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NET ECOSYSTEM CARBON FLUX OF AGE-SPECIFIC SUBARCTIC TUSSOCK TUNDRA STANDS FOLLOWING FIRE: IMPLICATIONS FOR ALASKA INTERAGENCY FIRE MANAGEMENT

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EXECUTIVE SUMMARY

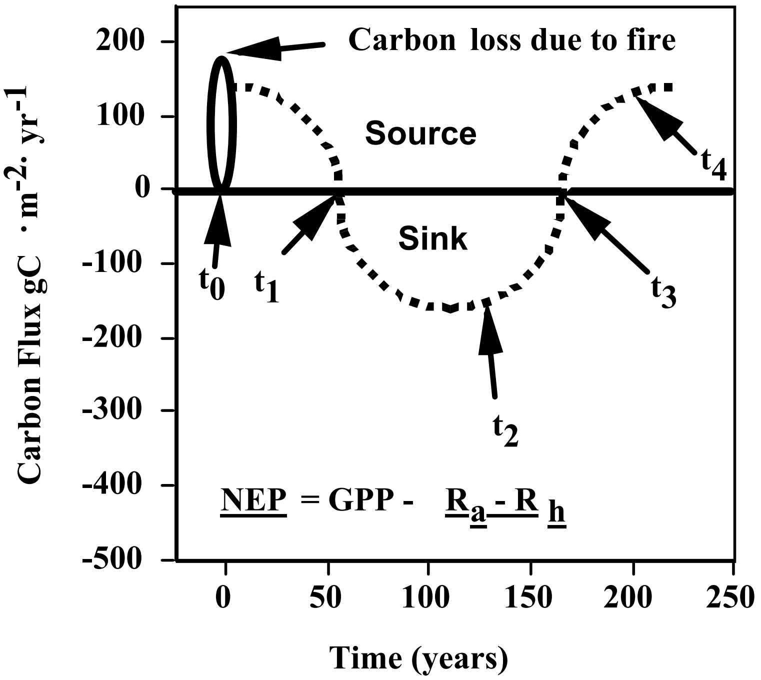
This is the Final Report on the Research to Determine the Net Ecosystem Carbon Flux of Age-Specific Subarctic Tussock Tundra Stands Following Fire: Implications for Alaska Interagency Fire Management. The objective of the study was to determine the annual carbon flux of tussock tundra on the Seward Peninsula of varying years since the last fire. This information provides part of the data needed to evaluate the Alaska Interagency Fire management plan. There are many factors to take into consideration in evaluating the suitability of a fire management plan including protection of lives, property and cultural resources as well as the various biotic and abiotic resources. With rising levels of atmospheric CO_2 concentrations and the potential for this to increase global temperatures, concern has turned to how the actions and decisions of the human population will effect the global carbon balance. The United Nations Conference on Global Warming held in Kyoto in the Fall of 1997 called upon nations throughout the world to reduce their input of CO_2 into the atmosphere. From a very basic standpoint, this could be accomplished by burning less fossil fuel, or managing for ecosystems with high carbon storing capabilities. The conclusion form this study shows that managing tussock tundra ecosystems on the Seward Peninsula for younger age stands will not result in them sequestering more CO_2 on an annual basis from the atmosphere compared to tundra with longer periods of time since the last fire. In fact, tundra systems tend to be less of a CO_2 sink or a greater source of CO_2 to the atmosphere the shorter the time that has elapsed since they last burned. Dryer years and warmer temperatures will tend to exacerbate these results while above average rainfall and cooler temperatures result in little or no effect of time since fire on the annual carbon balance of tussock tundra.

The paradigm in forestry management is that there is a trend of gradually increasing productivity during the pioneer and early tree stages, followed by decreasing productivity at the climax stage. Fire is considered a natural and necessary phenomenon that in part, acts to rejuvenate and maintain a healthy and diverse ecosystem. If one is attempting to minimize CO_2 loss to the atmosphere, it is not unreasonable to hypothesize that an arctic tundra ecosystem might have an optimum fire cycle such that net primary production is maximized and, that net carbon sequestered is greater than either a shorter or longer fire cycle.

Past studies of aboveground biomass increases in arctic tundra after fire imply that the highest sink capacity of arctic tundra may be the first 10 to 20 years immediately after a fire based on high net primary production values. It is felt that in part, higher nutrients and warmer soils enhancing photosynthesis with a minimal of plant maintenance and microbial respiration drive this. With the current fire cycle on the Seward Peninsula estimated at 250 years it may be that any form of fire suppression except that which is absolutely necessary would be counter productive to minimizing CO_2 emissions. Conversely, it may be that a mature, well established graminoid community has the greatest sink strength and exclusion of fire would be most beneficial. Many General Climate Models predict warmer and dryer weather conditions for the arctic that could lead to an increase in fire frequency. Thus, determining the optimal length of the fire

cycle to minimize CO_2 emissions is of interest for evaluation of the current fire management policy as well as for future weather scenarios.

It is important to understand exactly what was measured. Fig. i shows a hypothetical situation for changes in net carbon sequestered through time for the Arctic tussock tundra (carbon flux or net ecosystem productivity). Net Ecosystem Productivity is equal to Gross Primary Production (Gross Ecosystem Photosynthesis) minus respiration due to eterotrophs (animals, ngi, bacteria). Only NEP d the combined sum of $_a$ and R_h were measured d GPP determined by dition. At t_0, there is a ne time loss of carbon due fire. Then, from t_0 to t_1 ere is a period of time hen the ecosystem is covering from fire before hotosynthetic up take by e ecosystem exactly alances carbon loss due to respiration. From t_1 to t_2 represents the time it takes for the ecosystem to replace all the carbon lost at t_0 and from t_0 to t_1. The time from t_2 to t_3 represents the total period of time which the ecosystem has the potential to accumulate carbon in the ecosystem. Finally, from t_3 to t_4, the ecosystem is losing any carbon it had accumulated and after t4, the ecosystem is losing carbon. If in fact, this hypothetical example was indeed the situation for carbon flux over a fire cycle of tussock tundra, the optimal fire interval would be t_3.



ig. i. A hypothetical depiction of the change in carbon flux of a tussock tundra ecosystem with time after fire.

A fire induced chronosequence on the Seward Peninsula was identified and included arctic tundra that had last burned in 1992, 1990, 1977, 1971 and age of last fire unknown. Duplicate age stands were studied in 1993 and in 1994. However, in 1994, additional stands were identified such that there were 3 stands studied that burned in 1992 and 5 stands studied of unknown ages. Over the growing season in 1993 and 1994 (June 1 through August 31) diurnal net ecosystem carbon flux and ecosystem respiration was measured hourly for each stand every 10 to 15 days. Gross Ecosystem Photosynthesis was also calculated from the sum of the two carbon flux values measured. These data allowed us to estimate the seasonal Gross Ecosystem Photosynthesis, Ecosystem

Respiration and Net Ecosystem carbon flux for each age stand. In addition to monitoring weather parameters on a half hour basis over the entire season using an array of deployed weather stations, numerous ancillary measurements such as thaw depth, soil water table depth, vegetation cover and diurnal soil temperatures were measured each time a site was visited.

The loss of carbon on a seasonal basis by arctic tundra is a change from the 1970's when mature (age equal to or greater than the unknown age stands in this study) tundra was a sink for carbon. Indeed, geological evidence indicates that tundra systems have been sinks for carbon over the last 7,000 to 10,000 years. In related studies of the tundra on the north slope of Alaska, over a 25 year period, we reported the change in tundra from a carbon sink to that of a source. This is in part due to a ten year warming trend, drying of the soils and lowering of the water table. Over the growing season, the last few years indicate that these same areas have returned to that of a sink over the growing seasonal but due to carbon loss over the winter, are still sources of CO_2 on an annual basis. These are likely transient, short term deviations from the general trend of carbon loss reported for most northern, permafrost based ecosystems year round with their large stores of carbon in permafrost susceptible to melting, increased rates of mineralization and respiration. It should be pointed out that many models predict a return to sink activity in the north within 100-150 years, in part due to changes in community structure. Actively modifying the fire frequency may impede or enhance these changes in community structure.

This study has laid the groundwork for a multi-investigator, study of the Seward Peninsula in 1999-2001 as part of the NSF-LAII study on controls of regional carbon flux in the arctic. The next 50 years will be critical that we continue to monitor the carbon flux of the worlds ecosystems and try and understand the controls and feedback with the atmosphere.

ABSTRACT

It is now clear that in recent decades and over large areas, arctic tundra has warmed (Chapman and Walsh, 1993) and shifted from a state of carbon sequestration to carbon release to the atmosphere as CO_2 and other trace gases (Oechel *et al*. 1993, 1995, and 1997a,b). Despite year to year variability, and medium term adjustment to climate change, areas of past carbon sequestration are now sources of CO_2 to the atmosphere. Even when summer periods are sinks for atmospheric CO_2 (Vourlitis and Oechel, 1997, 1999) the high rates of winter loss may result in annual release to the atmosphere (Fig. 25, 26 and Table 9), Oechel *et al*. 1997b,c).

Under current conditions, therefore, large areas of tundra have ceased to be a sink for CO_2, and are now a source thereby constituting a positive feedback on atmospheric CO_2 increase and global warming (Oechel *et al*. 1993, 1995) in the US and other polar regions (see e.g. Zimov *et al*. 1993, 1996).

The research reported here was designed to test the interaction of stand age with net ecosystem carbon flux. Measurements were made during the summer seasons of 1993 and 1994 to determine the interaction of stand age (time since fire) and net ecosystem carbon sequestration or loss. In light of the Kyoto Protocol (IGBP, 1998; Kaiser, 1998) and global CO_2 flux modeling and analysis, it is now clear that terrestrial ecosystems can be important in understanding the fate of anthropogenic CO_2 emissions and in management options to offset and mitigate CO_2 emissions from human activity.

This research indicates that, in the Seward Peninsula, loss of CO_2 from tussock tundra ecosystems tends to decrease, overall, with increasing time since fire. While a source of CO_2 in most conditions and ages measured, net CO_2 fluxes to the atmosphere tend to be the greatest shortly after fire, and decrease with time thereafter. However, there was significant year to year variability in this response. In 1993, there appeared to be a clear decrease in CO_2 flux with stand age. In 1994, however, this effect was negligible, due to

a cooler, wetter summer. Shortening of the interval between fires would, at least in the near term, appear to increase the rate of CO_2 loss to the atmosphere, compounded when carbon loss due to the fire itself is considered.

It appears that fire frequency has increased over the last several decades (Fig. 27; Oechel and Vourlitis, 1997c). This may interact with recent increases in the rate of CO_2 loss to the atmosphere to further amplify this rate of loss.

These findings indicate that for the Seward Peninsula, increasing length of the fire cycle would help minimize the release of CO_2 from tundra ecosystems to the atmosphere. For the purposes of controlling atmospheric CO_2 concentrations, management to effect longer intervals between fires could reduce tundra CO_2 emissions. It is possible that this reduction in CO_2 emissions could be part of the US strategy to meet the Kyoto Protocol objectives.

Other considerations, however, include the impacts of fire suppression on GPP, NPP, forage quality, biodiversity, and other issues important to ecosystem management. Gross primary productivity, e.g., tended to be greatest after fire, and decrease with time. Appropriate management of arctic ecosystems depends on tradeoffs among competing objectives. One of which should be impacts on net ecosystem carbon sequestration and loss.

INTRODUCTION

Carbon dioxide concentration has increased by 25 % since the industrial revolution. A concomitant rise in arctic surface temperature of 11° C (Mitchel *et al.*, 1990; Schlesinger and Mitchel 1987) has been predicted. The environmental sensitivity of the arctic, the presence of permafrost, and the rapid and large anticipated increases in temperature at the high latitudes, make the arctic likely to be an early indicator of impacts of global change. The large quantities of soil organic matter and its susceptibility to global change, raises the potential for important feedbacks on the global environment. These considerations have caused land managers to reassess the impact of the Alaska Interagency Fire Management Plans. This plan may actually result in a net increase in carbon dioxide released into the atmosphere. Conversely, by selective burning of older tundra landscapes, the creation of younger more productive areas may increase (by higher levels of ecosystem respiration), diminish, compensate for, or even provide a sink for the carbon dioxide released during fires.

Northern ecosystems (arctic, boreal forest, and northern bogs) contain about 500 Gt of C worldwide (Miller, 1981; Miller *et al.*, 1983; Gorham, 1991; Oechel and Billings, 1992), an amount equal to about 2/3 of the approximately 750 Gt of C (1 gigaton, Gt = 10^{15} g) currently in the atmosphere as CO_2. The vast majority (≈83%) of this carbon is present in the soil as dead organic matter in the seasonally thawed upper soil layers, and in the uppermost layers of the permanently frozen ground (permafrost). Northern 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 of C per year (Schell 1983; Schell and Ziemann 1983; Marion and Oechel 1993; Miller *et al.*, 1983; Post, 1990; Gorham, 1991; Oechel and Billings, 1992). While primary production is slow, cold, waterlogged soils result in rates of soil decomposition which is even slower. This condition results from low rates of actual evapotranspiration, and from impeded drainage which is often the result of the presence of permafrost which creates an impervious layer near the surface. Carbon accumulation in northern ecosystems is largely the result of the soil conditions characteristic of much of the region. Changes in soil moisture and the distribution of permafrost could have significant effects on rates of soil decomposition (Silvola, 1986; Gorham, 1991; Billings *et al.*, 1983; Billings *et al.*, 1982; Billings and Peterson, 1990).

Under future conditions of elevated CO_2 and global climate change, northern ecosystems could be a sink for carbon, providing a negative feedback on atmospheric CO_2; alternatively, northern ecosystems could be a source for CO_2 and constitute a positive feedback (Billings, *et al*., 1982; Post, 1990; Oechel and Billings, 1992). New information presented below indicates that certain northern ecosystems have already altered their role in global carbon cycling, most likely in response to recent climatic change.

Arctic ecosystems alone contain about 60 Gt of C as living and dead organic matter, 92% of which is present below ground in the soil active layer and upper permafrost layers as dead organic matter. This carbon has been accumulating slowly, often over thousands of years. Net carbon accumulation or loss is the balance between gross primary productivity (photosynthesis) and plant and soil respiration. In the past, gross primary productivity has exceeded respiration over much of the arctic, and large carbon stores have accumulated belowground as soil organic matter (Gorham, 1991; Oechel and Billings, 1992).

Under this pattern, the arctic could be a net sink for carbon with respect to the atmosphere. However, predicting future response of arctic ecosystems to elevated atmospheric CO_2 and associated climate change is difficult. The net effect will depend on the relative response of photosynthesis to elevated CO_2 and other environmental changes in relation to changes in the rates of plant respiration and soil decomposition.

The arctic has the potential to store large amounts of carbon as dead organic matter. The wet, cold, anaerobic soils result in potentially low rates of soil decomposition, especially at depth in the soil (Gorham, 1991; Clymo, 1984). As soil organic matter accumulates, and the soil organic layer deepens, the permafrost migrates upward and incorporates new organic material. The decomposition rate of the organic matter in the permafrost is very slow, and would result in removal of the carbon from circulation for thousands of years (Gorham, 1991; Clymo, 1984).

Alternatively, higher temperatures and altered precipitation might result in increased depth of the soil active layer, increased depth to the water table, and greater soil aeration. These factors would tend to increase the rates of soil decomposition. Water table alone, is a major control on soil decomposition rates (Billings *et al*., 1983). If soil decomposition increases faster than net primary productivity, the system ceases to be a carbon sink and can become a carbon source.

High latitudes are anticipated to undergo the greatest increases in surface temperature, perhaps increasing by 4° C in summer and as much as 17° C in winter. Mean annual temperature, with a doubling of atmospheric CO_2 may therefore increase by as much as 11° C (Mitchell *et al*., 1990; Schlesinger and Mitchell, 1987). Although clouds and water vapor may feedback and limit the increase by as much as 50%, there is a general consensus of significantly increasing temperatures in the arctic.

The large predicted increase in temperature coupled with the huge carbon storage and the large rate of carbon flux in northern ecosystems makes knowledge of the magnitude and controls on carbon storage in northern ecosystems of considerable importance to understanding current dynamics of atmospheric CO_2 concentration, and to predicting future changes in atmospheric CO_2 and associated greenhouse warming. Northern ecosystems have the potential for important feedbacks on changing atmospheric CO_2 and associated climate change. Worldwide, recent rates of carbon accumulation in tundra have been estimated to be about 0.1 Gt of C per year. Tussock tundra, which is the largest store of carbon in Arctic terrestrial ecosystems (29.1 Gt of C), was estimated to be accumulating carbon at the rate of 23 g C m^{-2} y^{-1}, or 0.02 Gt of C per year worldwide, while, wet tundra was estimated to contain 14.4 Gt of C worldwide and to be accumulating carbon at the rate of 27 g C m^{-2} y^{-1}, or 0.03 Gt of C per year worldwide (Miller *et al*., 1983; Oechel and Billings, 1992), much higher rates of carbon uptake are of 40-120 g m^{-2} y^{-1} are estimated from cuvette measurements of photosynthesis and respiration, and aerodynamic measurements of ecosystem CO_2 flux made during the U.S. IBP in Alaska (Chapin *et al*., 1980). Low and tall shrub tundra have been calculated to have accumulation rates of 10 and 29 g C m^{-2} y^{-1} respectively, and together, account for an annual storage of 0.02 Gt of C per year (Miller, Kendall and Oechel, 1983).

The net balance between the amount of carbon lost to combustion during a fire and the amount sequestered following fire will determine the effect of fire on stand carbon flux to the atmosphere. Substantial quantities of greenhouse gases and particulates are released into the atmosphere each year by wildland fires in the State of Alaska, but little data exists describing the chemical characteristics of the smoke that is released. The ecosystem carbon loss through combustion, however, may be offset by rapid stand regeneration and enhanced primary productivity. Studies indicate that rates of plant growth and productivity are greater in recently burned tussock tundra sites compared to these same sites before burning (Johnson and Viereck, 1983). Increased plant productivity in recently burned stands is largely due to increased N mineralization (Chapin *et al*., 1988; Skre and Oechel, 1979; Van Cleve *et al*., 1983), resulting from increased soil heating and concomitant changes in site water balance (Haag, 1974; Haag and Bliss, 1974). Stand regeneration rates can be great, with 30 % plant cover by the end of the first season post fire, 50 % by the fifth year, and 100 % by the tenth year (Racine *et al.*, 1983). After a severe fire, however, stand recovery may occur more slowly, with only 30 % cover after the fifth year due to the removal of vegetation and the shallow organic layer (Johnson and Viereck, 1983).

Soil respiration rates may increase after fire as well. The removal of the insulating organic material and exposure to sunlight of the blackened surface following fire may cause soil warming, resulting in a deeper soil active layer and greater soil respiration rates (Haag and Bliss, 1974). In addition, subsidence of the soil surface due to the combustion of organic matter and hydrolic erosion may occur following fire. Light to moderate fires are thought to affect the depth of the active layer, surface subsidence, and erosion minimally (Walker *et al.*, 1987). The effects of severe burns on the depth of the active layer, soil surface subsistence, or hydrolic erosion, however, are unknown (Walker *et al.*, 1987).

The most frequently burned tundra vegetation type is tussock-sedge, mixed shrub tundra due to its susceptibility to drying and inherently flammable characteristics (Walker *et al.*, 1987). The natural fire regime in tussock tundra ecosystems is not well known. Due to differences in the prevailing climatic conditions, fire may play a significant role in some tundra areas while not occurring in others.

Fire, however, is ecologically significant in tundra areas even if occurrence is rare. The return interval may be as short as 100 years (Viereck and Schandelmeier, 1980), but can be as long as 250 years in the Seward peninsula (Walker *et al.*, 1987). Fire records maintained since 1955 indicate that the total acreage burned statewide ranges from 1,389 hectares in 1959 to 2,044,397 hectares in 1957 (Alaska Fire Service, 1990). Estimates indicate that over the past 23 years, approximately 4 million hectares of tussock tundra on the Seward peninsula have been burned (Walker *et al.*, 1987; Oechel and Vourlitis, 1997c). Data from the Alaska Fire Service suggests that fire frequency may be increasing (Oechel and Vourlitis, 1997c) possibly due to the reported increases in high latitude surface temperature (Lachenbruch and Marshall, 1986; Lachenbruch *et al.*, 1988; Beltrami and Mareschal, 1991; Kukla and Karl, 1992; Chapman and Walsh, 1993). A similar trend of increasing fire frequency has been observed in sub-arctic Canadian forests (Stocks, 1991). The reported increase in fire frequency may be an important consideration in future fire management strategies.

A major management question regarding tussock tundra ecosystems is whether the interagency fire management strategies are a compounding factor, thus increasing atmospheric carbon dioxide, or whether the strategy results in compensating mechanisms which minimize the release of carbon to the atmosphere. The management plans and the associated fire suppression actions have been praised as progressive, economically and ecologically responsible, and operationally feasible. The 1988 national review of fire management policies in national parks and wilderness areas affirmed the soundness of the Alaskan interagency fire management program.

Although the fire management plans are successful, one wonders how these plans affect the increase in atmospheric CO_2 and concomitant global climate change. With the threat of global warming due to the increase in greenhouse gases, it is necessary to review and re-evaluate fire management policies and practices. The existing interagency fire management plans (implemented in 1986) establish four fire protection categories ranging from immediate suppression to routine surveillance of fires allowed to burn. The intent of these categories is to protect human life and developments, while ensuring that suppression activities and costs are commensurate with value-at-risk. It is unknown, however, how these management practices affect the carbon balance of tussock tundra ecosystems, and their subsequent contribution of CO_2 to the atmosphere.

This research attempts to answer fundamental questions regarding the contribution of atmospheric CO_2 from tundra under the current fire management practices. For example, should the suppression of more tundra fires be attempted to reduce the amount of CO_2 contributed by wildfires in Alaska? Similarly, should fire management policies be changed in light of increasing concerns about climate change? The results reported here are an attempt to derive the relationship between carbon balance and stand age since the last fire. It is hoped that these data will help in determining appropriate fire management programs within the context of Global Change.

METHODS

Site Description

The study sites are located within the central portion of the interior of the Seward Peninsula of Alaska (Fig. 1, Table 1) varying in distance south of the arctic circle of between 50 and 200 km. All sites were located between 70 and 150 km from oceanic waters that forms the north, west and south border of the peninsula. For mid June, July and August of 1993, prevailing winds were southerly and averaged 2-3 m s^{-1} with maximum velocities of up to 16.1 m s^{-1}, summer average temperature was 10-11.6° C and precipitation was between 136 and 182 mm (Table 2). For the entire summer, minimum and maximum temperatures were -5° and 28° C respectively. Both average summer temperature and precipitation decreased 12 and 25 % respectively as one moved 100 km from the southern to the northern most sites. The southern most site was separated from all the rest by the Bendeleben Mountains that run in an east-west direction which in part accounts for its somewhat higher mean seasonal temperature and precipitation. East to west variation was much less, and on the order of 2 % for precipitation and 4 % for temperature. Based upon average daily Photosynthetic Available Radiation and Pyranometer values, intercepted radiation was similar, varying only 6% between sites. Imuruk Lake influenced the regional climate for the single site located near it as precipitation in the area was similar to the southernmost site. Temperature was significantly lower and precipitation was significantly higher for all sites in 1994 compared to 1993 and the significance of this on seasonal carbon balance is discussed later.

Initially, 50 different sites of varying age from the last fire were identified using fire history and fire perimeter maps provided by the U.S. Bureau of Land Management. In July of 1992, using fixed wing aircraft, sites which appeared to have similar slope, aspect, water balance, elevation and dominated by *Eriophorum vaginatum* (tussock tundra) were selected for study. In August of 1992, 28 sites were visited and carbon balance measurements made under ambient and saturating light intensities. Two sites that burned in 1992, 1990, 1977, 1971 and of unknown age were selected for measurement in 1993. Unlike the 1971 sites, no charred remains of burnt tussock or charcoal could be found at the base of any of the unknown stands or in the soil profile. The age of the sites with no fire record is estimated to be between 50 and 250 years old based on the % of lichen and the fire return interval for the Seward Peninsula (Arseneault *et al*., 1997; Walker *et al*., 1987). The number of sites measured in 1994 was increased by adding one that burned in 1992 and three more stands of unknown age. Locations and characteristics of each site are given in Table 1.

Soils were similar for all sites, and characterized as histic pergelic cryaquepts which varied from loamy to very gravely pergelic cryorthens (Exploratory Soil Survey of Alaska, USDA, 1979). A deep silty loess covers much of the area and soils are moderately to highly acidic. All had a thick organic mat of partially decomposed moss, sedges and, lichens of between 20 and 30 cm (Racine *et al*., 1983). The maximum, seasonal thaw layer is generally no more than 60 cm (Racine *et al*., 1983).

Excluding the 1992 and 1990 burns, average percent cover of *Eriophorum vaginatum* tussocks varied between 35 and 71 % with the exception of site 24 where 14% cover was observed. Other sedges present included *Carex bigelowii*, and the grass, *Calamagrostis canadensis*. Shrub species present included *Betula nana*, *Ledum decumbens, Salix planifolia*, *Vaccinium uliginosum*, *Vaccinium vitis-idaea*, *Empetrum nigrum*, *Dryas integrifolia* and the forb, *Rhubus chamaemorus* (Hulten, 1968). Moss flora was represented by *Hylocomnium spp*., *Hypnum spp*., *Polytrichum spp*. and *Sphagnum spp*. (Crum *et al*., 1973). Lichens were more abundant in the unknown stands and totally absent in the 1992 and 1990 stands, and included *Cetraria spp*., *Cladina spp*., *Cladonia spp*., and *Thamnolia* spp. (Hale and Culberson, 1970).

Microclimate Data

Four weather stations were dispersed throughout the sampling area, choosing locations which would encompass the regional climate of all the sites sampled. One weather station was placed at site 22, the western most site. Another weather station was placed at site 6 as it was expected that Imuruk Lake would have a large influence on the local climate. Weather stations were also placed at sites 7 and 14, the northern and southern most sites respectively. These data were intended to be used in elucidating potential differences in site carbon balance that could not be attributed to age. In addition, diurnal carbon flux could not be measured every day throughout the season on all 13 sites but utilizing the meteorological data from the four central stations, one can then estimate the flux between sampling dates by interpolating the flux of individual sites using the climate data based on the measured relationship between carbon flux with temperature and solar radiation (Vourlitis *et al*., in press).

Each station consisted of a CR 21X data logger, SM 192 storage module (Campbell Scientific, Logan, UT), pyranometer and quantum sensors (LI-190S and LI-200SA respectively, LI-COR, Inc., Lincoln, NE), wind speed and direction (model 05305, R.M. Young Corp, Traverse City, MI), relative humidity and air temperature (model HMP35C, Vasalia, Woburn, MA), soil temperatures at 0, 5 and 10 cm (1.5 cm was also measured in 1994) (type T thermocouple, Omega Engineering, Stamford, CT) and precipitation (model TE525, Texas Electronics, Inc., Dallas, TX). Data was collected every 10 seconds and hourly averages (30 min. in 1994) were stored throughout the sampling period.

Site sampling

Thaw depth was sampled each time a site was visited every 25 cm, along a 15 meter transect oriented N-S in 1993. In 1994, 15 tussocks and 15 intertussock areas at each site were measured at the same time that carbon flux measurements were made. Soil moisture (percent water per unit dry weight) was determined on samples obtained by cutting a 5 cm block of soil to a depth of 10 cm in 1994. During the course of each diurnal carbon flux measurement period, soil temperature in tussock and intertussock was recorded hourly at 0, 5 and 10 cm (1.5 cm depth was added to the measurements in 1994) using a thermocouple reader (model # HH-25TC) to read 4 electronically averaged thermocouples at depth, in tussock and intertussock areas using a 6 channel switching box (model # HH20SW-T, Omega Engineering, Stamford, CT). Percent coverage of tussock, lichen, moss and bare groundwas measured once during the growing season using ten, randomly placed quadrats. Quadrats were 1 m x 1 m with 5 cm squares and the number of squares which encompassed the various surface type was recorded.

Carbon Flux Measurement

Ecosystem carbon flux measurements were made using the methodology described by Vourlitis, *et al.*, 1993. Due to the fact that access to the majority of the sites was by helicopter, modifications were required in order to transport the cuvette. The chamber top consisted of 0.13 mm thick Mylar, the sides were made of clear, 3 mm thick acrylic, 40 cm on a side and 60 cm tall resulting in a total volume of 96 liters. Two, 12 volt DC radial fans (Model VD65L, Micronel, Vista, CA) provided thorough mixing of the air within the chamber. A LI-COR 6200 sensor head was attached to one of the chamber walls, linking the chamber/tundra complex with an IRGA system (model LI-6200, LI-COR, Lincoln, NE, USA) which consisted of software for programming, data collection and storage, analysis of the CO_2concentration by way of an infra-red gas analyzer and a sampling pump with a flow rate of 30 ml min^{-1}. The sensor head accommodated both gas sampling and return lines as well as measurement of chamber temperature using a shaded thermistor that protruded into the chamber and photosynthetically available radiation (PAR, LI-190S, LI-COR, Lincoln, NE) measured with a quantum sensor affixed to the top of the chamber. At each site, four tussock and intertussock areas were selected and 40 cm square polypropylene bases, 6.4 mm thick and 30.5 cm deep, were inserted into the tundra after cutting through the permafrost with a chain saw. All eight bases were accessible by way of an elevated wooden walk way to prevent trampling which could potentially change the energy balance of the local site (Hagg and Bliss, 1994) and subsequent changes in hydrology and nutrient status of the plants (Hastings *et al*., 1989; Chapin, *et al.*, 1988). Every 1-1.5 hours during a given diurnal, measurements of carbon flux and respiration were made on all four tussock and intertussock areas. Carbon flux measurements were made by placing the bottom edge of the cuvette, covered with closed cell foam tape to provide an air tight seal, onto the base and affixed to it with a rubberized cord. Care was taken to ensure that the chamber CO_2 concentration was equal to ambient before attaching the chamber to the base. At the time that the CO_2 concentration began to give a steady increase or decrease in concentration, logging was initiated and three, successive 20 second measurements of CO_2 change with time were made, with carbon flux calculated and stored using the LI-COR 6200 software. At the end of a measurement, the chamber was carefully removed, allowed to equilibrate with the atmosphere and affixed to the same base. An opaque cloth was placed over the cuvette and after approximately 20 seconds, a respiration measurement was made. Diurnal flux measurements were made at each site throughout the season, approximately every 10-15 days.

Calculation of Seasonal Carbon Flux

Daily carbon flux measurements were calculated by integrating all of the instantaneous flux measurements for each sample plot over the 24 hour measurement period using the trapezium method. The procedure was to take two successive measurements for a particular plot, average them and take the rate of flux times the decimal hour difference when the measurements were made. These integrated flux values were then summed to yield carbon loss or gain for the day. Tussock or intertussock flux was calculated from the four different plots at each site. As the area of tussock vs. intertussock varied among the different sites, in order to calculate carbon flux for tussock tundra, the tussock and intertussock flux values were weighted by their respective percent cover and summed. Seasonal carbon flux was calculated by first assuming to be zero just before snow melt in the spring (May 20) and at the time of freeze up in the fall (September 27). Gross Ecosystem Production was calculated by subtracting ecosystem respiration from net ecosystem flux. Flux to the atmosphere was positive while flux to the tundra was negative. An integrative procedure was then applied to the season using May 20th as the first date followed by the initial and successive measurement periods till September 27 in a manner similar to that which was done to calculate daily carbon flux.

RESULTS

Seasonal averages of the meteorological characteristics from each of the four weather stations as well as the combined average (all sites) are presented in Table 2 for the 1993 and 1994 sampling seasons. Air temperature at 1.5 m was 1.1 to 1.3 deg C warmer in 1993 than in 1994. With the exception of site 7, soil surface temperatures were between 2.6 and 4.0 deg C warmer in 1993. Soil temperatures at –5 and –10 cm were between 2.7 and 4.0 deg C cooler in 1994 with the exception of site 22.

The largest differences in abiotic conditions between the two years sampled was an increase of between 1.8 and 2.7 times as much precipitation fell between June and August of compared to 1993. As an independent check of the precipitation data, values were compared to those collected at a RAWS station (http://www.wrcc.sage.dri.edu/cgi-bin/raws2_pl) located at Quartz Creek near site 15 of this study. In 1993 the station reports 46.7 mm and in 1994 a value of 113.2 mm. While the magnitude of the difference in the precipitation is similar between the two years as reported in this study, the absolute values are considerably different. We report precipitation amounts of between 330 and 350% higher than the Quartz Creek station.

Weather data was obtained from the Western Regional Climate Center (http://www.wrcc.dri.edu/summary/climsmak.html) which includes monthly average temperature dating back to 1949 for four locations on the Seward Peninsula. These stations include Kotzebue to the north, Wales to the west, Nome to the south and Unalkleet to the east. Winds were predominately out of the south in both 1993 and 1994

(Table 2) and hence Nome is thought to be most representative of the precipitation characteristics for the Seward interior (Table 3). In 1993, Nome reported 113 mm while in 1994, 259 mm. Hoptkins Sigafoos (1951) approximated the amount of precipitation falling as rain to be on the order of 158 mm in the Immuruk Lake area (site 6, Fig. 1). As 1977 was an extreme fire year for the Seward Peninsula (Racine, 1981) one can compare precipitation for a dry year with the three years sampled in this study: 1992, 93 and 94. For Nome (and generally true for Kotzebue, Unalakleet, and Wales) 1994 had an above average rainfall, 1977 the lowest of the years compared, 1993 below average and 1992 greater than 1993 but still below average.

Photosynthetically active radiation was approximately 9 % higher in 1993 than 1994 as reflected in the higher air temperatures in 1993. Presumably the lower temperatures and lower solar radiation values for 1994 were the result of increased cloud cover and are supported by higher precipitation values in 1994 (Table 2).

Seasonal daily averages for all four sites are provided in Figs. 2-5 for air temperature and PAR, Figs. 6-9 for soil surface temperatures, soil at 5 cm depth and 10 cm, and Figs. 10-13 for precipitation.

Soil temperature of tussock and intertussock areas was measured hourly at each site along with flux measurements. These measurements were made at three time periods, mid July, late July and mid August at the surface, 5 and 10 cm soil depths. During the first two measurement periods, there was a significant decrease in soil temperatures with age at all depths and in tussock and inter tussock areas except at 10 cm in the intertussock locations July 16-23 and the tussock at 10 cm, July 26-August 3. Temperature differences in general were between 4 and 6°C (Table 4). During the last measurement period, temperature differences were between 2 and 4°C but in all cases, there was no significant differences among ages, or tussock and intertussock regions.

Depth to water table was measured both in 1993 and 1994 whenever a site was visited for diurnal carbon flux measurements. In June and early July of 1993, unless a visit coincided with a rain event, a water table was non-existent indicating nearly complete drainage of water in the active layer. For July and August, the average water table depth for all sites in 1993 was 38.3 cm deep (Fig. 14). This contrasts markedly with 1994 where for the same period of time, the water table depth was 26 cm higher or 12.2 cm deep. These differences were significant using a paired T test ($T_{(10)}$ =4.244; P<0.005).

Thaw depth was taken between July 26 and August 18 in 1992 and throughout the sampling period from June to August in 1994. During these two years, both tussock and intertussock area were sampled. In 1993, transects were laid and thaw depth in tussock and intertussock areas was not differentiated. Hence, comparisons between years are expressed using maximum thaw depth sampled in tussock tundra (tussock and intertussock thaw depths combined) for each season. A two way ANOVA was used to evaluate the effects of year sampled and age of stand (Table 5), both of which were found to be significant at P< 0.0001 and P< 0.005 level respectively. The significance observed was nearly all due to data collected in 1994 when unusually high precipitation was observed. Thaw depth in 1992 and 1993 were similar varying inversely with age of stand (Fig. 15). Values ranged from –45 to –51 cm in the newly burned sites and –42 to –48 cm in the unknown age stands. In 1994 a similar pattern was observed however on average thaw depth were ca. 15 cm deeper than in 1992 or 1993. Values ranged from -75 cm in the youngest stand to –54 cm in the oldest stands.

The overall pattern of seasonal GEP, Respiration and Net flux for intertussock, tussock and tundra over time is shown in Figs. 16 and 17 for 1993 and 1994 respectively. The response of specific tundra types (intertussock and tussock areas) and the whole ecosystem, respectively are shown in Figs. 18-20 where age, year of measurement and carbon fluxes are compared.

There was a general decrease in loss of carbon with age in intertussock due to a decline in respiration and a decline in the magnitude of positive net flux (source of CO_2 from the ecosystem to the atmosphere). The combination of a decrease in respiration while LAI of the intertussock vegetation gradually developed through time led to an increase in GEP with age (Fig. 18) in 1993. While GEP did not significantly differ between seasons sampled, both positive Net flux and Respiration were significantly lower in 1994 compared to 1993 (Fig. 18, Table 6).

Respiration significantly declined with age in the tussock areas while net flux was nearly constant (Fig. 19, Table 6). This led to a significant decline in GEP in tussock areas with increasing age (Fig. 19, Table 6). Similar to the intertussock areas, both respiration and the magnitude of net positive flux were significantly lower in 1994 vs 1993.

When the proportional contribution of intertussock and tussock areas were combined to determine tundra carbon flux (whole ecosystem flux), the larger arial coverage of intertussock tundra was the dominant factor with trends and significant differences being similar to that which was found for intertussock areas (Figs. 18 and 20, Table 6). This can be attributed to the dominance of intertussock respiration and high positive net carbon losses immediately after fire, declining through time as the percent cover of tussock areas increased (Fig. 21).

Discussion

1993

There is a tendency for CO_2 loss from arctic tundra to be reduced with increasing time since the last fire (Fig. 16). The net tundra flux is comprised of intertussock and tussock areas. The net fluxes of intertussock areas were more affected by time since fire than were the tussock areas (Fig. 16 and 17). This is because soil respiration decreased with time since fire in both tussock and inter tussock areas, but the greater LAI of tussock areas showed decreasing GEP with time after fire where as the inter tussock areas showed increasing GEP with time after fire. This is most likely due to the fact that Eriophorum resprouts rapidly after fire. The reduced shading by standing dead leaf material, and increased nutrient availability after fire presumably lead to increased GEP and GPP after fire. This tended to offset the increased soil respiration after fire. The inter tussock areas have a greater percentage of LAI in mosses and lichens. LAI of mosses and lichens develop more slowly after fire.

This clear difference between the reaction of tussock and inter tussock areas may help to predict the response of different systems with densities of tussocks to fire frequency effects.

1994

In1994 the effect of stand age on net ecosystem flux was minimal. 1994 was a much wetter year than 1993. Since higher soil water contents can suppress soil aeration and therefore soil respiration (Oechel *et al*., 1998), the effect of time since fire on soil respiration appears minimized. The same pattern of stimulation of GEP after fire was seen in 1994 as was seen in 1993, with tussock areas showing decreasing GEP with time after fire. Intertussock areas showed minimal effect or an increase in GEP with time. The net effect of differences in responses of different surface types and of respiration and GEP to time after fire is a minimal effect of time since fire on the CO_2 flux of tundra surfaces.

Combining the patterns seen in 1993 and 1994 indicates that increasing fire frequency will, overall increase net CO_2 loss to the atmosphere during the summer season. Since soil respiration, under dryer conditions, is higher after fire, one might expect that the winter losses of CO_2 to the atmosphere would be increased by fire as well. Further, decreasing soil moisture with global warming would be expected to increase the effect of fire on net ecosystem CO_2 efflux, at least over a period of decades.

Controls on Carbon Flux

Net primary production immediately after a fire, primarily due to Eriophorum vaginatum, has been reported to be higher, or of similar magnitude to unburned tundra (Wein and Bliss, 1973; Rawes and Welch, 1969; Racine *et al.*, 1983; Fetcher *et al.*, 1984). This led to the conclusion that fire may actually be a rejuvenating factor for arctic plant communities and that a combination of warmer soils, deeper thaw depth and improved nutrient conditions were primarily responsible for the rapid recovery of tundra following fire (Wein and Bliss, 1973). As an initial hypothesis, it is not unreasonable to predict that burned tundra may be a strong sink for carbon, declining with age as net primary productivity declines due to diminished effects of stimulation due to deeper thaw, higher temperature and higher nutrient levels.

In this study, we did not measure net primary productivity but rather carbon flux. Our net carbon flux values in 1993 do indicate that net primary productivity was similar in tussocks immediately after a burn compared to older stands (Fig. 16) in 1993. The lag in recovery of net primary productivity for intertussock areas is shown by increasing GEP with time (Fig. 16). The predominant plants responsible for rapid recovery after fire have been attributed to graminoids (Racine *et al.*, 1983; Racine, 1983), nearly absent in intertussock areas. The decline in respiration in both tussock and intertussock areas with time, the nearly constant net carbon flux of tussock areas, and the decline in loss of carbon due to net positive carbon flux in intertussock areas, presumably due to increasing net primary productivity with time, resulted in decreasing loss of carbon through time as positive net carbon fluxes diminished in magnitude with time since the last fire (Fig. 16).

Maximum seasonal thaw depth was only slightly lower in the younger age stands vs. the older stands (Fig. 15). Most studies indicate a dramatic increase in thaw immediately after a burn and up to 10-12 years post burn (Johnson and Viereck, 1983; Wein and Bliss, 1973). Racine *et al.*, 1983 reported an increase in thaw depth of 35-40% by the second year following fire with a return to unburned tundra thaw levels between the seventh and tenth years. However, Raciene *et al.*, 1983 point out that steeper slopes tended to show a greater and more long lasting thaw response. All sites in this study were on slopes between 0 and 3%. Seasonal differences, site to site variability and associated hydrological regimes may account for the lack of differences observed in the 1993 and 1994 sample periods. The differences in thaw depth between the young and old stand in 1994 are the same magnitude as differences found at site 6 (this study, Table 1), in 1979, two years after a burn (Racine, 1981). However, it is likely that climatic factors, interacting with the effects of fire, were primarily responsible for the increase thaw depth in the younger aged stands. Typically, as arctic tundra soil dry out, their insulation quality improves, minimizing transfer of heat to deeper layers. As soil water tables rise, heat is more efficiently transferred deeper in the soil horizon resulting in increased thaw compared to dryer peat surfaces (Hastings *et al.*, 1989; Haag and Bliss, 1974; Chapin *et al.*, 1988).

In general, our observations of higher temperatures at all soil depths in younger stands vs. older stands and tussock areas vs intertussock areas in 1993 are in agreement with other studies (Table 4; Racine *et al.*, 1983; Johnson and Viereck, 1983). Similar differences were not found in 1994 and is likely due to the fact that any temperature differences due to surface types (either age or tussock vs intertussock) were ameliorated by the higher soil water content. Differences in thaw depth and soil temperatures among years of measurements or between surface types do not indicate that these variables, in of them selves are the major controllers of carbon balance in a fire induced chronosequence. However, this does not change the fact that the magnitude of seasonal net carbon loss tends to decrease with age since the last fire or, in the case of wet years (1994), is relatively unaffected.

When carbon flux values in 1993 and 1994 are compared to measurements made on the North slope in tussock tundra area, seasonal values are similar in this study albeit exhibiting slightly greater seasonal carbon loss (Table 7). On the North Slope, values ranged from -0.88 to +1.15 $gC\cdot m^{-2}\cdot d^{-1}$ while on the Seward peninsula, values ranged from +2.78 to +0.95 in 1993 and +0.25 to +0.95 $gC\cdot m^{-2}\cdot d^{-1}$ in 1994. There is a significant relationship between increasing latitude and decreasing carbon loss, and in some cases, a change in sign indicating carbon gain (Fig.22, Table 8). Oechel *et al*., 1993 found a similar trend and attributed it in part to increasing temperatures with a decrease in latitude and over time (Lachenbruch and Marshall, 1986; Lachenbruch *et al*., 1988; Beltrami and Mareschal, 1991) but more likely, due to the indirect effects of a decrease in drainage, and soil aeration due to a decrease in the water table (Post 1990; Wigley, 1991).

Interannual Variability in Carbon Flux

The most significant difference between the 1993 and 1994 seasons was in the markedly higher water table depth in 1994 vs. 1993 by nearly a factor of three fold (Fig. 13) leading to a dramatic decrease in carbon loss in 1994 and minimal differences between carbon flux of varying age stands (Fig. 16 and 17). The 1994 seasonal precipitation was nearly two fold greater than in 1993. Recent studies have shown that dry and warmer seasons in the arctic regions result in a change in seasonal carbon balance from a sink to a source (Bubier *et al*., 1998; Alm *et al*., 1999; Shreader *et al*., 1998; Potter and Klooster, 1998) within two successive years. Longer term responses of ecosystem with respect to changing climate and carbon flux have been observed for the arctic tundra on the North Slope of Alaska (Oechel *et al*., 1995, Oechel *et al*., 1993; Oechel *et al*., in prep.). Carbon fluxes from 1970 to 1980 indicate that the North Slope tundra was a net annual sink for carbon (Fig. 23). From approximately 1983 through 1991, with warmer and drier areas higher in magnitude. In part, the change from sink to source can be attributed to higher average annual temperatures and (Fig. 23) and in part, to water deficits prior to 1993. This is supported by declining soil water content at Barrow and Prudhoe Bay between 1970 and 1990 (Fig. 24). Manipulative experiments (Oechel *et al*., 1998b; Billings *et al*., 1982) and short term field observations (Bubier *et al*., 1998; Alm *et al*., 1999; Shreader *et al*., 1998; Potter and Klooster, 1998; Oechel *et al*., 1995, Oechel *et al*., 1993) support this. The change from a source to a sink from 1991 to 1995 is more problematic and underscores the complexity of ecosystem response over decadal time-scales. The large net CO_2 loss observed during the mid-1980's and early 1990s, and in this study for 1993, implies high rates of organic matter decomposition and ultimately, N-mineraliztion (Shaver *et al*., 1992; Nadelhoffer *et al*., 1991; Morehead and Reynolds 1993). As growh of arctic plants is strongly N limited (Chapin and Shaver, 1985) enhanced rates of gross primary production should be stimulated by higher rates of nitrogen mineralization (Oechel *et al*., 1998b; Oechel *et al*., unpublished data). However, N-mineralization is often uncoupled from microbial decomposition due to the initial microbial N-immobilization (Waelboreck *et al*., 1997; Morehead and Reynolds, 1993). Thus, net N-mineralization, and subsequent increases in plant N-uptake, photosynthesis, and whole-ecosystem CO_2 uptake may lag behind initial climate induced increases in microbial respiration due to immobilization-induced lags in N availability (Oechel and Billings, 1992; Shaver *et al*., 1992; Waelboreck *et al*., 1997).

Winter fluxes

Year to year variability in temperature and precipitation can determine whether or not an area is a source or sink over the growing season (Bubier *et al*., 1998; Alm *et al*., 1999; Shreader *et al*., 1998; Potter and Klooster, 1998), however, this does not include winter fluxes which have been found to be of great significance (Fig. 25, Table 9; Oechel *et al*., 1997b). These data show that more carbon may be lost over the cold season than over the warm season. Moist wet sedge coastal tundra near Prudhoe Bay on average from 1994-97, was a net sink of 5 $gC \cdot m^{-2}$ during the summer while winter flux was a source of 44 $gC \cdot m^{-2}$ resulting in an annual loss of 39 $gC \cdot m^{-2}$ (Fig. 26; Oechel *et al*., in prep). Therefore, carbon losses in this study would be larger on an annual basis if winter carbon losses were included.

Fire Frequency

Fire frequency on the Seward Peninsula has increased over recent decades (Fig. 27; Oechel and Vourlitis, 1997c). A three fold increase in wildfires in boreal regions of Canada resulted in a 86% reduction in net ecosystem carbon sink (Apps *et al*., 1993). Increased availability of nutrients due to fire appears to stimulate growth of plants in the arctic (Chapin and van Cleve, 1981) however, a concomitant increase in nutrient stimulated soil decomposition (Bryant and Reichardt, 1992) appears to be the dominant factor resulting in a net carbon loss in recently burn tundra on the Seward Peninsula. An increase in fire frequency (Bryant and Reichardt; 1982) and or warmer temperatures (Chapin *et al*., 1995; Hobbie and Chapin, 1998) could increase the dominance of deciduous shrubs without changing the net carbon balance over the short term (Hobbie and Chapin, 1998).

Model predictions and the geological record

Most biome scale models predict an initial release of CO_2 from arctic regions over a 50-100 year scale due in part to global warming (Neilson *et al*., 1993; Smith and Shugart, 1993). These results are for the most part, supported by biogeochemical models (Waelbroeck *et al*., 1997; McKane *et al*., 1997a,b). A warmer climate is predicted to increase depth of thaw, increase mineralization rates, increased evapotranspiration, and decrease annual precipitation resulting in drier soils (Hogg *et al*., 1992; Kane *et al*., 1992; Vourlitis *et al*., 1999). Increased mineralization rates and the aerobic conditions resulting from drier soils will both tend to increase soil respiratory loss of CO_2 (Vourlitis *et al*., 1999). However, it is possible that a longer term adjustment of ecosystem physiology, plant community composition, and biogeochemical processes following climate change could result in a return to sink activity (Vourlitis and Oechel, 1999). It is speculated that the change from an initial sink to source would be driven by the increased nitrgoen made available for plant growth which would lag the initial respiratory based activity of soil mineralization. During the warmer, wetter mid - and late-Holocene period, arctic regions exhibited higher carbon accumulation rates (Marion and Oechel, 1993; Eisner and Peterson, 1998). The current fire frequency on the Seward Peninsula is estimated to be 250 years (Walker, *et al*., 1987). It may be possible that even before any change in fire management that might change fire frequency, the arctic tundra could return to a net annual sink for carbon. In fact, predictions have been made that fire may actually favor movement of boreal forest northward (Landhausser and Wein, 1993) replacing tundra vegetation and resulting in these areas becoming a net sink.

Conclusions

Alaskan arctic tundra, including that of the Seward Peninsula, has recently moved from that of sink activity to an annual source to the atmosphere. In many cases, even the summer period is a net source to the atmosphere (Figs. 16 and 17; Oechel *et al*., 1993; Oechel *et al*., 1995 and Oechel *et al*., in prep).

Increases in summer temperature, decreases in soil moisture, cloud cover, and dew fall will tend to increase the loss of CO_2 to the atmosphere (Nielson, 1993; Oechel *et al*., 1998; Schreader *et al*., 1998 and Alm *et al*., 1999). This tendency would be exaggerated by further increases in fire frequency.

Given the large amounts of carbon stored in arctic and boreal forest regions and the large aerial extent of arctic tundra and boreal forests worldwide, their contributions to the global CO_2 budget is significant.

Management of arctic areas should include an analysis of management options on net ecosystem sequestration or loss. Increasing fire frequency seems likely to increase carbon loss to the atmosphere in arctic regions, whereas decreasing fire frequency seems likely to decrease loss to the atmosphere or, in some cases, increase sequestration. Integrated ecosystem management considers the full range of ecosystem services and options. Net ecosystem flux is one which must be considered since arctic ecosystem flux can exceed 0.7 Gt C y-1 world wide, or more than 10% of current anthropogenic emissions.

Management Alternatives and Implications

It was initially hypothesized that the arctic tundra would have an annual net carbon lost the first 5 years after a fire, reach a maximal rate of net carbon gain 35-40 years after a fire and exhibit a net carbon loss in stands with no known fire history. The results from this research do not show any difference in net annual carbon flux between tussock tundra of varying ages since the last fire. In fact, for all age stands studied, on average, there was a net carbon loss of from 100 to 250 g m^{-2} over the growing season. Annual rates of carbon loss would be even higher if CO_2 loss over winter is added to that lost over the growing season. As shown in related studies, this indicates a change from tundra being a net annual sink for carbon to that of being a source. While we can state now that altering the fire cycle of the tundra will have no effect on it's annual carbon balance, this would not necessarily be true in the future. It appears that the rate of climate change over the next 25-50 years will ultimately determine the carbon balance trajectory for many ecosystems, and especially for the arctic with it large storage of carbon in permafrost. Presently, the respiration component of the arctic tundra exceeds that of the photosynthetic portion. In part, this is due to microbial based mineralization of partially decayed organic matter being released from melting of the permafrost as well as lower water tables favoring aerobic respiration. However, if the increase in mineralization also increases nutrient availability, photosynthesis could be stimulated and the tundra could return to a carbon sink. Warmer drier conditions could result in a change in community type to a forested landscape, which is predicted to be a net sink for carbon.

An additional consideration is not only year to year variability but unknown rates of change of processes driven by global warming with the potential to increase or decrease carbon sequestration through time. Add to this the possibility of changes in community structure through time, predicting the management plan to minimize CO_2 is difficult. While Alaskan tundra appears to be predictable, Table 10 show results from Russian Arctic tundra in the Eastern European area where maximum carbon sink of tundra was found to be 8 years after a fire when an unknown age stand seasonal carbon flux was compared to stands 2 and years after a fire.

Fortunately, the focus of Arctic research is on monitoring of year round flux using stationary eddy covariance towers as well as airborne eddy covariance platforms. These types of data, combined with advances in remote sensing and modeling should allow year to year monitoring of flux such that changes can be predicted both spatially as well as temporaly and management plans implemented.

Technology Transfer

Technology transfer and dissemination of the research results have taken place via a number of different channels. Collaboration with Drs. Zamolodchikov and Karelin began in 1991. In 1993, two of Russian researchers from their lab worked on the Seward Peninsula. As a result of this collaboration, two field seasons of measurement took place on the Taymir Peninsula in 1993 and 1994. Two additional seasonal measurements were made at Vorkuta in 1995 and 1996 in western Russia. In 1997 and 1998, research was conducted on the Chukotka peninsula. Funds to support this work were from the US State Department, National Science Foundation, National Geographic Society, Sorrus Foundation and the Rite Foundation. While NPS funds did not directly supports this work, they greatly facilitated the transfer of technology and resulted in numerous publications by Drs. Zamolodchikov and Karelin including a paper on postfire alterations of carbon balance in tundra ecosystems.

Russian Collaboration

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Papers on the effects of time after fire on tundra carbon flux are in preparation. Over the last eight years, numerous papers have been published and presentations given on northern and chaparral regions carbon flux and the factors that control them within the context of Global Change.

Arctic publications 1991-1998

Manuscripts

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Harazono, Y., M. Yoshimoto, G. L. Vourlitis, R. Zulueta, and W.C. Oechel. 1996 Heat, water and greenhouse gas fluxes over the Arctic tundra ecosystems at North slope in Alaska. Proceedings of IGBP/BAHC-LUCC Joint Inter-Core Projects Symposium, Kyoto, Japan (170-173).

Oechel, W.C. and G.L. Vourlitis. 1996. Direct effects of elevated CO_2 on arctic plant and ecosystem function. *In:* W. Koch and H. Mooney (eds.). *Terrestrial Ecosystem Response to Elevated Carbon Dioxide*. Academic Press, San Diego, pp. 163-174.

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Gilmanov, T.G. and W.C. Oechel. 1995. New estimates of organic matter reserves and net primary productivity. Journal of Biogeography 22: 723-741.

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Oechel, W.C., S.J. Hastings, G.L. Vourlitis, M.A. Jenkins, C.L. Hinkson. 1995. Direct Effects of CO_2 in Chaparral and Mediterranean-Type Ecosystems. *In:* J. Moreno and W. Oechel. (eds.). Global Change and Mediterranean-Type Ecosystems. Ecological Studies 117. Springer, New York, NY, pp. 58-75.

Oechel, W.C. and G. Vourlitis. 1995. Effect of global change on carbon storage in cold soils. Advances in Soil Science. *In:* R. Lal, J. Kimble, E. Levine, and B.A. Stewart (eds.). Advances in Soil Science: Soils and Global Change. CRC Press, Inc., Boca Raton, Florida, pp. 117-129.

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Oechel, W.C., S. Cowles, N. Grulke, S.J. Hastings, B. Lawrence, T. Prudhomme, G. Riechers, B. Strain, D. Tissue, and G. Vourlitis. 1994. Transient nature of CO_2 fertilization in Arctic tundra. Nature. 371: 500-503.

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Oechel, W.C., S.J. Hastings, M. Jenkins, G. Riechers, N. Grulke, and G. Vourlitis. 1993. Recent change of arctic tundra ecosystems from a net carbon sink to a source. Nature. 361: 520-526.

Vourlitis GL and Oechel WC. 1993. Microcosms in natural experiments. Workshop on the Design and Execution of Experiments on CO_2 Enrichment. *In*: Schulze, E.D. and H.A. Mooney (eds.) Design and Execution of Experiments on CO_2 Enrichment. Ecosystems Research Report 6, Proceedings of a Workshop held at Weidenberg, Germany, October 26 to 30, 1992. Belgium, pp. 199-210.

Vourlitis, G.L., W.C. Oechel, S.J. Hastings, and M.A. Jenkins. 1993. A system for measuring *in situ* CO_2 and CH_4 flux in unmanaged ecosystems: An arctic example. Functional Ecology. 7: 369-379.

Vourlitis, G.L., W.C. Oechel, S.J. Hastings, and M.A. Jenkins. 1993. The effect of soil moisture and thaw depth on methane flux from wet coastal tundra ecosystems on the north slope of Alaska. Chemosphere. 26: 329-338.

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Oechel, W.C., G. Riechers, W.T. Lawrence, T.I. Prudhomme, N. Grulke, and S.J. Hastings. 1992. CO_2LT, An automated null-balanced system for studying the effects of elevated CO_2 level and global climate change on unmanaged ecosystems. Functional Ecology. 6: 86-100.

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Sveinbjornsson, B. and W.C. Oechel. 1992. Controls on growth and productivity of bryophytes: Environmental limitations under current and anticipated conditions.

In: J.W. Bates and A.M. Farmer (eds.). Bryophytes and Lichens in a Changing Environment. Oxford University Press. pp. 77-97.

Marion, G.M., J.M. Moreno, and W.C. Oechel. 1991. Fire severity, ash deposition, and clipping effects on soil nutrients. Soil Science Society of America Journal. 55: 235-240.

Mooney, H.A., B.G. Drake, R.J. Luxmoore, W.C. Oechel, and L.F. Pitelka. 1991. Predicting ecosystem responses to elevated CO_2 concentrations. BioScience. 41: 96-104.

Moreno, J.M. and W.C. Oechel. 1991. Fire intensity and herbivory effects on postfire resprouting *Adenostoma fasciculatum* in southern California chaparral. Oecologia. 85: 429-433.

Moreno, J.M. and W.C. Oechel. 1991. Fire intensity effects on the germination of shrub and herbaceous species in southern California chaparral. Ecology. 72: 1993-2004

Strain, B.R., L.H. Allen, Jr., D. Baldocchi, F. Bazzaz, J. Burke, R. Dahlman, T. Denmead, G. Hendrey, A. McLeod, J. Melillo, W. Oechel, P. Risser, H. Rogers, J. Rozema, and R. Wright. 1991. Available technologies for field experimentation with elevated CO_2 in global change research. *In:* H.A. Mooney (ed.). Ecosystem Experiments. SCOPE 45. John Wiley & Sons Ltd., pp. 245-261.

Sveinbjornsson, B. and W.C. Oechel. 1991. Carbohydrate and lipid levels in polytrichum mosses growing on the Alaskan tundra. Holarctic Ecology. 14: 272-277.

Books and Reports:

Oechel, W.C., T. Callaghan, T. Gilmanov, J.I. Holten, B. Maxwell, U. Molau, B. Sveinbjornsson (eds.) 1997. Global Change and Arctic Terrestrial Ecosystem. Ecological Studies 124. Springer, New York, NY, 493 pp.

Moreno, J.M. and W.C. Oechel (es.). 1995. Global Change and Mediterranean-Type Ecosystems. 117. Springer Verlag, New York, 527 pp.

Moreno, J.M. and W.C. Oechel (es.). 1994. The Role of Fire in Mediterranean Ecosystems, Ecological Studies. 107. Springer Verlag, New York, 201 pp.

Oechel, W.C., J.I. Holten, T. Callaghan, H. Elling, T. Gilmanov, B. Maxwell, U. Molau, O. Rogne, and B. Sveinbjornsson. 1993. Report and recommendations of an international symposium: Global Change and Arctic Terrestrial Ecosystems. 21-26 August, Oppdal, Norway.

Moreno, J.M. and W.C. Oechel. 1992. Report and recommendations of the symposium and workshop "Anticipated Effects of a Changing Global Environment on Mediterranean-type Ecosystems. Valencia, Spain, September 14-17.

Invited presentations, participation, seminars.

Oechel, W.C. Invited Referee. SENSE-Symposium. “Interdependent changes in climate, land use, biogeochemical cycles and analysis of related policy options.” The Netherlands June 24-26, 1998.

Oechel, W.C. Invited Participation. National Research Council. ”New Vistas in Transatlantic Science and Technology Cooperation” Washington D.C. June 8-9 1998.

Oechel, W.C. Invited Participation. California Science Education Advisory Committee. San Francisco, California May 21, 1998.

Oechel, W.C. Invited Participation. The American Physical Society. San Diego Elementary Science Education Leadership Institute. San Diego, California May 16-20, 1998.

Oechel. W.C. Invited Participation. Polar Research Board, National Research Council. Washington, DC April 30-May 1, 1998.

Oechel, W.C. Invited presentation. “Impacts and Effects of Global Change in the Arctic.” IASC Annual Meeting. Fairbanks, Alaska April 26-28, 1998.

Oechel, W.C. Invited Presentation. San Diego Science Educators Association, 14th annual conference. San Diego, California March 13-14, 1998.

Oechel, W.C. Invited Participation. California Workshop on Regional Climate Change and Variability. National Center for Ecological Analysis and Synthesis. Santa Barbara, California March 9-11, 1998.

Oechel, W.C. Invited Participation. Ecosystem panel for the National Academy of Sciences. Portland, Oregon December 9, 1997.

Oechel, W.C. Invited Participation. IUPAC International Conference. Phuket, Thailand November 23-27, 1998.

Oechel, W.C. Invited Participation. Steering Committee. California Workshop on Regional Climate Change and Variability. Santa Barbara, California November, 24, 1997.

Oechel, W.C. Invited Presentation. Effects of Global change in Fire Frequency and Intensity. Fire in California Ecosystems: Integrating Ecology, Prevention, and Management. San Diego, California November 18-20, 1997.

Oechel, W.C. Workshop Chair. NOAA Contaminants Workshop. Silver Springs, Maryland November 10-11, 1997.

Oechel, W.C. Invited Presentation. Effect of land-use change and changing climate on ecosystem functioning and biodiversity. GCTE-BAHC-LUCC Core Projects: Prospects for Integrative Activities. Wageningen, The Netherlands November 16-19, 1997.

Oechel, W.C. Invited Participation. US Climate Forum. The Consequences of Global Change for the Nation. Washington, DC November 12-13, 1997.

Oechel, W.C. Invited Presentation. Land Atmosphere Feedback: The role of water and temperature in the Arctic. University of Illinois, Chicago, seminar series. Chicago, Illinois November 7, 1997.

Oechel, W.C. Invited Presentation. Measuring Gas Exchange at Different Spatial Scales. Symposium on Controls on Soil Respiration: Implications for Climate Change. Anaheim, California October 27-28, 1997.

Oechel, W.C. Invited Participation. Global Change Workshop. San Diego, California October 25-27, 1997.

Oechel, W.C. Invited Participation. 30th Anniversary Reunion Symposium of the National Resource Ecology Laboratory. Fort Collins, Colorado October 21, 1997.

Oechel, W.C. Conference Organizer. MEDECOS VIII Conference on Mediterranean Type ecosystems. San Diego, California October 18-26, 1997.

Oechel, W.C. Invited Participation. Project workshop for “The Role of High Latitude ecosystems in the Global Carbon cycle.” Martha’s Vineyard, Massachusetts October 12-14, 1997.

Oechel, W.C. Invited Participation. Critical assessment of the response of forest ecosystems to elevated atmospheric carbon dioxide. 3rd International IGBP-GCTE Workshop. Durham, North Carolina October 10-13, 1997.

Oechel, W.C. Invited Panelist. “Impacts of Climate Change.” Science Summit on Climate Change, Union of Concerned Scientists. Washington, DC September 30, 1997.

Oechel, W.C. invited Participation. IASC-GCTE working group meeting. Potsdam, Germany September 26-27, 1997.

Oechel, W.C. Invited Participation. Science Advisory Committee for the International Arctic Science Center. Washington, DC September 18-19, 1997.

Oechel, W.C. Invited Participation. Present and historical Nature-Culture Interactions in landscapes (experiences for the 3rd millennium). Prague, Czech Republic September 6-9, 1997.

Oechel, W.C. Invited Participation. Annual meeting of the Ecological Society of America, held jointly with the Nature Conservancy. Albuquerque, New Mexico August 10-14,1997.

Oechel, W.C. Invited Participation. Ecosystems Panel Meeting. national Academy of Sciences and National Research Council. Washington, DC August 7-8, 1997.

Oechel, W.C. Invited Presentation and Participation. Current and Past Carbon Fluxes of Barrow. Celebration of the 50th Anniversary of the Naval Arctic Research Laboratory. Barrow, Alaska August 4-8, 1997.

Oechel, W.C. Invited Participation. 1997 International Geoscience and Remote Sensing-A Scientific Vision for Sustainable Development. Singapore August 4-8, 1997.

Oechel, W.C. Invited presentation. Annual carbon balance estimates for the Kuparuk River Basin, Alaska. Land-Atmosphere-Ice Interactions Synthesis Workshop. Orcus Island, June 22-29, 1997.

Oechel, W.C. Invited Presentation. CO_2 flux from Arctic Tundra measured at three scales by chamber, eddy correlation tower, and aircraft techniques and extrapolation to a watershed scale. International Symposium on Physics, Chemistry, and Ecology of Seasonally Frozen Soils. Fairbanks, Alaska. June 10-12, 1997.

Oechel, W.C. Invited participant. WESTGEC Annual Meeting. Western Regional Center of the National Institute for Global Environmental Change. Oregon. June 8-10, 1997.

Oechel, W.C. Invited Presentation. Effects of elevated atmospheric CO_2 on production and water use in water-limited forests and woodlands: a review of past and current research. IUFRO Workshop: Forests at the limit. South Africa. May 11-17, 1997

Oechel, W.C. Invited Presentation. Large Scale Carbon Flux in the Arctic. European Geophysical Society. Vienna, Austria. April 21-25,1997.

Oechel, W.C. and G. Vourlitis. Invited Presentation. Environmental controls over CO_2 flux from Arctic ecosystems. UCSB Boreal Arctic Workshop. Santa Barbara, CA. April 7-10, 1997.

Oechel, W.C. Invited Participation. Land-Atmosphere-Ice Interaction 1997 Science Workshop. Arctic System Science. Seattle, WA. March 27-29, 1997.

Oechel, W.C. Invited Presentation and Participation. Mediterranean Shrublands and Desert. Terrestrial Global Productivity. Montpellier, France. March 20-22, 1997.

Oechel, W.C. Invited Participation. Environment and Climate Program. European Commission. Brussels, Belgium. February 2, 1997.

Oechel, W.C. Invited Presentation and Participation. Effects of elevated temperature on Ecosystems. Gordon Conference on Temperature Effects. Ventura, CA January 26-31, 1997.

Oechel, W.C. Invited Participation. Scientific Challenges Roundtable. Challenges of the Third Millennium Symposium. Valencia, Spain. January 22-25, 1997.

Oechel, W.C. and George Vourlitis. Invited Symposium Presentation. Carbon flux in arctic ecosystems. AGU. San Francisco, CA. December 15-19, 1996.

Oechel, W.C. Invited Presentation and Participation. A new FACE system for use in Mediterranean-type Ecosystems. FACE Protocol Meeting. Duke University. November 21-22, 1996.

Oechel, W.C. Invited Presentation and Participation. Effects of elevated CO_2 and drought on Mediterranean-type ecosystems. FACE Science Meeting. Duke University. November 17-20, 1996.

Oechel, W.C. Invited Presentation and Participation. Effects of Global Change on Arctic Ecosystems. IGBP/BAHC/INES Japan-Russia meeting. Yakutsk, Russia. October 6-12, 1996

Oechel, W.C. Invited Participation. Effects of global change and land use on the ecosystems of the Mediterranean Basin. Toledo, Spain. September 25-29, 1996.

Oechel, W.C. Invited Participation. DOE Terrestrial Carbon Program. Tahoe, CA. June 27-28, 1996.

Oechel, W.C. Invited Participation. DOE CMEAL analysis of models used to predict impacts of global change. Tahoe, CA. June 24-26, 1996.

Oechel, W.C. Invited Presentation. Acclimation to elevated CO_2. DOE/EPSCOR Meeting. Tahoe, CA. May 19-26, 1996.

Oechel, W.C. Invited Presentation. Effects of elevated CO_2 on Mediterranean-type Ecosystems. WESTGEC/NIGEC investigators meeting. UC Davis, Davis, CA May 7-8, 1996.

Oechel, W.C. Invited Presentation. ARCUS LAII All-Hands Workshop, Snowbird, Utah. April 30-May 4, 1996.

Oechel, W.C. Invited Participant. LAII Science Workshop. Seattle, Washington. February 22-23, 1996.

Oechel, W.C. Invited Participant. IASC Planning Meeting. Hanover, New Hampshire. December 2-4, 1995.

Oechel, W.C. Invited Participant. CO_2 Flux in Alaskan and Russian Arctic Tundra Regions from Chamber, Tower, and Air Craft Measurements and Plans for the Future. IGBP Northern Eurasia Study. Tsukuba, Japan. November 28-December 1, 1995.

Gilmanov, T.G., W.C. Oechel, D.G. Zamolodchikov, V.N. Nosov, and N.S. Panikov. First Measurements and Modeling of the Seasonal CO_2 Flux in the Russian Arctic (Taimyr Peninsula). IGBP Northern Eurasia Study. Tsukuba, Japan. November 28-December 1, 1995.

Harazono, Y., M. Yoshimoto, G.L. Vourlitis, and W.C. Oechel. Change of CO_2 Budget with Micrometerology at Arctic Coastal Tundra Ecosystem in Alaska. IGBP Northern Eurasia Study. Tsukuba, Japan. November 28-December 1, 1995.

Oechel, W.C. Invited Participant. Russian Arctic Land Shelf Systems Workshop. St. Petersburg, Russia. November 6-8, 1995.

Oechel, W.C. Invited Participant. NSF Workshop on Research Priorities for Russian Arctic Land Shelf Systems. Washington, DC. October 16-17, 1995.

Oechel, W.C. Invited Participant. Effects of Environmental Disturbance on Ecosystem CO_2 Flux. NATO Advanced Research Workshop on Disturbance and Recovery of Arctic Terrestrial Ecosystems. Riovaniemi, Finland. September 24-30, 1995.

Oechel, W.C. Invited Participant. Quantitative Analysis of Total Carbon Budget: A Case Study for Chaparral. GCTE Foci 1 and 3 Workshop on Plant-soil Carbon Below Ground: The Effects of Elevated CO_2. Oxford, England. September 20-23, 1995.

Cook, A.C., W.C. Oechel, S.W. Roberts, D. Tissue, and B. Sveinbjornsson. Effects of Elevated CO_2 from Natural CO_2 Springs on *Nardus stricta*. 80th Annual ESA meeting, Snowbird, Utah. July 30-August 3, 1995.

Hinkson, C.L., W.C. Oechel, F. Miglietta, and A. Raschi. Long-term Effects of Elevated CO_2 on Mediterranean Forest Vegetation of Northern-Central Italy. 80th Annual ESA meeting, Snowbird, Utah. July 30-August 3, 1995.

Oechel, W.C., G. Vourlitis, T. Crawford, R. McMillen A. Hope, D. Stow, and J. Fleming. Large-scale Estimates of the Patterns of and Controls on CO_2 Flux in Arctic Alaska in Relation to Global Change. 80th Annual ESA meeting, Snowbird, Utah. July 30-August 3, 1995.

Oechel, W.C. Invited Participant. Response of Mediterranean-type Ecosystems to Elevated Atmospheric CO_2 and Associated Climate Change. Program for Ecosystem Research. Principal Investigators Meeting. Knoxville, Tennessee. May 22-23, 1995.

Oechel, W.C. Oosting Memorial Lecturer. Terrestrial carbon processes in a changing world. Duke University, Durham, North Carolina. April 20, 1995.

Oechel, W.C. Invited Participant. 76th Polar Research board Meeting. Washington, D.C. March 30-April 1, 1995.

Oechel, W.C. Invited Participant. The Role of Science and Technology in Promoting National Security and Global Stability. National Academy of Sciences, Washington, D.C. March 29-30, 1995.

Oechel, W.C. Invited Lecturer. Japanese Government Research Awards for Foreign Specialists. CO_2 springs in Italy and FACE in natural vegetation in California. NIASE, Tsukuba, Japan. March 22, 1995.

Oechel, W.C. Invited Lecturer. Japanese Government Research Awards for Foreign Specialists. CO_2 springs in Italy and FACE in natural vegetation in California. University of Kyoto, Japan. March 16, 1995.

Oechel, W.C. Invited Lecturer. Japanese Government Research Awards for Foreign Specialists. Interactions of global warming and the arctic tundra ecosystems. NIAES, Tsukuba, Japan. March 15, 1995.

Oechel, W.C. Invited Participant. Long-term Flux Measurements over a Tundra Ecosystem. IGBP BAHC-GCTE-IGAC Workshop on Strategies for Long-term Studies of CO_2 and H_2O Fluxes over Terrestrial Ecosystems. La Thuile-Valle d'Aosta, Italy. March 5-9, 1995.

Oechel, W.C. Invited Participant. ARCSS LAII Science Workshop. Orcas Island, Washington. March 2-5, 1995.

Oechel, W.C. Invited Participant. Toolik Field Station Workshop. Bodega Bay, CA February 16-17, 1995.

Oechel, W.C. Invited Participant. EUROFACE Preparatory Meeting. Rapolano, Italy. January 20-23, 1995.

Oechel, W.C. Invited Participant. Workshop to Define Research Priorities for Russian Arctic Land Shelf Systems. Byrd Polar Research Center, Ohio State University. Columbus, Ohio. January 10-12, 1995.

Oechel, W.C. Invited Participant. Review of the Dutch National Research Programme on Global Air Pollution and Climate Change. Maastricht, The Netherlands. December 6-9, 1994.

Oechel, W.C. Invited Participant. The Climate Change Debate: Backlash and Upshot. An Issues Forum with the Union of Concerned Scientists. San Diego State University. November 10, 1994.

Oechel, W.C. and J.M. Moreno. Symposium Organizers. MEDECOS/GCTE Symposium on Effects of Global Change on Mediterranean-type Ecosystems. Vina Del Mar, Chile. October 23-29, 1994.

Oechel, W.C., C. Hinkson, and F. Miglietta. CO_2 and climate effects on photosynthesis and productivity of Mediterranean-type shrublands and oak woodlands. MEDECOS/GCTE Symposium on Effects of Global Change on Mediterranean-type Ecosystems. Vina Del Mar, Chile. October 23-29, 1994.

Harazono, W.C. Oechel, S.J. Hastings, and G. Vourlitis. CO_2 flux over chaparral vegetation of different ages. MEDECOS/GCTE Symposium on Effects of Global Change on Mediterranean-type Ecosystems. Vina Del Mar, Chile. October 23-29, 1994.

Oechel, W.C. Invited Participant. ARCSS 6th Annual Meeting. Washington, DC. October 9-12, 1994.

Oechel, W.C. Invited Participant. Peer Review Meeting of the Global Change Research Program. Biosphere Interactions Modeling at ERL-C. U.S. Environmental Protection Agency. Corvallis, Oregon. October 4-6, 1994.

Oechel, W.C. Invited Participant. Current patterns of and controls on CO_2 flux in the Arctic. GISP2 Workshop. Sterling, Virgina. September 11-14, 1994.

Gilmanov, T.G. and W.C. Oechel. New estimates of organic matter reserves and net primary productivity of the North American tundra ecosystems. First GCTE Science Conference. Woods Hole, Massachusetts. May 23-27, 1994.

Oechel, W.C. Invited Participant. Environmental Protection Agency 2nd Peer Review of project "Effects of CO_2 and Climate Change on Forest Trees." Corvallis, Oregon. May 12-13, 1994.

Oechel, W.C. Participant. Symposium on Brushfires in California Wildlands: Ecology and Resource Management. Annual Meeting of the Southern California Academy of Sciences, University of California, Irvine. Irvine, California. May 6-7, 1994.

Oechel, W.C. Invited Participant. Environmental Protection Agency Peer Review Panel of project "Soviet Union Carbon Cycle Dynamics and Management Options to Conserve and Sequester Carbon. Corvallis, Oregon. April 7-8, 1994.

Oechel, W.C. Invited Participant. Sustainable Biosphere Initiative Intergovernmental Panel on Climate Change (IPCC) Vulnerability Studies Workshop. Research Triangle Park, North Carolina. March 8-11, 1994.

Oechel, W.C. Invited Participant. ARCSS Presentation on Land/Atmosphere/Ice Interactions to the Arctic Research Commission. Washington, D.C. March 9, 1994.

Oechel, W.C. Invited Participant. LAII flux Study P.I. Meeting. Seattle, Washington, January 14-16, 1994.

Oechel, W.C. Invited Participant. Fourth Annual Review of Effects of CO_2 on Forests. Lake Tahoe, Nevada, January 11-13, 1994.

Oechel, W.C. Invited Participant. Expert Consultation on Global Climatic Change and Agricultural Production: Direct Effects on Hydrological and Plant Physiological Processes. Food and Agriculture Organization of the United Nations, Rome, Italy, December 7-10, 1993.

Oechel, W.C. Invited Participant. Implications of increasing atmospheric CO_2 for Mediterranean ecosystems. Workshop on Global Change and Landscape Dynamics in Mediterranean Systems. Toledo, Spain, November 15-18, 1993.

Oechel, W.C. Invited Speaker. Arctic Terrestrial Global Change Meeting. 74th Meeting Polar Research Board, Irvine, California, November 3-5, 1993.

Oechel, W.C. Invited Speaker. Biochemical Cycles. The Implications of Climatic Change: The Case of the Boreal Forests Workshop. U.S. Forest Service, National Center for Atmospheric Research, Boulder, Colorado, October 26-28, 1993.

Oechel, W.C. Invited Speaker. Global Climate Change and Its Impact on Protected Areas. Ranger Skills Course. Albright Employee Center, Grand Canyon, Arizona, October 25, 1993.

Oechel, W.C. Invited Speaker. Effects of Elevated CO_2 on Arctic Tundra Ecosystems. GCTE Symposium: "Terrestrial Ecosystem Response to Elevated CO_2", Pisa, Italy, October 18-21, 1993.

Oechel, W.C. Invited Speaker. Comparison of CO_2 vents to experimental manipulation of CO_2 for understanding the effects of elevated atmospheric CO_2 on natural ecosystems. International Workshop: "Carbon Dioxide Springs and their Use in Biological Research", Firenze, Italy, October 14-16, 1993.

Oechel, W.C. Organizer. Processes of Homeostatic Adjustment in Ecosystems to Global Change. XV International Botanical Congress, Tokyo, Yokohama, Japan, August 28-September 3, 1993.

Oechel, W.C. President. Global Change and Arctic Terrestrial Ecosystems: an International Conference. Oppdal, Norway. August 21-26. 1993.

Oechel, W.C. Participant. Impacts of Climatic Change on CO_2 Flux. Global Change and Arctic Terrestrial Ecosystems: an International Conference. Oppdal, Norway. August 21-26, 1993.

Oechel, W.C. Participant. ARCSS LAII Flux Study Site Selection meeting. Prudhoe Bay and Barrow, Alaska. June 14-17, 1993.

Oechel, W.C. Participant. Boreal Forest Proposal Writing Workshop. University of Alaska, Fairbanks. June 6-10, 1993.

Oechel, W.C. Invited Participant. Conference: From Rio to the State Capitols - State Strategies for Sustainable Development. Louisville, Kentucky. May 25-28, 1993.

Oechel, W.C. Organizer. Global Change and Arctic Terrestrial Ecosystems International Conference Organizing Committee meeting. Copenhagen, Denmark and Oppdal, Norway. May 16-22, 1993.

Oechel, W.C. Invited Participant. ORISE: Review Panel for Global Change Distinguished Postdoctoral Fellowships. Tucson, Arizona. April 27-28, 1993.

Oechel, W.C. Invited Participant. Viewpoints on Global Warming. Conference on Preserving the Human and Natural Environment: Critical Problems/Creative Solutions. University of San Diego, San Diego, California. 25-26 March, 1993.

Oechel, W.C. Invited Speaker. Effects of Climate Change and Elevated Atmospheric CO_2 on Carbon Flux in the Arctic. Harvard University, Boston, Massachusetts. 11 March, 1993.

Oechel, W.C. Invited Participant. FACE Workshop. Orlando, Florida. 11-17 March, 1993.

Oechel, W.C. Participant. Controlled Environment Facilities in the Ecological and Environmental Sciences Workshop. Lake Tahoe, Nevada 22-25 February, 1993.

Oechel, W.C. Organizer. Global Change and Arctic Terrestrial Ecosystems International Conference Organizing Committee meeting. Manchester, England. 31 January-1 February, 1993.

Oechel, W.C. Participant. ARCSS P.I. Flux Study meeting. Seattle, Washington. 17-18 January, 1993.

Oechel, W.C. Invited Participant. 3rd EPRI Forest Response to CO_2 Information meeting. Duke University, Durham, North Carolina. 13-15 January, 1993.

Oechel, W.C. Participant. Arctic Research Consortium of the U.S. Steering Committee meeting. Boulder, Colorado. 21-22 November, 1992.

Oechel, W.C. Invited Participant. Joint Russian-American Seminar on Cryopedology and Global Change. Pushchino, Russia. 15-16, November, 1992.

Oechel, W.C. Participant. American Water Resources Association 28th Annual Conference and Symposium on Managing Water Resources During Global Change. Reno, Nevada. 1-5 November, 1992.

Oechel, W.C. Invited Participant. CO_2 Workshop on the Design and Execution of Experiments on CO_2 Enrichment. Bayreuth, Germany. 26-30 October, 1992.

Oechel, W.C. Invited Participant. International Symposium on Disturbed Climate, Vegetation, and Foods. Tsukuba, Japan. 13-17 October, 1992.

Oechel, W.C. (Symposium Organizer) Growth and photosynthetic responses to elevated atmospheric CO_2. Symposium on Anticipated Effects of a Changing Global Environment in Mediterranean Ecosystems. Valencia, Spain. 13-18 September, 1992.

Hinkson, C. and W.C. Oechel. Effects of elevated CO_2 on the nitrogen relations of *Quercus agrifolia*. Symposium on Anticipated Effects of a Changing Global Environment in Mediterranean-type Ecosystems. Valencia, Spain. 13-18 September, 1992.

Langsford, D.H. and W.C. Oechel. Variation in physiological performance within *Ceanothus greggii* shrubs. 43rd AIBS Annual Meeting, Honolulu, Hawaii. 9-13 August, 1992.

Oechel, W.C. and C.H. Gluckman. The effects of anticipated global change including variations in atmospheric CO_2 and soil moisture on carbon balance and water use in the chaparral-associated tree, *Quercus agrifolia*. 43rd AIBS Annual Meeting, Honolulu, Hawaii. 9-13 August, 1992.

Gluckman, C.H. and W.C. Oechel. The effects of atmospheric CO_2 and drought on the nutrient relations of *Quercus agrifolia*. 43rd AIBS Annual Meeting, Honolulu, Hawaii. 9-13 August, 1992.

Oechel, W.C. Invited Participant. Managing Western Lands in a Changing Climate Workshop. Boulder, Colorado, 23-24 July, 1992.

Oechel, W.C. Invited Participant. UIMP Seminar on Desertification and Forest Fires. Santander, Spain. 13-17 July, 1992.

Oechel, W.C. Invited Participant. Managing Wetlands in a Changing Climate Workshop. Washington, D.C. 28-29 May, 1992.

Oechel, W.C. Invited Participant. Symposium on the Impacts of Climate Change on Resource Management of the North. Whitehorse, Yukon. 12-14 May, 1992.

Oechel, W.C. Invited Participant. International Symposium on the Future of Mediterranean-type ecosystems. Montecatini, Italy. 27 April-1 May, 1992.

Oechel, W.C. Invited Participant. Third International Workshop on Closed Ecological Ecosystems. Oracle, Arizona. 24-27 April, 1992.

Oechel, W.C. Professional Witness. Hearing on Global Change Research: Global Warming and the Biosphere. Washington, D.C. 6 April, 1992.

Oechel, W.C. Invited Participant. International Symposium on Global Change. Shinjuku, Tokyo, Japan. 27-29 March, 1992.

Oechel, W.C. Invited Participant. Arctic Research Consortium of the U.S. Annual Meeting, Washington, D.C. 23-25 March, 1992.

Oechel, W.C. Invited Participant. Discussions on Global Change Program. Institute of Geography Academy of Sciences, Moscow, Russia. 2-10 February, 1992.

Oechel, W.C. Invited Participant. International Tundra Experiment Workshop, Kalamazoo, Michigan. 23-24 November, 1991.

Oechel, W.C. Invited Participant. Climate Research Needs Workshop. Mohonk Mountain, New York. 19-22 November, 1991.

Oechel, W.C. Invited Participant. Arctic Research Consortium of the U.S. Planning Meeting. Washington, D.C. 28 October, 1991.

Oechel, W.C. Symposium Organizer. Anticipated effects of elevated CO_2 and climate change on plant processes and implications for the structure and function of Mediterranean-type ecosystems. MEDECOS VI International Conference on Mediterranean Climate Ecosystems. Maleme, Crete. 23-27 September, 1991.

Oechel, W.C. Invited Participant. Arctic Research Consortium of the U.S. Panel Discussions. Boulder, Colorado. 23-34 August, 1991.

Langsford, D.H. and W.C. Oechel. Variation patterns of seed weight in Ceanothus shrubs and controls thereon in Southern California chaparral. 42nd Annual Meeting of the Ecological Society of America, San Antonio, Texas. 4-8 August, 1991.

Oechel, W.C., M.A. Jenkins, S.J. Hastings, G. Vourlitis, N.E. Grulke, and G.H. Riechers. Effects of recent and predicted global change on arctic ecosystems. 42nd Annual Meeting of the Ecological Society of America, San Antonio, Texas. 4-8 August, 1991.

Jenkins, M.A. and W.C. Oechel. Effect of atmospheric CO_2 level and water stress on growth and physiology of two species of chaparral shrubs. 42nd Annual Meeting of the Ecological Society of America, San Antonio, Texas. 4-8 August, 1991.

Oechel, W.C. Invited speaker. Global Change and the Carbon Dynamics of Arctic Tundra. Duke University, Durham, North Carolina. 24 June, 1991.

Oechel, W.C. Invited Participant. DOE Carbon Dioxide Program CO_2 Workshop, Edgewater, Maryland. 30-31 May, 1991.

Oechel, W.C. Participant. BOREAL Ecosystem-Atmosphere Study (Boreas) Planning Workshop, Waskesiu Lake, Saskatchewan, Canada. 12-15 May, 1991.

Oechel, W.C. Invited Participant. GCTE Focus 1 Workshop on Ecosystem Physiology, Asilomar, California. 5-7 May, 1991.

Oechel, W.C. Invited speaker. Effects of Global Change on Arctic Ecosystems. University of California, Berkeley, Berkeley, California. 15 March, 1991.

Oechel, W.C. Invited participant. Arctic Research Consortium of the U.S. Panel Discussions. University of Massachusetts, Amherst, MA. 8-9 March, 1991.

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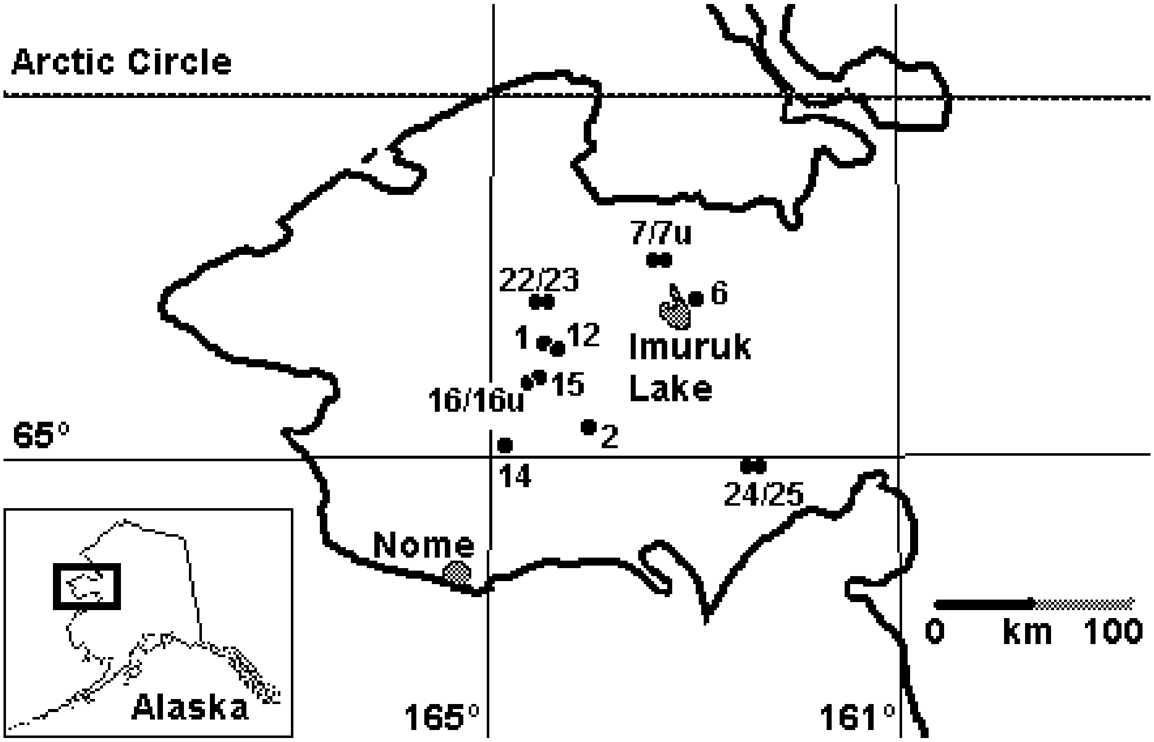

Fig. 1. Locations of the 14 sites that comprise the fire induced chronosequence of tussock tundra. Details of site characteristics and lat., long. are provided in Table 1.

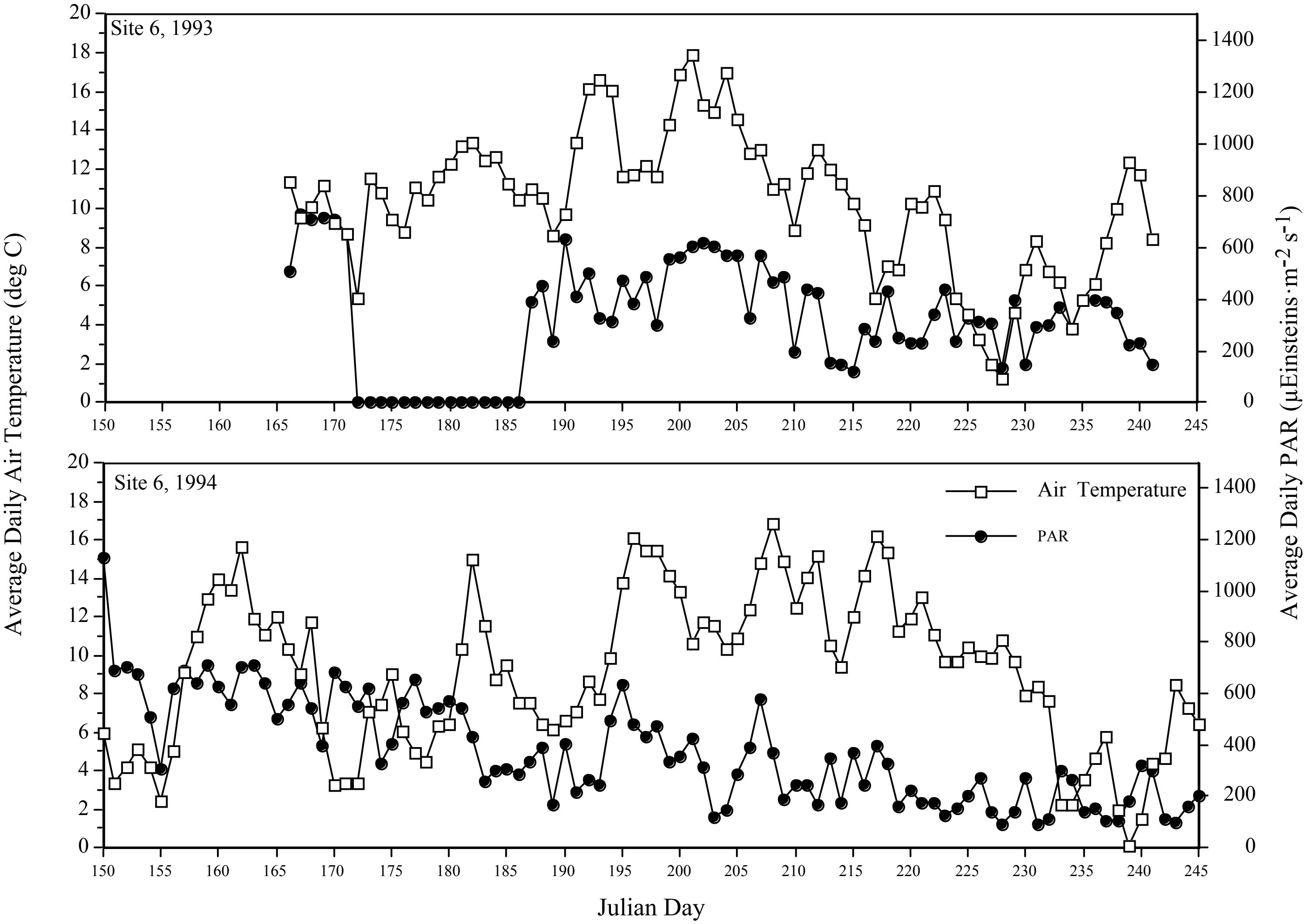

Fig. 2. Site 6, seasonal, daily average temperature (°C) and PAR (photosynthetically available radiation, μEinsteins m^{-2} s^{-1}) for 1993 and 1994. Site 6 is near Imuruk Lake and the eastern most site, see Table 1 and Fig.1 for details on location.

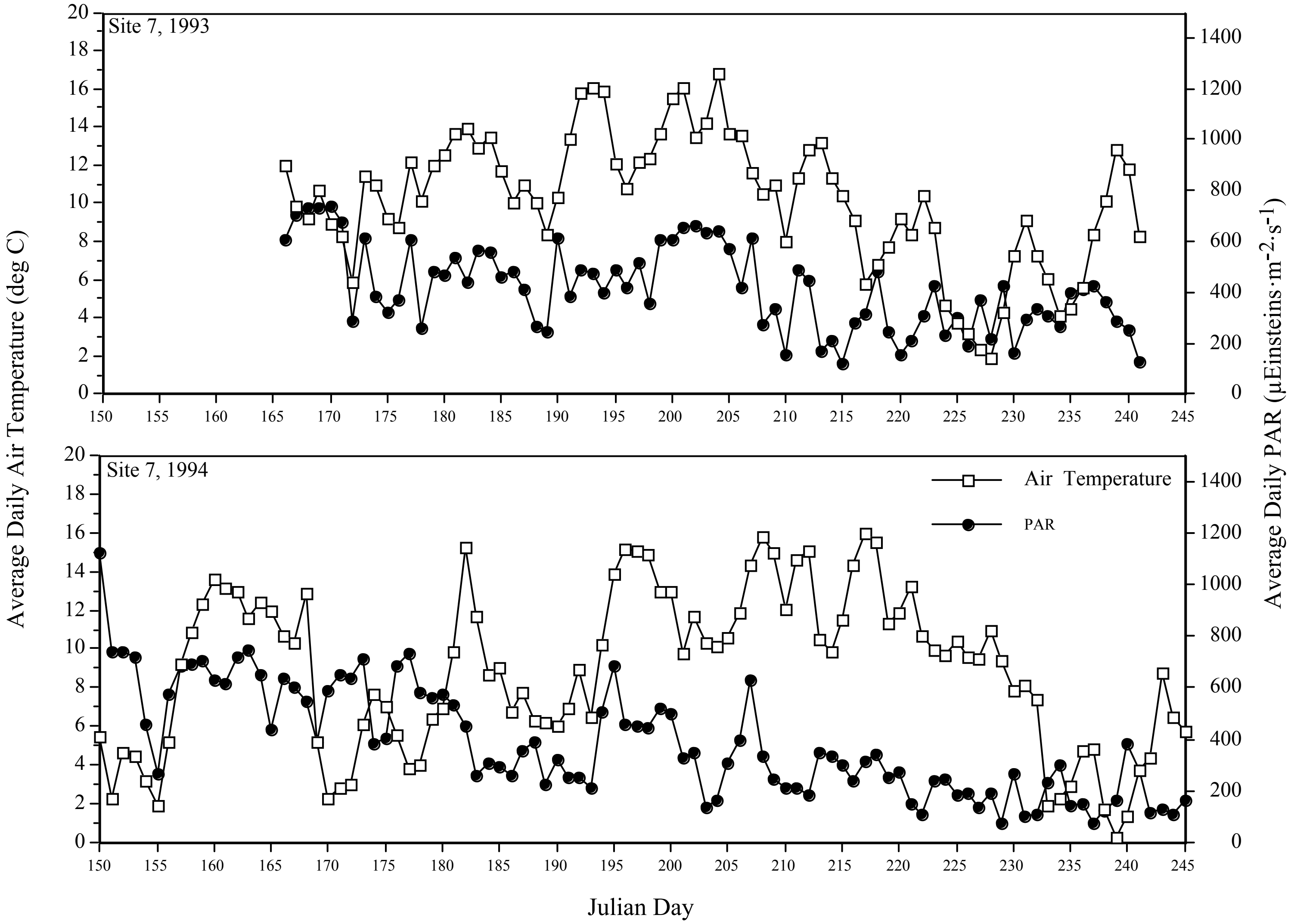

Fig. 3. Site 7, seasonal, daily average temperature (°C) and PAR (photosynthetically available radiation, μEinsteins m^{-2} s^{-1}) for 1993 and 1994. Site 7 is north of Imuruk Lake and the northern most site, see Table 1 and Fig.1 for details on location.

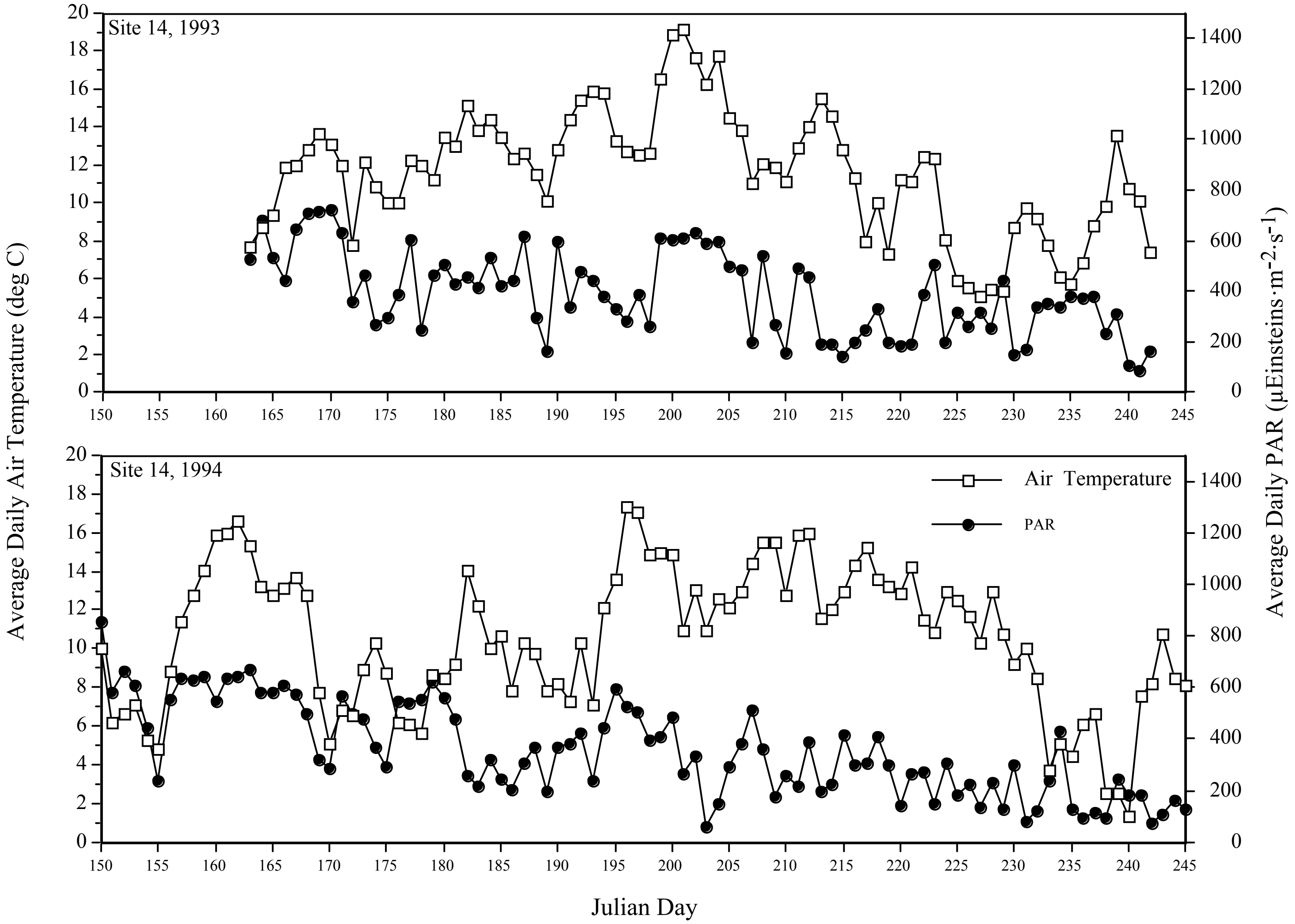

Fig. 4. Site 14, seasonal, daily average temperature (°C) and PAR (photosynthetically available radiation, μEinsteins $m^{-2} s^{-1}$) for 1993 and 1994. Site 14 is the southern most site, see Table 1 and Fig.1 for details on location.

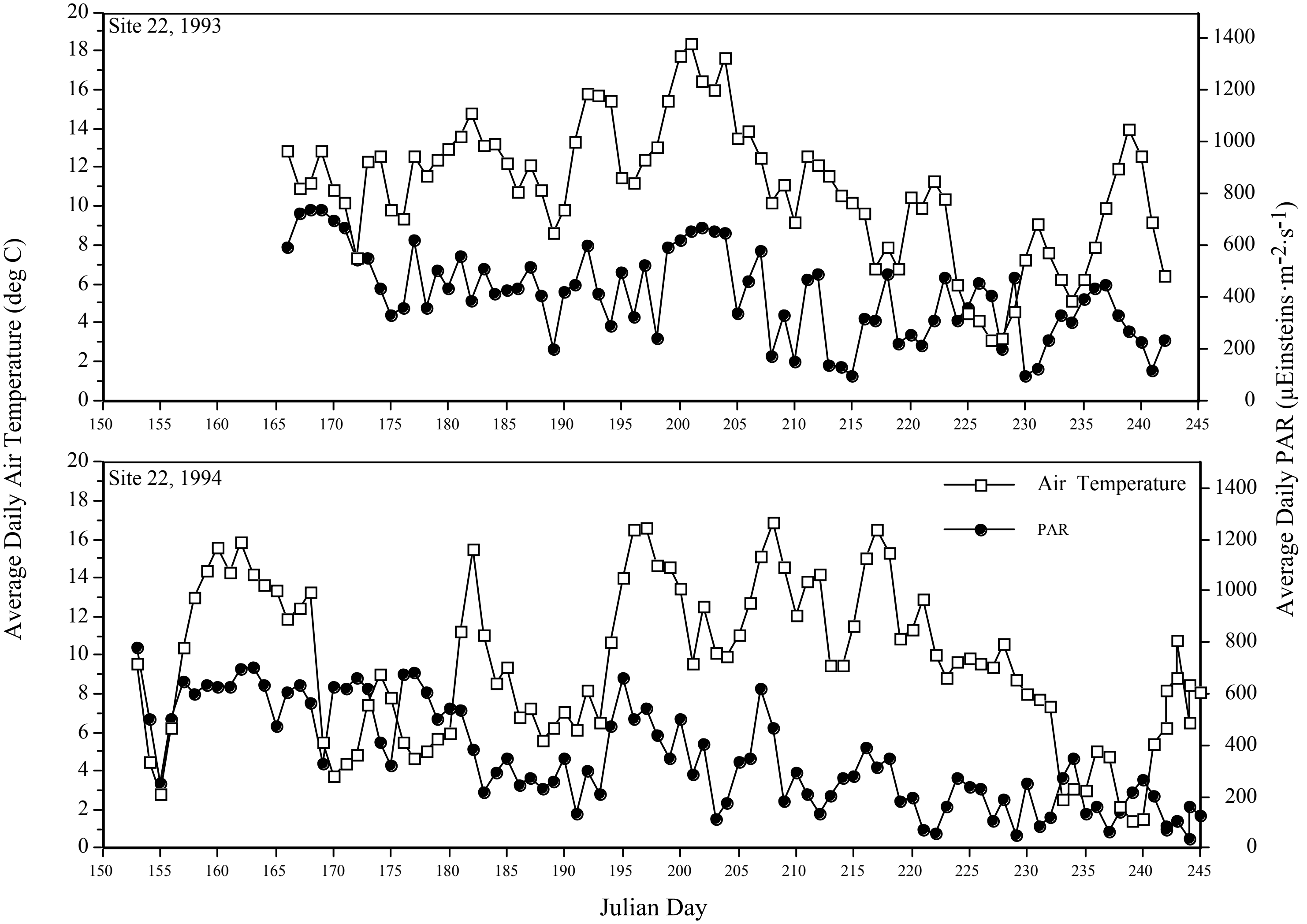

Fig. 5. Site 22, seasonal, daily average temperature (°C) and PAR (photosynthetically available radiation, µEinsteins $m^{-2} s^{-1}$) for 1993 and 1994. Site 22 is the western most site, see Table 1 and Fig.1 for details on location.

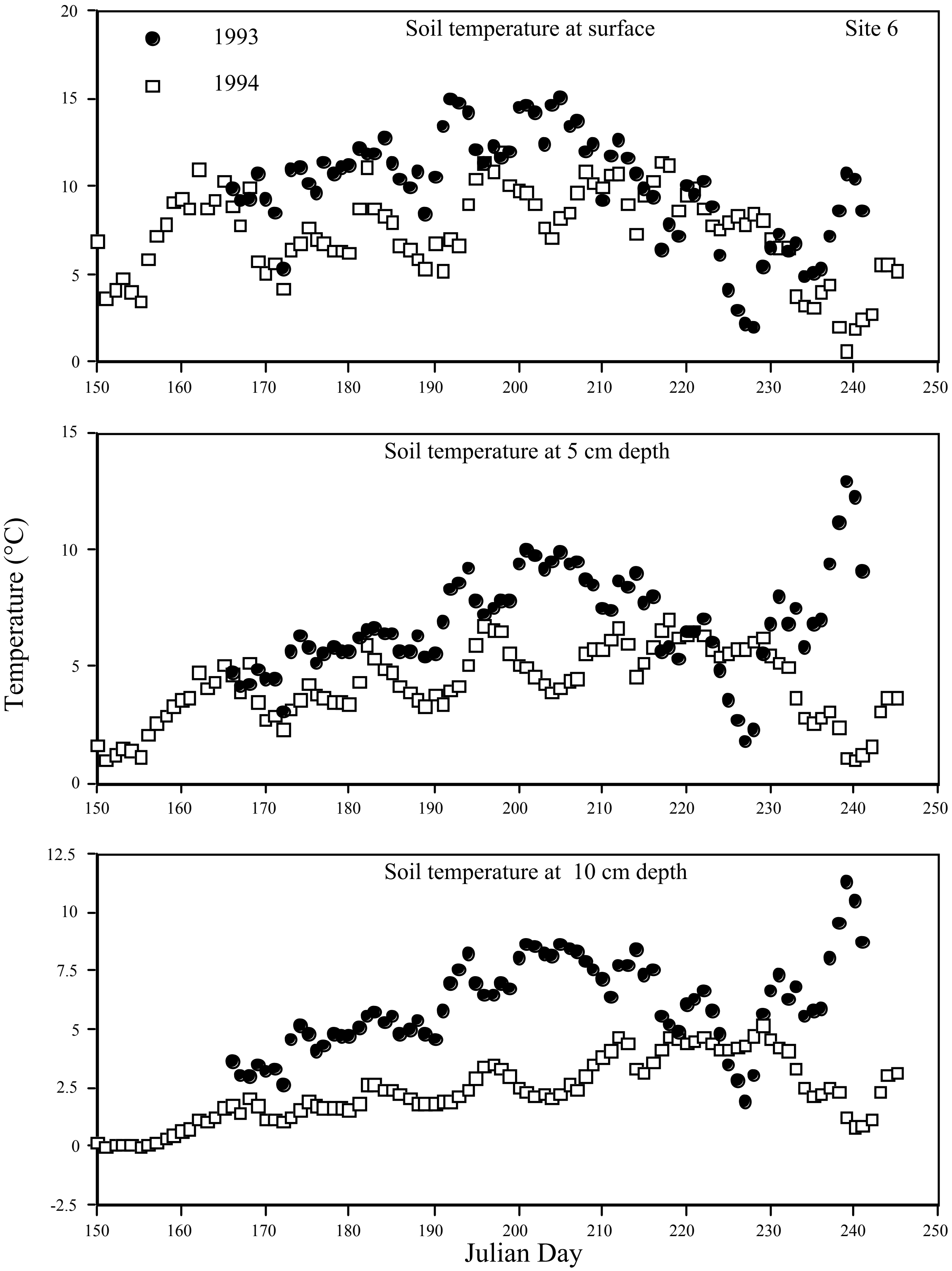

Fig. 6. Site 6 seasonal, daily average soil temperatures in 1993 and 1994 at surface (top), 5 cm soil depth (middle) and 10 cm soil depth (bottom).

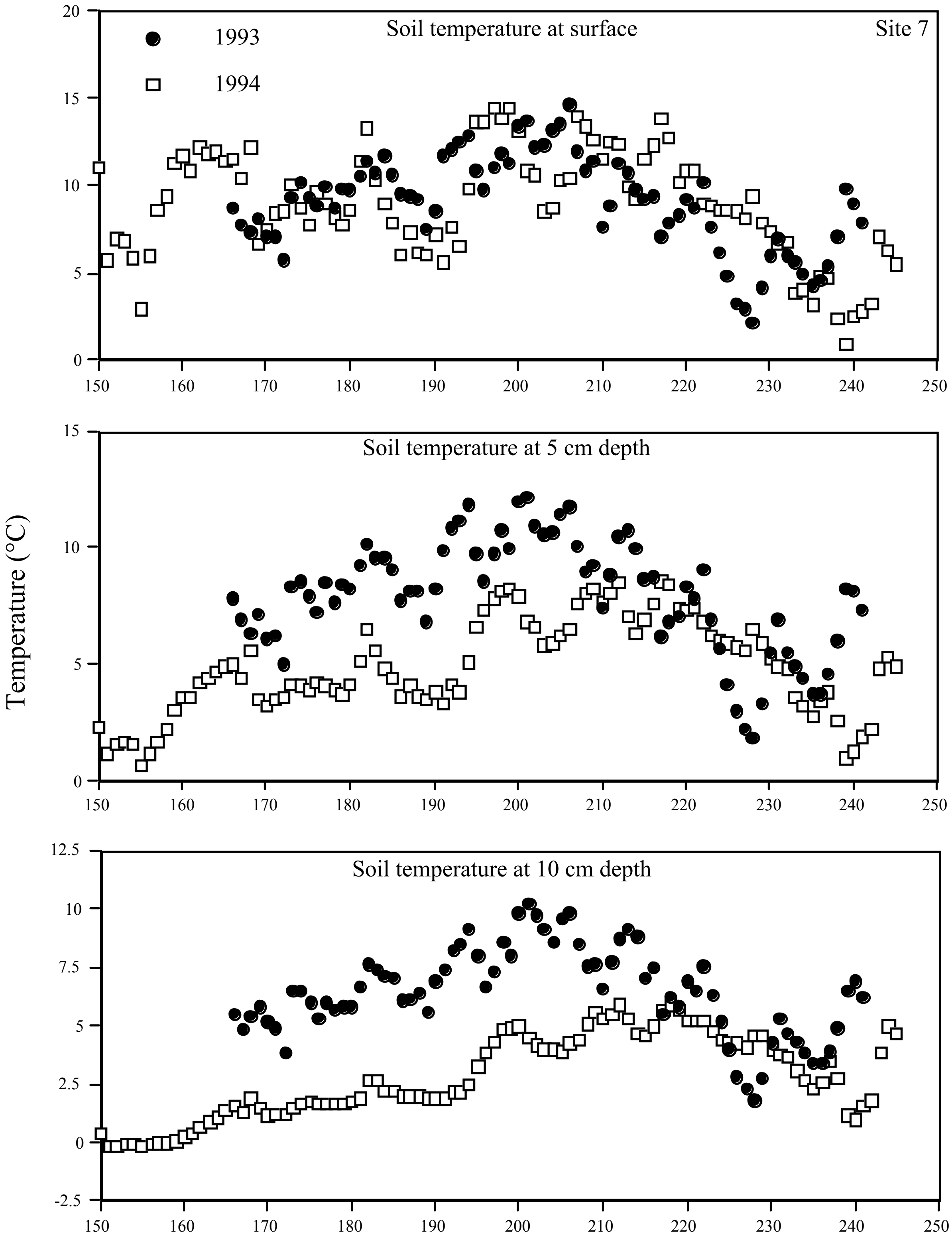

Fig. 7. Site 7 seasonal, daily average soil temperatures in 1993 and 1994 at surface (top), 5 cm soil depth (middle) and 10 cm soil depth (bottom).

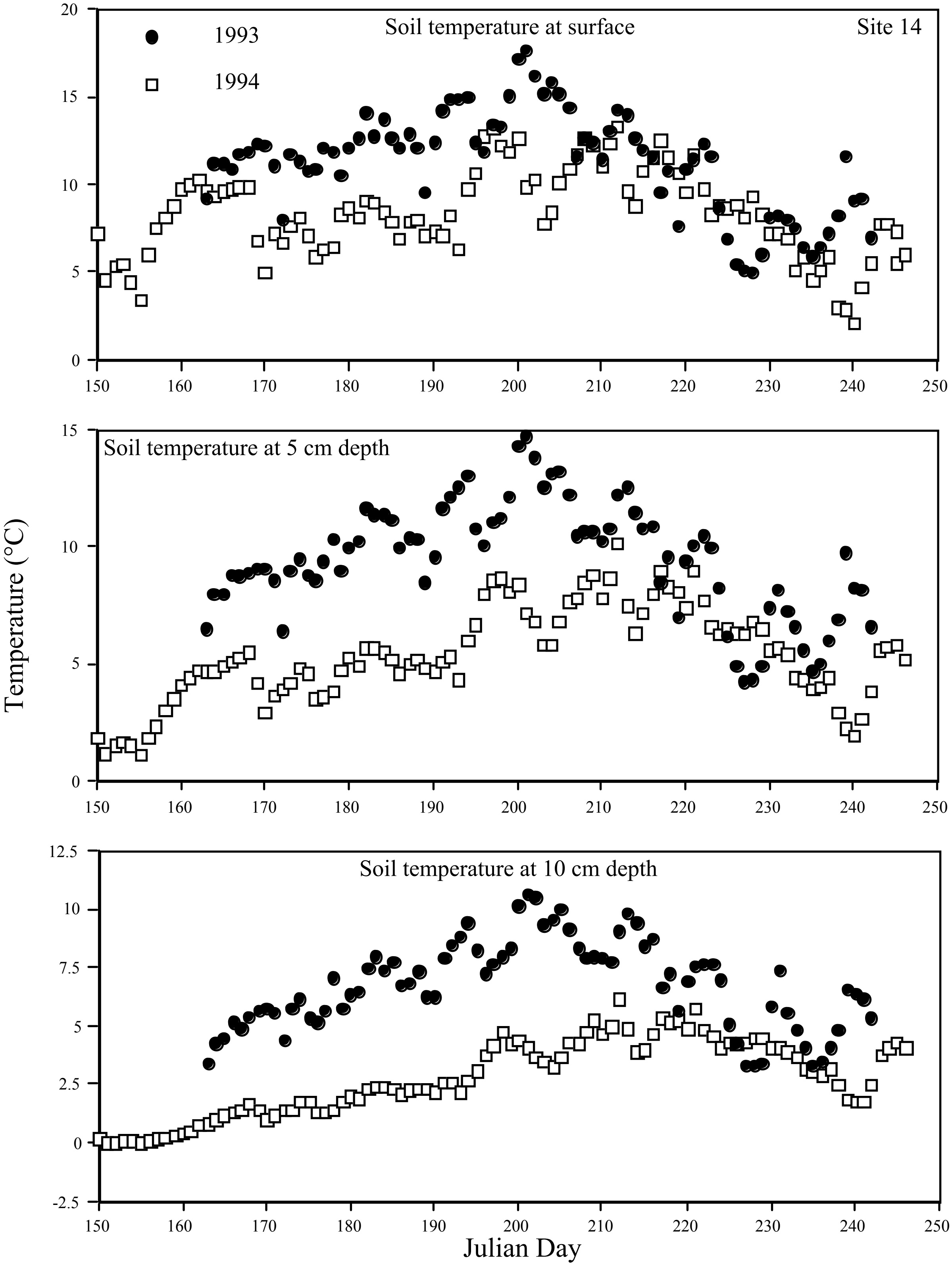

Fig. 8. Site 14 seasonal, daily average soil temperatures in 1993 and 1994 at surface (top), 5 cm soil depth (middle) and 10 cm soil depth (bottom).

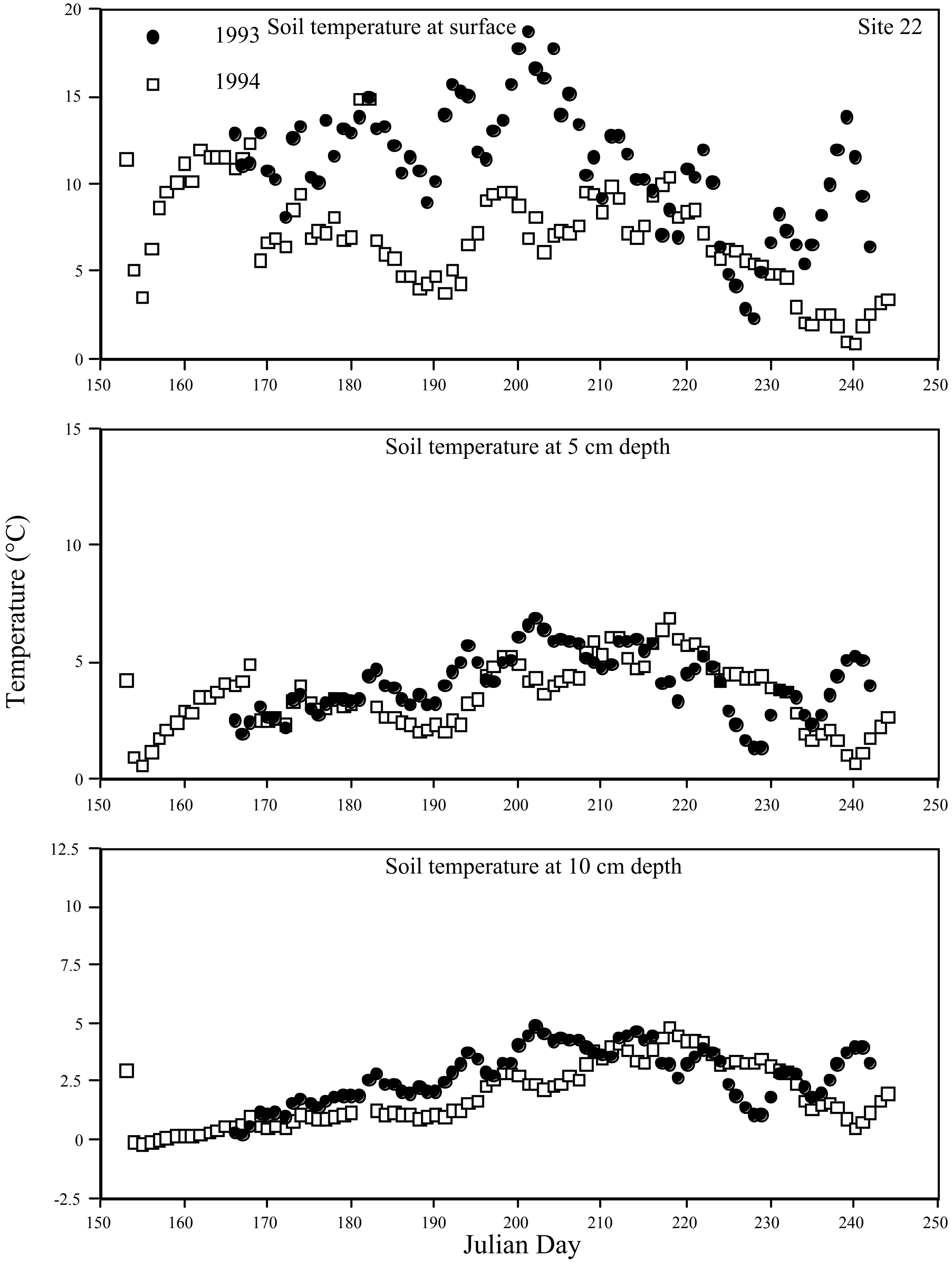

Fig. 9. Site 22 seasonal, daily average soil temperatures in 1993 and 1994 at surface (top), 5 cm soil depth (middle) and 10 cm soil depth (bottom).

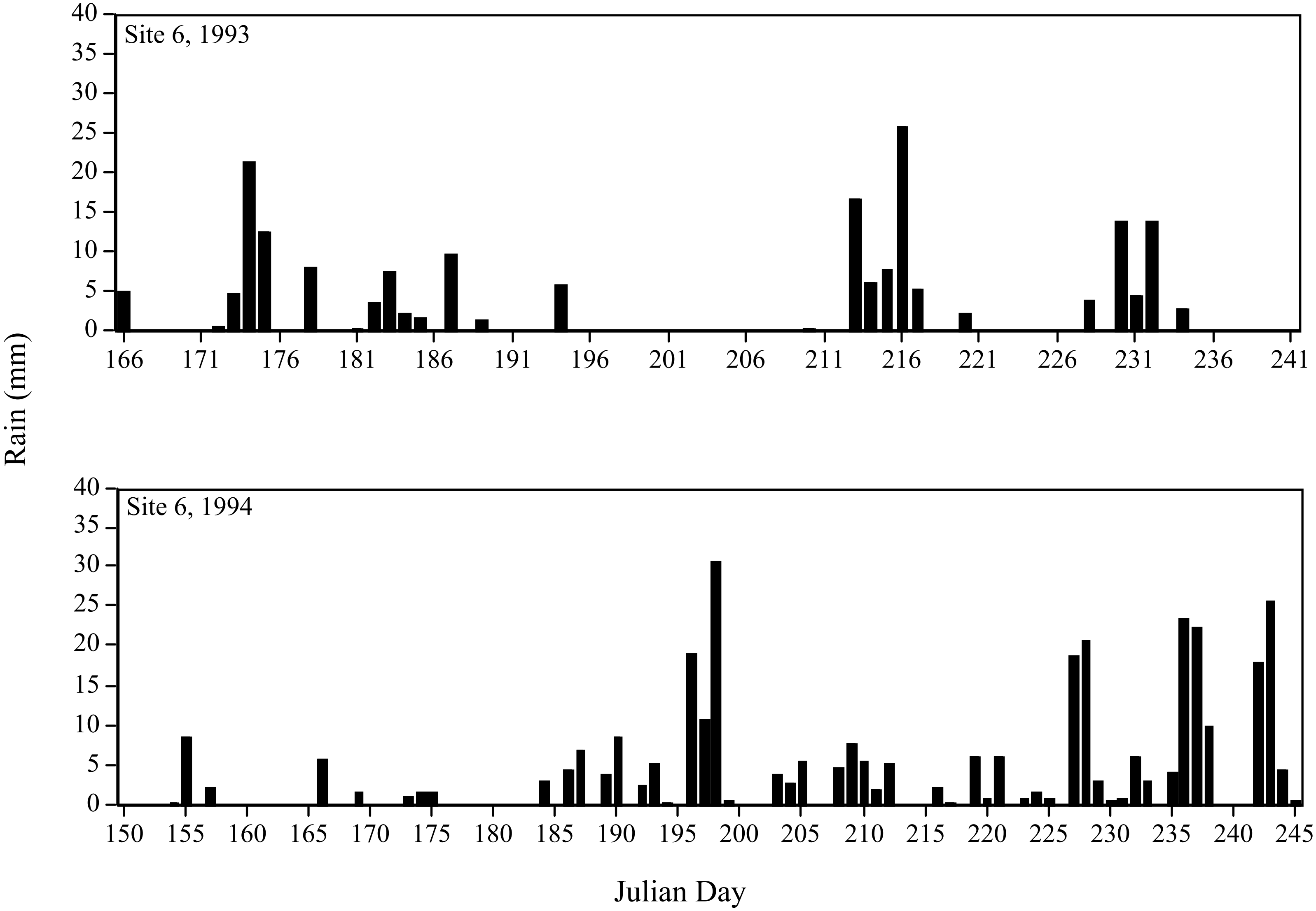

Fig. 10. Daily precipitation for site 6 for 1993 (top) and 1994 (bottom) measurement period.

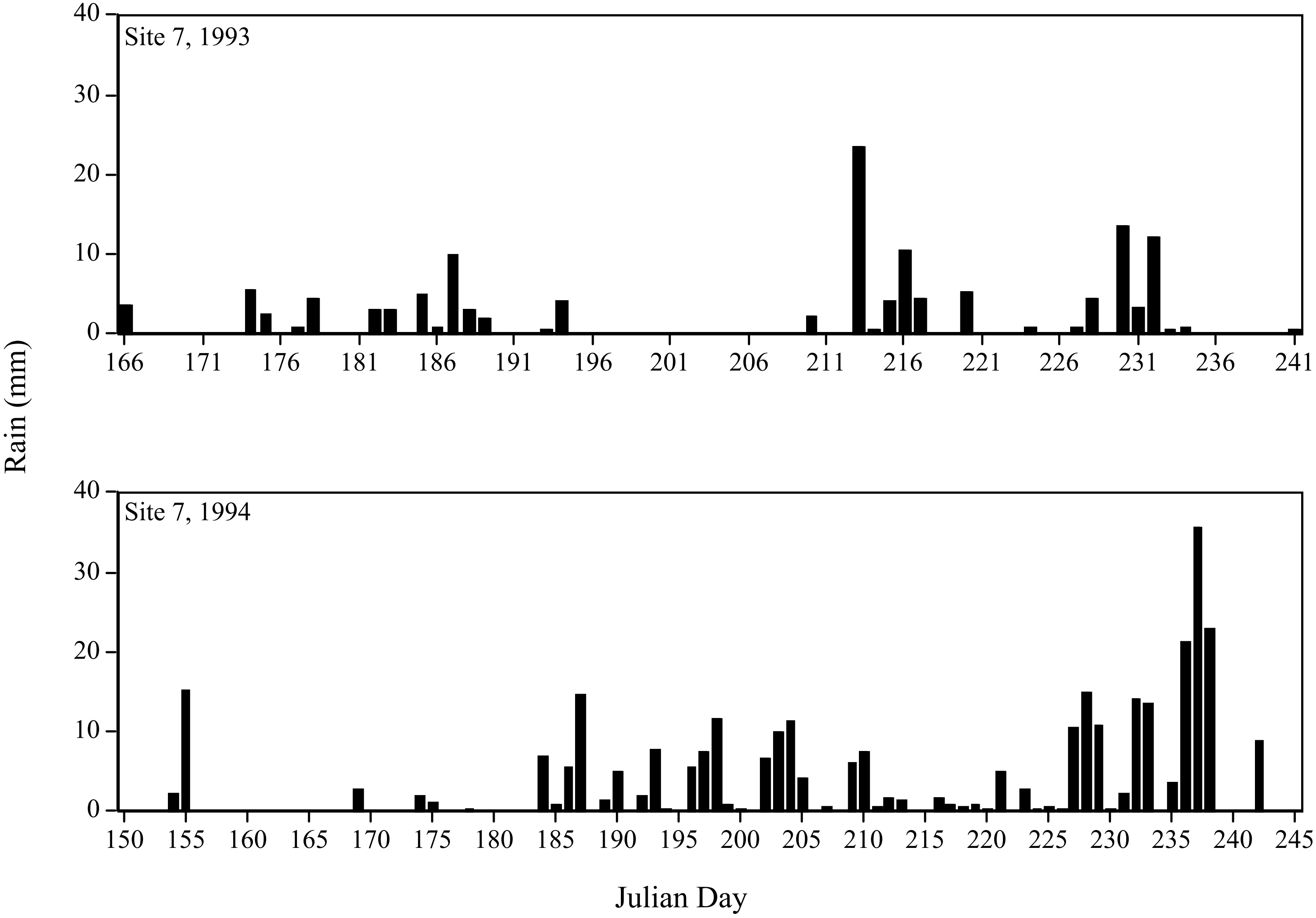

Fig. 11. Daily precipitation for site 7 for 1993 (top) and 1994 (bottom) measurement period.

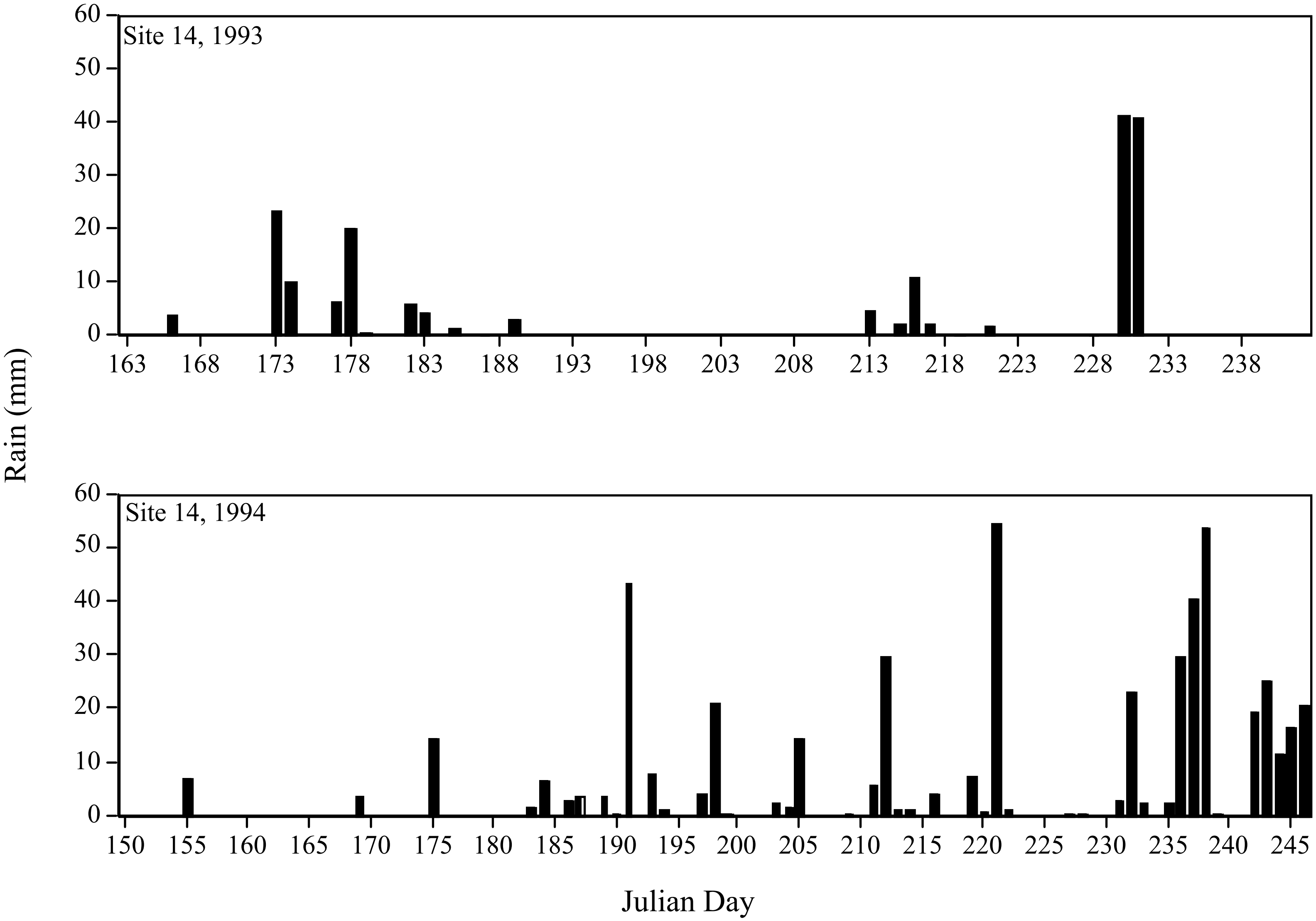

Fig. 12. Daily precipitation for site 14 for 1993 (top) and 1994 (bottom) measurement period.

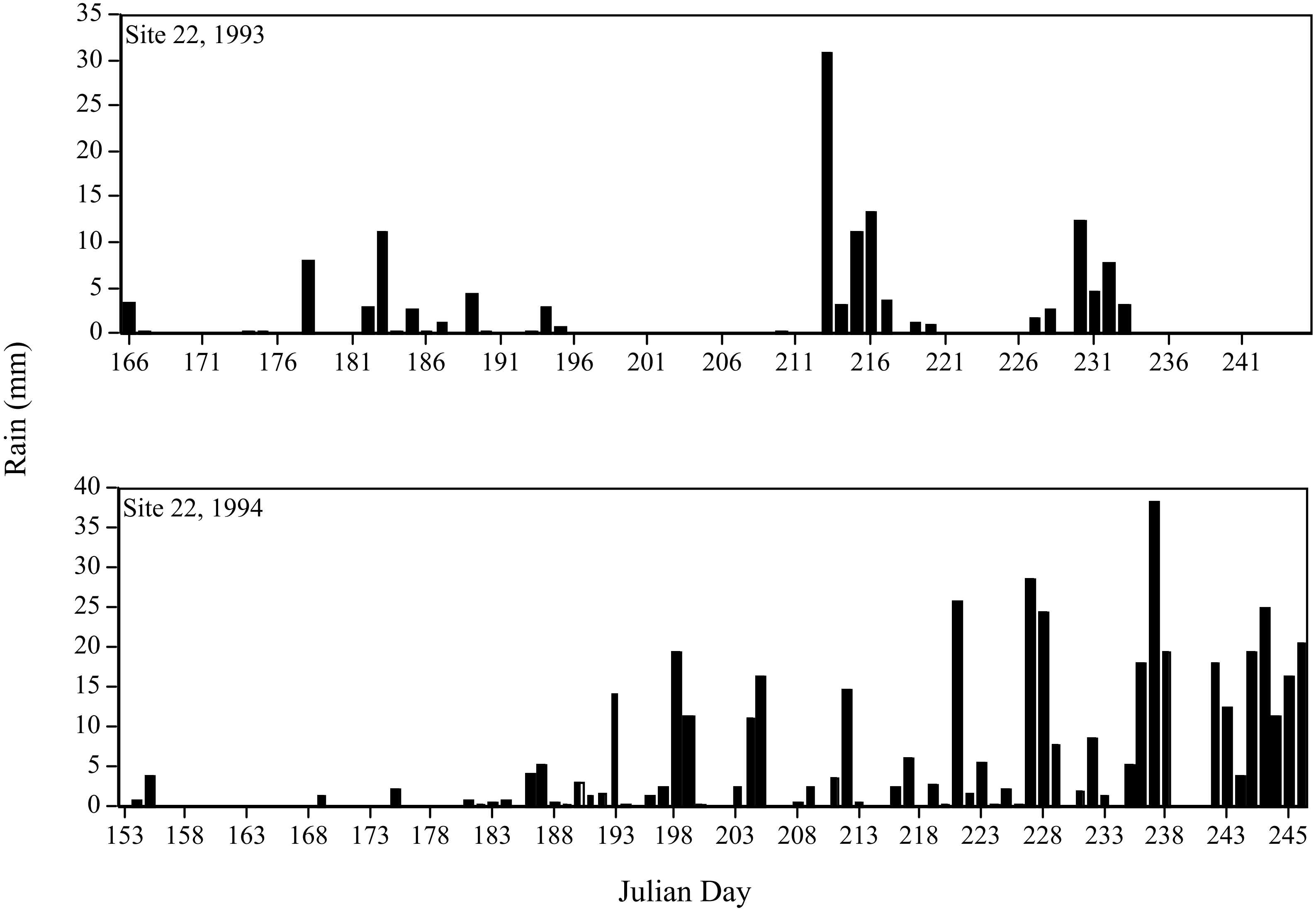

Fig. 13. Daily precipitation for site 22 for 1993 (top) and 1994 (bottom) measurement period.

Fig. 14. Comparison of water table depth between two different sampling years (1993 and 1994). Data are combined for all age stands from Julian day 214 through Julian day 231.

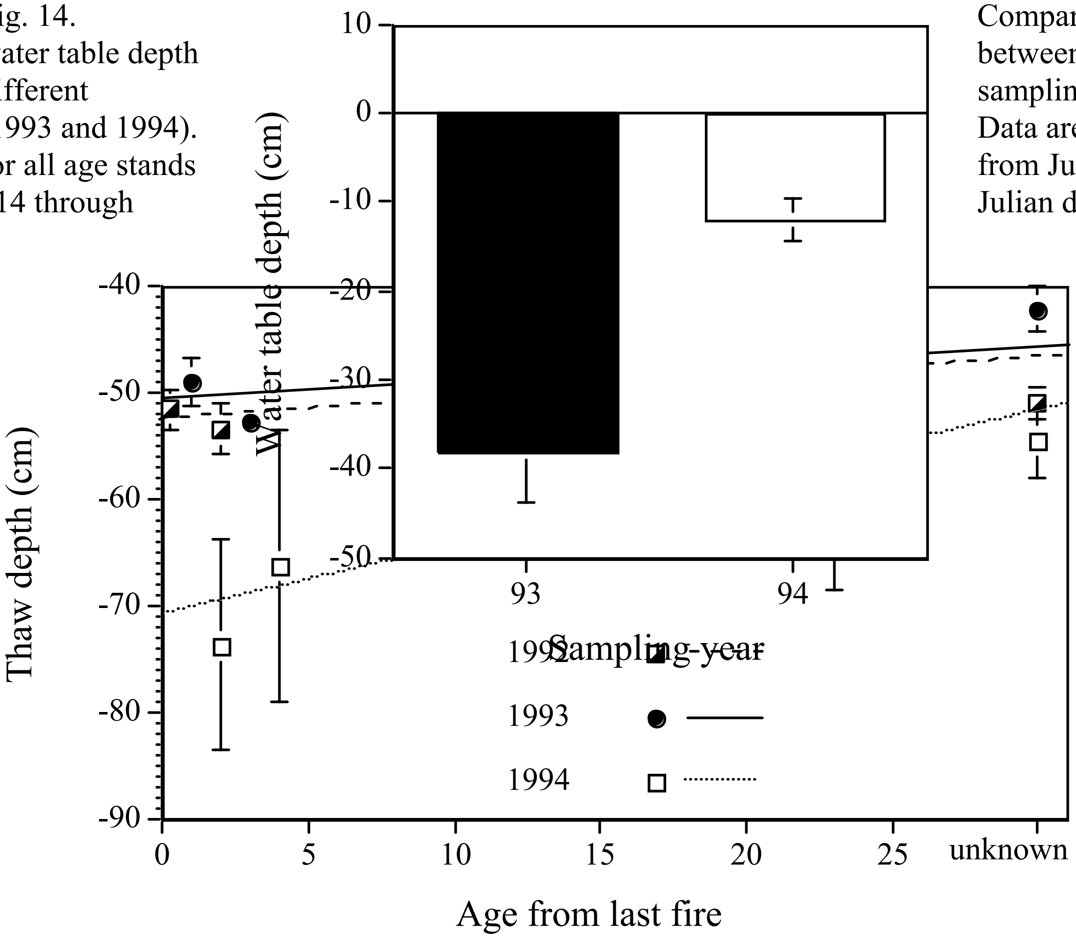

Fig. 15. Maximum seasonal thaw depth from an average of 15 tussock and 15 intertussock measurements (1992-1994). In 1992, thaw depth measurements were taken in late July and early August.

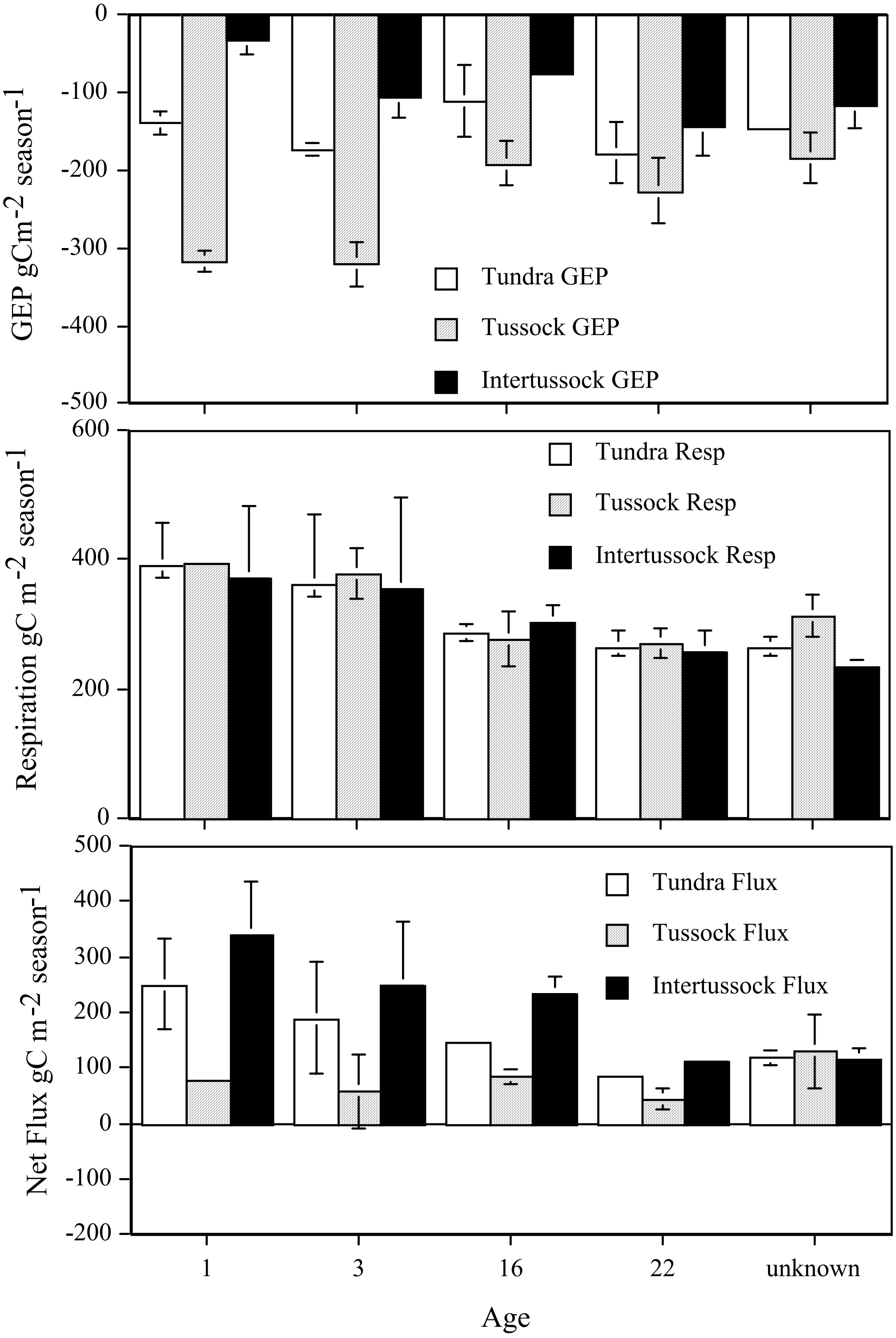

Fig. 16. Gross ecosystem photosynthesis (top), Ecosystem respiration (middle) and Net ecosystem flux (bottom) of carbon for a fire induced chronosequence of tussock, intertussock and tundra in 1993.

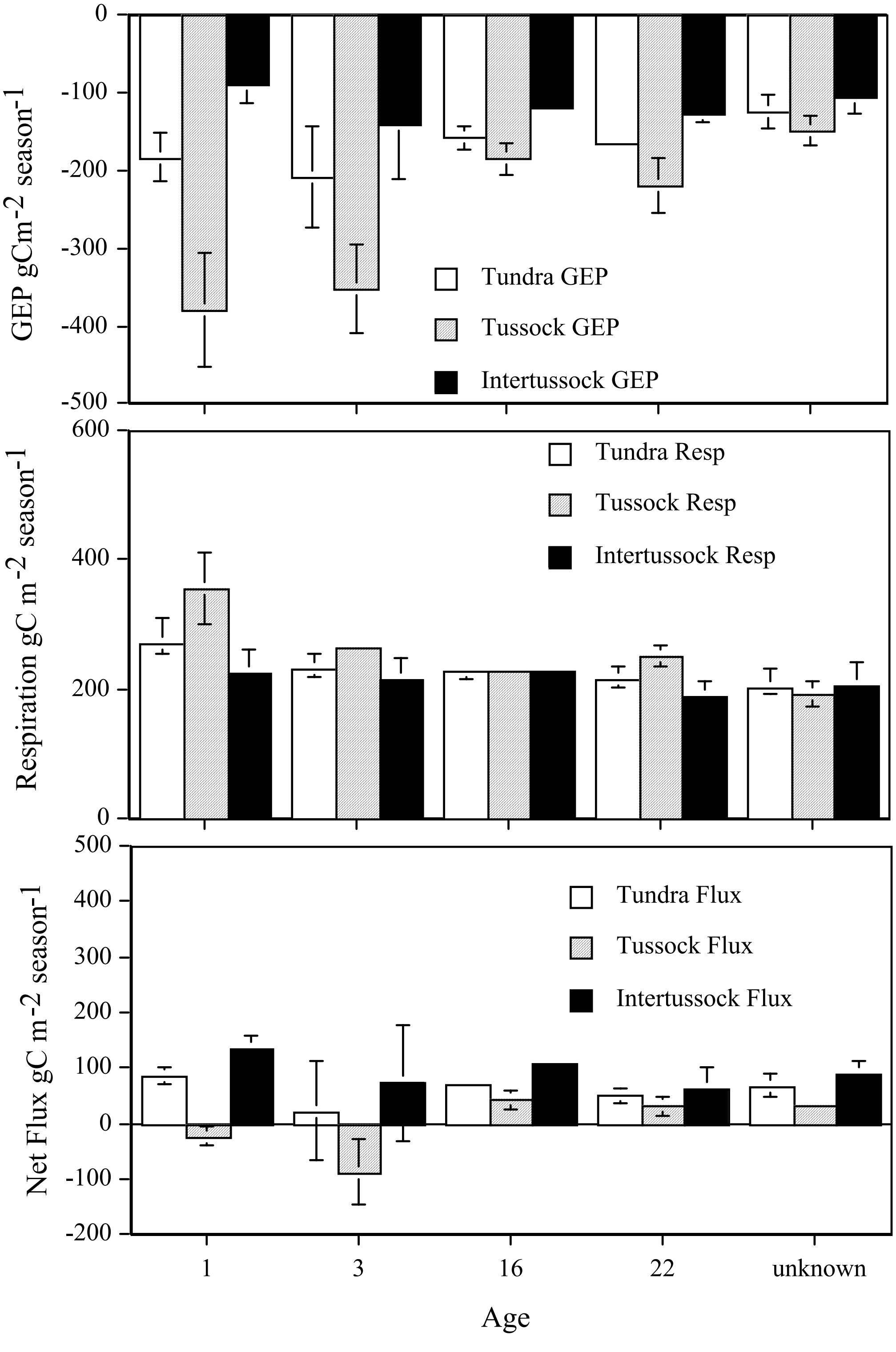

Fig. 17. Gross ecosystem photosynthesis (top), Ecosystem respiration (middle) and Net ecosystem flux (bottom) of carbon for a fire induced chronosequence of tussock, intertussock and tundra in 1994.

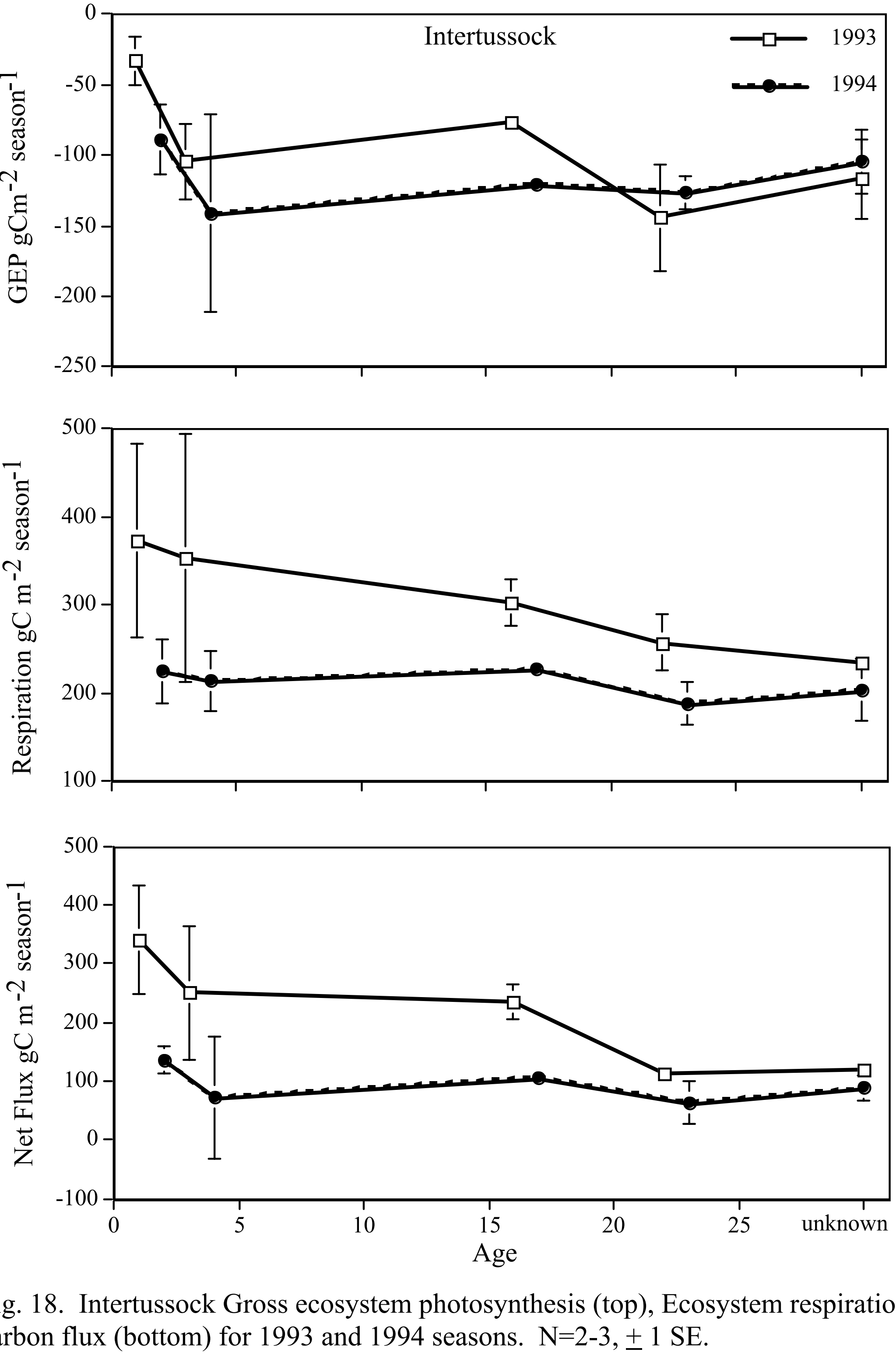

Fig. 18. Intertussock Gross ecosystem photosynthesis (top), Ecosystem respiration (middle), Net carbon flux (bottom) for 1993 and 1994 seasons. N=2-3, ± 1 SE.

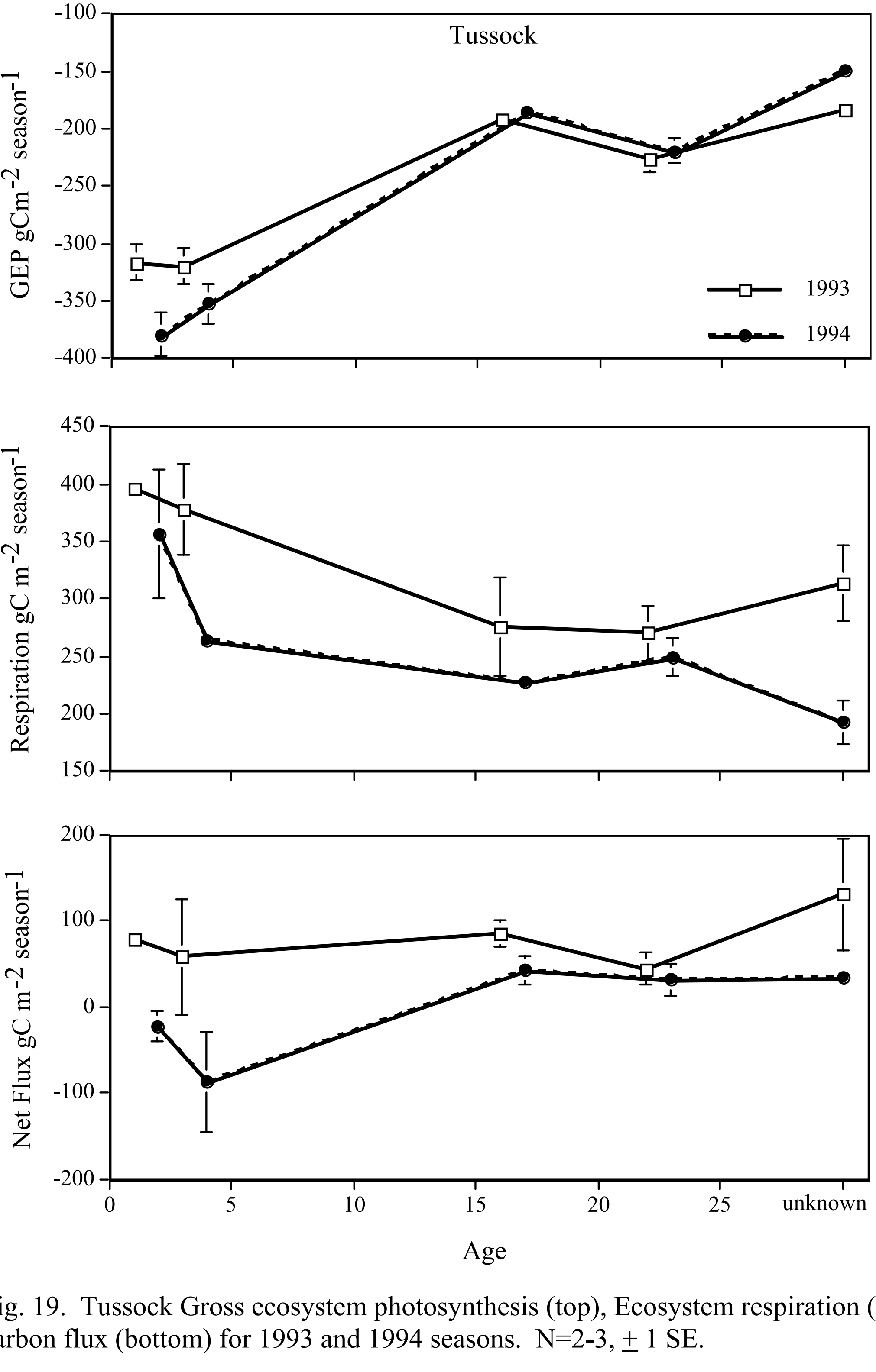

Fig. 19. Tussock Gross ecosystem photosynthesis (top), Ecosystem respiration (middle), Net carbon flux (bottom) for 1993 and 1994 seasons. N=2-3, ± 1 SE.

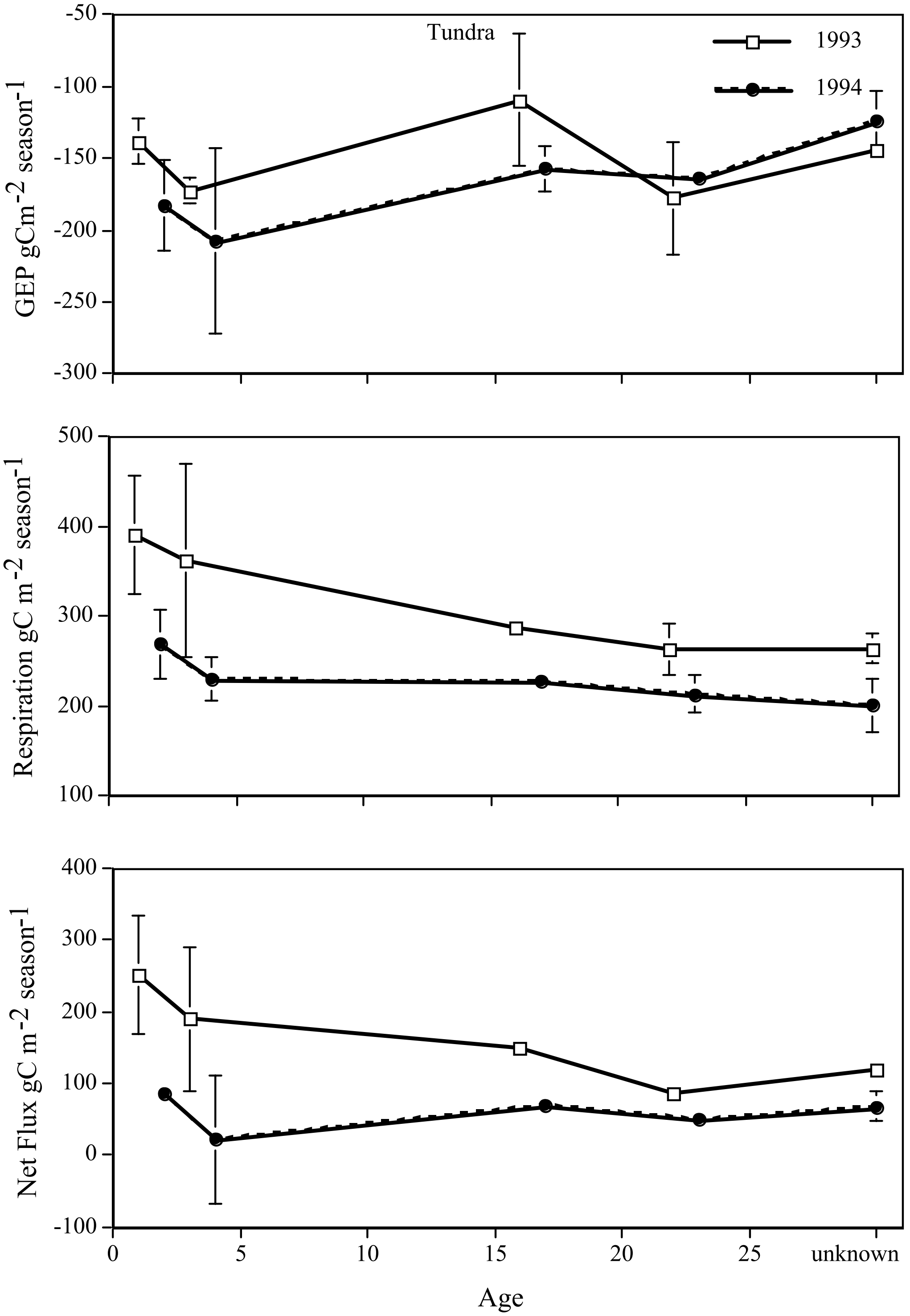

Fig. 20. Tundra Gross ecosystem photosynthesis (top), Ecosystem respiration (middle), Net carbon flux (bottom) for 1993 and 1994 seasons. N=2-3, ± 1 SE. Percent cover of Intertussock and tussock were used to calculate tundra flux values.

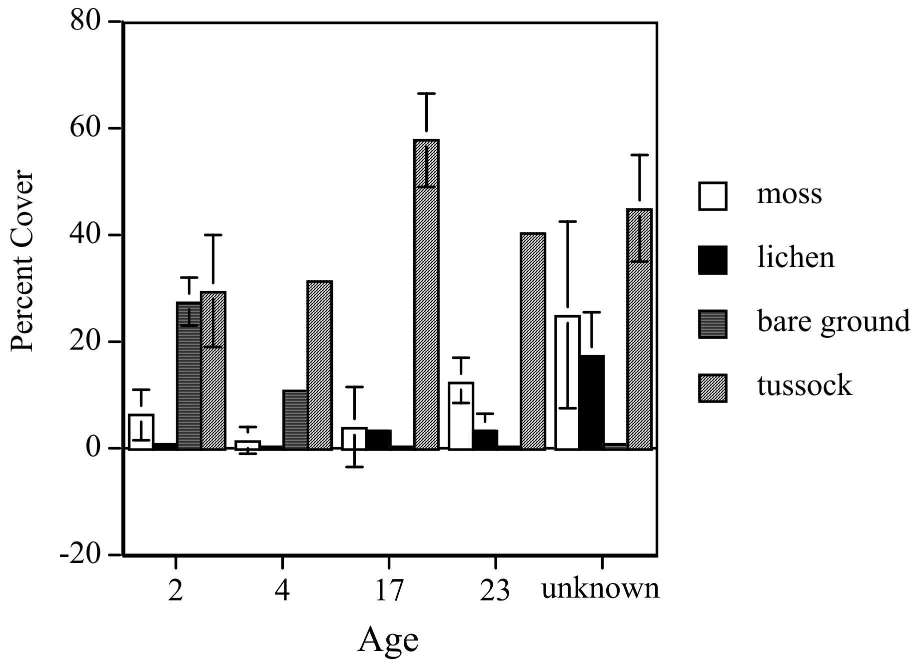

Fig. 21. Percent cover of moss, lichen, bare ground and
tussock areas ± 1 SD for the age stands studied.

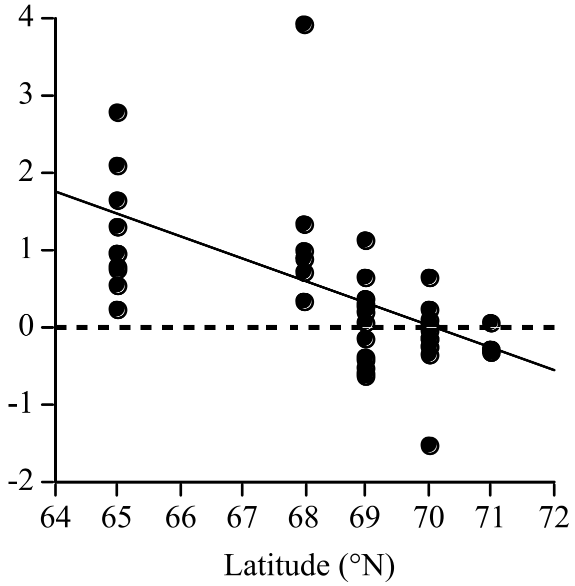

Fig. 22. All average daily net CO2 flux data vs. latitude from Table 4. High net flux values at 68°N are 1983 and 84 measurements made at Toolik Lake while large negative net flux value at 70°N represents flux measurements modeled for data collected at Meade River in 1966.

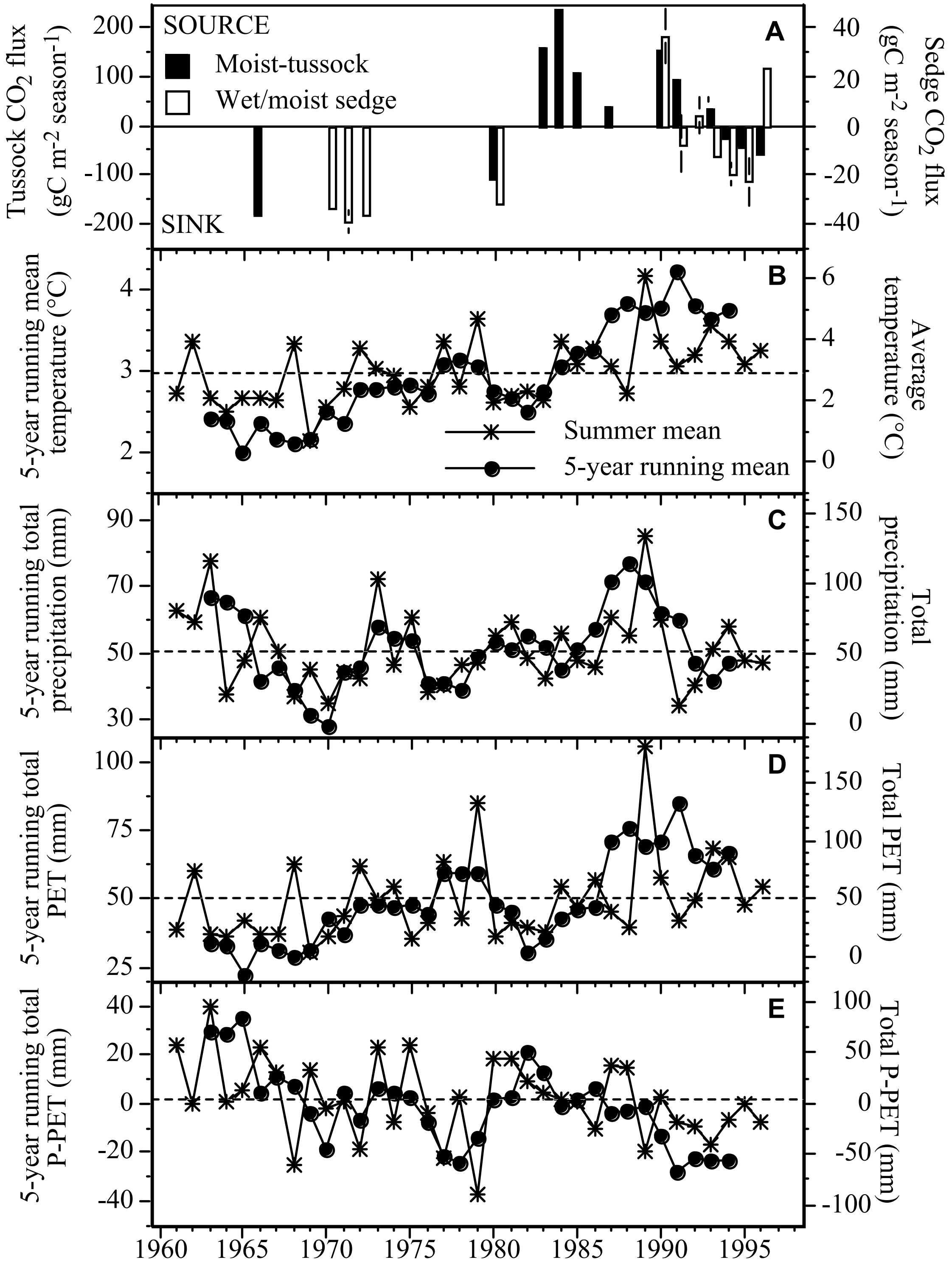

Fig. 23. (A) Summer (June-August) net CO_2 exchange for moist-tussock (closed-bars) and moist/wet-sedge ecosystems (open-bars) of the North Slope of Alaska[25]. Net CO_2 exchange data prior to 1991 are derived from literature values, while data collected after 1991 are from chamber and eddy covariance measurements[25]. Positive values depict net CO_2 loss to the

atmosphere. (B) The average summer air temperature, (C) total summer precipitation, (D) total summer potential evapotranspiration (PET), and (E) total summer precipitation minus PET (P-PET) for Barrow, AK between 1966 and 1996. Monthly temperature and precipitation data for Barrow, AK were compiled from the NOAA-National Climatic Data Center (NCDC) data archives[26]. Data are displayed as summer averages (temperature) and totals (precipitation, PET, P-PET) (asterix, dashed-line) and 5-year running averages (closed circle, solid-line). Horizontal dashed-lines indicate the average value calculated for the entire 1966-96 record.

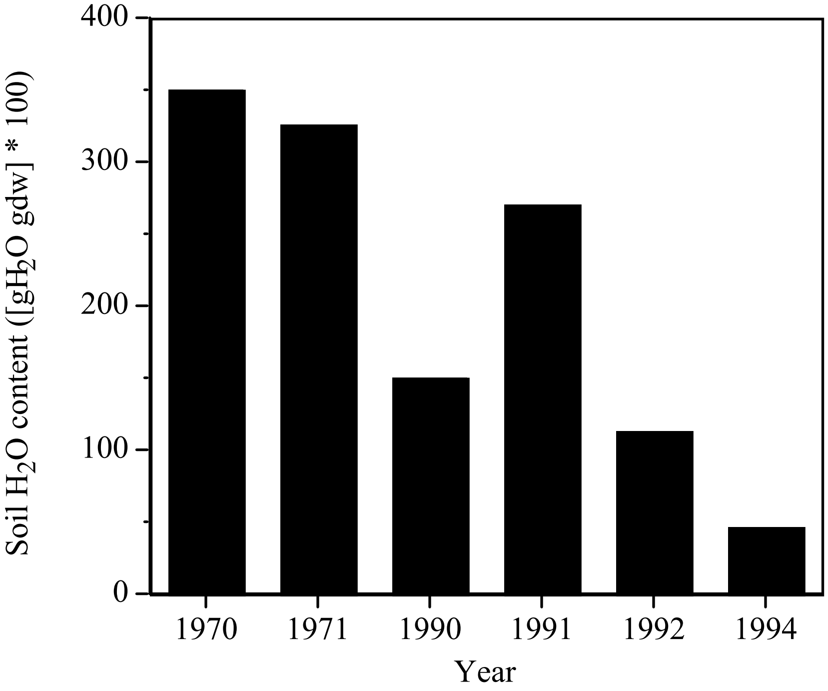

Fig. 24. Gravimetric soil water content in the top 0-10 cm of the soil profile for moist/wet-sedge ecosystems of Barrow and Prudhoe-Bay, AK. Data for 1970-71 and 1992 are from Barrow, AK, and data from 1990-91 and 1994 are from Prudhoe Bay. Data represent summer (June-August) averages calculated from 5-10 measurements conducted over the summer growing season.

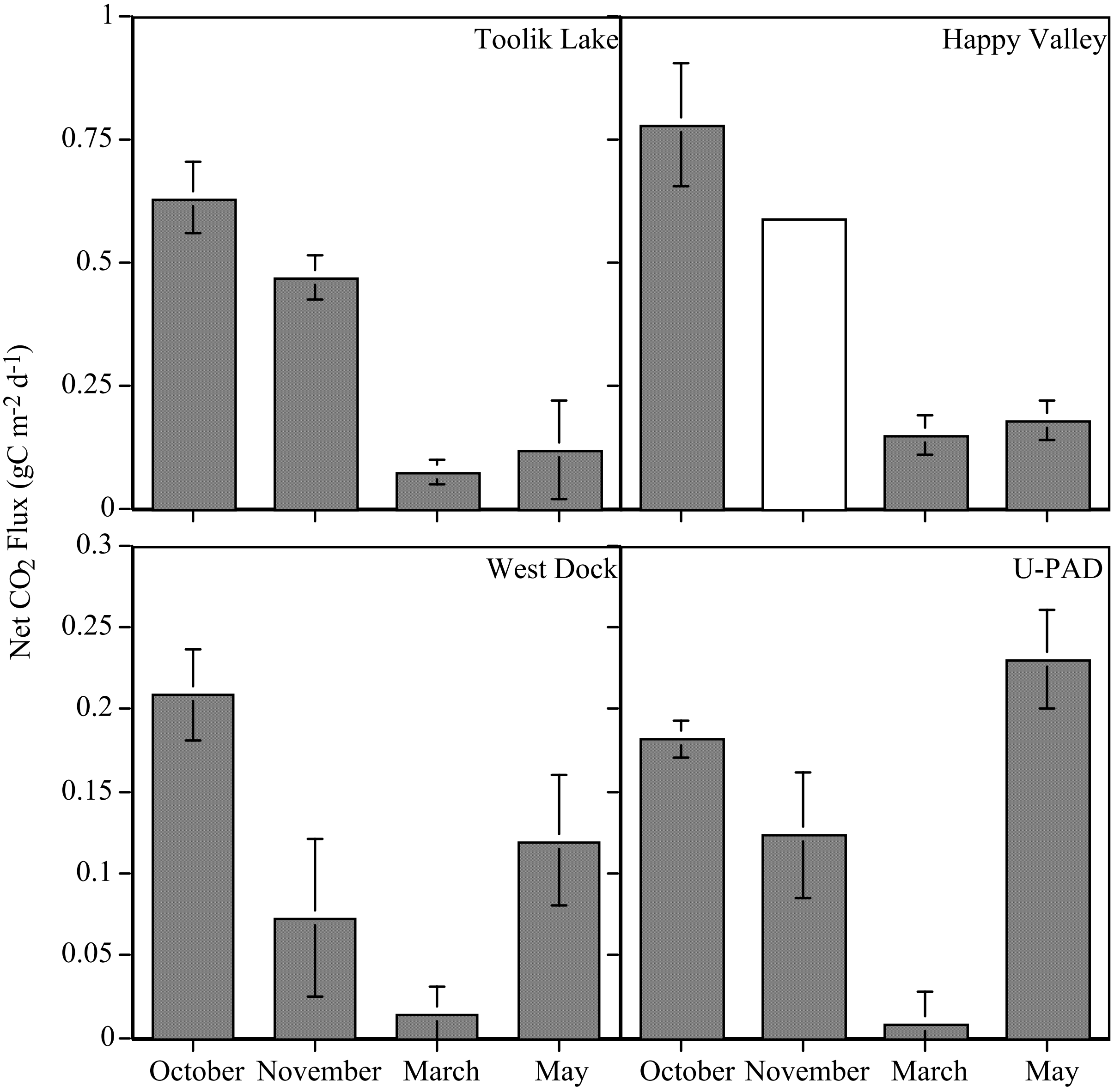

Fig. 25. Mean daily net CO$_2$ flux in October and November 1993 and March and late May through early June 1994 at Toolik Lake, Happy Valley, West Dock, and U-PAD. Data are means ± 1 SE; n (number of plots sampled) for October, November, March, and May-June are as follows: Toolik Lake (2,3,6,2); Happy Valley (3,NA,6,2); West Dock (3,3,6,2); and U-PAD (3,3,6,2). The open bar for the Happy Valley November flux estimate was estimated from the Toolik Lake data (Oechel et al., 1997).

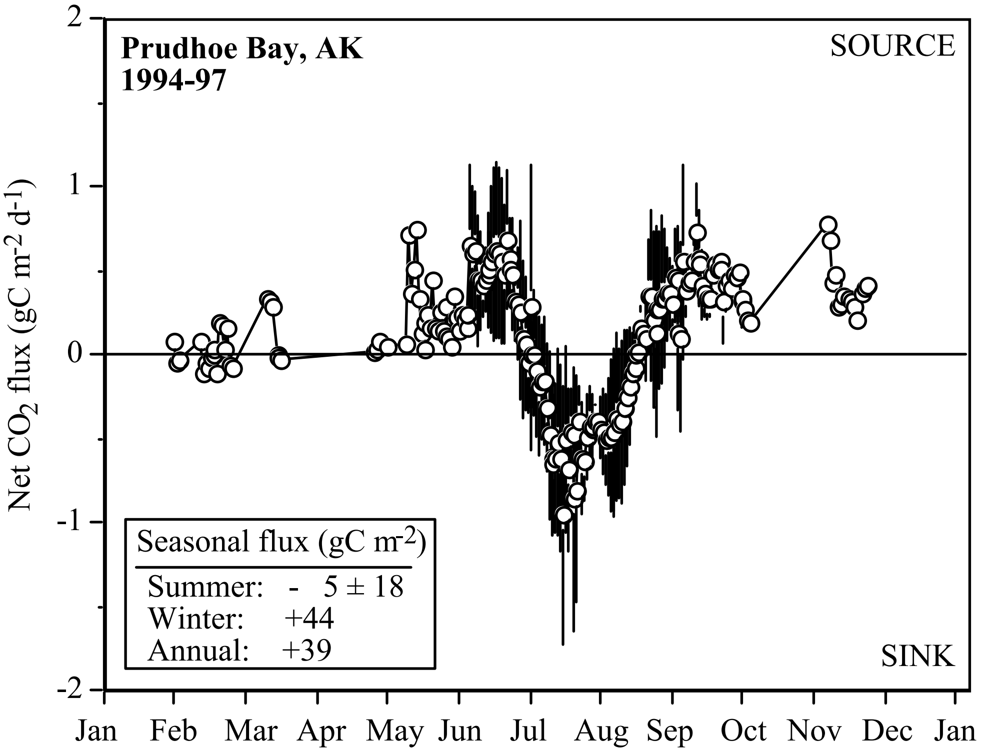

Fig. 26. Daily integrated net CO_2 flux for a moist/wet sedge coastal tundra ecosystem near Prudhoe Bay, AK (70°16'N:148°53'W). Net CO_2 flux was measured using eddy covariance. Data for summer months (June-August) represent an average (± 1SD, n=4 years) calculated from measurements made between 1994-97, while data for winter months (September-May) are from measurements made during the 1996-97 winter period. Values in the legend correspond to the integrated net CO_2 exchange calculated for the summer, winter, and annual periods. Positive values depict net CO_2 loss to the atmosphere.

Fig. 27. Number of reported wildfires in Alaska between 1955 and 1992. Missing data between 1969 and 1981 includd false alarms and were omitted from this analysis (Oechel and Vourlitis, 1997.

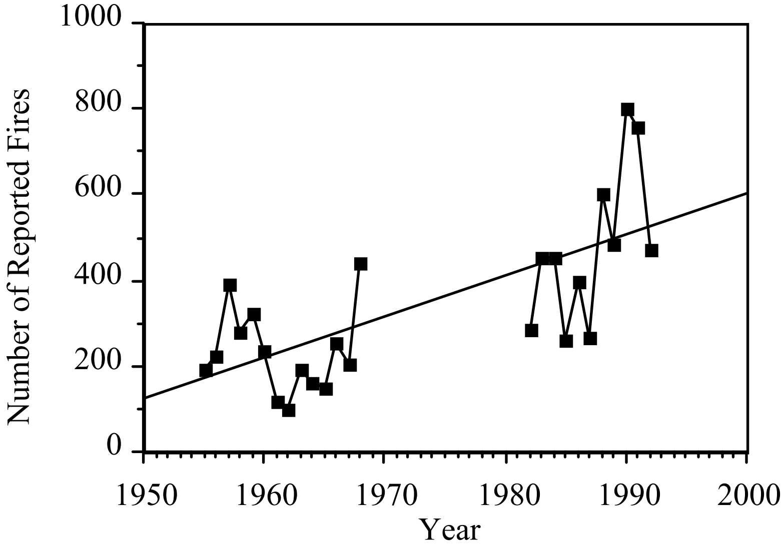

Table 1. Site designations, locations and characteristics. [1]Soil Type are: I) Histic pergelic cryaquepts, loamy, nearly level to rolling, II) Histic pergelic cryaquepts, loamy, nearly level to rolling, gravelly, III) Histic pergelic cryaquepts, loamy, nearly level to rolling, gravelly, hilly to steep association, IV) Pergelic cryaquepts, pergelic cryorthens, very gravelly, hilly to steep association. Data from Exploratory Soil Survey of Alaska, USDA, 1979. [2]Vegetation types are: A) Tussock turndra, B) Shrub meadow (mountain), C) Mixed shrub (tundra) D) Sedge (drainageway), lichen (tundra). *Additional sites measured in 1994.

Site	Year of burn	Lat./Long	Elevation (meters)	Aspect	Slope(%)	Cover (%)	Thaw Depth (cm)	Soil[1] Type	Vegetation[2] Type
16	1992-1	65°24'N : 164°43'W	127	SW	0.3	44	46.7	I	A
23	1992-2	65°33'N : 164°21'W	207	SE	3.0	29	47.0	I	B
25*	1992-3	64°55'N : 162°42'W	146	NW	1	14	43.8	IIII	D
1	1990-1	65°27'N : 164°31'W	213	NE	2.0	31	51.4	I	A
2	1990-2	65°16'N : 164°21'W	113	WSW	1.5	32	54.1	IV	A
6	1977-1	65°36'N :163°07'W	363	SW	3.0	58	51.4	II	A
7	1977-2	65°44'N : 163°32'W	280	S	2.0	57	43.4	III	A
12	1971-1	65°27'N : 164°28'W	152	SW	1.5	40	47.8	I	A
14	1971-2	65°04'N : 164°52'W	67	Flat	None	41	46.8	II	C
7U	Unknown-1	65°44'N : 163°32'W	280	S	2.0	42	35.9	III	A
15*	Unknown-2	65°24'N : 164°39'W	140	Flat	None	61	45.9	I	A
16U*	Unknown-3	65°24'N : 164°43'W	127	SW	0.3	71	N.D.	I	A
22	Unknown -4	65°33'N : 164°21'W	207	SW	2.0	35	43.5	I	B
24*	Unknown-5	64°55'N : 162°42'W	146	NW	2	14	53.6	II	D

Table 2. Seasonal average (June-August) of meteorological characteristics for individual sites (see Table 1 and Fig. 1 for specific locations) and all sites combined for 1993 and 1994. Details of measurements are found in materials and methods.

Average Weather Data for Season	All sites 93	All sites 94	Site 6 93	Site 6 94	Site 7 93	Site 7 94	Site 14 93	Site 14 94	Site 22 93	Site 22 94
wind m^2s^{-1}	2.70	3.06	2.80	3.42	3.07	3.33	2.21	2.49	2.76	2.99
dir deg	180	184	147	171	190	165	172	201	212	197
Kw m^{-2}	0.193	0.176	0.190	0.180	0.198	0.184	0.187	0.168	0.195	0.172
PAR μein m^{-2} s^{-1}	401.8	369.4	393.9	376.3	415.2	387.0	390.4	355.4	407.5	358.4
air 1.5 m deg C	10.76	9.53	10.33	9.15	10.20	8.89	11.58	10.52	10.89	9.56
RH %	71	74	74	74	70	77	70	71	70	75
soil surface deg C	10.38	7.97	10.01	7.43	9.05	8.95	11.31	8.36	11.10	7.09
soil 1.5 cm deg C	ND	6.16	ND	5.87	ND	6.69	ND	6.93	ND	5.09
soil 5 cm deg C	7.14	4.58	6.93	4.23	7.95	4.89	9.50	5.38	4.10	3.78
soil 10 cm deg C	5.53	2.55	6.11	2.38	6.45	2.83	6.75	2.80	2.79	2.16
rain mm	161.4	376.9	190.0	333.2	135.9	316.5	181.6	493.0	138.2	364.7

Table. 3. Metorological data from airport weather stations distributed over the Seward Penisula from 9-1-49 to 7-31-98, source: http://www.wrcc.dri.edu/summary/climsmak.html.

	Temperature (°C)				Precipitation (mm)			
Year/mean	June	July	Aug	Average	June	July	Aug	Total
Nome (64.3 N; 165.3 W)								
1977	7.3	13.5	13.5	11.4	16.0	8.1	38.4	62.5
1992	8.7	11.1	9.0	9.6	10.7	15.5	100.1	126.2
1993	11.0	13.4	9.9	11.4	9.9	23.4	80.0	113.3
1994	8.8	10.3	9.2	9.4	3.6	57.9	197.9	259.3
mean	7.9	10.7	10.0	9.5	27.7	53.8	84.3	165.9
Kotzebue (66.52 N; 162.38 W)								
1977	6.6	14.9	14.9	12.1	0.5	0.3	18.0	18.8
1992	6.6	14.1	9.9	10.2	12.7	9.4	76.2	98.3
1993	8.7	15.0	9.7	11.1	23.6	17.5	45.2	86.4
1994	6.5	13.1	10.3	10.0	6.1	78.0	119.4	203.5
mean	6.8	12.2	10.9	10.0	14.2	36.1	54.6	104.9
Unalakleet (63.53 N; 160.48 W)								
1977	9.1	14.5	14.7	12.8	14.0	7.9	38.4	60.2
1992	8.7	13.2	10.7	10.9	11.2	23.1	64.5	98.8
1993	14.0	15.0	11.6	13.5	6.4	0.3	52.3	58.9
1994	9.8	12.9	11.3	11.4	9.9	55.4	156.2	221.5
mean	8.9	12.4	11.6	11.0	26.9	59.4	83.3	169.7
Wales (65.4 N; 168.0 W)								
1977	3.4	10.1	11.7	8.4	6.9	23.1	24.6	54.6
1992	4.6	8.1	7.5	6.8	23.9	11.7	43.2	78.7
1993	4.0	11.1	7.6	7.5	3.0	18.3	43.2	64.5
1994	3.6	7.5	6.6	5.9	2.5	89.4	120.7	212.6
mean	3.5	8.0	8.0	6.5	17.3	36.1	67.3	120.7

Table 4. Soil temperatures from tussock and intertussock areas of stands with varying age since the last fire, sampled at three depths; surface, 5 and 10 cm. In cases where there were replicated age stands, ± the standard errors are given for N=2 (§ N=3, † N=4). For a given age stand, the multi-depth sensing probe was place in either four different tussock or intertussock areas and electronically averaged and recorded every 1-1.5 hours and averaged over 24 hours, resulting in a single number for a particular site, date, surface type and depth. Degrees of freedom = df, NS=not significant. P values refer to regression analysis which did not include the unknowns age stands.

Sampling Period	July 16-23		July 26-August 3		August 8-22	
Depth/ Age	Tussock	Intertussock	Tussock	Intertussock	Tussock	Intertussock
0 cm						
1	18.56	16.68	13.87 ± 0.26	11.56 ± 0.64	8.91 ± 0.85	6.84 ± 0.33
3	19.77	14.65	10.94 ± 0.06	9.16 ± 0.46	6.95	5.65
16	17.05 ± 0.20	12.71 ± 0.18	8.39 ± 1.21	6.53 ± 1.05	4.49	2.8
22	13.96	11.94	9.08	5.21	8.15 ± 1.10	6.74 ± .060
Unknown	13.23 ± 0.40	11.00	6.14	4.59	§5.78 ± 0.66	†5.51 ± 0.78
	F=12.4, df, 4 P<0.04	F=26.5, df, 4 P <0.02	F=10.2, df, 6 P<0.03	F=24.9, df, 6 P<0.004	NS	NS
5 cm						
1	16.11	11.42	§11.77 ± 0.41	§7.08 ± 0.56	8.3 ± 0.70	4.43 ± 0.23
3	17.01	8.90	10.27 ± 0.14	6.74 ± 0.70	6.15	3.30
16	14.19 ± 0.09	7.93 ± 0.00	7.41 ± 1.26	4.30 ± 0.88	4.34	2.48
22	11.36	7.97 ± 0.05	8.26	4.50 ± 1.29	6.94 ± 0.92	4.58 ± 0.06
Unknown	11.24 ± 0.37	7.32	5.80 ± 0.86	5.21 ± 1.18	§5.29 ± 0.50	†3.94 ± 0.54
	F=19.9, df, 4 P<0.03	F=8.0, df, 5, P<0.05	F=15.0, df, 7, P<0.008	F=10.6, df, 8 P<0.02	NS	NS
10 cm						
1	14.46	7.72	§9.50 ± 1.29	§4.54 ± 0.57	7.64 ± 0.65	2.80 ± 0.02
3	15.23	6.41 ± 0.96	9.60 ± 0.39	4.96 ± 0.45	6.87	2.36
16	12.40 ± 0.25	5.18 ± 0.09	6.72 ± 1.11	2.70 ± 0.70	4.20	1.85
22	9.21	6.26 ± 0.87	7.92 ± 0.52	2.69 ± 0.77	6.19 ± 0.84	3.47 ± 0.05
Unknown	10.00 ± 0.49	4.83	5.04 ± 0.67	3.84 ± 0.96	§4.80 ± 0.47	†3.19 ± 0.37

$F=18.4$, df, 4 $P<0.03$	NS	NS	$F=10.7$, df, 8 $P<0.02$	NS	NS

Table 5. Two way ANOVA for effects of year of measurement (field season 1992-94) and age of stand since fire on thaw depth. Both year and age are categorical variables.

Source of variation	df	MS	F
Year of measurement	2	731.0	15.89**
Age of stand	4	200.9	4.37*
Year x Age	8	70.8	1.54 ^{NS}
Error	40	46.0	

*P < 0.01, **P <0.0001, NS: Not significant.

Table 6. Two way ANOVA for effects of year of measurement (field season 1992-94) and age of stand since fire on flux (Net ecosystem flux, Ecosystem respiration, and Gross photosynthesis). Both year and age are categorical variables. Tussock and intertussock areas were measured separately, then, their respective % cover was used to weight each flux to calculate flux values for Tundra.

	Factors								
	Year			Age			Yr x Age		
Response	F	df	P	F	df	P	F	df	P
Tussock net	15.74	1	<0.005	2.80	4	NS	1.25	4	NS
Tussock resp	9.89	1	<0.01	5.43	4	<0.01	0.93	4	NS
Tussock gross	0.12	1	NS	7.98	4	<0.01	0.44	4	NS
Intertussock net	12.91	1	<0.005	2.85	4	NS	1.22	4	NS
Intertussock resp	6.37	1	<0.05	0.82	4	NS	0.42	4	NS
Intertussock gross	1.16	1	NS	1.69	4	NS	0.62	4	NS
Tundra net	12.74	1	<0.005	1.47	4	NS	1.03	4	NS
Tundra resp	8.81	1	<0.05	1.79	4	NS	0.35	4	NS
Tundra gross	0.84	1	NS	1.15	4	NS	0.572	4	NS

Table 7. Characteristic of the research sites and measured CO_2 fluxes. Fluxes were measured between 1 June-31 August, and positive values denote net CO_2 loss from the ecosystem. Net CO_2 flux was measured using a dynamic-closed chamber unless indicated (†), where flux was measured using eddy covariance. References are given at the end of table.

Site	Latitude	Longitude	Year	Tundra type	Average daily CO_2 flux ($gC\ m^{-2}\ d^{-1}$)	Ref.
Meade River	70°29’	157°25’	1966	Moist tussock	-1.52	1
Barrow	71°18’	156°40’	1970	Moist/wet-sedge	-0.26	2-5
Barrow	71°18’	156°40’	1971	Moist/wet-sedge	-0.30	2-5
Barrow	71°18’	156°40’	1972	Moist/wet-sedge	-0.28	2-5
Haul Road			1980	Moist tussock	-0.88	6, 7
Barrow	71°18’	156°40’	1980	Moist/wet-sedge	-0.29	6
Toolik Lake	68°38’	149°35’	1983	Moist tussock	+3.90	8
Toolik Lake	68°38’	149°35’	1984	Moist tussock	+3.90	8
Toolik Lake	68°38’	149°35’	1985	Moist tussock	+1.00	8
Toolik Lake	68°38’	149°35’	1987	Moist tussock	+0.72	8, 9
Toolik Lake	68°38’	149°35’	1990	Moist tussock	+1.34	8
Happy Valley	69°08’	148°50’	1990	Moist tussock	+1.15	8
Prudhoe Bay	70°22’	148°45’	1990	Moist-sedge	+0.66	8
Prudhoe Bay	70°22’	148°45’	1990	Wet-sedge	+0.03	8
APL-133	69°50’	148°45’	1990	Flooded-sedge	+0.09	8
APL-133	69°50’	148°45’	1990	Wet-sedge	+0.22	8
APL-133	69°50’	148°45’	1990	Moist-sedge	+0.39	8
Toolik Lake	68°38’	149°35’	1991	Moist tussock	+0.88	10
Happy Valley	69°08’	148°50’	1991	Moist tussock	+0.67	10
Sagwon	69°25’	148°45’	1991	Moist tussock	+0.32	10
Prudhoe Bay	70°22’	148°45’	1991	Moist-sedge	+0.11	10

Prudhoe Bay	70°22’	148°45’	1991	Wet-sedge	-0.25	10
APL-133	69°50’	148°45’	1991	Flooded-sedge	-0.39	10
APL-133	69°50’	148°45’	1991	Wet-sedge	-0.13	10
APL-133	69°50’	148°45’	1991	Moist-sedge	+0.27	10
Barrow	71°18’	156°40’	1992	Moist/wet-sedge	+0.07	11
Toolik Lake	68°38’	149°35’	1993	Moist tussock	+0.88	12
Prudhoe Bay	70°22’	148°45’	1993	Wet-sedge	-0.12	13
Toolik Lake	68°38’	149°35’	1994	Moist tussock	+0.34	12
Happy Valley	69°08’	148°50’	1994	Moist tussock	-0.38	12
Happy Valley	69°08’	148°50’	1994	Moist tussock	-0.51†	14
Prudhoe Bay	70°22’	148°45’	1994	Wet-sedge	-0.25	13
Prudhoe Bay	70°16’	148°53’	1994	Moist/wet-sedge	-0.12	15
Prudhoe Bay	70°16’	148°53’	1994	Moist/wet-sedge	-0.14†	15
Happy Valley	69°08’	148°50’	1995	Moist tussock	-0.58†	14
Prudhoe Bay	70°16’	148°53’	1995	Moist/wet-sedge	-0.13†	15
APL-133	69°56’	148°53’	1995	Moist/wet-sedge	-0.34†	15
Happy Valley	69°08’	148°50’	1996	Moist tussock	-0.60†	12
Prudhoe Bay	70°16’	148°53’	1996	Moist/wet-sedge	+0.24†	12
Prudhoe Bay	70°16’	148°53’	1997	Moist/wet-sedge	-0.04†	12
Seward	65°18’	163°82’	1993	Tussock	+2.78	This study
Seward	65°18’	163°82’	1993	Tussock	+2.11	This study
Seward	65°18’	163°82’	1993	Tussock	+1.64	This study
Seward	65°18’	163°82’	1993	Tussock	+0.95	This study
Seward	65°18’	163°82’	1993	Tussock	+1.32	This study
Seward	65°18’	163°82’	1994	Tussock	+.95	This study
Seward	65°18’	163°82’	1994	Tussock	+0.25	This study
Seward	65°18’	163°82’	1994	Tussock	+0.78	This study

Seward	65°18’	163°82’	1994	Tussock	+0.56	This study
Seward	65°18’	163°82’	1994	Tussock	+0.75	This study

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Table 8. ANOVA table for simple linear regression of average daily net carbon flux vs. latitude of measurement site, (see Table 7).

	Df	SS	MS	F	P
Regression	1	15.35	15.35	19.81	<0.0001
Residual	47	36.42	0.78		
Total	48	51.78			

Table 9. Estimates of Warm and Cold Season Net CO_2 Flux of Moist Tussock and Coastal Wet Sedge Ecosystems of the North Slope of Alaska During the 1993-1994 Calendar Year.

		Net CO_2 Flux ($\pm$ 1 SE) (gC m^{-2} $season^{-1}$) [a]		Regional net CO_2 Flux (PgC $Season^{-1}$)[b]	
Season	Number of Days/Season	Tussock	Wet Sedge	Tussock	Wet Sedge
Warm	136	44.1	4.4	0.040	0.004
Cold	229	68.5 $\pm$ 12.9	19.0 $\pm$ 4.3	0.061	0.019
∑	**365**	**112.6**	**23.4**	**0.101**	**0.023**

Warm season measurements were made on 12-0.5 m^{-2} plots per site using a portable photosynthesis system and a 257-L acrylic cuvette (Vourlitis *et al.*, 1993) and were conducted over 24-hour periods on weekly intervals. During each diurnal measurement period, each plot was sampled every 1.5-2 hours.

[a] Warm season (May 31 to October 14, 1993) tussock and wet sedge tundra; n=1 site per tundra type. Cold season (October 15, 1993 to May 30, 1994) tussock and wet sedge tundra; n=2 sites per tundra type.

[b] Circumpolar area of tussock tundra=9 x 10^{11} ·m^{2}; wet sedge tundra=1 x 10^{12} m^{-2} (Miller *et al.*, 1983).

Table 10. Seasonal carbon fluxes, weather characteristics of sampling period and depth of soil thawing at undisturbed and postfire places in dwarf-shrub moss-lichen tundra (Vorkuta region, Russia, 67°30'N; 63°44'E).

Parameter	Undisturbed	2 years postfire	8 years postfire
Date of first observation	06/17/96	06/19/96	06/24/96
Date of last observation	08/03/96	08/01/96	07/30/96
Sampling period, days	47	43	36
Seasonal respiration, gC m^{-2}	131.51	55.75	72.75
Seasonal gross production, gC m^{-2}	-117.78	-58.49	-107.99
Seasonal net flux, gC m^{-2}	13.72	-2.74	-35.24
Average PAR, MJ $\cdot$ m^{-2} day^{-1}	16.8	12.7	12.4
Average temperature of air, ^{o}C	12.6	12.0	9.1
Average soil temperature at 5 cm depth, ^{o}C	8.0	7.8	7.3
Average soil temperature at 10 cm depth, ^{o}C	5.2	6.1	6.5
Maximum depth of thawing, cm	79	107	115