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Development of Monitoring Techniques to Detect Change in Carbon Cycling in Relation to Thermokarst in National Parks and Preserves

Natural Resource Technical Report NPS/CAKN/NRTR—2010/383

ON THE COVER
Eight-mile lake watershed and sampling equipment.
NPS photograph by Larissa Yocum

Development of Monitoring Techniques to Detect Change in Carbon Cycling in Relation to Thermokarst in National Parks and Preserves

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Executive Summary

Long-term monitoring of changes in ecosystem carbon cycling in response to permafrost thawing and thermokarst development is an important component of understanding the rate at which northern ecosystems are changing. The Central Alaska Inventory and Monitoring Network of the National Park Service is in the process of developing a comprehensive permafrost monitoring program that can contribute significantly to this understanding. This report provides recommendations for monitoring ecosystem carbon cycling processes that can be affected as a result of permafrost thawing and thermokarst. This report is based in part on a pilot study in the Eight Mile Lake watershed near the northeast corner of Denali National Park and Preserve. These recommendations should be combined with complementary remote sensing interpretation and borehole monitoring pilot studies to design the formal monitoring permafrost monitoring protocol.

This report suggests a tiered carbon monitoring structure based on support of intensive monitoring in a few locations combined with more extensive monitoring across a range of sites. The intensive monitoring sites correspond to recommendations for monitoring permafrost temperature while the extensive monitoring sites may intersect with other National Park Service monitoring efforts such as that for vegetation. The intensive sites should be stratified to include thermokarst features where permafrost is, or has been, thawing, and in other areas with no obvious thaw feature at the surface.

The specific carbon monitoring measurements range from more basic and extensive, to more complex and intensive:

- long-term monitoring of **terrestrial carbon pools** in vegetation and soil in a range of extensive sites;
- isotope monitoring of **dissolved organic and inorganic carbon** in hydrologic fluxes in a range of extensive sites;
- terrestrial **ecosystem carbon balance** using eddy covariance in core, intensive permafrost monitoring sites; and
- remote sensing of **vegetation biomass and productivity**, which can be validated using the terrestrial carbon pool data.

Acknowledgements

This research was supported by the National Park Service, Task Agreement #J9836 05 0108.

Introduction and Background

Four hundred and fifty billion tons (Pg) of soil carbon (C) are estimated to be stored in the surface of high latitude ecosystems (Gorham 1991, Gilmanov and Oechel 1995). This represents almost a third of the soil C stored in terrestrial ecosystems globally, and is several orders of magnitude greater than current annual anthropogenic CO_2 emissions (Post et al. 1982, Dixon et al. 1994, Houghton et al. 1996, IPCC 2001). If deeper permafrost soil is considered, another 500 Pg of soil C could be frozen there (Zimov et al. 2006). Latitudinal gradients of soil carbon (Post et al. 1982), field experiments (Van Cleve et al. 1990, Rustad et al. 2001), and laboratory incubations (Kirschbaum 1995, Kirschbaum 2000, Dutta et al. 2006) all show that soil C cycling in these northern ecosystems is likely to be strongly influenced by the effect of cold temperatures on rates of decomposition of soil organic matter (SOM) (Davidson and Janssens 2006). This 'old' soil C, climatically protected from microbial decomposition in frozen or waterlogged soil, has been accumulating in these ecosystems throughout the Holocene since retreat of the last major ice sheets (Harden et al. 1992).

Climate change scenarios predict that the greatest magnitude of warming will occur at high latitudes (Houghton et al. 1996, IPCC 2001, ACIA 2004). This predicted warming is supported by observational evidence over the last 25 years (Serreze et al. 2000) and is associated with warmer ground temperatures, permafrost (permanently frozen soil) thawing, and thermokarst (ground subsidence as a result of ground ice thawing) (Lachenbruch and Marshall 1986, Osterkamp and Romanovsky 1999). Permafrost thawing and thermokarst have the potential to alter ecosystem C cycling by changing the vegetation structure and growth rates, and by altering soil microbial decomposition rates and other C loss pathways. These changes in turn can affect the C storage of ecosystems, which is the net balance of these processes (Randerson et al. 2002), and can cause feedbacks to climate change (Cox et al. 2000)

Long-term monitoring of changes in ecosystem C cycling in response to permafrost thawing and thermokarst development will be an important component of understanding the rate at which northern ecosystems are changing, and how they may affect local and global C cycling. Indeed, ecosystem C storage can be considered an ecosystem service because the majority of C removed from terrestrial ecosystems ends up in the atmosphere, contributing to climate warming. The Central Alaska Inventory and Monitoring Network (CAKN) of the National Park Service (NPS) is in the process of developing a comprehensive permafrost monitoring program that can contribute significantly to this understanding. This report provides recommendations for monitoring ecosystem C cycling processes that can be affected as a result of permafrost thawing and thermokarst. This report is based in part on a pilot study in the Eight Mile Lake watershed near the northeast corner of Denali National Park and Preserve (DENA). These recommendations should be combined with complementary remote sensing interpretation and borehole monitoring pilot studies to design the formal monitoring permafrost monitoring protocol.

Carbon Cycle Monitoring Methods

Ecosystem Carbon Cycle Overview

Ecosystem C cycling is comprised of pools and fluxes. The main terrestrial **pools** of organic C are contained in vegetation and soil, about 40-60% C and 1-50% C respectively. Inorganic C is contained in carbonate rocks and soils in some ecosystems, depending on the parent material type. Because the amount of C in carbonates is not likely to be dramatically affected by permafrost thawing or climate change, this inorganic C pool will not be considered further here. The amount of C contained in vegetation and soil is not static and is determined by the **fluxes**, or rates of inputs and outputs of C. Photosynthesis and plant growth is the dominant pathway of C into ecosystems, as atmospheric C is fixed (stored) into plant biomass. A small fraction of plant biomass is eaten by herbivores (<5-10%) while the rest of the plant biomass over time senesces and enters the soil organic matter pool where it is decomposed by soil animals and microbes. The processes that consume live and dead plant biomass for energy, converting it ultimately back to atmospheric CO_2, are together referred to as **heterotrophic respiration**. This respiration flux of C out of ecosystems is dominated by microbial decomposition of organic C. Other C fluxes out of ecosystems tend to be small in comparison to respiration, but do contribute to the overall C balance of an ecosystem. These include leaching of dissolved inorganic C (DIC) and dissolved organic C (DOC) into surface water exported to streams and lakes, and emissions of other C gases such as methane under anaerobic conditions. Over longer times scales (or spatial scales), other fluxes become important to the C balance, notably disturbance, such as fire (rapid oxidation of organic C), or erosion (lateral export of C). All of these processes may be affected by permafrost thawing and thermokarst; below is a brief review of methods for monitoring some of these C pools and fluxes.

Vegetation

Carbon is contained in plant biomass, and the annual input of new plant biomass is called **net primary productivity** (NPP). Changes in both the pool of vegetation C and the flux through time are of interest to a monitoring program, and can be assessed remotely or at the plot scale.

Plot scale

Vegetation C pools can be quantified destructively or non-destructively, with the former providing the more accurate assessment. For repeated sampling that is part of a monitoring program, there is a clear preference for non-destructive sampling, but a comprehensive program could include both. A typical destructive harvest of boreal forest or tundra vegetation comprises removal of small quadrats of understory vegetation (0.25-0.4 m^2) where all plant species are sorted into new and old growth, dried and weighed. Such a plot can be non-destructively quantified first using a point-intercept method to describe the frequency of plant species and tissue types. The point-intercept data and the destructive harvest can be combined to produce allometric relationships for future, or more widespread, measurements The basal diameter of larger stature shrubs and the diameter at breast height (DBH) of trees are typically measured on larger plots (e.g. 100 m^2) and converted to biomass by destructively sampling a subset of shrubs and trees and constructing allometric relationships between diameter and total biomass. For both methods, point-intercept allometries and tree diameter allometries already exist from other studies in Alaska (e.g. Shaver et al. 2001, Mack et al. in prep.), but some accuracy is sacrificed when allometries are not constructed at the site. Net primary productivity is quantified by separating and weighing the newly grown plant parts during the destructive harvest for the understory, and by using littertraps on the soil surface to collect falling tree leaves on an annual basis. These measurements of leaf growth or turnover are combined with re-measurements of tree biomass to calculate aboveground net primary productivity, or the amount of plant growth per m^2 per year.

Belowground plant biomass and productivity is often ignored in many studies that quantify only aboveground biomass. Fine root biomass is measured destructively by collecting soil cores and separating roots by hand in the surface soil. Non-destructive imaging of root growth (**belowground net primary productivity**) is possible by installing clear tubes and using a digital camera system to record changes in root biomass surrounding the tubes. These measurements need to be calibrated with destructive measurements of biomass, and are generally a high-intensity effort.

Remote Sensing

Leaf area can be imaged remotely (satellite/aircraft) using the normalized difference vegetation index (NDVI) that combines measurements of reflected visible and infrared light. Using algorithms, leaf area can be converted to net primary productivity. These measurements are best used to determine differences in leaf area among different vegetation types where there are larger differences, or over longer time periods. Remote sensing was not used in the pilot study and will not be discussed further here.

Soil

Carbon is contained in soil organic matter (SOM), both in the mineral soil and in thick surface organic horizons that are typical of high latitude ecosystems. Carbon pools belowground can be larger than C stored in plants aboveground in these ecosystems, and the influence of freezing temperatures and waterlogging on microbial decomposition means that SOM pools are likely to be affected by changes in climate. But, because soil C pools are large and spatially variable it is often difficult to detect changes in the pool size. Fluxes of C out of the soil pool (respiration) are more sensitive for detecting interannual change and will be addressed in the following **Ecosystem Carbon Dioxide Exchange** section.

Organic Horizons

Soil OM accumulates in organic horizons as partially decomposed plant material on the mineral soil surface. These horizons tend to be ~5-40 cm thick, and those with deeper organic horizons are classified as peat soils. These soils have high percent C, but low bulk density (mass per unit volume), and contain a large amount of the potentially decomposable C pool. Soil C pools are quantified by soil coring. The surface organic is usually removed with a 10x10 cm quadrat and a serrated knife due to its low bulk density. Organic horizons are separated by depth with the bottom of the green moss defined as the soil surface. In the laboratory, each layer with known dimensions is weighed wet, then the sample is homogenized. Because sieving (typical for soil analyses) is not possible for organic horizons, large roots and organic chunks are removed by hand. A subsample is weighed wet and then dried at 110°C for soil moisture, and another subsample is dried at 70°C for C elemental analysis. Carbon is expressed as kg m^2 to the sampling depth.

Mineral Horizons
Organic C also accumulates in mineral soil horizons, which by definition are <20%C, but typically range from 1-10%C. While the %C is lower, the bulk density is higher so the mineral soil contains the larger proportion of the total C pool down to 1 m depth. Carbon is deposited in the mineral soil by downward transport and by **cryoturbation**, freeze-thaw mixing of the soil. Since the **active layer** depth (seasonally thawed layer) often corresponds to the surface of the mineral soil, much of the C in mineral horizons is currently in permafrost, and may be particularly susceptible to climate change. Deeper soil horizons can be collected with a soil core and separated by depth. Some sampling issues include identifying the mineral soil surface, which can be difficult due to cryoturbation, and the need for a permafrost drill to sample below the active layer. A typical soil C quantification might include the surface 1 m of soil, but there may be a significant amount of C below that point (2 to 3m depth) that can be retrieved with a permafrost drill. Mineral soil separated by depth is then returned to the laboratory and C pools are quantified as described above for the organic horizons. In carbonate soils, acidification of samples is necessary in order to quantify the organic C pool separate from inorganic C that may be present.

Ecosystem Carbon Dioxide Exchange
Changes in C pools are often hard to detect given spatial variability. In contrast, measurements of fluxes in and out of ecosystem C pools are often more sensitive for detecting change on annual time scales. The predominant path of C in and out of terrestrial ecosystems is through CO_2 exchange with the atmosphere. Plants take in CO_2 via photosynthesis and return it to the atmosphere via plant respiration. Soil respiration (primarily the activity of microbes) also returns CO_2 to the atmosphere. This CO_2 exchange can be monitored to quantify the movement of C in and out of an ecosystem and is referred to as **net ecosystem exchange** (NEE) or **net ecosystem production** (NEP) when described over a year.

Chambers
A clear chamber can be used to enclose a small patch (50x50 cm) of vegetation and soil. Air is withdrawn from the chamber and circulated through an infra-red gas analyzer (IRGA) to determine the CO_2 concentration, and then returned back to the chamber. By monitoring the CO_2 concentration over several minutes, a rate of C exchange with the atmosphere can be determined (units of mg C m^2 hour). In daytime conditions in the summer, chamber CO_2 concentrations typically decline as photosynthesis is greater than respiration and net C is moving into the ecosystem from the atmosphere. This net flux can reverse in the dark, or in winter, when respiration is higher than photosynthesis. A chamber can be placed by hand in different replicate locations or autochambers can be employed for greater temporal resolution. Measurements are needed in all environmental conditions in all seasons (monitored by climate stations) and total C exchange can be estimated for periods that were not measured. The chamber technique is primarily limited by the vegetation stature and works best when the vegetation is <50 cm in height.

Eddy Covariance Tower
For taller-statured vegetation or to avoid chamber biases, CO_2 exchange can be monitored with the eddy covariance technique. Here, no chamber is needed to enclose the ecosystem. Instead a tower is deployed with instruments above the vegetation canopy. Along with CO_2 concentration measurements as described above, the 3-D wind velocity is also measured. These continuous

measurements, along with measurements of the ecosystem energy budget and micrometerologic conditions, can be used to determine total ecosystem CO_2 exchange as eddies of wind move air past the sensing station. Both chamber and tower techniques measure the net exchange of CO_2 only, so miss some smaller but potentially important C losses described in the following sections.

Hydrologic Carbon Losses

Other than direct exchange of CO_2 between terrestrial ecosystems and the atmosphere, C can be exported from ecosystems in water. While this represents a small, one-way flux of C, it can be significant when compared to the net exchange of CO_2, as described above. Carbon is exported in water as inorganic CO_2 or as organic forms of C, both dissolved in water (DIC and DOC), or as particulate organic carbon (POC).

Dissolved Inorganic Carbon

Excess CO_2 (measured as pCO_2) is a product of water that is supersaturated by CO_2 in the soil profile as the soil atmosphere is elevated in CO_2 from root and microbe respiration. Excess CO_2 degasses to equilibrate with the atmosphere in streams and lakes. Remaining DIC is a product of soil and rock weathering where the DIC balances other **cations** (positively charged elements) in solution, thus will not immediately degas. Lateral transport of DIC is important because it means that the exchange of C with the atmosphere will not be measured by the chamber or tower techniques described above. Also, excess DIC represents soil processes deep in the profile which are expected to be most sensitive to permafrost thawing and thermokarst. Total DIC can be measured with *in situ* sensors based on the pH chemistry of the CO_2-bicarbonate system. Excess CO_2 is measured by headspace equilibration and subsequent concentration measurement using an IRGA.

Dissolved Organic Carbon

Dissolved OC exported to streams and rivers from SOM, and produced *in situ*, comprises C compounds that are soluble in water, but that have not been immediately decomposed by microbes. DOC represents a large range of C compound types. A portion of the DOC pool is resistant to microbial decomposition because of its chemical structure. Another portion of the DOC pool may be exported to streams and rivers because it is lost from a part of the soil profile where microbial activity is restricted either by temperature or waterlogging. The latter portion of the DOC pool may be subject to further microbial decomposition within aquatic ecosystems, ultimately ending up as CO_2. Resistant DOC can be exported all the way to the ocean, or be sorbed to particulates in the stream and end up in sediment. DOC concentrations can be measured in filtered water samples (0.45 μm filter) with an elemental analyzer. Different pools of DOC can be isolated by charge with resin exchange columns, or by size with ultrafiltration. Both charge and size roughly correspond, in some situations, to different parts of the total DOC pool. As with DIC, total DOC export need to be quantified by concentration measurements coupled with hydrologic flow measurements.

Particulate Organic Carbon

This pool is defined as C in water that is trapped on the filter (0.45 μm filter) when DOC is collected. It represents a range of material from suspended sediments to dead aquatic organism, to material eroded from terrestrial ecosystems. It can be quantified at the same time as DOC by measuring the quantity of material and the %C using an elemental analyzer. Because some types of thermokarst can cause significant soil erosion, POC monitoring may be particularly important for monitoring lateral C fluxes.

Carbon Isotopes

All the methods reviewed above quantify either pools or fluxes of ecosystem C. This C (and all C in the world) comes in slightly different forms corresponding to the number of neutrons present. While about 99% of C has 6 neutrons, about 1% of all C has 7 neutrons, while ~$1x10^{-10}$ % of all C has 8 neutrons. The latter two forms of C are referred to as ^{13}C (because it has 7 neutrons and 6 protons) and ^{14}C (or radiocarbon, which has 8 neutrons and 6 protons). ^{13}C is chemically stable whereas ^{14}C radioactively decays with a half-life of 5730 years. Carbon isotope measurements in ecosystem pools and fluxes provides information as to the processes that have influenced that C in the past. Various physical and biological processes can change the amount of ^{13}C as C moves from one pool to another, whereas the content of ^{14}C is affected by the time spent within the ecosystem. Because of this, C isotope measurement can provide integrated information as to the sources and rates of particular C fluxes over longer time scales where direct observation is not possible.

Stable Carbon

The ^{13}C content of ecosystem C reflects physical and biological processes that have moved C from one pool to another. Because ^{13}C is slightly heavier than the more common ^{12}C, this usually causes a recipient C pool to have slightly less ^{13}C compared to the pool where the C is coming from (referred to as discrimination). Biological processes accelerate this discrimination process as enzymes act faster on ^{12}C compounds since the diffusion rate is quicker for the lighter atom. The result of these discrimination processes is that different ecosystem C pools have different amounts of ^{13}C. This information can be used to determine, in some cases, which pools contribute to a particular C flux if the isotope ratio of the pools and fluxes is measured. Carbon can be extracted from organic (plant, soil, POC) and inorganic pools (respiration, DIC, DOC) and fluxes and converted to CO_2, which is then measured by a mass spectrometer that detects the ^{13}C abundance of the sample material.

Radiocarbon

The ^{14}C content of ecosystem C reflects the rate of C exchange between ecosystems and the atmosphere. Nuclear bomb testing conducted in the 1960's enriched background levels of ^{14}C to approximately two times the normal atmospheric levels of radiocarbon, which has declined since. The enrichment of ecosystem C with "bomb" ^{14}C records a history of C uptake by these ecosystems in the time since weapons testing. Over longer time scales, the natural decay rate of ^{14}C acts as an atomic clock. Radioactive decay causes older C, such as that found deeper in soil, to be depleted in ^{14}C. Radiocarbon measurements then provide an indication of age, and also can help differentiate source pool, such as detecting old C loss from permafrost thawing. Radiocarbon measurements are technically challenging because of its low abundance relative to other C isotopes. The extraction procedures from different C fluxes or pools are similar to that described for ^{13}C. The sample must then be converted to CO_2, reduced to graphite, and finally ^{14}C is then measured on an accelerator mass spectrometer.

Pilot Measurements

Study Site Description & History

This pilot study made use of a watershed in the northern foothills of the Alaska Range just outside the DENA boundary near the end of the Stampede Road (Figure 1). Ground temperature has been monitored for several decades at this site, before and after the permafrost was observed to thaw on a gentle north-facing slope (Osterkamp and Romanovsky 1999). The thaw area drains down to Eight Mile Lake, which lies at the foot of these slopes. While permafrost thawing can sometimes result in inundation depending on local topography, the terrestrial site is relatively well drained. The Eight Mile Lake watershed is relatively small (< 8 km2) and is bounded on two sides by moraines deposited by early Pleistocene glaciers (Wahrhaftig 1958). Water enters Eight Mile Lake through a single small stream on the southeast side, and there are some small rivulets off the hillsides where the permafrost is thawing directly into the lake. The lake has a single channelized outflow.

The biogeochemistry of terrestrial C cycling has been studied in the watershed for five years over the course of a NASA-funded project to Schuur to determine the fate of old, temperature-stabilized organic matter from thawing soils. Now, the watershed is the focus of continuing NSF-funded research to Schuur and Dr. James Sickman to continue the terrestrial C cycling research and to make the first link to the aquatic ecosystem via dissolved organic carbon (DOC) measurements in streams. The site is also co-sponsored by the Bonanza Creek Long Term Ecological Research program based at the University of Alaska, Fairbanks where Schuur is a co-Principle Investigator.

Study Design

Terrestrial

In this area, we have established three terrestrial sites that represent differing amounts of disturbance from permafrost thaw: **1)** relatively undisturbed tussock tundra, dominated by the tussock-forming sedge *Eriophorum vaginatum* with *Sphagnum spp* mosses and shrubs (hereafter called '**Minimal Thaw'**), **2)** a site adjacent to the borehole that started documented permafrost thawing in 1985 ('**Moderate Thaw**'), and **3)** a site located where permafrost appeared to have thawed more than three decades prior to the thawing at the borehole based on visual observation of thermokarst features from 1951 aerial photographs ('**Severe Thaw**') (Figure 1). The warming ground temperature and loss of ice wedges from these sites has had multiple direct and indirect effects on the tundra ecosystem. In addition to warmer soil temperature and deeper thaw depth, soil moisture and the overall hydrology of the area has been altered where ice wedges have thawed and drained away. The soil surface collapsed in areas overlying ice wedges, and the undulating surface microtopography (thermokarst) caused water to accumulate in lower areas, leaving higher areas dry. While there are no significant differences among sites in the mean moisture, the coefficient of variation in moisture is higher where subsidence is more pronounced. These thermokarst features are most dramatic in the Severe Thaw site, are just starting to develop in the Moderate Thaw site, and are largely absent in the Minimal Thaw site. Together, these three terrestrial sites are a natural experimental gradient that appear to represent the long-term effects of permafrost thawing and thermokarst on terrestrial ecosystem dynamics in areas that are relatively well-drained.

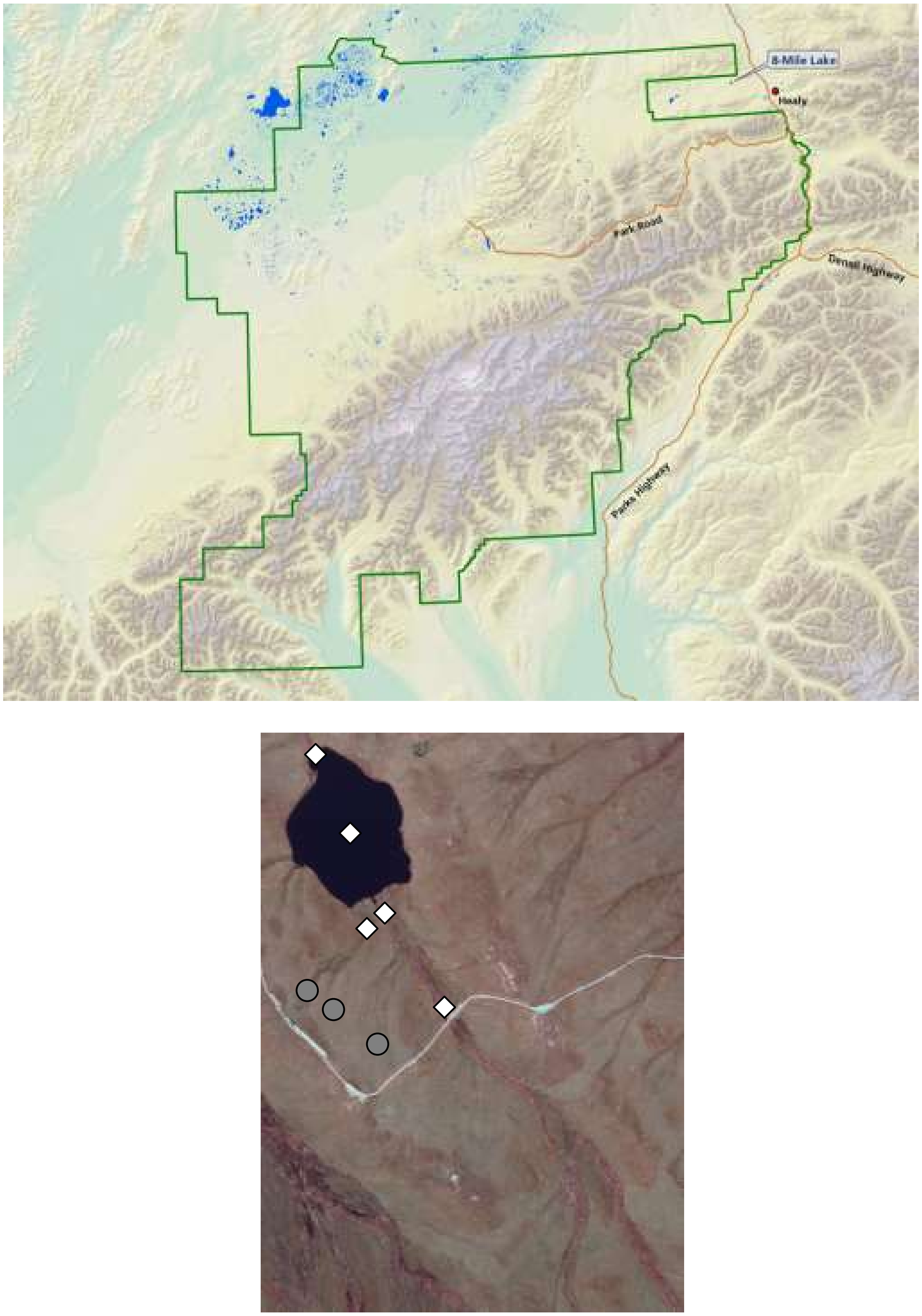

Figure 1. Location (DENA boundaries in green) and aerial infrared photograph of Eight Mile Lake and its watershed. Thermokarst regions can be detected by dark coloration within the drainage network. The Eight Mile Lake watershed has been the subject of climate change research since 1985 when a borehole was installed (T. Osterkamp pers com), and with a more intensive focus on C cycling since 2001. Grey circles are the terrestrial sampling locations and white diamonds are the aquatic sampling locations.

Aquatic

The terrestrial measurements are linked to the overall watershed hydrology through several permanent water monitoring stations distributed throughout the basin (Figure 1). The water sampling is designed to capture changes in water chemistry from when water leaves the terrestrial ecosystem to when it leaves Eight Mile Lake. To do this, water is periodically collected from four different locations: **1)** from soil profile wells at each of the three terrestrial sites, **2)** from small drainage rivulets that drain water tracks descending directly from the sites to the lake, **3)** the main inlet stream to Eight Mile Lake, and **4)** within the lake adjacent to the outlet stream. These stations are monitored regularly throughout the summer for element concentrations, and sporadically during the winter. Water flow is measured at the lake inlet stream and the water track drainage. The lake level itself is also gauged to bound the water flow measurements. In addition to typical water chemistry measurements (pH, base cations, anions, etc), periodic isotope measurements on the DIC, DOC, and POC are also being made at these stations. The sampling station design provides information about carbon processing within this small watershed before water is exported to the larger river system (in this case, eventually the Tanana and Yukon rivers).

Data

Presented here are some representative results on C pools and fluxes in response to permafrost thawing and thermokarst measured over the past several years at the Eight Mile Lake study area.

Plant Biomass and Productivity

We quantified plant biomass and net primary productivity using destructive sampling at the three terrestrial sites. In this upland tundra ecosystem where permafrost has been thawing over the past several decades and thermokarst has developed, we observed large differences among our sites in plant community composition. Aboveground plant biomass ranged from being dominated by sedges, to becoming increasingly dominated by deciduous and evergreen shrubs across our sites as thermokarst became more developed (Figure 2).

Aboveground vascular net primary productivity followed this same pattern, with graminoids dominating productivity in the Minimal and Moderate sites, while the Severe site productivity was dominated by shrubs (Figure 3). Non-vascular plant productivity was an important component of plant biomass, especially when considering only the apparently photosynthetic (green) biomass alone. And, non-vascular productivity contributed significantly to total aboveground plant growth, especially at the Severe site where moss growth equaled the production of the deciduous shrubs, likely as a result of favorable moisture conditions.

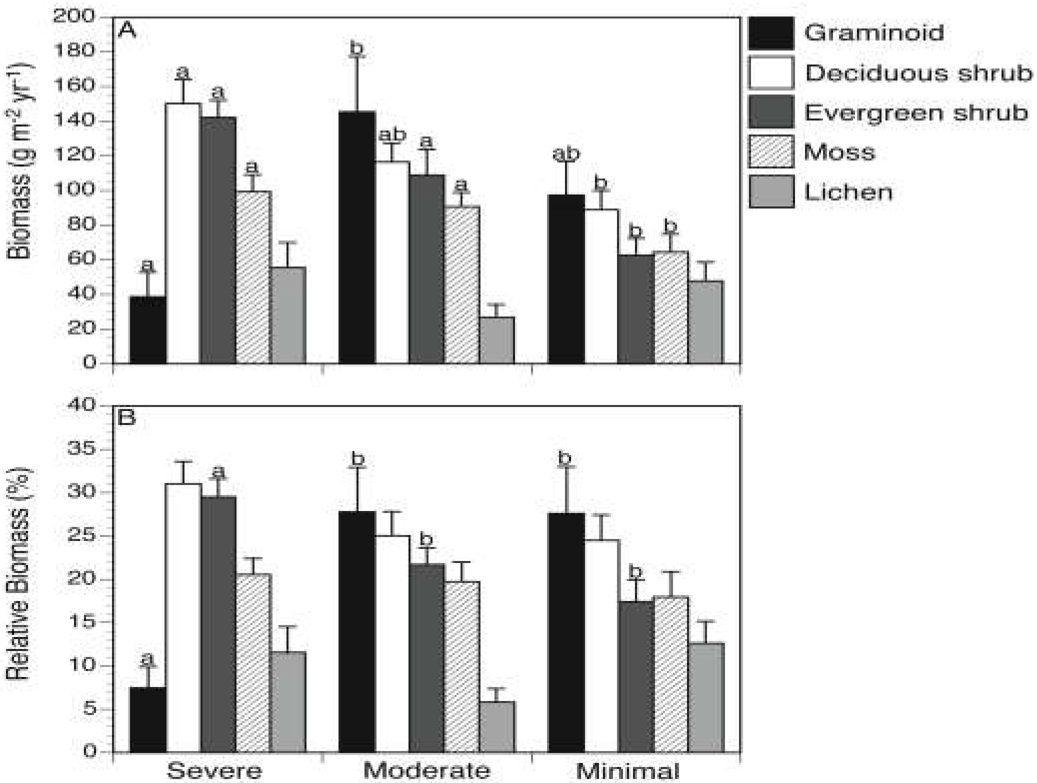

Figure 2. Aboveground biomass (A) and relative abundance aboveground biomass (B) by functional group for the three sites that differ in degree of permafrost thawing and thermokarst. Different letters denote significant pairwise differences among sites, within a species or functional group. Species without letters did not differ significantly among sites.

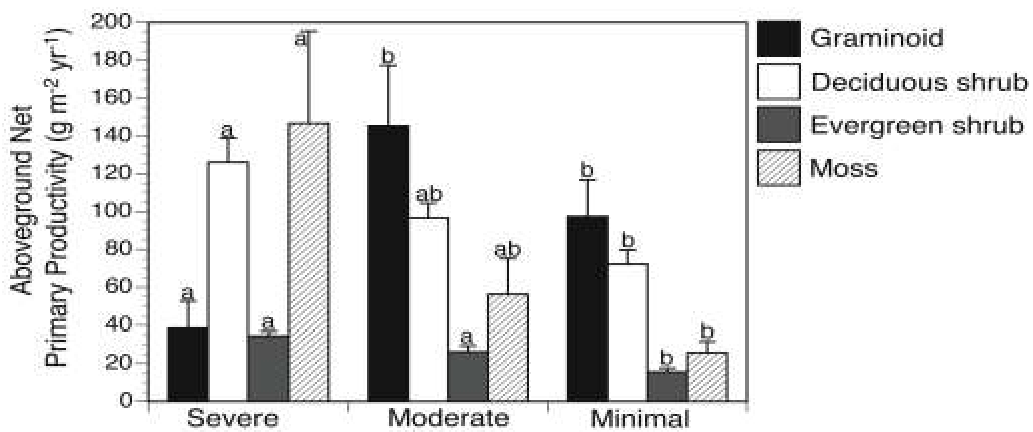

Figure 3. Annual net primary productivity by functional group for the three sites that differ in degree of permafrost thawing and thermokarst. Different letters denote significant pairwise differences among sites, within a species or functional group. Species without letters did not differ significantly among sites.

Net Ecosystem Exchange

We quantified carbon dioxide exchange at the terrestrial sites using autochambers over the past three years. There were differences among our three sites in carbon exchange both during the summer growing season, and in the annual estimate when winter exchange was included. Net carbon exchange during the summer growing season from May until September (Figure 4) showed that the Severe Thaw site and the Moderate Thaw site had the most net carbon uptake in two out of three years as photosynthesis and plant growth was higher in these sites compared to the Minimal Thaw site. This corresponded to the aboveground net primary productivity measurements made in 2004 (Figure 3). In 2005, net uptake was reduced in all sites; this may have been due to a particularly dry summer.

Net carbon exchange for the whole year (Figure 5) includes the growing season measurements integrated with estimates of winter respiration. While growing season fluxes were monitored continuously, winter respiration measurements were made periodically throughout the winter and modeled using microclimate data. Winter 2006-2007 measurements are underway and thus not shown on the graph. Positive numbers show that net carbon is lost from most sites, with the exception being the first year in the Moderate Thaw site. Annual net uptake in that site was due to large amounts of growing season photosynthesis and plant growth during 2004. It is important to recognize that this graph represents annual net exchange of CO_2; it is likely that other losses (discussed in **Methods** section) are of the magnitude such that any measurement of ~20 g m^{-2} yr^{-1} net uptake is likely to represent a site that is in neutral balance.

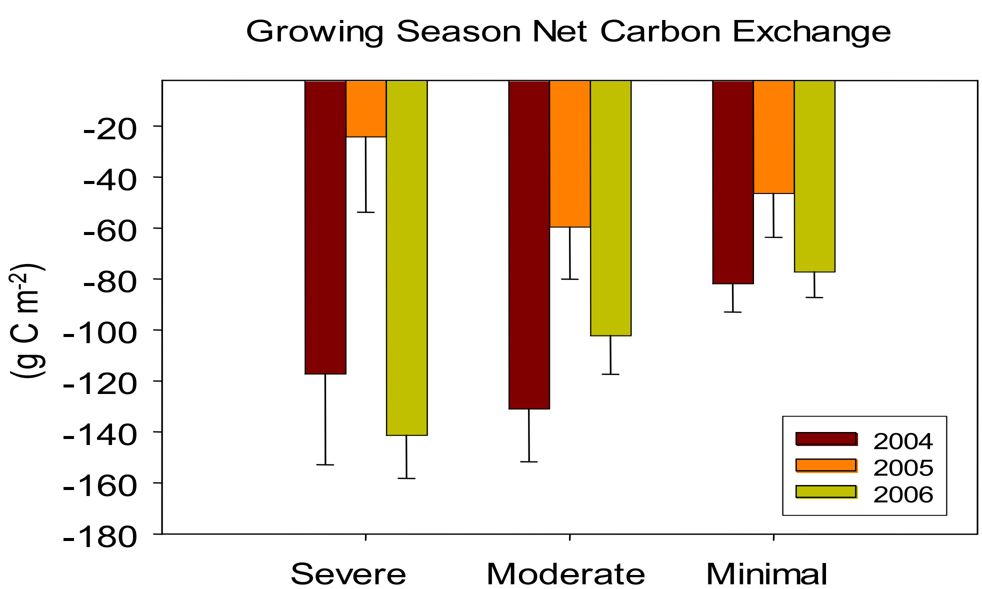

Figure 4. Net carbon exchange during the summer growing season from May until September. Negative values indicate that net carbon moved into the ecosystem as photosynthesis was greater that respiration.

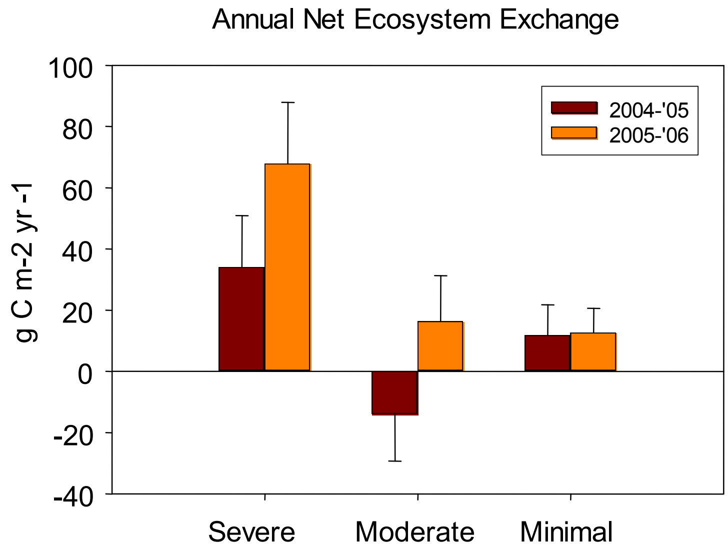

Figure 5. Net carbon exchange including the summer growing season and winter respiration measurements. Positive values indicate that net carbon moved out of the ecosystem to the atmosphere as total respiration was greater than carbon taken up by photosynthesis.

Radiocarbon

We quantified radiocarbon in both the terrestrial and aquatic sites in a full range of carbon fluxes: 1) ecosystem respiration, 2) respiration from the soil profile, 3) DIC, and 4) DOC. Relative to the atmospheric value, there were a number of both terrestrial and aquatic samples that showed loss of significant amounts of 'old' carbon to the atmosphere.

A seasonal cycle in respiration radiocarbon is evident with lower values in the early and late season (Figure 6). The late season decline in radiocarbon values can be explained by more old carbon exposed in the soil profile as the active layer progressively thickens throughout the growing season. The low early season values are less easily explained, but may be due to the delayed release of wintertime respiration that was trapped in soil air pockets within ice layers. During the middle of the growing season (June, July, August) the higher radiocarbon values relative to the atmosphere represent the contribution of plant respiration and heterotrophic decomposition of litter that was fixed over the past years to decades. Site differences are more apparent during the shoulder seasons and less during the middle of the growing season with the exception of August where the Severe Thaw site had a large release of old carbon.

Soil profile radiocarbon values (Figure 7) are more negative compared to ecosystem respiration at the surface (Figure 6). Negative radiocarbon values indicate significant contribution of pre-bomb carbon to the respiration flux. This is due to the fact that ecosystem respiration includes aboveground plant respiration and the surface litter horizon. These components are typically near to, or enriched in radiocarbon, relative to the atmosphere. Similar to ecosystem respiration, there is a seasonal cycle of radiocarbon, but this is slightly shifted later in the season compared to the total ecosystem radiocarbon fluxes. In contrast to the ecosystem respiration, the Moderate Thaw site has older C compared to the Severe Thaw site. In both cases, the Minimal Thaw site had the least amount of old C.

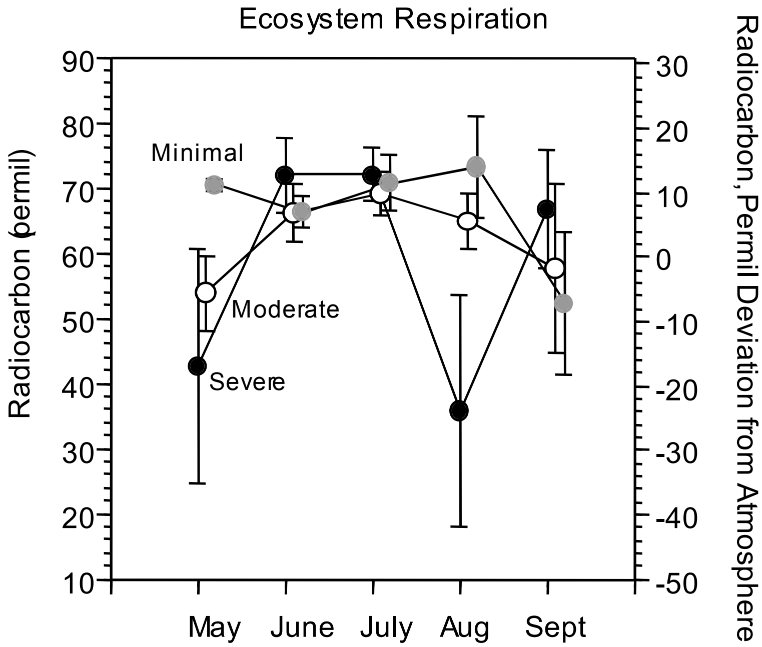

Figure 6: Growing season radiocarbon value for total ecosystem respiration. The left axis shows the actual radiocarbon values of CO_2, and the right axis is relative to the 2006 atmosphere, which was +59 ‰ in 2006. Chambers that are below zero on the right axis have significant contributions from old carbon respired by heterotrophs.

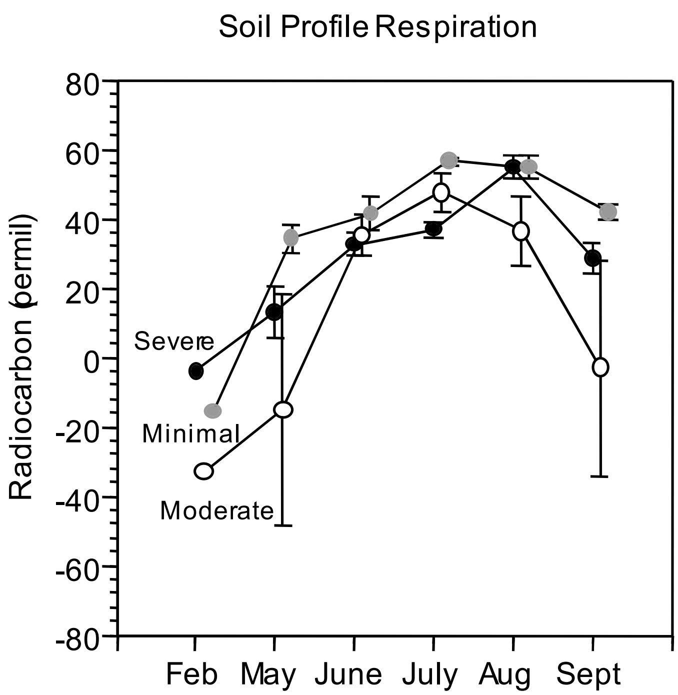

Figure 7. Radiocarbon values from CO_2 in the soil profile. These measurements represents an average of samples taken from 10 and 20 cm depths at all of the sites.

Dissolved OC radiocarbon values (Figure 8) are relatively depleted compared to the atmosphere, but approach the atmospheric value later in the growing season. There was a significant difference in apparent C age between the two sampling locations, with the Thermokarst Drainage releasing older DOC compared to the Inlet Stream. Negative radiocarbon values indicate significant contribution of pre-bomb C to the DOC flux from the terrestrial sites. It is likely that this older C is diluted with the addition of younger C in the Inlet Stream.

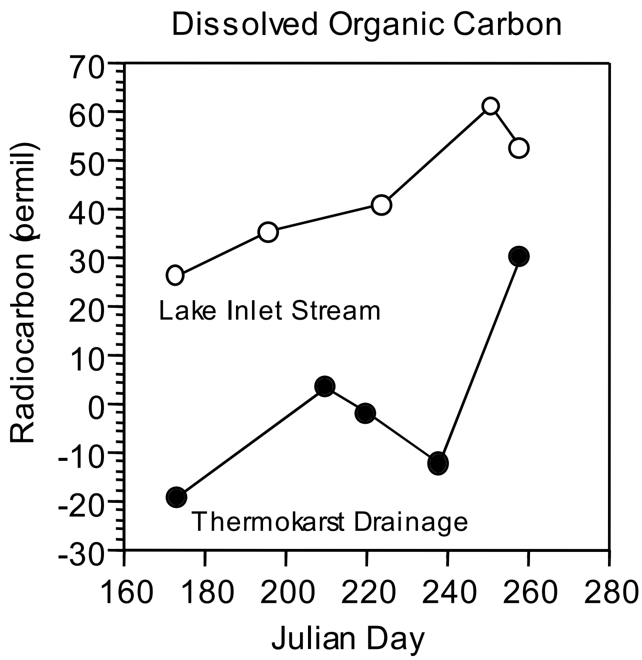

Figure 8: Radiocarbon of DOC from two locations in the Eight Mile Lake watershed. The thermokarst drainage represents surface water flow directly integrated from the terrestrial sampling sites. The Lake Inlet Stream is the main drainage to the lake and integrates more water than the Thermokarst Drainage. Measurements were made periodically from late May until September.

DIC radiocarbon values are generally higher compared to DOC and have the reverse seasonal pattern (Figure 9) with lower values occurring generally later in the season. DIC is a product of soil respiration and mineral weathering with the latter less significant in this permafrost watershed. The two sampling locations differ in the early season response as the Thermokarst Drainage has radiocarbon values lower than the atmosphere, while the Inlet Stream was higher. The Thermokarst Drainage values reflect the soil profile pattern throughout the growing season. The Inlet Stream had high radiocarbon values in the early season, reflecting an influx of respiration from recently fixed carbon.

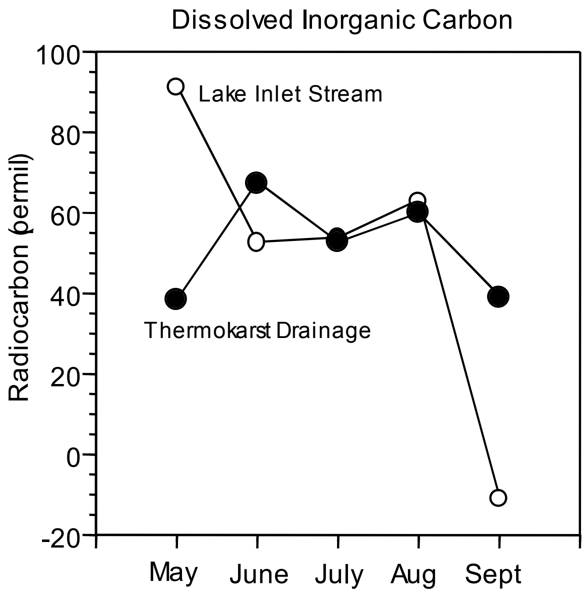

Figure 9. Radiocarbon values of DIC, primarily pCO_2, for the two sampling locations in the Eight Mile Lake Watershed.

Recommended Strategy

Monitoring Site Requirements

The recommendations of this report are intended to be combined with complementary remote sensing interpretation and borehole monitoring pilot studies to design the formal monitoring permafrost monitoring protocol. As such, much of the sampling design for the carbon monitoring should be done using the permafrost monitoring sites. The basic elements of the permafrost monitoring sites have been detailed in the report by T. Osterkamp and will not be repeated here. Listed below are some additional elements that may not have been covered by the permafrost monitoring report.

Site Conditions

Site selection should parallel that for the permafrost temperature monitoring. Site stratification may be desirable where thermokarst sites (chosen based on surface features) and more stable permafrost sites (chosen by stratified random sampling; no surface evidence of thawing) are both monitored to give a range of permafrost change on the landscape. Many of the permafrost monitoring site conditions detailed in the Osterkamp report are related to the area directly surrounding a permafrost borehole. In order to quantify hydrologic C losses, some attention should be made to the surrounding watershed hydrology. Monitoring of small watersheds, including first and second order streams and rivers, will be very useful for comparison to large scale monitoring programs by agencies such as U.S. Geologic Survey (USGS), described in more detail below. Monitoring sites will then be dependent on both access to a terrestrial measurement location, and also to downstream aquatic sampling locations. Hydrologic monitoring for C is most useful where streamflow data is being collected, so pre-existing gauge data should be taken into account.

Existing Data and Sites

Outside of the Eight Mile Lake study site described in this report, there are no other intensive field-based studies of C balance in response to permafrost thawing and thermokarst inside, or adjacent to, the CAKN. This is good reason to establish new monitoring sites to effectively evaluate park resources. Because C balance studies can be intensive, an effort should be made to use pre-existing sites (i.e. Eight Mile Lake), and to make links to other C balance measurements at sites such as the Bonanza Creek Long Term Ecological Research sites whenever possible.

At much larger spatial scales, there have been recent USGS monitoring efforts (Striegl et al. 2005) to determine DOC losses in the Yukon River, and this effort may be extended in the future to monitor the DOC losses in the major rivers that feed the Yukon. The monitoring proposed here would complement these large river surveys by providing information about processes in the headwaters.

Sampling Strategy

It is not usually possible to do a complete C inventory of pools and monitoring of fluxes in many sites due to prohibitive costs. It is therefore recommended that monitoring be supported **intensively** in a few sites, and more **extensively** across a range of sites. These recommendations are listed in approximate order from the most basic C monitoring, to more intensive monitoring efforts.

1) **Terrestrial C pools**; basic long-term monitoring should start with an inventory of C pools in vegetation and soil. This is relatively low-cost and can be used to detect change over long time periods. This can be completed at a single time point in many locations (**extensive measurement**), and would be repeated on no less than a **five-year** interval. This can be done on a more widespread basis beyond the permafrost monitoring sites, and could occur in conjunction with other monitoring efforts, such as that for vegetation.

2) **Isotope monitoring of aquatic C fluxes**. This provides the only information about old C loss, which is of particular importance to permafrost monitoring. Isotope measurements of hydrologic fluxes have the advantage of integrating large areas and could be done annually, or less frequently if necessary. This can also be done on a more widespread basis beyond the permafrost monitoring sites, but would be most useful in watersheds with other hydrologic monitoring, or with permafrost monitoring.

3) **Terrestrial C fluxes** using eddy covariance technique. This is somewhat more labor and cost intensive, but provides the most detailed information on seasonal and yearly C balance for terrestrial ecosystems. This could be done at the core permafrost monitoring sites. Support for a few intensive sites would increase the interpretability of more extensive, but less frequent measurements.

4) **Remote sensing of vegetation**. Although not covered in detail by this report, change in vegetation structure and biomass can be detected by remote sensing, either by satellite or aircraft. The advantage is that it covers large areas, and can be coupled to 1) **Terrestrial C pools** for ground truthing of algorithms used to determine biomass and productivity.

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