IN SITU CARBON DIOXIDE FLUX FROM ARCTIC TUNDRA DURING FREEZE-UP

by

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INTRODUCTION

It has been hypothesized that microbiological activity of tundra microorganisms is restricted by the harsh environmental conditions. Consequently the slow decomposition of organic matter and debris limits nutrient recycling in tundra. These nutrient deficiences in turn may be one of the rate limiting parameters in regulating the production of fauna and flora in the ecosystem. It was demonstrated by a number of investigators at different circumpolar sites during the International Biological Program that decomposition is not limited *per se* by a low decomposer biomass (26). The slow decomposition reported in tundra may be caused by: high soil carbon/nitrogen ratios, limited aeration, low levels of inorganic nutrients, short annual period of above freezing temperatures, and generally low temperatures.

Since CO_2 is the major end product of decomposer metabolism, field measurements of CO_2 flux represent a convenient indication of the decomposition processes in the system. The pioneering paper of Douglas and Tedrow was one of the first attempts to measure decomposition rates in tundra (4). This study was conducted in the vicinity of the Arctic Research Laboratory near Barrow, Alaska which has been a focus for tundra research since the 1950's. During the International Biological Program (IBP) in 1973, Peterson and Billings determined the rate of CO_2 flux from tundra at Barrow during the summer months using the infrared technique in a darkened chamber (12). Concurrently Coyne and Kelly used an aerodynamic method to estimate CO_2 flux (2), and Benoit used an *in situ* CO_2 alkali absorption method on one of the IBP sites where different habitats expressed in polygon ground development were investigated (1). The CO_2 alkali absorption method permitted extensive replication on each habitat over the extremely heterogenous tundra at a reasonable cost where electrical power was not available. The habitats varied from moderately productive to very barren. These habitats develop several meters apart horizonally and centimeters apart vertically by thousands of years of annual freeze-thaw cycles. Benoit measured the CO_2 flux from undisturbed cores in the different habitats on a rotation system from the period of late June to early September 1973. This method measured the net CO_2 flux from all the biological components in the system, therefore, the contributions of the individual components must be estimated by other methods, which are probably not possible at present. However, one perturbation which featured stripping of flora attempted to crudely estimate the decomposer vs. primary producer contribution to the CO_2 flux.

No investigations have measured the CO_2 flux of tundra during the early winter freeze-up period. Tundra soil may remain at 0 C for an extended period of time in early winter when the air temperatures are below 0 C because tundra is acting as a heat sink. When the heat is dissipated the soil temperatures decrease in response to the cold air temperatures. The freezing point of soil water adsorbed on soil colloids will be lower than 0 C, and some microorganisms have metabolic activity between 0 C and -7 C under laboratory conditions (11). These two observations provide a theoretical rationale for predicting the synthesis of significant quantities of CO_2 from tundra microorganisms during freeze-up. It was the objective of this work to measure CO_2

output as a function of soil temperature during the freeze-up period under field conditions using the same undisturbed cores at the Barrow IBP site investigated by Benoit the previous summer. The formation of ice crystals in some cells of plants, animals and microorganisms will cause the death of the cells and thereby increase the pool of dissolved organic matter which some microorganisms may use for metabolism. The large quantities of CO_2 observed being produced under tundra snow cover by Kelly during parts of the winter provides indirect evidence that microorganisms are active at subzero celsius (8).

METHODS AND MATERIALS

Site Description

The experimental site was located on the International Biological Program Intensive Site near Barrow, Alaska. These soils have been described by Gersper (5) as highly organic with an elevated C/N ratio, acidic, high moisture content, low redox potential and consisting of a complex of Pergelic Cryosaprists, Histic Pergelic Cryaquepts, and Pergelic Cryosaprists with a thin histic horizon overlying a silty clay loam mineral horizon. The habitats examined included: flat centered wet meadow (plot 206 - 1973 data only), polygon trough (plott 440), polygon ridge (plot 441), and polygon basin (plot 442). The wet meadow site had a moss sedge vegetation with a minimum development of surface polygon features; this habitat was more uniform from the standpoint of plant standing crop and soil features than the habitats in the well-developed polygon study area. The polygon trough had a plant canopy which was similar to the wet meadow, but the soil was wetter and the soil profile was variable because of the intense effects of freeze-thaw cycles. The polygon ridge was well drained, had a high organic matter content and a moss-lichen cover dominated the soil surface. The polygon basin was poorly drained, high in organic matter, and the vegetation consisted of a sparse lichen cover.

The microbial characteristics of the decomposers have been described by Benoit (1) and Harris (7).

CO_2 Assay Procedure

CO_2 was collected *in situ* from the soil surface of 15 cm diameter cores. The PVC cores were 0.5 cm in thickness. Each core extended approximately 3 cm above the soil surface and 4 cm below the soil surface. Each core remained in place after installation for a two year period. There were some discontinuities in the data of the polygon troughs due to flooding. In several cases, during the second year of the study some trough cores were relocated to drier sites; otherwise the replication would be reduced.

A modification of the alkali absorption technique was used. This method was used because reliable power sources were not available on the well-developed polygon site and this method permitted extensive replication under a variety of conditions in a variety of habitats. Five ml of standardized 0.1N NaOH solution was prepared in the laboratory and carefully carried to the field in screw cap culture tubes. The alkali was distributed in 3 cm diameter plastic culture dishes which were placed on the soil surface. The cores were sealed with parafilm and a plexiglass cover (31 cm square) which had a black opaque top was placed on top of each core. CO_2 was collected over a 24 hr period. In several cases extreme weather conditions prohibited sample collection for 48 hrs. These cases occurred during the coldest period of the study when activity was low. It was also necessary during the colder periods of this study to add NaCl to the alkali before standardization to lower its freezing point. The alkali from each plastic culture dish was returned to the same screw cap tube which had been used to transport it to the field. Distilled water was used to rinse the alkali from each dish. The alkali was collected at midnight during the summer 1973 season and 8 am during the fall-winter 1974 season. The midnight change was the closest hour to the daily minimum soil temperature reading which was administratively feasible. The 8 A.M. change during 1974 was chosen for a similar reason, except the safety of field personnel during adverse weather conditions was an additional factor. Six cores were used to sample each habitat each day. A sufficient number of cores were placed in the habitat study areas to permit each core to be sampled every fourth day. In the interim the core was 'in equilibrium' with the environment. A random number table was used to pick the set of cores for the original sample dates. Subsequent samples used the same cores on the same date. Daily triplicate controls were used in the field to determine the amount of CO_2 contributed by the atmosphere. Each control consisted of a core sealed at both ends with parafilm and covered by plexiglass. The controls were placed on a plywood board which was located at ground level. All alkali tubes were returned to the laboratory and immediately titrated with standardized 0.1N HCl to an endpoint using phenolphthalein. A 5 ml microburet was used for the analysis. The CO_2 absorption values were reported as mg CO_2/m^2 of soil surface. The method of Stozky (16) was used to calculate these values.

This method produced a value which estimates the net output of CO_2 from the soil-plant system and does not discriminate between producers and decomposers. The living and standing dead portion of the plant canopy in addition to the litter were removed from an additional series of cores in the polygon basin and polygon ridge habitats. Although a substantial portion of the surface decomposers were also removed by this stripping of the soil surface, this perturbation was designed to estimate what the remaining decomposer population could produce in CO_2 output.

A subset of the stripped cores were treated with 0.1167 g of Na_2HPO_4/ core which represented 150 lbs of phosphorus/acre. This treatment was designed to test the hypothesis that the extremely low phosphorus levels limit microbial growth and activity.

Soil temperatures represent average daily values obtained from thermistors sampled at three-hour intervals by a Grant recorder. The values obtained from the 5 cm depth were reported. Air temperature data was obtained from the United States Weather Bureau at Barrow, Alaska.

The data was analyzed statistically by use of the Scheffe Analysis of Variance test at the 5% confidence level (14). This test performed a multiple comparison of treatments resulting in significant subsets at the 5% level (the significant subsets are given in the Appendix Tables II, IV, and VI).

RESULTS

The rate and time which the tundra freezes is subject to considerable variation as a function of abiotic events. Light frosts are often observed during August. Freezing conditions become more frequent during September when the average daily minimum, maximum and mean air temperatures at Barrow Weather Station are -2.7, 0.7 and -0.9 C respectively. The freezing process becomes intensive during October when the average daily minimum, maximum and mean air temperatures are -12.0, -7.4 and -9.3 C respectively (17). This study was initiated during an unseasonably warm period in late August 1974 and was terminated when the soil was extensively frozen on 19 October. The soil temperatures at the 5 cm depth at the study area during this period are shown in Figure 1 (the data are given in the Appendix Table VII). The soil temperatures at the start of the study were unusually warm. Soil temperatures approached 10 C briefly during mid-summer in 1973, and were approximately 3 C during the late August - early September period. The break in the temperature data for 1974 shown by the dotted line in Figure 1 was due to a mechanical malfunction of the recorder which coincided with a drop to seasonal temperatures. The soil temperatures dropped after the warm period and remained relatively constant during the first twenty days of September at 2 to 3 C. For the next 20 days the soil temperature remained slightly above 0 C which corresponded to the "zero window" period. The soil temperature then dropped quickly after October 7 to temperatures less than -5 C. During the latter period it was often difficult to locate the experimental area because the

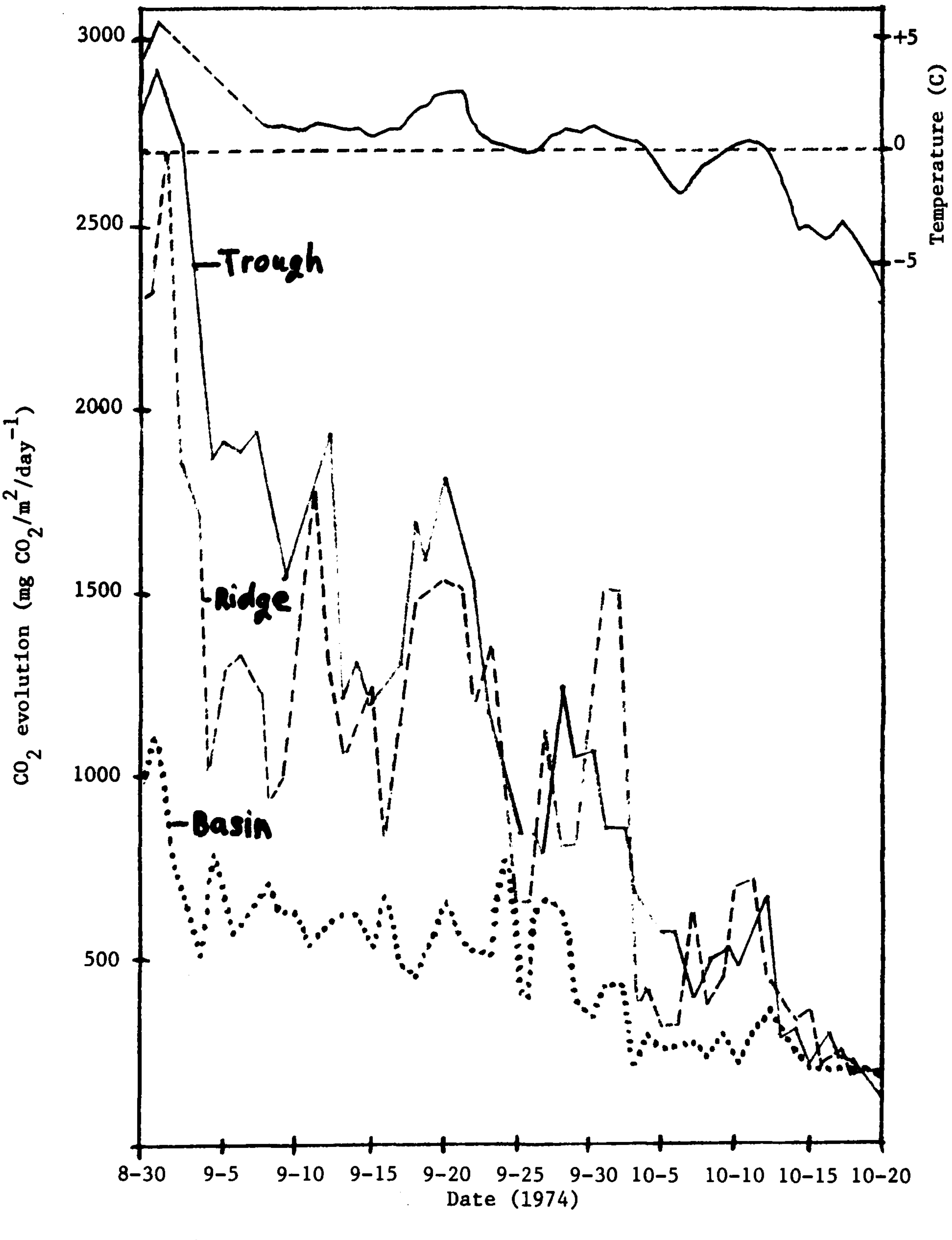

Figure I. Daily CO_2 evolution from polygon trough, ridge and basin habitats on tundra during freeze-up 1974 with 5 cm depth soil temperature shown as daily mean temperature, at IBP site 4, Barrow, Alaska.

cores were often completely covered by snow. The basin and trough cores were particularly difficult to locate. NaCl was used to lower the freezing point of the NaOH. Near the end of the experiment the alkali would freeze during the field incubation especially in the ridge habitat. Furthermore it was more difficult to seal the core at low temperatures. Under conditions of subfreezing temperatures and blowing snow, the quantitative recovery of the NaOH from the core was difficult.

The CO_2 daily averages for the three habitats on the Barrow IBP site 4 are also shown in Figure I. The CO_2 production from the trough, ridge and basin at the start of the study when soil temperatures were near 10 C were approximately 2900, 2300 and 1100 mg CO_2/m^2/day on 31 August and 1 September. These values were greater than any other value obtained from the identical cores the previous year. When the soil temperature decreased radically on 2 September to a plateau near 2 to 3 C, the CO_2 production from the trough, ridge and basin dropped approximately 35, 40 and 45 percent respectively from the 1 September maxima. During the three day warming trend at the end of the plateau, there was an increased CO_2 level from the trough and ridge habitats, but not the basin. When the soil temperature dropped into the "zero window" phase from September 23 to October 6, the trough, ridge and basin CO_2 production dropped 70, 57 and 64 percent from the 1 September maxima. When the soil temperature decreased several degrees below 0 C on 3 October with the onset of a cold period, CO_2 declined but continued in the trough, ridge and basin to levels 17, 26, 22 percent that of the 1 September maxima. With the onset of deep winter conditions when the soil temperatures dropped below -5 C on 14 October, the CO_2 release continued in all three habitats at levels of approximately 150 mg $CO_2/m^2/$ day which corresponds to 5, 7 and 14 percent of the values observed during the warm period on 1 September. Five day mean values of the CO_2 flux are shown in Figure 2. A comparison of daily vs 5 day means illustrates the considerable variation caused by variations in temperature, wind velocity, moisture and snow cover.

It may be concluded from these data that CO_2 production from tundra decreases as soil temperature decreases, but the decrease appears to be an asymptote rather than a sharp extinction point as the system freezes. Most of the variation in CO_2 evolution could be accounted for by variations in the daily soil temperature. A multiple regression comparing CO_2 evolution rates of the three habitats with temperature accounted for 72% of the overall variation in the data. Correlation coefficients between individual habitats and temperature were also determined and the relationship between CO_2 evolution and soil temperature was observed. The regression equation for predicting temperature was: Temperature = 4.67054 + (0.00263) basin + (0.00180) trough + (0.00223) ridge.

The Scheffe Analysis of Variance test was used to compare differences of CO_2 evolution in the three habitats at the 5% confidence level (14). The ridge and trough were different 22% of the days tested. The ridge is not as productive a habitat as the trough, but when conditions of temperature and moisture are favorable decomposition on the ridge can be significant. The ridge was consistently less than the trough (Fig. II) during early September when moisture may have been less available on the ridge than the trough. When moisture was adequate in late September and early October, the quantities of CO_2 evolved were very similar. The

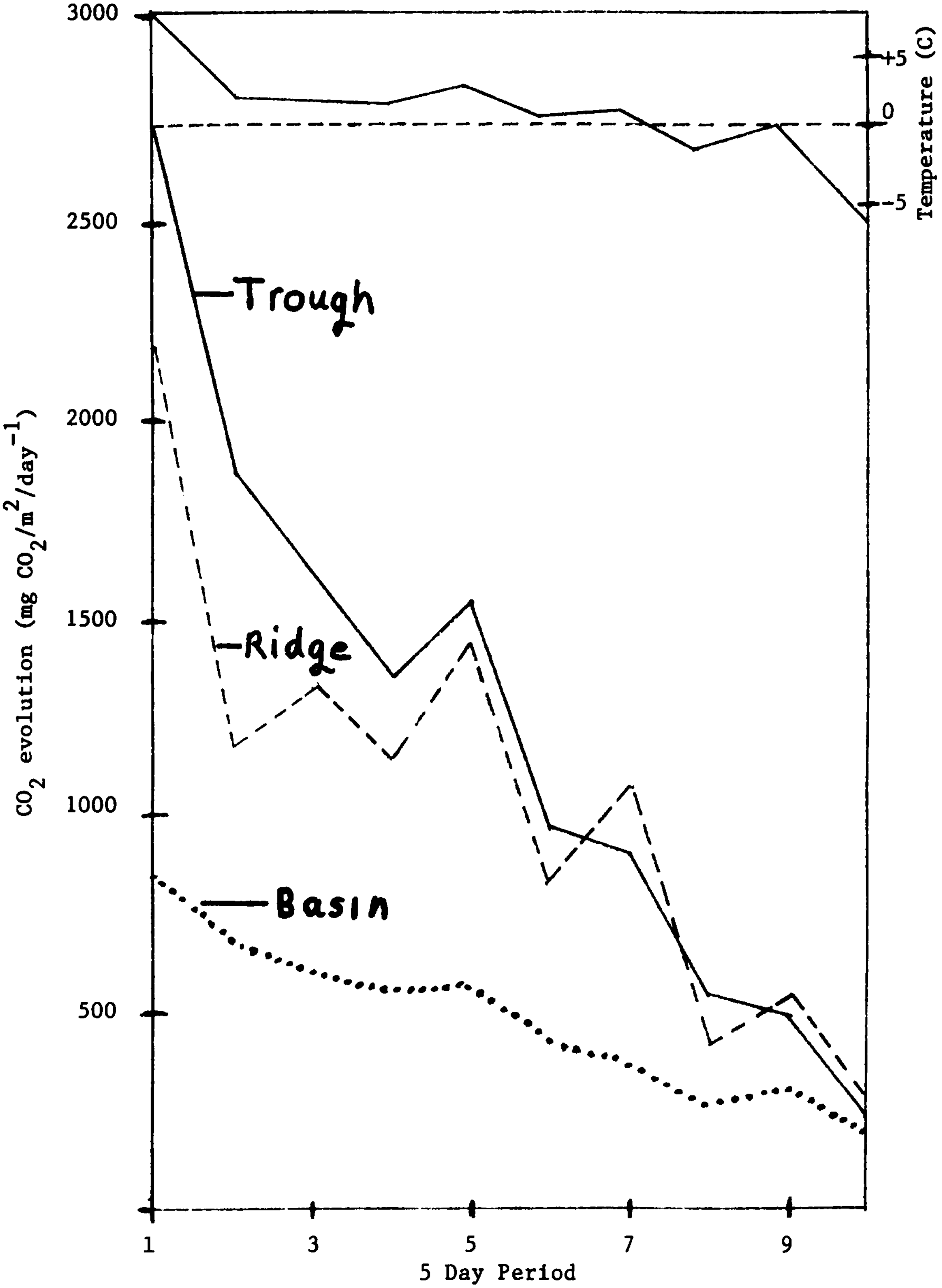

Figure II. CO_2 evolution from polygon trough, ridge and basin habitats on tundra reported as 5 day means during freeze-up 1974 with 5 cm depth soil temperature shown as 5 day means at IBP site 4, Barrow, Alaska.

basin was significantly different than the trough and ridge on 68 and 42% of the days tested respectively. These data are consistent with differences observed during the 1973 season. The very low CO_2 flux recovered from all three habitats coupled with the increased variation between cores within habitats during the coldest period reduced the number of times the habitats were significantly different in contrast to the 1973 summer period.

The CO_2 flux from the ridge and basin which had the litter and above ground live material removed are given in the Appendix Tables III and V. During the entire period of this study the stripped ridge and basin habitats were significantly different from the unstripped habitats 9 and 23 percent of the time respectively (Table I). Removing the surface layer removes much of the substrate which is readily available to microorganisms and exposes the more recalcitrant organic matter. This perturbation demonstrated that a very high percent of CO_2 flux from tundra surface can originate from microbial degradation of organic matter. This perturbation only shows the potential for decomposition because the surface canopy has an important regulatory effect on the decomposition of the soil organic matter. Mechanical and temperature perturbation of the tundra at Barrow demonstrates that destruction of plant canopy usually stimulates decomposition (1) and the addition of phosphorous did not increase the decomposition during a two year period although the level of available phosphorous was extremely low. The iron content of tundra was very high and apparently the phosphorous was rapidly complexed into iron phosphates in which the phosphorous was only slowly available to microorganisms and plants in the system.

TABLE I

Treatments	# time differences were significant vs. total number of observations.	Percent
Basin/Ridge	21/50	42%
Basin/Trough	34/50	68%
Ridge/Trough	11/50	22%
Basin/Basin No canopy w/PO_4	6/22	27%
Basin/Basin No canopy/No canopy w/PO_4 / w/o PO_4	0/22	0%
Basin/Basin No canopy w/o PO_4	5/22	23%
Ridge/Ridge No canopy w/PO_4	1/22	5%
Ridge/Ridge No canopy/No canopy w/ PO_4/w/o PO_4	0/22	0%
Ridge/Ridge No canopy w/o PO_4	2/22	9%

Significant Differences: CO_2 flux differences between different habitats or treatments on IBP Site 4, Barrow, Alaska during the 1974 freeze-up at the 5% confidence level.

The tundra is an extremely heterogenous soil system. The high standard deviation between cores within a habitat is evidence for the diversity in substrate, levels of nutrients and differences in the geometry of the matrix in the soil profile. When a fungus developed a fruiting body inside one of the cores of the stripped ridge treatment on 4 September 1974, the level of CO_2 flux was 271 percent greater than the other cores in the treatment.

DISCUSSION

If temperature is one of the major limiting parameters of decomposition than the usually warm soil temperatures observed at the start of this study should have stimulated CO_2 production. In fact, the observed CO_2 production values from the trough, ridge, and basin habitats during this warm period were greater than any value observed during the previous summer on the same sites. The trough, ridge and basin habitats produced CO_2 values of 2925, 2715 and 1102 mg CO_2/m^2/day respectively. Since the trough produced the greatest quantity of substrate for decomposer activity higher CO_2 flux values on that habitat were expected. A good correlation (r = 0.813) between CO_2 production and soil temperature was observed in the trough. When the trough became water logged the CO_2 production was depressed even when temperatures were favorable. A marked depression in CO_2 production in the trough was observed the previous summer during an extremely wet period in early August. There was a high biomass of bacteria and fungi on the trough habitat with the fungi located primarily at the soil surface. A good correlation (r = 0.794) was also obtained between the soil temperature and ridge CO_2 production. On this habitat such positive correlation was less favorable. The fungi appear to dominate the decomposer biomass of the ridge habitat. The poorest correlation between soil temperature and CO_2 production was obtained on the basin habitat (r = 0.723). The basin remains a decomposer enigma. There was very little primary production on this habitat and there was very little decomposition although there were high quantities of organic matter. A combination of poor aeration, high quantity of relcitrant molecules, low inorganic nutrient status (especially phosphorous) and the soil matrix may insure stagnant gas and moisture conditions. The biomass of bacteria and fungi was much lower on this habitat than any other soil habitat on the Barrow site.

The CO_2 flux values observed from tundra under the most favorable conditions in this study were considerably lower than those obtained in low latitude ecosystems. Schultz used an in situ CO_2 absorption technique in which above ground plant parts had been removed to demonstrate that soil respiration rates in tropical soils varied between 300 and 2500 mg $CO_2/m^2/hr$ (15). The lowest value observed in this study was observed in a soil under drought and high temperature (42 C) conditions. Wanner measured CO_2 production in East Asian rain forest using methods similar to the technique used in this study and he observed rates between 120 - 300 mg $CO_2/m^2/hr$ (20). The high values obtained by Schultz may represent an extremely productive habitat or the clipping of the above ground parts may have stimulated soil and root respiration. Temperate zone values of 450, 220 and 1000 mg $CO_2/m^2/hr$ were observed on Missouri tall grass prairies (9), Tennessee oak forest (25), Minnesota forest (13) respectively.

The CO_2 values reported in this study represent the combined effect of soil fauna and flora. It is difficult, if not impossible at present, to measure the contribution of the individual components in the field. An unknown portion of the CO_2 collected in this study was CO_2 derived from respiration of above ground plant parts. Peterson and Billings claim that about one third of CO_2 from the trough habitat originates from above ground plant parts (12). During the freeze-up period when air temperatures are less than soil temperatures, the above ground CO_2 respiration component should decrease relative to below ground respiration output (2). Tundra plants have large root/shoot ratios (3) and therefore root respiration can be a large portion of below ground CO_2 output. MacFadyen has summarized the various estimations of soil and root respiration and he estimated that 15 - 50 percent of the soil respiration can be attributed to roots (10). The lower values were observed in forest ecosystems, whereas the upper values reflected grassland ecosystems. Kucera and Kirkham (9) examined tall grass prairie soil and concluded that 60 percent was produced by microbial components and the balance was attributed to root respiration. In their investigation a large part of the below ground CO_2 production in the trough habitat was probably produced by the root component. Since the ridge and basin habitats have a very limited root component because lichens and mosses dominate the flora, the soil microorganisms probably contribute a larger percent of the below ground CO_2 flux than was observed in the trough. When the plant components were stripped from the ridge and basin habitats, the CO_2 flux was only reduced by 9 percent in the ridge and 23 percent in the basin. These values represent a conservative estimate of the microbiological decomposition because the removal of the plant material also removed a significant portion of the soil microorganisms. Many of the estimates of soil decomposition vs. plant respiration do not consider the rhizosphere. Implicitly, many investigators consider the rhizosphere microorganisms as part of the plant root. During the freeze-up period there may be more root exudation and sloughing of plant cells in response to mechanical damage due to freezing and rhizosphere microorganisms may have more readily available energy sources released than is available during mid-summer. The soil layer of tundra will freeze from the permafrost up and from the surface down, therefore, the 15 cm soil depth may be the last portion of the system to freeze and as the freeze-up progresses a larger component of the CO_2 flux may be due to soil microorganisms than to plants.

Different methods used to determine CO_2 flux may produce different values. The alkali absorption method may underestimate CO_2 flux because of the lack of air turbulence in the test chamber, formation of artificial convection layers through temperature changes within the absorption chamber and changes in CO_2 diffusion rates caused by changes in the alkali during the test period (15). Haber noted that the alkali absorption technique could absorb 75 ± 4.65 percent of the CO_2 released in a defined chemical system (6). Kucera and Kirkham compared the relative recovery of CO_2 from the alkali absorption and infrared techniques on subsamples of the same field soils. The alkali absorption technique CO_2 flux values were 61.3% less than that observed by infrared analysis (9). The infrared technique requires the transmission of gas through the collection chamber and consequently CO_2 may be "pumped" out of the test system. The infrared method may overestimate the precise flux value but the criticism that the alkali absorption method underestimates the precise value is probably also valid. The comparable values of CO_2 from wet meadow by Peterson and Billings (12) and the alkali absorption method by Benoit (1) on the same dates on a similar soil at Barrow indicate the two methods gave similar results at lower temperatures, but the infrared method was more efficient in recovering CO_2 during the period when soil temperatures were at the seasonal maximum.

A close relation between soil temperature and CO_2 flux has been observed by numerous investigators (4,8,9,13,19,21,22,23,24). In this investigation a close relationship between soil temperature and CO_2 flux between the range of 10 C and -7 C was noted. Van Cleve and Sprague used the differential respirometer technique to measure respiration of Alaskan Boreal forest soil and observed zero respiration between the range of 1 and 5 C (19). Wiant noted that CO_2 production from Connecticut soil followed a Q_{10} of 2 between the temperatures of 20 to 40 C using an infrared gas analyzer (21). However, he was not able to detect any CO_2 production at 10 C. CO_2 flux from an <u>in situ</u> Missouri soil was determined using the infrared technique and noted a marked seasonal effect (9). The winter values of this Missouri study were equal to the maximum values obtained from tundra in this study. Wildung et al. used the alkali absorption technique to measure CO_2 flux during a two year period of soil from arid shrub-steppe (22). The winter values in this Washington state study showed lower CO_2 flux at 1 C than was observed at Barrow in this study at 1 C. However, the maximum CO_2 evolved during the summer period in Washington state was less than 50 percent the maximum rate shown in this tundra study. Douglas and Tedrow did not measure CO_2 production from tundra at Barrow during the late season, but they did note significant soil respiration during the period of soil thaw in June when soil temperatures were 0 - 4 C (4).

Benoit used a differential respirometer to measure soil respiration of Barrow soil between the range of -2 and 28 C and noted a Q_{10} of 1.8 over that range (1). The Q_{10} of soil respiration decreased in the temperature range of 28 to 37 C, but the Q_{10} increased in the range of -7 and -2 C. Soil respiration ceased at -7 C. Based upon the sub-zero celsius activity field values obtained in this study and the laboratory data of Benoit (1), the microflora of tundra soil appears to be physiologically capable of metabolism in the range of -7 to 0 C. If this hypothesis is correct, it provides the answer to why relatively high CO_2 values were obtained under the snow of tundra from the first snowfall until early December and also the period preceeding snow melt (8). Benoit observed that the number of bacteria in soil as measured by the aerobic spread plate technique was always at a seasonal maximum when the soil thaws in spring (1). Therefore, microorganisms not only carry on endogenous metabolism at sub-zero celsius conditions, but they may be capable of slow reproduction under these same conditions. The dynamics of soil microbiological growth has not been examined under freeze-up conditions.

Based upon theoretical grounds Vallentyne predicted that -18 C is the lower limit of active life on earth (18). Psychrophilic bacteria have been grown under laboratory conditions between 0 and -7 C (11). As the soil temperature drops below zero Celsius other inhibitory factors in soil affect microbial activity such as desiccation and increased ionic content of the water left in the unfrozen state, therefore, in tundra activity ceases before -18 C. The CO_2 flux observed during the freeze-up of tundra was consistant with the idea that microbial activity occurs through the period of the "zero window" and continues at a reduced rate when the soil-water mixture, known on tundra, passes through the physical transition of a slurry to a slush to a solid.

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Appendix I. Daily CO_2 Evolution (mg $CO_2/m^2/day^{-1}$) with Standard Deviations for Polygon Trough, Ridge and Basin During Freeze-up 1974 at IBP Site 4, Barrow, Ak.

Date (1974)	Trough	SD	Ridge	SD	Basin	SD
8-30	2782	104	2297	511	824	257
8-31	2925	122	2334	371	1102	144
9-1	2856	218	2715	281	965	191
9-2	2729	225	1860	723	743	186
9-3	2450	375	1708	611	571	222
9-4	1867	165	1054	374	779	147
9-5	1914	546	1291	386	693	184
9-6	1893	447	1331	651	537	232
9-7	1946	516	1247	464	648	84
9-8	1722	351	943	229	725	85
9-9	1521	479	1096	450	623	118
9-10	1615	353	1422	702	617	139
9-11	1777	211	1802	841	528	107
9-12	1933	243	1261	442	596	55
9-13	1213	344	1063	620	617	151
9-14	1311	386	1118	508	613	132
9-15	1181	154	1257	673	531	148
9-16	1230	287	833	207	677	159
9-17	1316	305	1056	421	492	94
9-18	1700	277	1470	682	453	33
9-19	1593	100	1524	700	538	117
9-20	1812	210	1545	422	669	59
9-21	1619	378	1529	411	574	122
9-22	1526	293	1191	319	535	90
9-23	1169	119	1377	647	504	116
9-24	1029	293	785	186	772	140
9-25	847	386	667	150	418	172
9-26	848	383	682	352	607	214
9-27	761	225	1143	659	665	266
9-28	1253	399	814	342	627	375
9-29	1046	446	831	354	385	163
9-30	1075	296	1073	420	354	137
10-1	861	123	1527	187	428	263
10-2[a]	861	123	1527	187	428	263
10-3	695	246	393	75	207	77
10-4	644	158	435	146	300	70
10-5	578	97	330	0	265	87
10-6[a]	578	97	330	0	265	87
10-7	378	83	649	425	270	113
10-8	501	239	366	122	228	53
10-9	532	229	459	242	303	156
10-10	470	150	714	351	200	53

[a] 48 hr sampling due to extreme weather conditions.

Appendix I. (continued)

Date (1974)	Trough	SD	Ridge	SD	Basin	SD
10-11	519	86	714	278	307	194
10-12	689	269	466	67	366	200
10-13	304	45	414	172	310	174
10-14	311	134	350	211	233	113
10-15	200	48	377	121	185	138
10-16	311	176	214	97	192	88
10-17	230	110	256	157	209	119
10-18	203	91	182	92	178	58
10-19	131	65	182[a]	92	178[a]	58

[a] 48 hr sampling due to extreme weather conditions.

Appendix II. Daily Significant Subsets at the 5% Level for Polygon Trough (T), Ridge (R) and Basin (B) During Freeze-up 1974 at IBP Site 4, Barrow, Ak.

(1974) Date	Subset 1	Subset 2	Subset 3	Date	Subset 1	Subset 2	Subset 3
8-30	B	TR		9-25	BRT		
8-31	B	R	T	9-26	BRT		
9-1	B	TR		9-27	BRT		
9-2	B	R	T	9-28	BR	TR	
9-3	B	R	T	9-29	BR	TR	
9-4	BR	T		9-30	B	TR	
9-5	BR	TR		10-1	B	T	R
9-6	B	TR		10-2	B	T	R
9-7	BR	T		10-3	BR	T	
9-8	BR	T		10-4	BR	TR	
9-9	BR	TR		10-5	BR	TR	
9-10	B	TR		10-6	BR	TR	
9-11	B	TR		10-7	BRT		
9-12	B	R	T	10-8	BR	TR	
9-13	BRT			10-9	BRT		
9-14	BR	TR		10-10	BT	TR	
9-15	B	TR		10-11	BT	TR	
9-16	BR	T		10-12	BRT		
9-17	B	TR		10-13	BRT		
9-18	B	TR		10-14	BRT		
9-19	B	TR		10-15	BRT		
9-20	B	TR		10-16	BRT		
9-21	B	TR		10-17	BRT		
9-22	B	TR		10-18	BRT		
9-23	B	TR		10-19	BRT		
9-24	BRT						

Appendix III. Daily CO_2 Evolution (mg $CO_2/m^2/day^{-1}$) with Standard Deviations for Polygon Basin, Basin No Canopy with PO_4 and Basin No Canopy Without PO_4 During Freeze-up 1974 at IBP Site 4, Barrow, Ak.

(1974) Date	Basin	SD	Basin No canopy with PO_4	SD	Basin No canopy without PO_4	SD
8-30	824	257	576	57	642	126
8-31	1102	144			624	101
9-1	965	191			529	80
9-2	743	186	391	42	407	143
9-3	571	222	335	46	506	237
9-4	779	147			470	258
9-5	693	184			423	104
9-6	537	232	401	110	402	55
9-7	648	84	426	22	605	326
9-8	725	85			503	219
9-9	623	118			407	54
9-10	617	139	406	96	412	53
9-11	528	107	342	17	388	99
9-12	596	55			444	241
9-13	617	151			410	117
9-14	613	132	312	82	410	49
9-15	531	148	236	69	470	243
9-16	677	159			417	229
9-17	492	94			334	112
9-18	453	33	340	164	301	43
9-19	538	117	334	24	410	114
9-20	669	59			317	71
9-21	574	122			298	38
9-22	535	90	375	154	311	71
9-23	504	116	438	102	481	197
9-24	772	140			582	287
9-25	418	172			323	81
9-26	607	214	619	312	365	175
9-27	665	266	517	79	407	167
9-28	627	375			280	123
9-29	385	163			268	122
9-30	354	137	438	400	166	80
10-1	428	263	276	156	236	101
10-2[a]	428	263	276	156	236	101
10-3	207	77			308	307
10-4	300	70			316	150
10-5	265	87			245	170
10-6[a]	265	87			245	170
10-7	270	113	211	97	298	167
10-8	228	53			158	86
10-9	303	156			174	39

[a] 48 hr sampling due to extreme weather conditions.

Appendix III. (continued)

(1974) Date	Basin	SD	Basin No canopy with PO_4	SD	Basin No canopy without PO_4	SD
10-10	200	53	130	107	136	52
10-11	307	194	315	203	171	105
10-12	366	200			257	158
10-13	310	174			269	39
10-14	233	113	99	43	188	80
10-15	185	138	85	74	144	84
10-16	192	88			181	83
10-17	209	119			194	123
10-18	178	58	149	43	199	33
10-19[a]	178	58	149	43	199	33

[a] 48 hr sampling due to extreme weather conditions.

Appendix IV. Daily Significant Subsets at the 5% Level for Polygon Basin (A), Basin No Canopy with PO_4 (B) and Basin No Canopy without PO_4 (C) During Freeze-up 1974 at IBP Site 4, Barrow, AK.

Date (1974)	Subset 1	Subset 2	Subset 3
8-30	ABC		
8-31	A	C	
9-1	A	C	
9-2	A	BC	
9-3	ABC		
9-4	A	C	
9-5	A	C	
9-6	ABC		
9-7	ABC		
9-8	A	C	
9-9	A	C	
9-10	A	BC	
9-11	A	BC	
9-12	AC		
9-13	A	C	
9-14	A	BC	
9-15	AC	BC	
9-16	A	C	
9-17	A	C	
9-18	ABC		
9-19	AC	BC	
9-20	A	C	
9-21	A	C	
9-22	AB	BC	
9-23	ABC		
9-24	AC		
9-25	AC		
9-26	ABC		
9-27	ABC		
9-28	AC		
9-29	AC		
9-30	ABC		
10-1	ABC		
10-2	ABC		
10-3	AC		
10-4	AC		
10-5	AC		
10-6	AC		
10-7	ABC		
10-8	AC		
10-9	AC		
10-10	ABC		
10-11	ABC		
10-12	AC		
10-13	AC		
10-14	ABC		
10-15	ABC		
10-16	AC		
10-17	AC		
10-18	ABC		
10-19	ABC		

Appendix V. Daily CO_2 Evolution (mg $CO_2/m^2/day^{-1}$) with Standard Deviations for Polygon Ridge, Ridge No Canopy with PO_4 and Ridge No Canopy without PO_4 During Freeze-up 1974 at IBP Site 4, Barrow, AK.

Date (1974)	Ridge	SD	Ridge No canopy with PO_4	SD	Ridge No canopy without PO_4	SD
8-31	2334	371	2139	708	2266	843
9-1	2715	281	2170	536	2147	791
9-4	1054	374	1727	788	1580	953
9-5	1291	386	934	260	1117	772
9-8	943	229	1495	859	1339	881
9-9	1096	450	820	213	903	653
9-12	1261	442	1740	835	1615	914
9-13	1063	620	825	292	721	271
9-16	833	207	1505	861	1204	877
9-17	1056	421	865	344	514	85
9-20	1545	422	1819	718	1650	787
9-21	1529	411	1145	253	1152	692
9-28	814	342	1148	898	1179	503
9-29	831	354	1041	628	1344	1019
10-3	393	75	2109	1044	1479	954
10-4	435	146	857	707	1089	1088
10-8	366	122	683	235	1225	552
10-9	459	242	542	252	646	633
10-12	466	67	509	274	1177	670
10-13	414	172	465	252	372	207
10-16	214	97	525	175	565	151
10-17	256	157	422	230	369	165

Appendix VI. Daily Significant Subsets at the 5% Level for Polygon Ridge (A), Ridge No Canopy with PO_4 (B) and Ridge No Canopy without PO_4 (C) During Freeze-up 1974 at IBP Site 4, Barrow, AK.

Date (1974)	Subset 1	Subset 2	Subset 3
8-31	ABC		
9-1	ABC		
9-4	ABC		
9-5	ABC		
9-8	ABC		
9-9	ABC		
9-12	ABC		
9-13	ABC		
9-16	ABC		
9-17	ABC	BC	
9-20	ABC		
9-21	ABC		
9-28	ABC		
9-29	ABC		
10-3	AC	BC	
10-4	ABC		
10-8	AB	BC	
10-9	ABC		
10-12	ABC		
10-13	ABC		
10-16	ABC		
10-17	ABC		

Appendix VII. Daily Minimum, Maximum and Mean Soil Temperatures at 5 cm Depth of Tundra During Freeze-up 1974 at IBP Site 4, Barrow, AK.

Date (1974)	Minimum	Maximum	Mean	Date	Minimum	Maximum	Mean
8-29	5.8	10.6	9.5	9-28	1.4	2.0	1.8
9-7[a]	0.6	5.0	2.15	9-29	1.6	2.2	1.8
9-8	0.8	3.4	1.9	9-30	1.4	1.8	1.8
9-9	1.0	3.2	1.8	10-1	0.6	1.4	1.2
9-10	1.0	2.4	1.5	10-2	0.4	1.4	0.9
9-11	1.0	3.6	1.8	10-3	-0.4	0.4	-0.1
9-12	1.6	2.4	2.0	10-4	-0.6	0.2	-0.3
9-13	1.6	2.0	1.8	10-5	-2.8	-1.4	-2.2
9-14	1.4	2.0	1.6	10-6	-3.2	-2.6	-3.0
9-15	1.4	1.4	1.4	10-7	-2.4	-0.2	-1.1
9-16	1.4	1.8	1.7	10-8	-0.6	0.4	-0.2
9-17	1.6	2.8	2.0	10-9	-0.4	0.6	0.1
9-18	1.6	4.2	2.7	10-10	0.4	1.4	0.8
9-19	1.6	8.0	4.1	10-11	-0.2	1.6	0.7
9-20	1.8	7.4	4.2	10-12	-0.8	-0.2	-0.5
9-21	2.4	5.6	4.1	10-13[a]	-	-	-
9-22	1.0	2.0	1.5	10-14	-5.2	-4.8	-5.0
9-23	0.4	1.0	0.8	10-15	-5.6	-5.2	-5.4
9-24	0.4	1.0	0.6	10-16	-6.6	-5.6	-6.0
9-25	0.2	0.6	0.4	10-17	-5.6	-4.2	-4.9
9-26	0.2	0.4	0.4	10-18	-7.4	-5.6	-6.5
9-27	0.6	1.8	1.2				

[a] recorder malfunction.

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IN SITU CARBON DIOXIDE FLUX FROM ARCTIC TUNDRA DURING FREEZE-UP

by

Tyree Woodrow Kessler, Jr.

(ABSTRACT)

The relationship between soil temperature and CO_2 flux from undisturbed soil cores was examined during freeze-up of arctic tundra. Three habitats which dominate tundra topography, polygon trough, ridge and basin, produced significantly different amounts of CO_2 when soil temperatures were above 0 C. A significant positive correlation between soil temperatures between 10 to -7 C and CO_2 flux from each habitat was established. Substantial quantities of CO_2 were produced during freeze-up period when soil temperatures remained near 0 C for an extended period, and the CO_2 production continued at reduced levels as the soil temperature dropped below 0 C. When soil temperatures reached -7 C and the study was terminated, the CO_2 flux was reduced to a low level, but did not reach extinction. A maximum CO_2 flux of 2925 mg CO_2/m^2/day from the trough habitat was observed when the soil temperature was 10 C, and the minimum CO_2 flux of 131 mg/m^2/day was observed when the soil temperature was -7 C. These data are consistant with the hypothesis that soil microorganisms in arctic tundra are capable of physiological activity in the range of 0 to -7 C.