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Dr. Walter Oechel

Response of a Tundra Ecosystem to Elevated Atmospheric Carbon Dioxide and CO₂-Induced Climate Change

A Continuation Proposal

Submitted to:

U.S. Department of Energy
Office of Health and Environmental Research

Submitted on behalf of:

Dr. Walter C. Oechel
Department of Biology
San Diego State University

Submitted by:

San Diego State University Foundation
San Diego, CA 92182

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February, 1993

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San Diego State University Foundation
San Diego, CA 92182

Principal Investigator:

Dr. Walter C. Oechel
Department of Biology
San Diego State University
San Diego, CA 92182-0057

Telephone: (619) 594-4818

Facsimile: (619) 594-7831

E-mail(internet): oechel@sunstroke.sdsu.edu

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ABSTRACT

Northern ecosystems contain up to 455 Gt of C in the soil active layer and upper permafrost, which is equivalent to approximately 60% of the carbon currently in the atmosphere as CO₂. Much of this carbon is stored in the soil as dead organic matter. Its fate is subject to the net effects of global change on the plant and soil systems of northern ecosystems. The arctic alone contains about 60 Gt C, 90% of which is present in the soil active layer and upper permafrost, and is assumed to have been a sink for CO₂ during the historic and recent geologic past.

In situ experimental manipulations of atmospheric CO₂ indicate that there is little effect of elevated atmospheric CO₂ on leaf level photosynthesis (Tissue and Oechel, 1987) or whole-ecosystem CO₂ flux (Oechel and Billings, 1992; Oechel *et al.*, 1993) over the course of weeks to years, respectively. However, there may be longer-term ecosystem responses to elevated CO₂ that could ultimately affect ecosystem CO₂ balance (Oechel and Billings, 1992). In addition to atmospheric CO₂, climate change may have a significant effect on net ecosystem carbon balance.

Depending on the nature, rate, and magnitude of global environmental change, the arctic may have a positive or negative feedback on global change. Results from the DOE-funded research efforts of 1990 and 1991 indicate that the arctic has become a source of CO₂ to the atmosphere. Measurements made in the Barrow, Alaska region during 1992 support these results. This change coincides with recent climatic variation in the arctic, and suggests a positive feedback of arctic ecosystems on atmospheric CO₂ and global change. There are obvious potential errors in scaling plot level measurements to landscape, mesoscale, and global spatial scales.

In light of the results from the recent DOE-funded research, and the remaining uncertainties regarding the change in arctic ecosystem function due to high latitude warming, a revised set of research goals is proposed for the 1993-94 year. The research proposed in this application has four principal aspects:

- ✓ A) Long-term response of arctic plants and ecosystems to elevated atmospheric CO₂.
- B) Circumpolar patterns of net ecosystem CO₂ flux.
- C) *In situ* controls by temperature and moisture on net ecosystem CO₂ flux.
- D) Scaling of CO₂ flux from plot, to landscape, to regional scales (in conjunction with research proposed for NSF support).

In Iceland, we have begun to evaluate the long-term (hundreds to thousands of years) effect of atmospheric CO₂ enrichment from cold, CO₂-rich springs on plant photosynthesis, ecosystem CO₂ flux, and community composition and structure.

CO₂ flux estimates at a circumpolar scale will be initiated with research in the Russian arctic and Iceland. Measurements in Iceland will be obtained in the process of determining the long-term effect of elevated CO₂ on arctic ecosystems.

Temperature and moisture will be manipulated in the field to determine their effects on net ecosystem CO₂ flux. The equipment and methodology was extensively tested during the 1992 field season.

In cooperation with a project funded from NSF's ARCSS LAII program, CO₂ and other trace gas flux measurements will be carried out at the plot, landscape, and mesoscale levels using

chamber, tower-based eddy correlation, and aircraft-based eddy correlation techniques, respectively during the 1993-1995 field seasons on the north slope of Alaska (Fig. 1). The information obtained from each of these techniques will be analyzed and compared to define the most efficient approaches for estimating large spatial scale CO₂ flux in the arctic. Remotely-sensed spectral indices, GIS, process models, and phenomenological models will be used to develop a methodology for efficiently estimating ecosystem CO₂ flux over meso- and global scales. Initial testing of the applicability of these methods will be undertaken. Support from the Department of Energy will be for plot level measurements. NSF is supporting the other aspects of scaling.

PROGRESS REPORT

Results to Date

The vast majority of the organic carbon found in northern ecosystems ($\approx 83\%$) is present in the soil as dead organic matter in the seasonally thawed upper soil layers (soil active layer), and in the uppermost layers of the permanently frozen ground (permafrost). Northern ecosystems (arctic, boreal forest, and northern bogs) contain up to 455 Gt of C (1 gigaton (Gt) = 1 petagram = 10^{15} g) in the permafrost and soil active layer (Miller, 1981; Miller *et al.*, 1983; Gorham, 1991; Oechel and Billings, 1992), an amount which may be as much as 60% of the approximately 750 Gt C currently in the atmosphere as CO₂. Arctic tundra ecosystems alone contain about 60 Gt C as living and dead organic matter, 90% of which is present belowground in the soil active layer and upper permafrost layers as dead organic matter.

Net carbon accumulation or loss is the balance between gross primary productivity (photosynthesis), plant and soil respiration, and losses to herbivory which are generally very small. Net primary productivity often exceeds heterotrophic respiration in northern ecosystems (Gorham, 1991; Oechel and Billings, 1992). As a result, these ecosystems in the historic and recent geologic past have been net sinks for carbon with respect to the atmosphere of about 0.1 to 0.3 Gt C per year (Schell, 1983; Schell and Ziemann, 1983; Marion and Oechel, *accepted for publication*; Miller *et al.*, 1983; Post, 1990; Gorham, 1991; Oechel and Billings, 1992). Tussock tundra is the largest store of carbon in arctic terrestrial ecosystems (29.1 Gt C), and was estimated to be accumulating carbon at the rate of $23 \text{ g C m}^{-2} \text{ y}^{-1}$ (0.02 Gt C per year worldwide), while wet tundra was estimated to contain 14.4 Gt C worldwide, and to be accumulating carbon at the rate of $27 \text{ g C m}^{-2} \text{ y}^{-1}$, or 0.03 Gt C per year worldwide (Miller *et al.*, 1983; Oechel and Billings, 1992). Higher rates of carbon uptake ($40\text{--}120 \text{ g C m}^{-2} \text{ y}^{-1}$) were estimated from cuvette measurements of photosynthesis and respiration, and from aerodynamic measurements of ecosystem CO₂ flux made during the U.S. IBP in Alaska (Chapin *et al.*, 1980; Coyne and Kelley, 1975).

Recent measurements of CO₂ flux in arctic ecosystems indicate that tussock and wet tundra are now sources of CO₂ to the atmosphere (Fig. 2), possibly as a result of a recent change in climatic patterns (Oechel *et al.*, 1991a and b, 1993). The magnitude of efflux was found to increase from north to south, primarily due to the increase in temperature and the decrease in soil moisture which is superimposed on this latitudinal gradient. Sink strength of these ecosystems is greatest during the mid-season period (Fig. 2), when environmental conditions are most favorable and plants have reached their seasonal photosynthetic maximum. This may be the first significant observation of a major variation in ecosystem function from greenhouse warming and associated

Fig. 1. Research sites for plot chamber measurements (triangles), tower eddy correlation landscape measurements (Prudhoe Bay and Happy Valley), and proposed flight lines for aircraft-based eddy correlation measurements (dashed lines).

global change. However, there are uncertainties in extrapolating these plot level observations to regional and global scales.

Low temperatures, reduced rates of actual evapotranspiration, and impeded drainage (often due to the impervious layer created by permafrost) frequently result in cold, saturated soils near the surface, despite low rates of precipitation. These conditions result in decreased rates of soil decomposition, especially at depth in the soil (Gorham, 1991; Clymo, 1984). As soil organic matter accumulates, permafrost migrates upward incorporating and freezing new organic material. The decomposition rate of the organic matter in the permafrost is near zero, removing carbon from biospheric circulation for thousands of years or until the permafrost melts.

Fig. 2. Seasonal net ecosystem CO₂ flux as a function of latitude on the north slope of Alaska during the 1990 (top panel) and 1991 (bottom panel) growing seasons.

Under future conditions of elevated CO₂ and global climate change, northern ecosystems could become a sink for carbon, providing a negative feedback on atmospheric CO₂. It is likely, however, that northern ecosystems will be a source of CO₂ and will have a positive feedback on the global climate (Billings, *et al.*, 1982; Post, 1990; Oechel and Billings, 1992).

Climate change could result in higher temperatures and altered precipitation which could possibly increase the depth of the soil active layer and water table, resulting in warmer soil temperatures and greater soil aeration. These factors could increase soil decomposition rates (Silvola, 1986; Gorham, 1991; Billings *et al.*, 1982, 1983, 1984; Billings and Peterson, 1992). If soil decomposition increases more rapidly than net primary production, the system ceases to be a carbon sink and becomes a carbon source.

High latitude ecosystems are anticipated to undergo the most significant increases in surface temperature with a doubling of atmospheric CO₂. Surface temperature increases of 4°C in summer and as much as 17°C in winter have been predicted for northern latitudes (Mitchell *et al.*, 1990; Schlesinger and Mitchell, 1987). Although clouds and water vapor may feed back and limit the increase by as much as 50%, there is a general consensus of significantly higher temperatures in the arctic. These projected increases in temperature are of importance in both the absolute and relative sense.

Global warming may already be occurring in arctic Alaska, where current temperatures appear warmer than in the historic or recent geologic past. Thermal profiles in the permafrost indicate a temperature rise across the north slope of Alaska of 2-4°C within the last century, and most likely within the last few decades (Lachenbruch and Marshall, 1986). Weather records indicate a distinct warming trend in much of the Canadian arctic and boreal forest (Hengeveld, 1991). Analysis of summer temperatures at Barrow (71°18' N, 156°47' W) for the last 70 years (1921-1990) and Prudhoe Bay, Alaska for the last 20 years (1969-1990) shows a trend of increasing temperatures culminating in the warmest summer temperatures on record (Oechel *et al.*, 1993).

While it is impossible to definitively ascribe these recent temperature increases to greenhouse warming of the atmosphere, it is clear that current arctic temperatures are elevated over those of the historic and recent geologic past. The temperature increases are not inconsistent with global climate model predictions for greenhouse warming, given the 25% rise in atmospheric CO₂ and higher atmospheric methane and other trace gas concentrations which have occurred since the initiation of the Industrial Revolution. Summer increases of 2-4°C would result in well above mean summer temperatures experienced by these ecosystems in the historic and recent geologic past, and would have profound impacts on ecosystem structure and function.

Our past DOE research has documented short-term changes in the photosynthetic response of arctic plants grown under controlled conditions on the time scale of minutes to months (Oberbauer *et al.*, 1986). Plants grown at a CO₂ concentration of 350 ppm but measured at 675 ppm showed a CO₂ enhancement of photosynthesis. However, after two months, plants grown at 675 ppm, with photosynthesis measured at the same high growth CO₂ concentration, exhibited similar rates to those grown and measured at 350 ppm CO₂. A prolonged enhancement of photosynthesis by elevated CO₂ generally requires that nutrients are abundant (Oechel and Strain, 1985), temperatures are warm (Kimball *et al.*, 1986), or water is limited (Oechel and Strain, 1985). Biomass attributes of the plants in the growth chamber study were strongly enhanced by nutrients, but there was no interaction between nutrition and CO₂ concentration (Oberbauer *et al.*, 1986). Increased nutrients had little or no effect on maintaining a CO₂ enhancement of photosynthesis. This suggests that the physiological limitations to use additional CO₂ may be inherent to the arctic species studied.

The results of the growth chamber studies are similar to those of plants treated and measured in the field (Tissue and Oechel, 1987) using a similar time scale. In the field, *Eriophorum vaginatum* showed a nearly perfect homeostatic adjustment to higher CO₂ levels (Oechel *et al.*, 1992). This pattern may reflect the carbohydrate sufficiency in *E. vaginatum* and many other arctic plants (Shaver and Chapin, 1980; Chapin *et al.*, 1986; Tissue and Oechel, 1987). Without adequate sinks, accumulated carbohydrates may feed back to reduce the amount of RuBP with a concomitant reduction in photosynthesis (Tissue and Oechel, 1987). An increase in temperature and CO₂ did not stimulate the field plants with respect to leaf area (Tissue and Oechel, 1987). However, a nearly threefold increase in tiller production was observed in the plants grown under elevated vs. ambient CO₂. This could profoundly affect plant population dynamics, competition, species composition, biomass, and production (Tissue and Oechel, 1987).

When the water table was held constant in field microcosms, elevated temperature resulted in greater net ecosystem carbon sequestering under elevated atmospheric CO₂. In laboratory microcosms under ambient CO₂, elevated temperature caused a reduction in net carbon sequestering. This reduction was larger where the water table was lower (Oechel and Billings, 1992). These results indicate the importance of soil temperature and moisture on ecosystem C balance.

Information regarding the controls on photosynthesis of individual plants in laboratory and field microcosms, can to a degree, be used to predict whole-ecosystem response to elevated CO₂ and climate change. However, the time period for adjustment of whole-ecosystem flux to elevated CO₂ was found to be on the order of one to three years (Oechel and Riechers, 1986; Grulke *et al.*, 1990) and even longer-term processes may be important in controlling carbon flux with respect to global change. These longer-term processes include changes in population dynamics, competition, ecosystem composition, ecotypic differentiation, vegetation migration, and natural selection (Oechel and Billings, 1992; Oechel *et al.*, 1992).

We have measured whole-ecosystem CO₂ flux over seven seasons (1983-1985, 1987, 1990, and 1991) at Toolik Lake and along a latitudinal transect in 1990 and 1991, from the Arctic Ocean at Prudhoe Bay to Toolik Lake, Alaska. During 1992, we re-sampled the IBP-II site in the Barrow, Alaska region (Fig. 3) to determine if ecosystem CO₂ flux had changed over the last two decades, and to determine if the change in C balance observed in other wet sedge ecosystems was general for arctic Alaska. We report current rates of CO₂ flux from tussock tundra and wet tundra ecosystems and consider possible effects of global change on future carbon balance.

Current Rates of CO₂ Flux in the Barrow, Alaska Region

Intensive measurements of whole-ecosystem CO₂ flux and respiration were carried out during the 1992 sampling season at the IBP-II sites and the Coyne and Kelley (1975) eddy correlation tower site at Central Marsh (Fig. 3). Net ecosystem CO₂ flux and whole-ecosystem respiration was measured with a closed gas exchange system described above (Vourlitis *et al.*, *in press*). Flux measurements were repeated every 1-1.5 hours over a 24- or 48-hour cycle, every 5-7 days between 25 June and 30 August. Diurnal CO₂ flux was calculated by integrating hourly measurements over the 24- or 48-hour cycle.

Efflux of CO₂ to the atmosphere was generally greatest during late night and early morning hours, while accumulation was greatest during mid-day (Fig. 4). Photosynthetic rates increased relative to whole-ecosystem respiration as light intensity increased during the early to mid-morning hours, and the systems became net sinks for CO₂ (Fig. 4). As soil temperatures increased during early afternoon, CO₂ accumulation decreased as respiration rates increased relative to

Fig. 3. Study sites used during the 1992 field season in the Barrow, Alaska region.

Fig. 4. Diurnal trend in net ecosystem CO_2 flux ($\square$), whole-ecosystem respiration ($\blacksquare$), GPP ($\blacklozenge$), light intensity, and soil temperature at depth of 10 cm ($\square$), 5 cm ($\blacklozenge$), and at the soil surface ($\blacksquare$) on 16 and 17 July, 1992 in moist meadow wet sedge tundra. Data are means $\pm$ 1 SE, $n=3$.

photosynthetic rates (Fig. 4). Sites became net sources of CO₂ to the atmosphere as light intensity diminished during the evening hours.

Seasonal C loss was highest in high center polygon habitats (Table 1). High-centered polygons lost approximately 14 ± 5 gC m⁻² during the 1992 growing season. Moist and wet meadows and low-center polygons were on average slight sources during 1992, while ice wedges were slight sinks (Table 1).

We believe that the change from carbon accumulation to carbon loss in these arctic ecosystems is not directly due to a rise in temperature, but instead results from indirect effects of increased temperature which causes enhanced drainage and soil aeration, and a decrease in the water table (Oechel and Billings, 1992; Post, 1990). IBP sites during the 1991 and 1992 sampling years were significantly drier compared to conditions experienced during the early 1970's (Oechel, SDSU, personal observation). Gersper *et al.* (1980) reported that these soils were almost completely saturated during the summers of 1970-1972 within the 5-15 cm depth interval. In 1992, however, only ice wedge habitats were saturated during the early and middle season periods, and water table depth was only slightly higher than the permafrost depth.

Table 1. Net ecosystem CO₂ flux (means $\pm$ 1 SE) during the 1992 growing season. Positive values indicate net CO₂ efflux, while negative values indicate net accumulation of atmospheric CO₂. Seasonal flux was calculated by integrating daily totals over the period of snow melt to the first significant snowfall, which is assumed to correlate with soil freezing. The beginning and end of season dates are based on surface albedo changes monitored by the NOAA Climate Lab near Barrow. Flux measurements were not made on the beginning and end of season dates (13 June and 14 September, respectively = 93 days), and CO₂ flux was assumed to equal zero on these dates. Water table depth is an annual average $\pm$ SD for the season.

Habitat Type [†]	Dominant Vegetation	Water Table Depth (cm)	Net CO ₂ Flux gC m ⁻² Season ⁻¹
High Center	<i>Carex aquatilis</i> / <i>Eriophorum russeolum</i>	-12.8 $\pm$ 4.0	13.9 $\pm$ 4.9
Ice Wedge	<i>Carex aquatilis</i> / <i>Dupontia fischeri</i>	-6.5 $\pm$ 6.9	-4.0 $\pm$ 4.4
Low Center	<i>Carex aquatilis</i> / <i>Eriophorum angustifolium</i>	-15.5 $\pm$ 7.9	3.6 $\pm$ 4.5
Moist Meadow	<i>Carex aquatilis</i> / <i>Dupontia fischeri</i>	-9.3 $\pm$ 6.8	1.3 $\pm$ 3.7
Wet Meadow	<i>Arctophila fulva</i> / <i>Dupontia fischeri</i>	-6.3 $\pm$ 4.5	6.0 $\pm$ 7.4

[†]n=3 for high- and low-center polygons and moist meadow habitats; n=2 for ice wedge and wet meadow habitats.

Carbon efflux was greatest during the early and late season periods when rates of primary productivity were low (Fig. 5). Ecosystem sink strength was at a maximum during the month of July, as plants neared their seasonal potential photosynthetic peak and environmental conditions became more suitable for plant growth (Fig. 5). As the season progressed, GPP decreased relatively more than respiration, and each habitat became more of a source of CO₂ to the atmosphere (e.g. early August; Fig. 5). The decrease in GPP was probably due to the decrease in mean daily photosynthetically active radiation (PAR) and the onset of quiescence (Fig. 5). Whole-ecosystem respiration remained high through August, as average daily soil temperatures were generally above the seasonal mean (dotted line, Fig. 5), and water table depth reached its lowest point (Fig. 5). This combination of phenological and environmental conditions would act to reduce ecosystem sink strength relative to respiration, and promote greater rates of net ecosystem C loss.

Fig. 5. Seasonal trend in net ecosystem CO₂ flux (□), whole-ecosystem respiration (■), and GPP (◆), light intensity, soil temperature (10 cm), and water table depth in polygonized wet sedge tundra. Carbon flux and water table data are means $\pm$ 1 SE, $n = 3$. Light intensity and soil temperature data are daily means; daily means are averages of 24-1 hour intervals.

Direct comparisons between the plot level measurements reported here and aerodynamic measurements made by Coyne and Kelley (1975) over a comparable growing season indicate that the sink strength of these ecosystems has diminished significantly over the past 20 years (Fig. 6). Wet meadow ecosystems were reported to accumulate approximately $25 \text{ gC m}^{-2} \text{ season}^{-1}$ in 1971 (Coyne and Kelley, 1975), while the current ecosystems are now sources of approximately $6 \text{ gC m}^{-2} \text{ season}^{-1}$ (Fig. 6). Peak of season sink strength appears to have completely diminished, as the current ecosystem was actually a slight source during this period (Fig. 6). For example, these wet meadow ecosystems accumulated on average $1.5 \text{ gC m}^{-2} \text{ day}^{-1}$ during late July of 1971 (Coyne and Kelley 1975; Fig. 6). In contrast, the current ecosystems were found to accumulate only about $0.3 \text{ gC m}^{-2} \text{ day}^{-1}$ during the same period in 1991, and lose approximately $0.1 \text{ m}^{-2} \text{ day}^{-1}$ during 1992. These results point to a consistent reduction in sink strength during the mid-season peak in ecosystem productivity, and a concomitant reduction in overall seasonal C accumulation.

Fig. 6. Seasonal net CO₂ flux measured in wet meadow ecosystems during the 1971 (□) Coyne and Kelley, 1975) and 1992 (■) growing seasons. Data are daily CO₂ flux totals calculated over a 24-hour period. Positive values indicate net CO₂ efflux, while negative values indicate net accumulation of atmospheric CO₂. Data for 1992 are means ± 1 SE, $n = 2$.

These results represent a change in ecosystem functioning, possibly due to greenhouse warming and concomitant alteration of site water balance. These ecosystems are particularly susceptible to high latitude warming, due to the controlling presence of permafrost, and the huge soil C stocks. The change in the rate and direction of C flux has the potential to feed back on global atmospheric CO₂ concentration and global warming.

Measurement of Cold CO₂-enriched Springs in Iceland and Plant Photosynthetic Response to Long-term Exposure to Elevated CO₂

A joint U.S./Icelandic team surveyed the cold, CO₂-rich springs on the Snaefellsnes Peninsula in Iceland during the spring and summer of 1992 to locate suitable springs for intensive study describing the long-term photosynthetic acclimation to elevated CO₂. Selection criteria for spring suitability was based on:

1. Minimal disturbance to the spring and the surrounding vegetation.

2. CO₂ levels released by the spring must be similar to levels predicted for the middle of the next century.
3. Springs must be cold to exclude any confounding effects of elevated temperature.
4. Springs must be free of other contaminating gases such as CO and SO₂.
5. Springs must be free of other cations (e.g. NH₄⁺) or anions (NO₃⁻, PO₄⁻).
6. Springs must be logistically easy to sample and research.

During the 1992 field season, the spring of Olafsvik, located on the northern portion of the Snaefellsnes Peninsula was studied most intensively. A second spring which fit the selection criteria, Bjarnarfoskot, on the southern side of the Snaefellsnes Peninsula, was located as well.

Water samples from Olafsvik spring were collected and analyzed during 1992, and the spring was found to be virtually free of contaminating gases, cations, or anions (Table 2). Efflux of CO₂ was determined at Olafsvik using a LI-COR 6200 portable photosynthesis system over 16 hour periods on both calm and windy days. Preliminary measurements indicate that the vegetation in some areas surrounding the spring are constantly exposed to elevated CO₂ (Table 3).

Table 2. Water chemistry of Olafsvik spring. ND = below detection limits.

		Sample 1	Sample 2	Detection Limit
Gas Composition (%)	Oxygen/Argon	4.1	3.3	0.01
	Nitrogen	15.5	13	0.01
	Carbon monoxide	ND	ND	0.01
	Methane	ND	ND	0.001
	Carbon dioxide	80.4	83.6	0.01
Contaminants (ppm)	Hydrogen sulfide	ND	ND	0.5
	Carbonyl sulfide	4.5	5.9	0.1
	Carbon disulfide	ND	ND	0.5
	Dimethyl sulfide	ND	ND	0.1
	Dimethyl disulfide	ND	ND	0.1
	Methyl mercaptan	ND	ND	0.1
	Ethyl mercaptan	ND	ND	0.1
	Propyl mercaptan	ND	ND	0.1
	Ammonium	ND	ND	0.2
Cations (ppm)	Calcium	12.0	12.0	0.2
	Lithium	ND	ND	0.2
	Magnesium	3.2	3.1	0.2
	Potassium	0.78	0.78	0.2
	Sodium	12.0	12.0	0.2
Anions (ppm)	Bromide	ND	ND	0.2
	Chloride	16.0	16.0	0.2
	Fluoride	ND	ND	0.2
	Nitrite	ND	ND	0.2
	Nitrate	ND	ND	0.2
	Orthophosphate	ND	ND	0.2
	Sulfate	3.9	4.0	0.2
	Boron	ND	ND	0.09

Table 3. Mean and range of CO₂ concentrations sampled over a 16-hour period under calm (21 August) and windy (21 August) conditions during the 1992 field season at a mineral spring in Olafsvik, Iceland.

Sample Point	Windy Day- 21 August, 1992		Calm Day- 22 August, 1992	
	Mean [CO ₂] (ppm)	Range	Mean [CO ₂] (ppm)	Range
A	373	364-396	419	388-454
B	390	361-423	405	383-433
C	398	370-466	426	368-489
D	439	365-646	429	393-460
E	487	392-625	532	462-602
F	612	478-852	570	481-693
G	430	408-469	457	388-568
H	397	380-420	432	370-477
I	484	383-555	515	410-855
J	1201	855-1528	899	640-1540
K	492	412-606	599	522-733
L	403	382-442	480	445-523
M	749	516-1026	932	539-1850
N	1293	949-1837	1785	883-2319
O	472	398-567	1020	634-1662
P	418	362-454	719	483-1142
Q	814	441-1250	1450	588-2314
R	421	385-481	981	423-1928
S	387	358-426	518	418-752
T	404	376-454	958	586-1564
AMBIENT	363	348-378	363	348-378

During the 1992 field season, preliminary measurements were made to determine the photosynthetic potential of *Nardus stricta* (previously referred to as *Eriophorum angustifolium*). We hypothesized that *N. stricta* would exhibit down regulation of photosynthesis (homeostatic adjustment) following long-term (decades to centuries) exposure to elevated CO₂. Plants were measured in ambient and elevated CO₂ habitats in the vicinity of Olafsvik spring over a gradient of CO₂ concentrations (150, 350, 500, 750, 1000, and 1500 ppm CO₂). The photosynthetic response curve was virtually identical for plants exposed to ambient and elevated CO₂, indicating a lack of homeostatic adjustment to elevated CO₂ (Fig. 7).

These preliminary results refute the hypothesis that *N. stricta* exhibits acclimation to long-term elevated CO₂, however, these results support the hypothesis that *N. stricta* is able to utilize elevated CO₂ due to genetic selection of genotypes capable of utilizing elevated CO₂. These results are tenuous at this time. However, due to the inability to understand the mean concentration of the CO₂ plume that the elevated CO₂ habitats are exposed to. In addition, these hypotheses will also be better addressed using carbon isotope comparisons of plants exposed to elevated and ambient CO₂ and reciprocal transplant experiments.

Fig. 7. Photosynthetic response of *Nardus stricta* to long-term (decades to centuries) exposure to ambient and elevated CO₂ along a CO₂ concentration gradient. Data are means $\pm$ 1 SE. $n = 7$ for ambient grown plants and $n = 8$ for elevated CO₂ plants.

CONTINUATION RESEARCH OBJECTIVES

1. Determine the effects of short- and long-term (i.e. $\geq$ centuries) exposure to elevated atmospheric CO₂ on photosynthesis and respiration of the dominant vascular plant species and certain other plant species. Determine the effect of exposure to elevated atmospheric CO₂ on net ecosystem carbon flux, biomass, and species composition.

Explanation. Ecophysiological measurements of photosynthesis and respiration will be made on *Nardus stricta*. Net ecosystem CO₂ flux and other ecosystem attributes will be compared between systems with and without long-term exposure to elevated atmospheric CO₂. Also, preparations for reciprocal transplant and controlled-environment growth chamber studies for the evaluation of genetic adaptation will be made.

2. Determine the seasonal carbon balance along a latitudinal transect on the Taimyr Peninsula and in western Iceland.

Explanation. These data will be used to evaluate the generality of results from Alaska to areas of the Russian and Icelandic arctic. Much of the arctic falls outside Alaska. If recent changes in climate at high latitudes are reflected in carbon flux of the circumpolar arctic tundra, the feedbacks on atmospheric rise in CO₂ could be significant.

3. Determine the influence of soil environmental variables on CO₂ flux within the dominant habitat types.

Explanation. These studies help us understand the controls on carbon flux in arctic tundra and the mechanisms involved. This information will allow us to predict the effect of anticipated scenarios of climate change on net ecosystem CO₂ flux. *In situ* field and controlled-environmental studies will be used. Where possible, this research objective will utilize manipulations in the arctic established as part of the NSF's ITEX (International Tundra Experiment) contribution.

4. Determine the contribution of local vegetation terrain units (ecosystem and habitat types) to landscape and regional fluxes.

Explanation. This information will allow understanding of the contribution of differing vegetation-habitat types to the landscape and regional patterns of CO₂ flux. In conjunction with research sponsored by NSF's ARCSS LAII, this research will allow a development of scaling from the plot to regional levels. Techniques and models developed in the course of this research will allow evaluation of the impacts of changing vegetation patterns and distribution on regional CO₂ flux patterns with the atmosphere.

APPROACH

Long-term Response of Arctic Plants and Ecosystems to Elevated CO₂ in Iceland

Initial identification of CO₂ evolving springs has been completed. During 1992, the temporal variability of the CO₂ plume, temperature, pH, sulfur dioxide concentration, humidity, nutrient availability, wind speed, wind direction, aspect, and soil moisture of each spring was monitored. Two springs, Olafsvik and Bjarnarfosskot on the Snaefellsnes Peninsula, were isolated to be used for intensive research during 1993, 1994, and 1995. Springs were selected according to CO₂ concentrations which bracket those anticipated over the next century, and which are not compromised by changes in other environmental factors.

Physiological measurements made along a CO₂ gradient ranging between 150-1500 ppm during the 1992 field season at Olafsvik indicated that plants exposed to elevated CO₂ for decades, or even centuries, lacked any acclimation to elevated CO₂. These same measurements will be re-taken during the 1993 field season, and the mean concentration of the CO₂ plume that they are exposed to will be characterized. Plant tissue samples will be taken for ¹²C/¹³C natural abundance analyses, which will determine the long-term CO₂ source acquired by the plants adjacent to, and away from the enriched CO₂ springs. Ecosystem CO₂ flux at various CO₂ concentrations will also be determined. Seed from populations exposed for long periods of time to various CO₂ levels will be collected and returned to controlled-environment growth chambers at SDSU to further test the genetic difference as they affect photosynthetic response to elevated atmospheric CO₂. Seed collected from the same populations will also be saved for future transplant experiments to determine the extent of genetic variability *in situ*.

Circumpolar Patterns of Net Ecosystem CO₂ Flux

Russian Arctic

Seasonal carbon balance studies will be initiated in the Taimyr Peninsula (Appendix II) along a latitudinal transect similar to the one measured in Alaska (Oechel *et al.*, 1993). Flux measurements will be made using a LI-COR portable photosynthesis system and an ecosystem clapp cuvette (Vourlitis *et al.*, *in press*). A minimum of four replicate plots will be measured every 1-1.5 hours over a 24-hour period at each site along the latitudinal transect. During each diurnal measurement, gravimetric soil moisture and thaw depth will be determined. If possible, methane flux will be measured as well by placing the chamber over the plot, sequentially removing gas samples over a 15-20 minute period, and determining the increase in chamber CH₄ concentration by gas chromatography (Vourlitis *et al.*, *in press*).

Iceland

Seasonal net ecosystem CO₂ fluxes will be determined at four CO₂ gradients established around CO₂ springs in Iceland (above). Measurement protocol will follow that used in Alaska.

In situ Controls of Temperature and Moisture on Net Ecosystem Carbon Flux

Soil temperature will be elevated through the use of Sun-Lite™ HP fiberglass open-top cones placed over the vegetation in four manipulation plots (1.5 x 1.5 m each). Soil temperature will be monitored continuously using Type-T thermocouples and a Campbell Scientific CR21 Micrologger (Campbell Scientific, Inc., Logan, Utah) along with average, hourly weather data. Thaw depth in each manipulation plot will be determined during each sampling event. The effect of soil temperature on CO₂ and CH₄ flux will be determined using sampling methods previously described (Oechel *et al.*, 1993; Vourlitis *et al.*, *in press*). We have already assessed the effectiveness of the cones during 1992 in Barrow, and they appear to raise soil surface temperatures by approximately 1°C. However, weather conditions were generally cold and overcast during our field trials, and the cones are probably much more effective than we observed. Dr. Giles Marion (CRREL) is continuing to evaluate approaches to modify temperatures, and our approach will vary to incorporate his new findings and those of NSF's ITEX program.

Water table depth will be lowered in four experimental plots at each site through the use of water wells with pumps. Each water well will contain a float-activated water pump which will maintain the water level at the desired level. This level will be lowered through the growing season. Vertical cuts to the extent of the maximum seasonal thaw depth will be made and plastic barriers inserted to prevent water from entering the circumscribed plot. Areas with no observable water table (as may be the case at certain times for tussock tundra on a slope), will have

precipitation restrained by rain exclusion shelters which will be erected during precipitation events to maintain soil water content approximately 30% below control values. We assessed the effectiveness of this technique during 1992 in Barrow, and we were able to lower the water table by approximately 6 cm over a one-week period.

Water levels will be increased by pumping water into other manipulation plots from local sources. Water will be kept from leaving the plots by use of plastic barriers described above. Depending on the site, the goal will be to reduce the distance from the water table to the surface by 30% or increase the water content of the upper 10 cm by 30%. In tussock tundra on a slope, vertical baffles cut into the permafrost to block or enhance flow will be erected as necessary. CO₂ flux measurements will be made every 1 to 1.5 hours throughout a 24-hour cycle every six to ten days from snow melt to soil freeze-up.

Scaling of CO₂ Flux from Plot, to Landscape, to Regional Scales

The characterization of landscape heterogeneity is a central concern of investigations dealing with the scaling of ecological processes. Two types of spatial heterogeneity are defined by Philip (1980), namely, deterministic and stochastic heterogeneity. Deterministic heterogeneity refers to properties varying in a spatially known way, while stochastic heterogeneity relates to irregular spatial variability which is essentially random (Philip, 1980). Similarly, Avissar (1991) concluded that two types of spatial heterogeneities need to be considered in the representation of the earth's surface in climate models (landscape patchiness, and intra-patch variability). Spatial heterogeneity cannot be regarded as independent of the size of the area under investigation (Wetzel and Chang, 1988). The probability of greater variability increases as the area considered expands, and at some scale, deterministic variability may be included in the parameterization of stochastic variability.

In order to model or study the relationship between land-surface fluxes and the controlling process variables at different scales, it is necessary to make observations at a range of scales. The importance of this principle has been recognized by FIFE and BOREAS scientists in designing these two large experiments sponsored by NASA. A second requirement in such studies is the development of an appropriate scheme for characterizing the landscape heterogeneity (patch). The proposed field instrumentation and aircraft flux observations to be employed in our NSF research are consistent with the requirements for scaling from detailed plant observations to regional estimates of carbon fluxes. As part of the NSF study, we plan to use remotely-sensed imagery as the basic source of data for establishing the "deterministic" heterogeneity of the study area. The heterogeneity within these deterministic classes will then be treated as stochastic heterogeneity and may be described by a probability density function (PDF) of the variable of concern. If the variables are categorical (e.g. species), then relative proportions may be assigned to each deterministic class on a probabilistic basis.

The overall approach will be to measure CO₂ and CH₄ fluxes using three approaches: chamber (DOE, proposed here), tower-eddy correlation (NSF), and aircraft (NSF) which represent three spatial scales: plot, landscape, and mesoscale (McCauley and Meier, 1991). Methods for scaling will be developed and analyzed under the NSF-sponsored activities, and will include a statistical analysis of the contributing elements to measured fluxes, remote sensing to identify landscape variables that can be used to estimate state of activity, and modelling of ecosystems processes which affect trace gas fluxes of interest.

During the next three field seasons, we will be scaling up our plot level CO₂ and CH₄ flux measurements to a regional basis through a cooperative effort between our NSF study and the DOE study. According to our NSF ARCSS LAII proposal, NSF is sponsoring the regional sampling effort, which consists of eddy correlation towers and aircraft measurements. The DOE research will quantify the contribution of various habitat types in the footprint of the tower and

aircraft measurements in order to understand the contributions of these units to the airborne and tower measurements.

Towers will be run continuously at Prudhoe Bay in the north, and Happy Valley (or Toolik Lake) in the south during the period of aircraft measurements (Fig. 1). The greatest concentration of chamber measurements will be in the areas of the towers, in order to document and understand the elements contributing to the signature derived by tower measurements over the area of the upwind footprint, and comparing this to a statistical sampling in the region of the tower. Chambers will also be deployed along the Haul Road (Fig. 1). Data collection for remote sensing and GIS (NSF) will be concentrated along belt transects between Prudhoe Bay in the north, and Toolik Lake to the south, and between Barrow in the West, and ANWR (southeast of Barter Island) in the east (Fig. 1).

Flight patterns for the NSF-sponsored aerodynamic flux measurements will include a "t" sampling pattern from Barrow to ANWR and from Prudhoe Bay to Toolik Lake giving a 500 km transect from west to east, and a 200 km transect from north to south (Fig. 1). These flight lines will not be entirely straight. Rather, they will be developed to ensure adequate sampling of all significant landscape units of the area, and to include areas of past and current intensive research activities relevant to this study and will hopefully include DOE's ARM site. Other flight lines will be developed as weather and air time permit in order to maximize the spatial coverage of trace gas flux over arctic Alaska, including areas and vegetation types not previously measured.

During the 1993-1995 summers, field measurements of trace gas flux will be made within vegetation types (vegetation/surface feature types) which are thought to be contributing significantly to the measured CO₂ flux at the landscape scale (tower) and mesoscale (aircraft). Plot measurement locations will be selected from the areas sampled by the aircraft and towers. We will also measure other, less dominant, vegetation types in order to obtain a statistical sampling of all vegetation types likely to be contributing significantly to the regional carbon flux. In addition, we will be measuring environmental variables (including light, temperature, depth to the water table, and soil moisture content), vegetation and soil properties (including leaf, stem, belowground biomass, and soil organic matter content), and processes (i.e. gross ecosystem productivity (GPP), ecosystem respiration, and net ecosystem CO₂ flux) needed to model the patterns of and controls on CO₂ flux.

We envision about 5-10 (possibly up to 15 depending on the area studied) vegetation/surface types to be sampled around each tower location. Each type will be replicated four times. Measurements will be made every 1 to 1.5 hours throughout the 24-hour measurement period. Sampling location will be determined by the wind direction and tower footprint at the time of measurement in order to sample the area contributing to the tower measurement. Similarly, sampling will be carried out along the flight line corresponding to the location of footprint primarily contributing to the aircraft measurement of trace gas flux and vegetation-surface feature indices. Measurements of plot trace gas flux (CO₂ and CH₄) will be conducted as previously described (Oechel *et al.*, 1993; Vourlitis *et al.*, *in press*). Diurnal measurements (replicated four times each) will be taken every hour throughout the day to correspond with tower and aircraft observations. Methane flux will be determined each hour during the course of CO₂ flux determinations using a gas chromatograph and samples drawn from separate chambers (Vourlitis *et al.*, *in press*). Extensive sites will receive less frequent monitoring, and instantaneous values will be compared to seasonal patterns developed for the intensive sites.

Measurements over the last two years concentrated on the dominant vegetation types in tussock and wet coastal tundra ecosystems. There are, however, a variety of other habitat types within these ecosystems. For example, tussock tundra ecosystems have water tracks and lichen heath habitats which have markedly different vegetation, soil moisture, soil temperature, and thaw depth. As a result, CO₂ and CH₄ flux is probably quite different compared to the dominant

tussock tundra habitats. If time permits, we plan to expand our measurements to incorporate these different habitat types, which will allow us to characterize the carbon balance of complete ecosystems.

If time permits, we propose to measure CO₂ and CH₄ flux in Barrow, Alaska. Tower measurements (NSF) will take place at the IBP site-2 and/or Central Marsh, while chamber measurements (DOE) will take place in the tower footprint to quantify the contribution of different habitat types to the regional flux. The Barrow area offers a variety of wet coastal tundra ecosystem types. In addition, temperature records taken over the last 70 years indicate that surface temperatures during the summer months (June-August) have increased by approximately 1.5°C over the last 10 years, suggesting that global warming may already be occurring in this region (Oechel *et al.*, 1993). Wet coastal tundra ecosystems in the Barrow region were sampled intensively during the U.S. IBP effort of the 1970's, and thus offer historical baseline data that can be used to determine the effect of climate change on the CO₂ and CH₄ balance of wet coastal tundra ecosystems. We sampled several sites in Barrow over a 10-day period in 1991 and throughout the entire 1992 growing season, and found that the IBP site-2 was no longer a sink for atmospheric CO₂.

Due to the heterogeneous nature of the wet sedge landscape in the Barrow region, it is important to scale up these plot level measurements to the landscape level to determine whether the observed change in CO₂ flux holds true for the entire region. The scaling up of these flux measurements will be accomplished using an eddy correlation tower (NSF), while chamber measurements (DOE) will be made within the tower footprint to assess the contribution of the various habitat types to the observed landscape level flux. We plan to accomplish this during the summer of 1993 and 1994.

RESEARCH LOCATIONS

Iceland

Icelandic mineral springs have existed for millennia. Many of them emit CO₂ to various degrees from either mantle, carbonate mineral, or decaying organic matter (Barnes *et al.*, 1978). Most of the mineral springs throughout the world have been disturbed; the hot ones used as mineral baths and health spas, and the cold, very CO₂-rich ones for mineral water and carbonating soft drinks. The mineral springs on the Snaefellsnes Peninsula of Iceland, however, are relatively undisturbed and have not been exploited for these purposes as they are too remote and have too little flow to be profitable. Near the fishing village of Olafsvik are relatively pristine springs, namely the Olafsvik and Bjarnarfosskot Springs. Water chemistry of Olafsvik has been found to be free of gaseous and ionic contaminants, and the vegetation near these springs has been exposed to elevated levels of CO₂ for thousand of years. There is a cold mineral spring near Lysuhol whose water chemistry is similar in chemical composition and CO₂ content to that from precipitation (Arnorsson and Barnes, 1983) which could be used as a control.

Russian Arctic: North Eastern

Research will be conducted at two sites on the Kolyma Lowlands near the city of Cherskiy (Appendix II, Figure 1). These sites are under the direction of Dr. Sergey Zimov who is currently the director of the North East Scientific Station (the on-site field station) of the Far-East Scientific Center, Pacific Ocean Institute of Geography, Russian Academy of Science. Dr. Zimov has measured CO₂ and CH₄ flux of the tundra ecosystems in the region. At the other site, carbon flux and methane flux has been measured by Dr. V. A. Samarkin of the Russian Academy of Sciences, Puschino.

Russian Arctic: North Central

Research will be conducted on the Taimyr Peninsula (Appendix II, Figures 1, 2, and 3). This area is ideal for the research proposed for several reasons. First, every habitat type found in arctic ecosystems (from arctic desert to southern tundra) is found in the region. Secondly, Russian scientists have worked extensively in this region in the past. Data on vegetation types, soil C stores, and weather are quite complete, so the physical and biological characteristics of the site are well known. Thirdly, Russian scientists have set up base camps at some of the proposed research sites (Pura River, Appendix II, Figure 3) that are equipped with housing, food, and fuel facilities. Finally, transportation can be provided by helicopter and motor boat at significantly lower cost compared to U.S. equivalents.

Research sites on the Taimyr Peninsula are run by the Institute of Far North Agriculture, Siberian Subdivision of the Russian Academy of Sciences, and are supported by Moscow State University. We have established contacts through Moscow State University with Drs. Tagir Gilmanov and Victor Nosov, who are also collaborating scientists in the NSF and DOE-funded research projects. Dr. Gilmanov is currently at SDSU, and is making preparations for his role in the NSF-sponsored circumpolar C flux modelling effort. Dr. Nosov will be arriving at SDSU in the next month to begin his work with Drs. Allen Hope and Doug Stow of SDSU in the GIS portion of the NSF-sponsored circumpolar C flux modelling effort. There are six possible sites in the region where measurements of CO₂ and CH₄ flux would be carried out. Various research projects have been conducted at all sites by Russian scientists in the past. The following are proposed research sites on the Taimyr Peninsula (Appendix II).

1. Pura Site (72°30'N, 85°40'E). This site is well supplied with long-term information on weather, vegetation, and soil characteristics, and includes most of the relief elements of the Western Taimyr. There are a total of 240 vascular plant species, and 10 main tundra habitat types with widely varying soil moisture, topographical, and community characteristics.
2. Ust-Tareya Site (72°40'N, 91°30'E). This site is similar to the Pura site. It is also well documented with long-term information about vegetation, soil type, and climate. Tussock tundra is the most prominent vegetation at this site.
3. Agapa Site (71°30'N, 88°50'E). Well-documented, long-term records and information on soil type, vegetation, and climate are available for this site. This site is the northern limit of the south shrub tundra, and has 244 species of vascular plants. In addition, there is a soil moisture and tundra habitat gradient that is oriented perpendicular from the Pyasina River which is adjacent to the site.

In addition to these sites, there are three other sites of interest which have received less research attention, but still have well-documented information on vegetation, soil, and climate characteristics. South of the Agapa site and north of Lake Pysina lies a site along the Pysina River. This site is similar to the Agapa site, but has more elements of southern shrub tundra than the Agapa site. Another site is located north of the Pura site, near the town of Mys Khodnoy, which is near the mouth of the Pyasina River and located on the coast of the Arctic Ocean. Finally, the last site is near the town of Dikson which is also located on the coast of the Arctic Ocean, approximately 150 km west of the Mys Khodnoy site. Climate data at this site has been collected since 1916, so there are extensive records on monthly temperature and precipitation for over 75 years that are available.

Russian Arctic: North Western

The principal site of interest is approximately 200 miles SE of the city of Vorkuta in the Komi Republic (Appendix II, Figure 1). The site is accessible by train, and is under the direction of Dr. Margarita Getsen of the Komi Scientific Center. Dr. S. K. Nazarov's group has been actively sampling photosynthesis and CO₂ flux at this site, while Dr. G. A. Siminov's group has been sampling CH₄ flux and soil C stores as well.

Alaska: Manipulations

The manipulative experiments as well as the sampling of various other habitats within the broad categories of tussock tundra and coastal tundra will be carried out at Happy Valley and Prudhoe Bay (both wet and dry coastal tundra sites, see Fig. 1). In addition to the fact that all sites have been extensively sampled for seasonal carbon balance in 1990 and 1991, Happy Valley and Prudhoe Bay are established logistic locations. Temperature treatments are planned at Toolik Lake and Barrow, Alaska as part of the NSF-funded International Tundra Experiment (ITEX). These additional site locations will be monitored if the project is funded.

Alaska: Scaling

The flight center will be based at Prudhoe Bay, Alaska. This site offers extensive wet coastal tundra vegetation, indoor heated hanger space, ample accommodations for the scientific and flight crews, access to the Haul Road transect along which there is ample data, and from which chamber measurements will continue to be made, and access to other areas of interest including Barrow. The back-up location for staging is Barrow. Flight patterns will include a "t" sampling pattern from Barrow to ANWR and from Prudhoe Bay to Toolik Lake giving a 500-km transect from west to east, and a 200-km transect from north to south (Fig. 1 and described above).

INTERAGENCY COOPERATION

CRREL/NSF ITEX

Work described in the 1993 DOE continuation proposal will be based at Happy Valley and Prudhoe Bay. This will interface well with the NSF/ITEX-sponsored work which will take place at Toolik Lake and Barrow. We continue to coordinate with Dr. Giles Marion at CRREL, who is responsible for the ITEX/NSF manipulations, and we are currently evaluating and standardizing our experimental approach.

NPS

The U.S. Department of Interior's Fire Coordinating Committee (with the National Park Service) has recently funded the first year of a three year project entitled: "Net Ecosystem Carbon Flux of Age-specific Subarctic Tussock Tundra Stands Following Fire: Implications for Alaska Interagency Fire Management." This project is being carried out on the Seward Peninsula on the west coast of Alaska, and is an extension of our DOE work in that we are able to quantify CO₂ flux in other tussock tundra ecosystems and determine the flux pattern with post fire stand recovery. The National Park Service has expressed interest in expanding this project into the Chukotka Peninsula in eastern Russia. This effort would certainly complement our continuing DOE research in quantifying circumpolar CO₂ flux in northern latitude ecosystems.

NSF's Arctic System Science (ARCSS-LAI)

The National Science Foundation has recently funded the first year of a three year project entitled: "Large Area Estimates of Carbon Fluxes in Arctic Landscapes." This research is intended to yield the current CO₂ flux for the east central north slope of Alaska, the contribution to CO₂ flux of various landscape elements, the sensitivity of net ecosystem CO₂ flux to altered environmental conditions, models and methodology to predict CO₂ flux in the arctic, and efficient techniques for estimating meso- and global scale CO₂ and other trace gas fluxes.

The NSF-sponsored work includes the cooperative efforts of SDSU, National Research Board of Canada, the Centre for Land and Biological Resources Research, Agriculture Canada, the Flight Research Laboratory, Institute for Aerospace Resource, National Research Council, the Department of Renewable Resources, McGill University and Moscow State University. This will draw together expertise in ecosystem modeling, ecosystem function, ecophysiology, carbon flux measurements at the plot, landscape, and mesoscale levels, remote sensing, and GIS. Initially research will be directed to Northern Alaska with subsequent extrapolation to arctic regions in North America and at a circumpolar scale in the Russian arctic.

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CURRENT AND PENDING SUPPORT

Walter C. Oechel

Current Support

Funding Source:	U.S. Department of Energy
Project Title:	"Response of a Tundra Ecosystem to Elevated Atmospheric Carbon Dioxide and CO ₂ -Induced Climate Change"
Award Amount:	\$300,000
Period Covered:	9/1/92-8/31/93
% Effort:	25%
Location:	Alaska and California
Funding Source:	Department of Interior - Interior Fire Coordinating Committee
Project Title:	"Net Ecosystem Carbon Flux of Age-specific Subarctic Tussock Tundra Stands Following Fire: Implications for Alaska Interagency Fire Management"
Award Amount:	\$278,755
Period Covered:	7/6/92-4/30/93
% Effort:	25%
Location of Research:	Alaska and California
Funding Source:	NSF, ARCSS LAII
Project Title:	"Large Area Estimates of Carbon Fluxes in Arctic Landscapes"
Award Amount:	\$282,337
Period Covered:	9/1/92-8/31/93
% Effort:	20%
Location of Research:	Alaska and California
Funding Source:	Southern California Edison
Project Title:	"Effects of Global Climate and Atmospheric Change on the Structure and Function of Mediterranean Shrub Ecosystems and Associated Forest Ecotones in California"
Award Amount:	\$48,640
Period Covered:	4/1/92-3/31/93
% Effort:	10%
Location:	California
Funding Source:	The United States-Spanish Joint Committee and Educational Cooperation
Project Title:	"Factors and Mechanisms Controlling Postfire Resprouting of Spanish and Mediterranean-type Shrubs"
Award Amount:	\$8,250
Period Covered:	12/1/90-11/30/93
% Effort:	5%
Location of Research:	Spain and California
Funding Source:	Water Resource Center, University of California, Riverside
Project Title:	"Effects of Global Climate Change and Increased Atmospheric CO ₂ on Water Use and Productivity of Mediterranean-type Ecosystems"
Award Amount:	\$20,000

Period Covered: 7/1/92-6/30/93
% Effort: 5%
Location: California

Funding Source: Western Regional Center, National Institute for Global
Environmental Change
Project Title: "Effects of Global Climate and Atmospheric Change on
the Structure and Function of Mediterranean Shrub
Ecosystems and Associated Forest Ecotones in California"
Award Amount: \$78,650
Period Covered: 9/1/92-8/31/93
% Effort: 10%
Location of Research: California

Pending Support

Funding Source: National Park Service
Project Title: "Net Ecosystem Carbon Flux of Age-specific Subarctic Tussock
Tundra Stands Following Fire: Implications for Alaska"
Award Amount: \$151,494
Period Covered: 5/1/93-4/30/94
% Effort: 25%
Location: Alaska and California

Funding Source: National Science Foundation, Division of International Programs
Project Title: "The Evolutionary Response of *Nardus stricta* Plants
to Naturally Elevated Levels of Atmospheric CO₂"
Award Amount: \$20,000
Period Covered: 5/15/93-9/15/95
% Effort: 5%
Location: Iceland

Funding Source: U.S. Department of Energy
Project Title: "Response of Mediterranean-type Ecosystems to Elevated
Atmospheric CO₂ and Associated Climate Change"
Award Amount: \$1,191,328
Period Covered: 7/1/93-6/30/96
% Effort: 25%
Location: California

Funding Source: Water Resources Center, University of California, Riverside
Project Title: "Effects of Increased Atmospheric CO₂ and Drought on
Water Use and Soil Moisture Availability in *Quercus agrifolia* in the
Chaparral of California"
Award Amount: \$88,554
Period Covered: 7/1/94-6/30/97
% Effort: 5%
Location: California

Funding Source:
Project Title:

U.S. Department of Energy (this proposal)
"Response of a Tundra Ecosystem to Elevated Atmospheric
Carbon Dioxide and CO₂-Induced Climate Change"

Award Amount:

\$300,000

Period Covered:

9/1/93-8/31/94

% Effort:

40%

Location:

Alaska and California

 
and their implications.

BUDGET *Removed at*