.11
	AL 5A	0.5	0.5	17.10	<0.1	1.3	0.87	4.88
	AL 6	3.7	0.5	16.39	<0.1	0.7	0.88	4.63
			2.5	17.64	<0.1	0.7	1.11	6.89
	AL 7	3.2	0.5	17.07	<0.1	0.8	0.92	4.88
		2.5	21.11	<0.1	0.9	0.57	4.37	
29 Jul 82	AL 1	1.5	0.5	17.69	<0.1	2.0		5.44
	AL 2	3.0	0.5	17.68	<0.1	1.1	4.30	4.88
			3.0	18.56	<0.1	0.7	1.88	4.63
	AL 3	3.5	0.5	18.09	<0.1	0.5	1.28	4.37
			3.5	18.30	<0.1	1.0	1.17	4.88
	AL 4	1.0	0.5	18.64	<0.1	0.9		5.44
	AL 5	0.5	0.5	16.74	<0.1	0.9	0.57	4.88
	AL 6	2.0	1.0	16.89	<0.1	0.9	1.11	5.89
	AL 7	3.5	0.5	17.93	<0.1	0.6	7.38	4.88
			3.0	18.04	<0.1	0.7	1.58	4.88
AL 2*	3.0	0.5	17.40	<0.1	1.8	1.07	5.38	
AL 5*	0.7	0.5	18.33	<0.1	0.7	0.67	3.87	
		0.5	15.96	<0.1	0.8	0.87	3.87	
31 Jul 82	AL 1	1.0	0.5	18.16	0.1	0.9	1.33	4.72
	AL 2	3.0	1.0	18.29	<0.1	1.3	1.45	5.49
			2.5	18.33	<0.1	0.7	1.15	5.44
	AL 3	3.5	1.0	18.04	0.1	0.8	1.11	6.89
			3.0	18.19	<0.1	0.7	1.22	5.20
	AL 4	1.0	0.5	18.02	<0.1	1.5	2.36	4.72
	Bay	1.5	1.0	15.84	<0.1	8.8	5.56	5.38

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Table 5-2 (cont'd)

Date	Station No.	Depth (m)		Salinity ‰	Nitrate-N	Nutrients (µg-atoms/liter)		
		Bottom	Sample			Ammonia-N	Phosphate-P	Silica te-Si
31 Jul 82	AL 5	1.0	0.5	15.82	<0.1	0.6	0.92	4.47
	AL 6	2.5	0.5	18.34	<0.1	1.2	1.33	5.9
			2.0	18.55	<0.1	0.7	1.15	4.4
			1.0	19.95	<0.1	0.7	1.22	8.09
	Bay*	1.0	0.5	N.D.	<0.1	7.7	5.11	5.38
4 Aug 82	AL 1	1.0	0.5	17.32	<0.1			5.38
	AL 2	3.5	1.0	17.89	<0.1	0.6	1.17	6.40
			3.0	18.79	<0.1	0.5	0.97	6.16
			1.0	18.82	<1.1	0.4	1.17	4.96
	AL 3	3.5	3.0	18.83	<0.1	0.6	0.91	5.68
			1.0	18.90	<0.1	0.7	1.17	4.88
	AL 4	1.5	1.0	17.00	<0.1	0.6	0.97	5.89
	Bay	1.5	0.5	14.97	1.2	0.5	1.17	6.14
			1.0	17.56	<0.1	0.4	1.07	4.88
	AL 6	2.0	1.0	N.D.	<0.1	0.5	0.87	5.23
	AL 7	5.0	0.5	17.91	<0.1	0.9	1.07	5.68
			2.0	18.37	<0.1	0.5	0.97	5.44
			4.5	18.72	0.4	0.6	0.87	5.63
	AL 8A	4.0	1.0	16.80	<0.1	0.6	0.77	5.38
			3.0	17.44	<0.1	0.6	0.97	5.38
1.0			16.93	<0.1			6.40	
AL 8	5.0	4.0	17.56	<0.1	0.4	1.17	5.89	
		0.5	0.5	18.61	<0.1	1.5	1.17	4.37
(Angun Lagoon) Peat Point (K)								
5 Aug 82	AL 8	4.5	0.5	16.75	<0.1	1.3	1.33	5.38
			2.0	16.77	<0.1	0.7	0.99	5.38
			4.0	16.85	<0.1	0.8	0.99	5.38
	AL 9	8.0	0.5	16.51	<0.1	1.3	1.07	7.90
			1.0	16.56	<0.1	0.5	0.87	5.92
			3.0	16.75	<0.1	0.9	1.15	5.13
			5.0	17.24	<0.1	1.0	1.11	5.63
			7.0	18.05	<0.1	0.9	1.11	5.38

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Table 5-2 (cont'd)

Date	Station No.	Depth (m)		Salinity ‰	Nitrate-N	Nutrients (µg-atoms/liter)		
		Bottom	Sample			Ammonia-N	Phosphate-P	Silicate-Si
6 Pug 82	N 1	2.5	0.5	16.79	<0.1	1.2	1.15	11.71
			2.0	17.84	<0.1	1.2	1.38	9.30
	N 2	3.3	0.5	16.99	<0.1	1.4	1.33	8.57
			2.7	18.11	<0.1	1.4	1.22	8.09
	N 3	3.0	0.5	16.34	<0.1	0.9	0.76	8.91
			2.5	18.12	<0.1	1.0	1.27	7.37
	N 4	0.5	0.5	16.36	<0.1	2.2	1.68	7.90
	P 1	1.5	1.0	17.71	<0.1	1.3	1.06	8.09
	P 2	3.5	0.5	17.96	<0.1	1.5	1.27	5.89
			3.0	19.16	<0.1	1.2	1.22	5.20
	P 3	3.5	0.5	18.11	<0.1	1.0	1.22	9.05
			3.0	18.58	<0.1	1.2	1.45	6.89
	B 1	2.5	0.5	17.80	<0.1	1.0	1.11	5.89
			2.0	18.72	<0.1	1.0	1.11	8.09
B 2	2.5	0.5	18.25	<0.1	0.7	0.77	4.88	
		2.0	18.73	<0.1	0.6	0.71	5.38	
		0.0	0.004	19.2	0.1	0.57	35.46	
	Angun River	0.1	0.0	0.00	2.4	0.5	0.37	26.80
	Sikrelurak R.	0.5	0.0	0.26	0.4	0.6	0.37	46.42
	Aichilik R.	0.5	0.0	0.07	0.1	0.3	0.27	47.72
21 Sep 82	RS 1	2.5	0.5	24.01	0.6	N.D.	0.7	6.0
			2.0	24.17	0.7	N.D.	0.7	5.0
	EL 3	2.0	0.5	20.10	0.3	N.D.	0.7	6.0
			1.5	20.40	0.3	N.D.	0.7	8.0
	NL 5	2.0	0.5	20.34	0.1	N.D.	0.7	10.0
			1.5	20.35	No.	N.D.	N.D.	N.D.
	NL 6	3.0	0.5	19.07	0.1	N.D.	0.7	6.0
1.5			19.12	3.0	N.D.	2.0	19.0	
		2.5	19.05	0.1	N.D.	0.7	6.0	
23 Sep 82	Angun R.	0.7	0.4	0.10	15.4	N.D.	1.0	26.0
	Sikrelurak R.	0.8	0.4	0.01	3.2	N.D.	0.9	30.0

* Repeat sampling same day.

4-5 August Angun Lagoon. Current flow out of the lagoon during sampling is reflected in the salinity values measured off the entrance.

It is apparent from salinity data that the water column in Angun Lagoon becomes mixed by wind within a few weeks of the disappearance of the ice cover. We cannot unequivocally state that *in situ* produced meltwater is the main source of the dilution water, because spring runoff of the Angun and Sikrelurak rivers must contribute a large quantity of water to the lagoon by early July. Flow in these streams declines rapidly after snowmelt, and we estimated the flow at $60 \times 10^3 \text{ m}^3/\text{day}$ in late July. Since Angun Lagoon contains approximately $16 \times 10^6 \text{ m}^3$, the turnover time from river input is near 325 days, much too long for the rivers to contribute significantly to the observed water structure. Only near the stream mouths is the dilution by freshwater measurable. These streams respond rapidly, however, to rains or melting snow cover. On 23 September, flow rates from Angun and Sikrelurak rivers were $180 \times 10^3 \text{ m}^3/\text{day}$ and $240 \times 10^3 \text{ m}^3/\text{day}$, respectively. This runoff was in response to the melting of snow which had fallen during the previous few days.

Meltwater from pack ice provides a ready source to account for the observed decline in offshore surface salinities over the summer. Stringer et al. (1982), describes how the promontory at Barter Island serves to force pack ice hard against the shore in the Beaufort Lagoon area, creating relatively high numbers of pressure ridges parallel to shore. This onshore movement coupled with summer melting greatly reduces nearshore salinities in this area, a phenomenon described first by Leffingwell (1919).

We compared the slow turnover time expected from river inputs with that anticipated from tidal flushing and storm surges. A mean fluctuation of only 10-20 cm per tidal cycle would be sufficient to exchange the lagoon waters in about 10-12 days. Since longshore transport seaward of the barrier islands is rapid under the influence of the prevailing winds, water pulsing out of the lagoon is shifted westward and is replaced with seawater during the incoming tide. In actuality, storm surges and wind-driven currents reduce the exchange time for the lagoon waters. Nevertheless, the relatively restricted entrances compared to Simpson

Lagoon or Stefansson Sound require a longer flushing time under similar conditions for water replacement. This exchange of lagoon waters is important in controlling the nutrient chemistry and salinity of Angun Lagoon.

Nutrient Chemistry and Primary Production

Nutrient analyses for nitrate-nitrite, silicate, ammonia and phosphate concentrations have been run on all samples collected during the summer. Similarly, all ^{14}C uptake-rate measurements have been calculated and all of the chlorophyll determinations have been completed. Carbon isotope determinations for $\delta^{13}\text{C}$ and ^{14}C have been processed at a commercial laboratory specializing in this service.

Our results indicate that, as elsewhere in the Arctic, phytoplankton uptake of nitrate is essentially complete by late July and regeneration processes dominate nitrogen supply to the plant populations. We obtained no information on offshore deep nutrient concentrations because of heavy ice conditions. Primary productivity rates are lower than rates measured in the Simpson Lagoon area at the same time of the year. Chlorophyll concentrations were similar to concentrations measured in Simpson Lagoon. One unusual feature of Angun Lagoon was a dense benthic algal mat tentatively identified as Enteromorpha spp. in a stream mouth (Sikrelurak River). We had not observed similar algal mats in either Simpson Lagoon or the Harrison Bay area. The algal mats observed by Matheke and Homer (1974) in the Chukchi Sea at Barrow were in gravel substrates off the beach and in much more saline water. The existence of this bed was ascribed to the protection offered by the topography and the inputs of nitrogenous nutrients from stream runoff. The area involved, however, is small relative to the lagoon as a whole, and the contribution of this algal mat to the productivity of the lagoon is probably small.

Instantaneous primary productivity rates in the surface waters were similar in July, August, and September and ranged from 0.1-0.5 mg C/m³-hr. In the bottom waters, however, September instantaneous rates were substantially lower than in July and August. These lower rates in September are presumed due to declining light intensities. At this same time, however, peak concentrations of chlorophyll-a reached the highest

values observed. Although the very limited measurements of primary productivity prevent accurate **estimation of** seasonal production in the lagoons, the similarity in observed rates and environmental variables in this area and **in** the Simpson Lagoon area allows a reasonable projection based upon assumptions that seasonal patterns are essentially the same. If we divide the **season** into two periods of production--ice-covered and ice-free--we can summarize anticipated carbon inputs.

Since we have no observational data **available**, we assume ice algae production is the same as estimated for Simpson Lagoon, $0.1 \text{ g C/m}^2\text{-yr}$. Under-ice **phytoplankton** productivity is also assumed low and similar to rates observed in **Stefansson Sound** (**Schell** et al. 1982) and off Narwhal Island (**Horner** and Schrader 1981). Although we are assuming that the ice cover in the lagoons is predominantly sediment-free, similar to Simpson Lagoon (although unlike ice in **Stefansson Sound** which is predominantly turbid), this predication is based solely upon the limited wind fetch in the small lagoons which should encourage rapid ice cover formations and less supercooling and turnover than in an open water column during the fall. For estimation of seasonal production we assumed the following average monthly rates and day lengths, which are similar to those we used to estimate production in Simpson Lagoon.

Ice algae = 0.1 g C/m^2

June: $0.18 \text{ mg C/m}^3\text{-hr}$
 24 hour day length
 1.5 rewater (1 m ice)
 $0.2 \text{ g C/m}^2\text{-month}$

July : $0.36 \text{ mg C/m}^3\text{-hr}$
 24 hour day length
 2.5 m water depth
 $0.7 \text{ g C/m}^2\text{-month}$

August: $0.52 \text{ mg C/m}^3\text{-hr}$
 21 hour day length
 25 m water depth
 $0.8 \text{ g C/m}^2\text{-month}$

September: 0.27 g C/m³-hr
12 hour day length
2.5 m water depth
0.2 g C/m²-month

Total annual production = 2.0 g C/m²

This total value is considerably lower than **the** estimate for Simpson Lagoon; it reflects the much lower average measures of productivity rates. This estimate is, however, based upon very limited data and may vary by a factor of 2-5 times **if** the temporal and spatial variabilities are similar to those measured in the Simpson Lagoon area. It may **also** be true that the lagoons of the eastern Beaufort are less productive because of the longer time required to exchange lagoon waters with offshore water. Nutrient concentrations in the few samples taken from the water column off the lagoon entrance were very low. Since melting ice produces **low-nutrient** brackish water which stabilizes the water column and retards mixing, deeper nutrient-rich water from offshore is probably not advected very effectively to the nearshore areas where transport into the lagoons is likely. The comparisons listed in Table 5-3 between **Angun** and Simpson lagoons are inferred from highly variable parameters. The relative comparisons would almost certainly change with larger sample sizes over longer periods. Water exchange rates, **for**'example, are calculated from tidal range data and do not include the effects of storm surges which are often more important in flushing the lagoons.

Carbon Isotope Determinations

The feeding habits and energy requirements of top consumers in arctic coastal food webs are usually readily accessible from studies of stomach contents and metabolic rates. However, as one approaches the base of estuarine food **webs**, the numbers of prey species increase and the sources of energy are often difficult to determine. In coastal arctic waters, inputs of **allochthonous** carbon from terrestrial vegetation and peat are often of greater magnitude than the **in situ** production by **microalgae** (Schell et al. 1982). Since the digestibility of peat particles is difficult to determine in comparison to **algal** cells, feeding studies offer

Table 5-3. Comparison of physical and biological characteristics of **Angun** and Simpson lagoons.

	<u>Angun Lagoon</u>	<u>Simpson Lagoon</u>
Period when lagoons become ice-free	First week of July	mid-July
Time required for water exchange with-offshore (days)	10-14	1-10
Mean salinity of water, open water season (ppt)	16-20	20-26
Mean depth (m)	2.5	2.5
Mean salinity of offshore waters, 0-5 m, August (ppt)	16-18	25-28
Estimated annual primary production (g C/m ²)	1.6	5-7
Average chlorophyll-a standing stocks, August (mg/m ³)	0.3	1.1

little help in assessing the importance of these energy sources in driving the trophic energetic. We have sought to avoid the intricate pathways in trophic transfers by using natural carbon isotope abundances as built-in tracers of carbon flow. By comparing the natural abundances of ^{13}C and ^{14}C in source materials (peat, terrestrial vegetation, marine algae) with the abundances found in top level consumers, it is possible to determine the relative amounts of carbon derived from each source. We have used this technique to demonstrate that top level consumers in the Simpson Lagoon-Prudhoe Bay area are not utilizing much of the terrestrial carbon entering the marine water (Schell 1983). In this study, we selected several representative taxa and tested the validity of extending our findings to the eastern Beaufort Sea region of Alaska. Table 5-4 lists the radioactivities of basal peats in Beaufort (Nuvagapak) Lagoon and Angun Lagoon, and the radioactivities of several resident fishes and two oldsquaw ducks.

Carbon source allocations were determined by comparing the observed ^{13}C and ^{14}C abundances in samples of lagoon organisms with the corresponding values found in obligate freshwater or pelagic organisms (Schell et al. 1982) using the following mixing equations

$$F_m = \frac{\delta^{13}\text{C}_s - \delta^{13}\text{C}_{fw}}{\delta^{13}\text{C}_m - \delta^{13}\text{C}_{fw}} \quad F_p = \frac{^{14}\text{C}_s - ^{14}\text{C}_m - (^{14}\text{C}_{fw} - ^{14}\text{C}_m) F_m}{^{14}\text{C}_p - ^{14}\text{C}_{fw}}$$

where

F_m = fraction marine carbon

F_p = fraction peat carbon

$\delta^{13}\text{C}$ = ^{13}C abundance in per mil for marine (m), freshwater (fw) and sample (s).

The $\delta^{13}\text{C}$ of pelagic marine organisms (n=22) was -2.10 ± 1.2 ppt and the percent ^{14}C from marine modern sources was 106 ± 3 . Those organisms that recently spent some portion of their life in terrestrial environments reflected the "average" values for peat ($^{14}\text{C} = 63 \pm 10\%$; n=6) and freshwater modern sources ($^{14}\text{C} = 122 \pm 1\%$; $\delta^{13}\text{C} = 27.4 \pm 1.8$ ppt). The freshwater ^{14}C values were derived for summer radiocarbon concentrations

Table 5-4. Carbon isotope abundances and energy allocation in birds, fish and peat from Beaufort (Nuvagak) and Angun lagoons.

Sample No.	Sample	$\delta^{13}\text{C}^*$ (ppt)	$^{14}\text{C}^{**}$ (%)	Carbon sources (%) ⁺		
				Peat	Terrestrial Modern	Marine Modern
82-29	Basal peat, Nuvagak Lagoon	--	34.7 ± 0.7	--	--	--
82-30	Basal peat, Angun Lagoon	-27.22	33.1 ± 2.3	--	--	--
82-31	Arctic cisco, Nuvagak Lagoon	-23.56	104.4 ± 0.9	14	26	60
82-32	Arctic cisco, Angun Lagoon	-24.47	100.5 ± 0.8	17	37	46
82-33	Arctic char, adult, Angun Lagoon	-16.26	107.1 ± 1.0	0	0	100
82-34	Arctic flounder, Angun Lagoon	-26.43	103.0 ± 0.9	28	57	15
82-35	Oldsquaw, female, young-of-year	-24.72	106.2 ± 0.6	15	43	42
82-36	Oldsquaw, male, young-of-year	-27.93	95.8 ± 1.1	44	56	0

⁺Percentages of peat, terrestrial modern, and marine modern carbon were allocated from the mixing equations given in the text.

*Expressed as per mil relative to PDB standard.

**Expressed as percent modern, 1950 AD = 100%, normalized to $\delta^{13}\text{C} = -24$ per mil.

in algae and aquatic **macrophytes** (n=3) and the freshwater ^{13}C values were from obligate freshwater fishes (n=19).

Although the **sample** sizes are small, these data indicate that terrestrial carbon may be of greater importance to organisms in lagoons of the eastern Alaskan Beaufort Sea. The **two** arctic **ciscoes** contained higher percentages of terrestrial carbon than specimens taken from the **Colville River area**, as indicated by $^{13}\text{C}/^{12}\text{C}$ ratios. The radiocarbon activities of these fish also indicated a relatively higher proportion of peat carbon in fish from the eastern Alaskan Beaufort Sea. We estimate a terrestrial carbon content of up to 54%, of which 14-24% was derived from peat. This is a surprisingly large proportion in view of the findings from Simpson Lagoon where terrestrial carbon was almost undetectable in fish during the summer. Further corroboration of the importance of terrestrial carbon was found in the $^{13}\text{C}/^{12}\text{C}$ ratios in an arctic flounder (*Liopsetta glacialis*) which were composed of about 85% terrestrial carbon. Radiocarbon activity in this fish also indicated the presence of about 15% peat carbon. Flounder prey heavily on **benthic infauna**, particularly **polychaetes**, which are effective scavengers of detritus. **Figure 5-2** depicts these differences between the two lagoons mentioned above. It should be noted, however, that the statistical variability inherent in radiocarbon determinations could account for an increase or decrease in peat content of about 8%.

The **oldsquaw** ducks analyzed were young of the year birds that had recently fledged from tundra ponds and moved to the marine lagoons to feed prior to fall migration. These birds contained stable and radiocarbon isotopic abundances that confirm patterns found in **oldsquaws** collected near the **Colville** delta. Since they are reared on the tundra, the birds have terrestrial carbon isotopic signatures with a high peat content when arriving on the lagoon. One of the birds (sample 82-35) had apparently been feeding on marine modern prey for sufficient time to dilute its terrestrially-derived carbon, indicated by both $^{13}\text{C}/^{12}\text{C}$ ratios and ^{14}C content, whereas sample 82-36 was undistinguishable from terrestrial fauna and had a peat carbon content of about 44 percent. These birds apparently derive a large portion of their peat carbon from **chironomid** larvae on which they prey in the lakes and ponds (E. Taylor, Univ. of Alaska, **pers.**

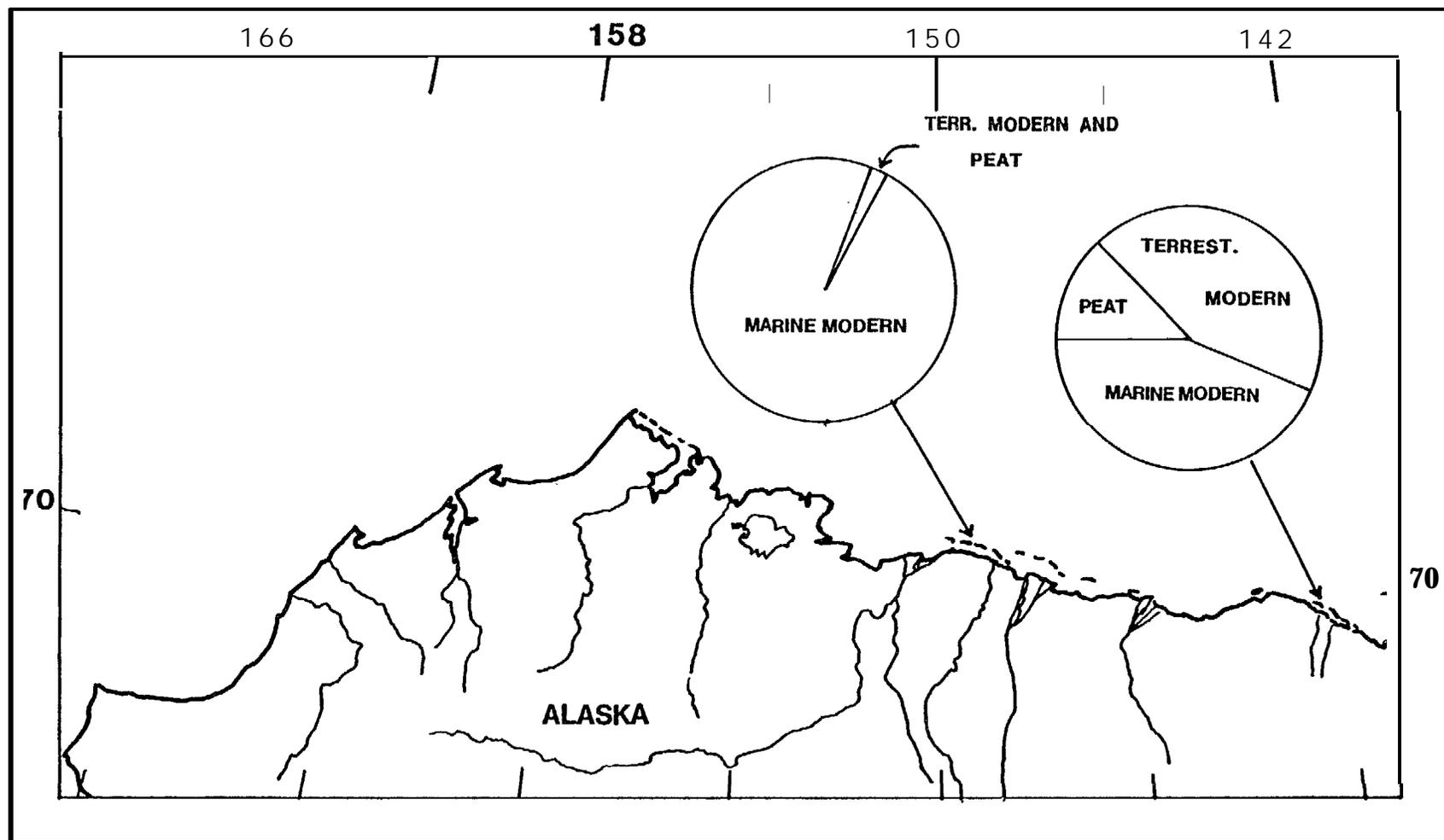


Figure 5-2. Energy sources supporting arctic cisco, flounder and sculpins from Simpson Lagoon (left) and Angun-Nuvagapak lagoons (right). Allocations are made on the basis of average carbon isotope distributions in faunal muscle tissue.

comm. 1982). These insects have been sampled and found to contain a large percentage of peat tartan in their makeup (Schell, unpublished data).

DISCUSSION

Lagoon Waters and Trophic Structure

The lagoons of the eastern Beaufort Sea of Alaska have many similarities to Simpson Lagoon with regard to the primary producers and water column characteristics. Shorelines are bordered with low bluffs of peaty soils and are actively eroding along much of their length. Particles of peat are evident in beach and bottom waters. Thus the major inputs of allochthonous carbon and organic nitrogen to the lagoon food webs must be addressed in constructing energy budgets. In addition, the streams emptying into the lagoons were found to have a wide range of nutrient concentrations (nitrate) which may reflect differing hydrologic conditions in the watersheds. Angun River contained the highest nitrate concentrations (19 $\mu\text{g-atoms N/l}$ in August, 15 in September) we have observed in arctic slope rivers. Hufford (1974) reports 15.3 and 18.6 $\mu\text{g-atoms N}_3\text{-N/l}$ for the Kuparuk and Sagavanirktok rivers, respectively, indicating that high nitrate concentrations may be typical of some rivers of this area. In contrast, Hufford's data on the Canning River and our samples from the Sikrelurak River revealed much lower nitrate concentrations (<5 $\mu\text{g-atoms N/l}$). Comparisons of drainage basins and their topographic relief gave no indication of the reasons for these large differences. More data are needed to explain the high variations in nutrient concentrations in these rivers. The fauna collected and the radiocarbon data for the samples from Angun and Beaufort lagoons indicate that these waters support similar food web structures, but differing energy dependencies compared with waters in the Simpson Lagoon region.

The limited data we acquired show that a significant fraction of the energy supporting marine organisms in these lagoons is derived from the land. Since the August and September sampling dates coincide with the

period of peak annual **phytoplankton** production in the marine environment, the evidence of terrestrial carbon was somewhat surprising. However, our estimates of annual production for Angun Lagoon are only about **25%** of the Simpson Lagoon values; therefore, terrestrial carbon may be of greater relative importance to these food **webs**. **Although we** do not have enough spatial and temporal data on carbon isotope abundances to generalize, the marked difference apparent **in** our samples caution against assuming that the **trophic** structures **of** Simpson Lagoon and the eastern Alaskan Beaufort Sea lagoons are similar. Even though the prey densities and **faunal** relationships are superficially the same, the energy sources and, therefore, the developmental impact sensitivities may be quite different.

Large-scale Structure and Primary Productivity

The rivers and shorelines of the eastern **Beaufort** Sea contribute large quantities of inorganic and organic nitrogen, as well as the organic carbon mentioned above, to the nearshore zone. Although the isotopic data indicate that moderate amounts of the terrestrial carbon *are* present in higher **trophic** levels, the role of the **allochthonous** nitrogen is less certain. As the organic carbon is oxidized by **microflora** (with the consequent release of ammonia), nitrogen may then be significant to the nutrient requirements of nearshore **phytoplankton** populations. The ammonia produced is assimilated by **phytoplankton** populations and is used as an energy source by vitrifying bacteria in winter months. Although we have no winter data from the Barter Island area, there is no evidence that winter circulation patterns and sea ice formation processes are appreciably different from the Prudhoe Bay region where we have sampled earlier and observed that winter salinity **increases** during ice *formation* in nearshore waters. Figure 5-3 shows nitrate concentrations and salinities along a transect north of **Stefansson** Sound in May. **Hypersaline** water, forming in **Stefansson** Sound as the ice freezes, drains downslope at a rate sufficient to turnover the water volume of the sound in about 40 days. (For a detailed consideration see **Schell et al. 1982**). **In**

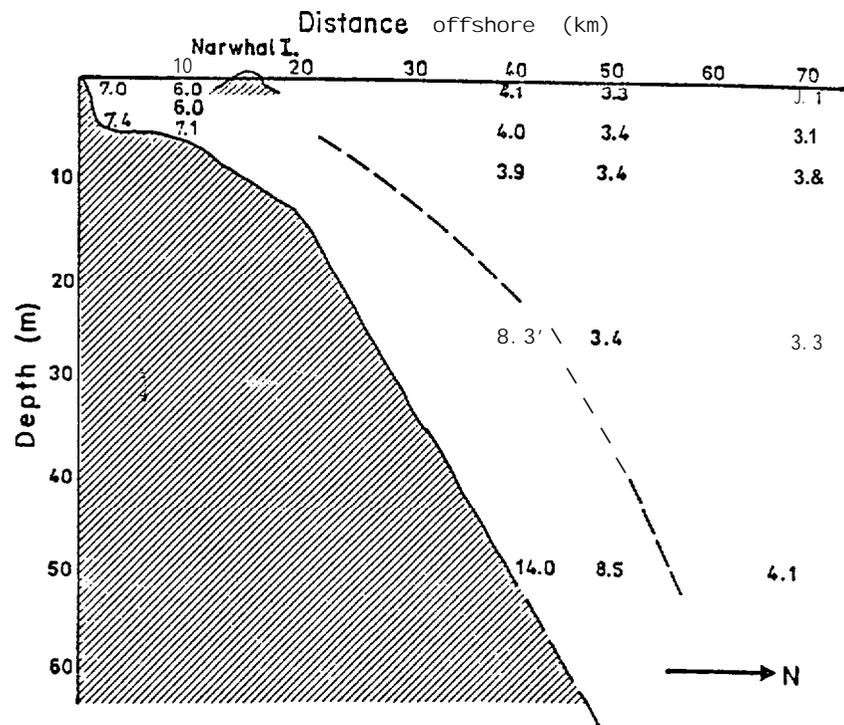
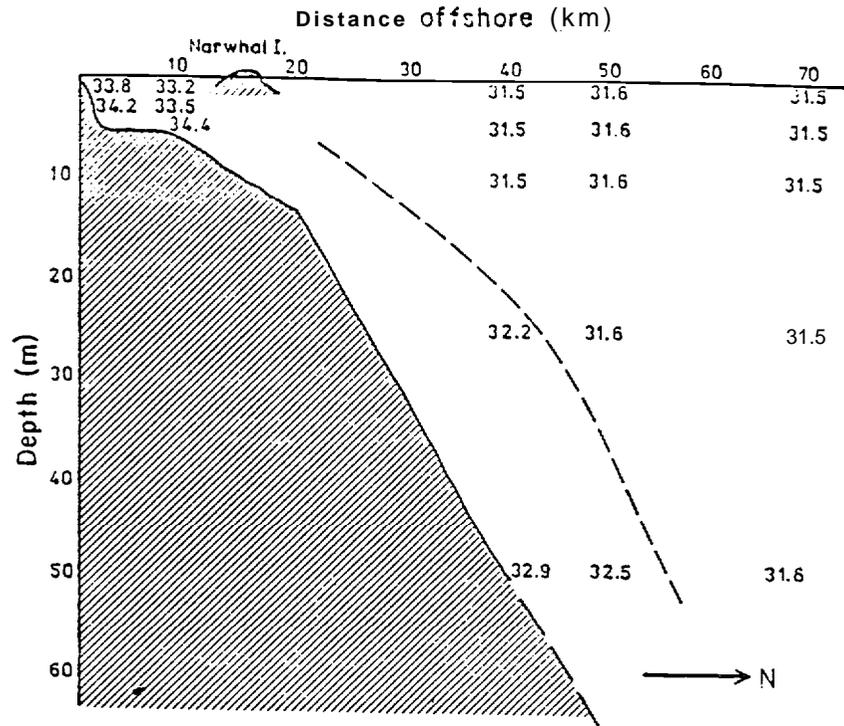


Figure 5-3. Salinity (ppt, top) and nitrate (bottom) concentrations ($\mu\text{g-atoms N/l}$) along a transect north of Stefansson Sound, May 1982.

contrast, the nitrate concentrations increase very rapidly indicating active **nitrifier** populations with a consequent increase of nitrate-N equivalent to about 0.1 $\mu\text{g-atoms}$ of N/L-day. This nutrient rich water apparently moves **downslope** to a depth below that sampled on the transect.

The fate of this nitrate may be deduced from the **work of Aagaard et al.** (1981) and **Melling and Lewis** (1982) which addressed the formation of **hypersaline** under ice water in the eastern Beaufort Sea. They describe a **downslope** drainage in winter with the cold dense water then spreading horizontally outward on deeper water of higher density. This shelf water "interleaves" in a layer out to an estimated 100 km in the situation which they described. If this water acquires a high nitrate concentration from the nutrient regeneration in the nearshore zone, this mechanism may serve as a means of offshore transport of nitrogen and loss to the system. Schematically, this sequence is shown in Figure 5-4.

A possible mechanism by which a portion of this nitrate may be reintroduced to the **euphotic** zone is coastal **upwelling** due to wind stress during the open water **months**. **Increase** in the speed of the Beaufort Gyre and **Coriolis** effects may **result** in the offshore transport of low density surface water and **upwelling** of deep water onto the **shelf**. Continued transport shoreward coupled with higher light intensities **would** result in phytoplankton blooms *in* this nutrient rich water. Figure 5-5 schematically depicts this mechanism. Since this represents a recycling of part of the original inputs of organic nitrogen derived from **terrigenous** sources, the feedback effect may support **a region of** higher primary production in the zone **of** open water along the Beaufort Sea coastline. Integration of these processes in a word model is presented in Figure 5-6. Although the processes described are supported by experimental data (**Schell** 1974) and oceanographic measurements (**Hufford** 1974, **Matthews** 1981), there are no quantitative data which would enable the assessment of the importance of these processes to annual productivity of the nearshore regions. As additional data are acquired, the role of the physical processes in dominating the biological productivity may become clearer.

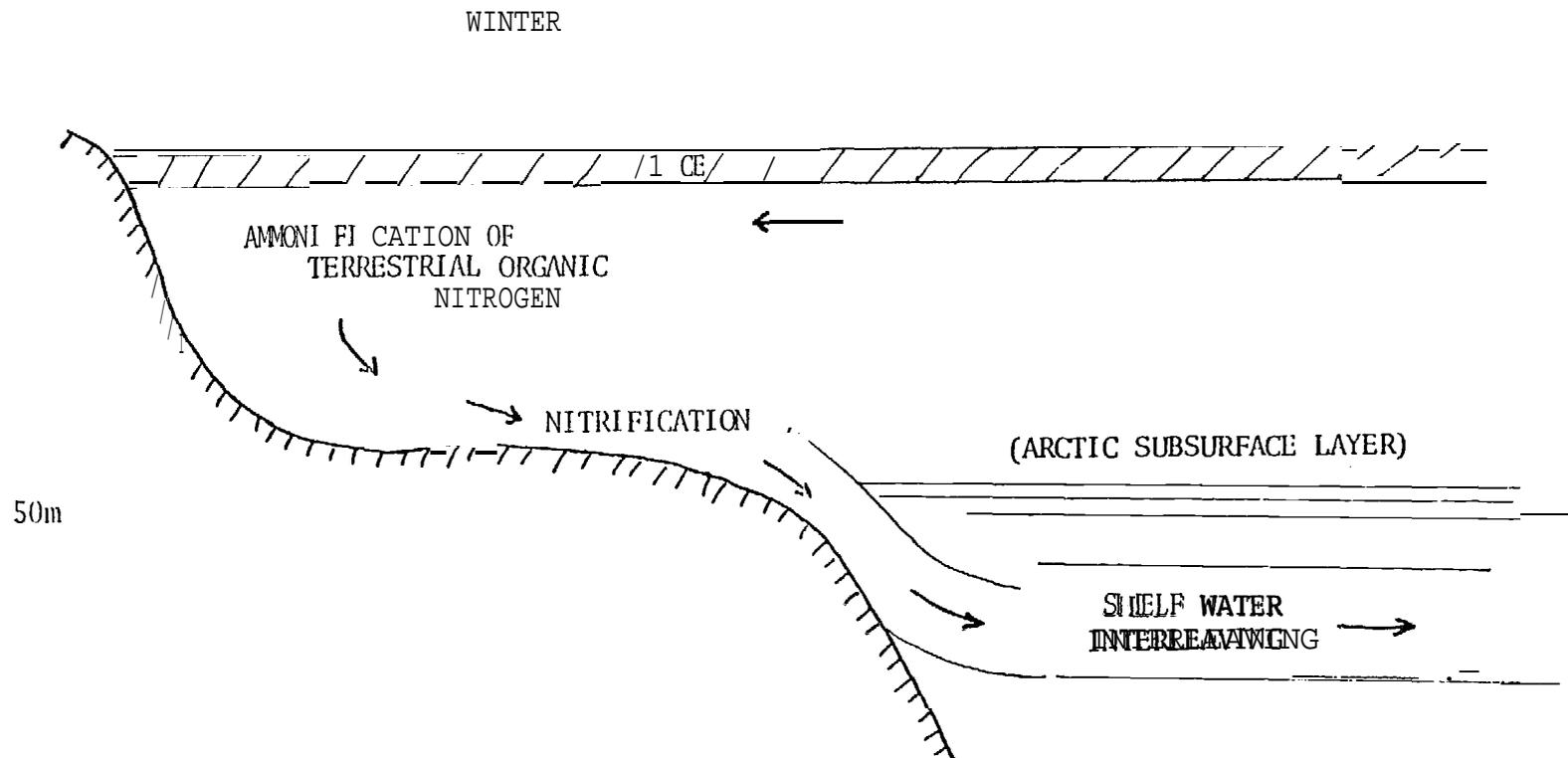


Figure 5-4. Winter processes controlling nutrient concentrations in Beaufort Sea waters inferred from late winter salinities and nitrate concentrations (after Melling and Lewis 1982).

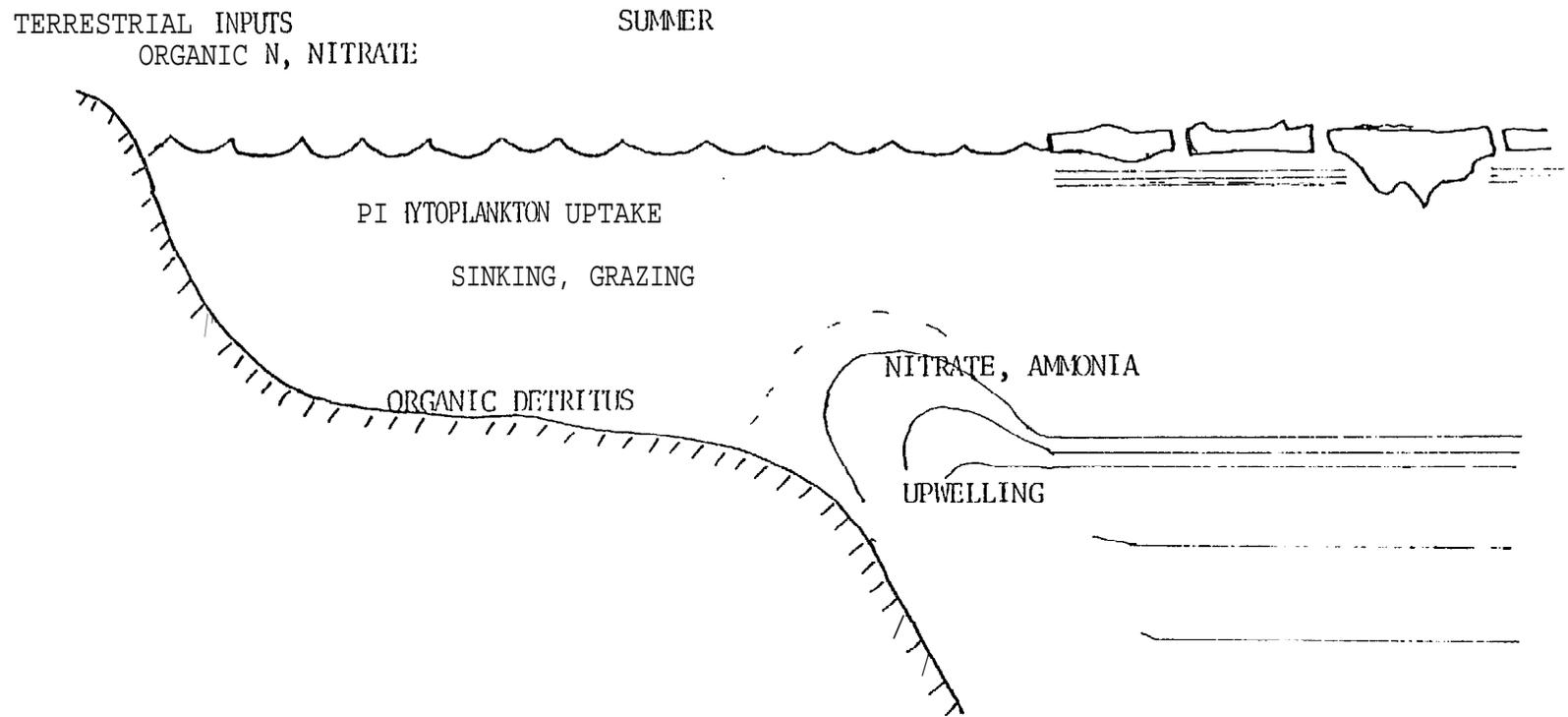


Figure 5-5. Summer processes supplying nutrients to shelf phytoplankton populations. Offshore perennial ice and summer meltwater stratification effectively prevent mixing of deep water into the upper 75-100 m.

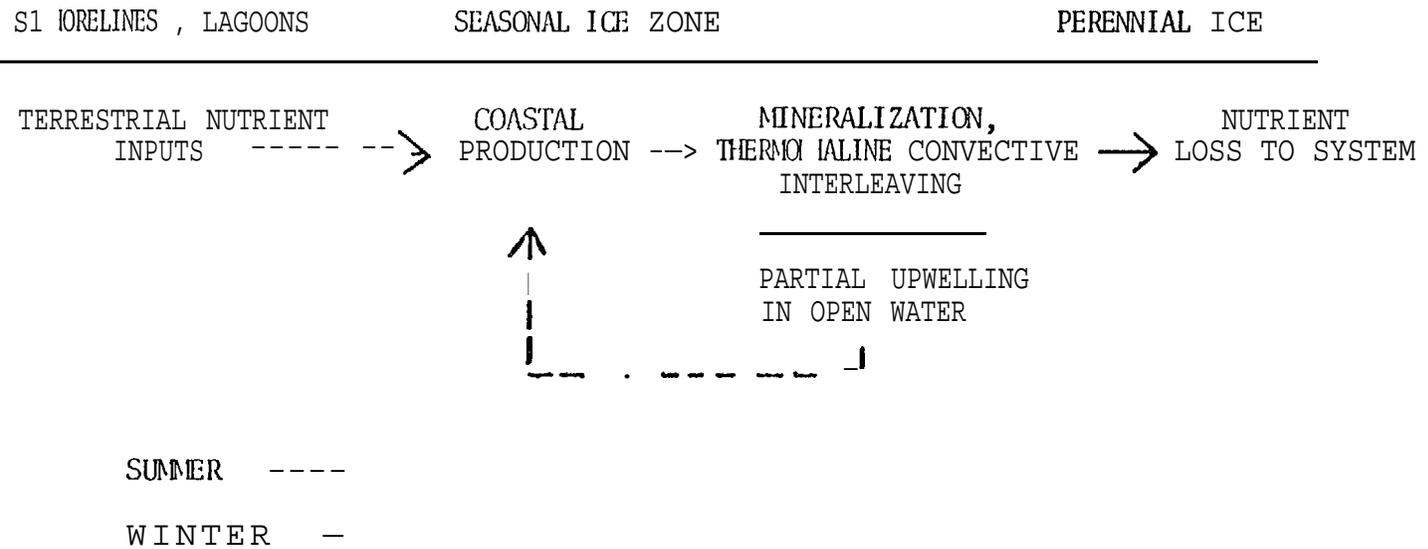


Figure 5-6. Word model of nutrient dynamic processes in Beaufort Sea shelf waters. Loss of nutrients results from winter convection to depths below the euphotic zone at distances offshore where perennial ice prevents advection upward.

RELEVANCE TO PROBLEMS OF PETROLEUM DEVELOPMENT

Unlike marine **phytoplankton** primary production, inputs of terrestrial carbon to the lagoons occur in discrete areas--shorelines and stream mouths. It is not difficult to conceive of mechanisms by which pollutants could contact and become adsorbed onto peat particles and then be fed upon by **benthic** invertebrates. The high cation exchange capacity of peat would also make it an efficient scavenger of heavy metal ions. Drilling muds or industrial effluents containing toxic ions might, therefore, affect the eastern lagoons more severely than Simpson Lagoon, because of the synergism of the longer residence times and heavier dependence on terrestrial carbon.

In contrast to the importance of terrestrial carbon in lagoon food webs, the pelagic food web is totally dependent upon **in situ production**. The diffuse and large-scale nature of phytoplankton primary production renders the process intrinsically less sensitive to perturbation than the impacts on localized concentrations of vertebrate consumers. Therefore, when assessing impacts on primary producers we are forced to consider mechanisms by which indirect impacts on consumers may occur. Two major processes can be identified by which **phytoplankton** stresses can be significant to the ecosystem: (1) recycling of discharged pollutants to the **euphotic** zone by **upwelling**, and (2) **biomagnification** of toxic substances through incorporation *into* plant tissue. The first process requires consideration of the physical oceanography of the nearshore waters. If a pollutant (drilling **muds**, hydrocarbons, terrestrial runoff of land-discharged toxic substances) enters marine waters during fall or winter, the offshore movement of bottom water will entrain and transport the substances downslope and offshore to considerable distances. Because under ice currents are very slow relative to **summer**, pollutants may accumulate to higher than tolerable concentrations, and density gradients **will** keep the water in close contact with surface sediments and the **benthos**. Then, as the following summer arrives and **upwelling** begins, the polluted water can be returned to the **euphotic** zone and the pollutants incorporated into the **phytoplankton** biomass. Since the denser bottom

water formed in winter also contains the highest nutrient concentrations? this positive feedback mechanism **may** result in high rates **of** incorporation of pollutants.

Once a pollutant is in the phytoplankton biomass, **biomagnification** may occur as it is passed up the food chain. The high concentrations of fats **in** many arctic animals would tend to accumulate **halogenated** hydrocarbons, aromatic compounds, or other hydrophobic pollutants. Since many of these organisms are used by Native subsistence hunters, a transmission to human populations is feasible. The seriousness of these potential problems will need to be assessed as offshore development progresses **in arctic** Alaska.

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