Using Radiocarbon to Detect Change in Ecosystem Carbon Cycling in Response to Permafrost Thawing

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Abstract

There are more than 450 billion tons of carbon frozen in permafrost in high latitude ecosystems. This carbon is now subject to release into the atmosphere due to climate warming and permafrost thawing. Radiocarbon measurements of ecosystem carbon losses provide the means to measure whether old carbon is released in response to permafrost thawing. Radiocarbon values of ecosystem carbon losses showed a significant contribution from old carbon in areas where the permafrost has been observed to thaw. These measurements made at observation locations through time will be a useful long-term monitoring tool for detecting significant changes in the carbon cycle due to permafrost thawing.

Introduction

At least 450 billion tons of soil carbon (C) are estimated to be stored in high latitude ecosystems *(Gorham 1991)*. This represents almost one-third of the soil carbon stored in terrestrial ecosystems globally, and is several orders of magnitude greater than current annual anthropogenic carbon dioxide (CO_2) emissions *(IPCC 2001)*. Latitudinal gradients of soil carbon, field experiments, and laboratory incubations all show that soil carbon 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. This 'old' soil carbon, 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. This predicted warming is supported by observational evidence over the last 25 years and is associated with warmer ground temperatures, permafrost (permanently frozen soil) thawing, and thermokarst (ground subsidence as a result of ground ice thawing) *(ACIA 2004)*. Permafrost thawing and thermokarst have the potential to alter ecosystem carbon cycling by changing the vegetation structure and growth rates, and by altering soil microbial decomposition rates. Together, these changes in plant and soil processes can alter the balance of carbon cycling processes in these ecosystems and cause feedbacks to climate change.

Our overall research program is designed to answer three main questions:

- 1) Does permafrost thawing cause a net release of carbon from the ecosystem to the atmosphere?
- 2) Is the source of this carbon release from old carbon that comprises the bulk of the soil carbon pool?
- 3) What is the relative importance of old carbon export in water compared to direct respiration losses from land?

This summary addresses our use of radiocarbon measurements to determine the age of carbon lost from ecosystems in order to detect significant changes ecosystem carbon cycling that are a result of permafrost thawing and thermokarst formation.

Methods

Site Description This summary describes measurements made in the Eight Mile Lake Watershed (63° 52'42.1" N, 149° 15'12.9" W) on the north slope of the Alaska Range *(Figure 1)*. Ground temperature in a borehole has been monitored for several decades at this site, before and after the permafrost was observed to thaw *(Osterkamp and Romanovsky 1999)*. In this watershed, our study has defined three sites that represent differing amounts of disturbance from permafrost thawing based on observations of the vegetation and the borehole measurements:

- Site 1) tussock tundra typical of arctic ecosystems, dominated by the sedge *Eriophorum vaginatum* and *Sphagnum spp* mosses.
- Site 2) a site near the borehole used for permafrost temperatures where the vegetation composition has been shifting to include more shrub species, such as *Vaccinium uliginosum* and *Rubus chamaemorus*.

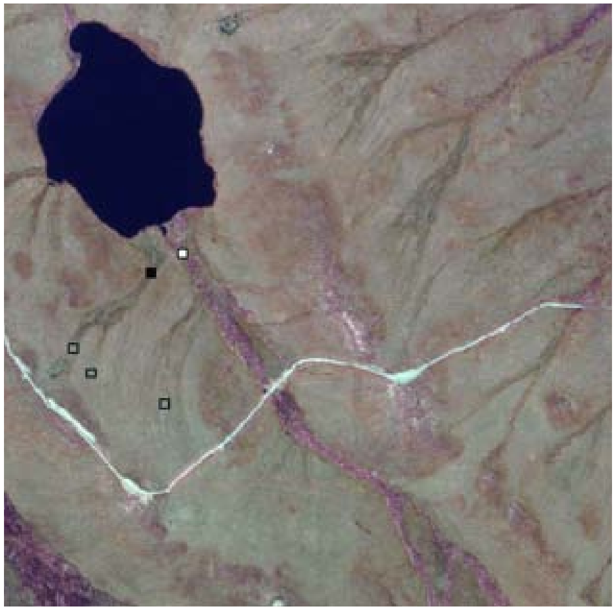

Figure 1. Aerial photo showing sampling locations: ecosystem respiration (grey), thermokarst drainage (black), and the main stream (white) in the Eight Mile Lake watershed. The white line is the Stampede Road.

- Site 3) a site located where permafrost thawed more than several decades ago, now largely dominated by shrub species *(Schuur et al. 2007)*.

These three sites are a natural experimental gradient representing the long-term effects of permafrost thawing on carbon loss.

Radiocarbon: Detecting the Loss of Old Carbon The $^{14}C/^{12}C$ isotope ratio of ecosystem carbon reflects the rate of exchange between carbon pools and the atmosphere. Nuclear bomb testing conducted in the 1960s enriched background levels of ^{14}C to approximately two times the normal atmospheric levels of radiocarbon *(Figure 2a) (Levin and Hessheimer 2000)*. Following the test ban treaty, the level of radiocarbon in the atmosphere decreased as ^{14}C was transferred into the ocean, vegetation, and soils, accompanied by the continuing dilution of the atmosphere by fossil fuel combustion. The enrichment of ecosystem carbon with "bomb" ^{14}C records a history of carbon uptake by these ecosystems in the time since weapons testing *(Trumbore 2000)*. Surface organic matter that has incorporated significant bomb carbon has positive isotopic delta values relative to the 1895 wood standard. Radiocarbon is expressed in units of permil (‰) as compared to wood from the year 1895, the standard primary radiocarbon reference material.

Over longer time scales, the natural decay rate of ^{14}C acts as an atomic clock as radioactive decay causes older carbon stored deeper in the soil and permafrost to be depleted in ^{14}C. Thus, soil organic matter frozen in permafrost generally has negative delta values. In turn, carbon lost by terrestrial ecosystems when permafrost thaws, either directly respired as CO_2 to the atmosphere, or indirectly lost through water as dissolved inorganic or dissolved organic carbon (DIC, DOC) will reflect the age of carbon decomposed by bacteria and fungi. The radiocarbon imprint of old carbon on ecosystem carbon losses will help determine whether significant changes in ecosystem carbon cycling are occurring in response to permafrost thawing.

Radiocarbon: Measurements All radiocarbon measurements were made using a similar processing methodology that differed slightly depending on the original form of the carbon (CO_2, DIC, DOC). Briefly, dark chambers were placed over the soil and air was drawn through a molecular sieve that quantitatively traps ecosystem-respired CO_2 until ~1.0 mg of CO_2-C was adsorbed. Gas wells installed in the soil were used to trap soil air at different depths in the soil profile in the same manner. For water samples, DIC was collected by bubbling water samples with a CO_2-free air headspace, while trapping evolved CO_2 on a molecular sieve. In the laboratory, the molecular sieve traps were heated to 625° C, which desorbs CO_2 for radiocarbon analysis. Radiocarbon content of DOC was measured on water samples that were filtered and acidified in the field, then freeze-dried and combusted in the laboratory. Carbon dioxide from the molecular sieves and the DOC was purified, graphitized, and analyzed for ^{14}C content.

Results

Ecosystem carbon loss is primarily generated by plant and microbial respiration (CO_2, DIC), and by direct leaching of DOC. Respiration from each source has a particular radiocarbon value depending on the residence time (or age) of carbon in the ecosystem *(Figure 2b)*. Carbon respired by plants has a radiocarbon value largely similar to, or sometimes slightly higher than, the contemporary atmosphere *(Schuur and Trumbore 2006)*. The radiocarbon value of heterotrophic respiration is more complex. Recent plant detritus (leaves, roots, stems, etc.) has higher radiocarbon values because the bomb pulse labeled growing plant parts over the past 40 years. Microbial decomposition of these substrates will release carbon with radiocarbon values elevated relative to the atmosphere. The only material with radiocarbon values below the current atmosphere is carbon present in the ecosystem long enough for radioactive decay. This so-called 'old' carbon can be as little as 50 years old (pre bomb), up to 10,000 years old, or even older.

Radiocarbon measurements of carbon losses from the

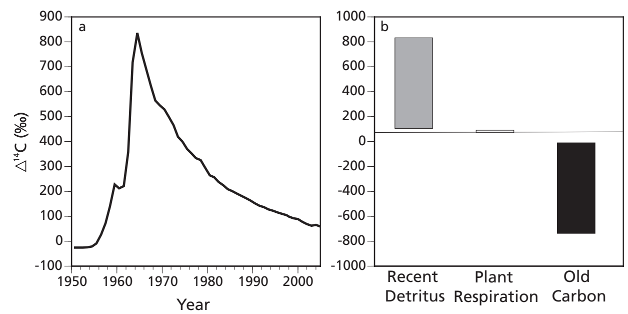

Figure 2. (a) Atmospheric content of radiocarbon in carbon dioxide during the bomb period. Radiocarbon ($\Delta^{14}C$) is expressed in units of permil (‰) compared to a pre-bomb material that is defined as having a value of zero. (b) Generalized values for possible respiration sources. The atmospheric value of +63‰ for the year 2004 is depicted by the line on the graphs. Because radiocarbon in the atmosphere is currently declining, plant respiration is very close or slightly above current atmospheric values whereas detritus fixed over the past 50 years is enriched in radiocarbon up to +900‰. Old soil C (>60 years) is the only source of C that could bring total ecosystem respiration below the atmospheric value.

Eight Mile Lake watershed reflect a mixture of these three component sources (plant, recent detritus, old C) that change in their relative proportion. Radiocarbon values of ecosystem respired CO_2 ranged from +30 to +60‰ and were at or below atmospheric value *(Figure 3a)*. These values were generally lower than DIC values that ranged from +50 to +105‰, generally above the atmospheric value *(Figure 3b)*. Subsequent measurements of ecosystem respiration at other time points (data not shown) did show radiocarbon values above atmospheric, revealing that temporal variation can be important. Radiocarbon measurements of DOC from two locations in the watershed showed both the temporal and the spatial trends *(Figure 3c)*. Almost all measurements of DOC were below the atmospheric value, with the lowest values occurring in the early season and generally increasing by about 30‰ throughout the growing season. Water collected directly from thermokarst runoff was typically about 40‰ more depleted in radiocarbon throughout the growing season compared to the main stream.

Discussion

In most ecosystems, the proportional contribution of plant carbon typically comprises ~30-70% of CO_2 loss to the atmosphere, heterotrophic decomposition of recent litter comprises the majority of the remainder, with old carbon typically contributing perhaps <10%. Our measurements demonstrate that a significant amount of ecosystem respiration is derived from old C, enough to isotopically offset the contribution of carbon from plants and detritus to bring the bulk respiration radiocarbon below the atmospheric value. It is especially noteworthy since all other ecosystems where respiration radiocarbon has been measured, including a range of boreal, temperate, and tropical forests, and Mediterranean grasslands, have respiration values above atmospheric values because the contribution from old carbon is generally small relative to recent detritus and plant respiration *(Trumbore et al. 2000)*. Our data are compelling evidence that high latitude ecosystems may be already be undergoing significant losses of old C. The radiocarbon of DOC confirmed this trend. Water draining directly from thermokarst areas contained more old carbon than the main stream, suggesting that permafrost thawing was releasing old carbon into the aquatic ecosystem. We did not detect a large contribution of old carbon as DIC, which suggests that the DOC may be stable. However, our measurements were too limited at this point to make this last conclusion with any certainty.

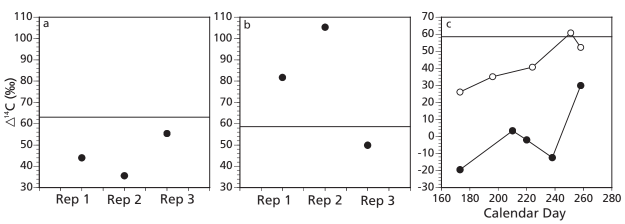

Figure 3. (a) Terrestrial ecosystem respiration from replicate chambers relative to the atmospheric value in July 2004 (solid line). (b) Dissolved inorganic carbon from three locations at the main stream that enters Eight Mile Lake relative to the atmospheric value in July 2005 (solid line). (c) Dissolved organic carbon at two locations in the watershed in 2005: the main stream (open circles) and a smaller surface runoff stream that directly drains the thermokarst area (closed circles). Note that the scale is different for the last graph, and the atmospheric value differs in 2004 and 2005.

Management Implications

Changes in ecosystem carbon cycling and storage have the potential to be an important indication of overall ecosystem functioning. However, detecting these changes over time is often difficult due to high temporal variability in carbon cycling processes and the difficulty of measuring proportionally small changes in carbon stocks. Radiocarbon measurements may prove to be an important integrative tool for detecting these changes. Because radiocarbon changes as a function of age of carbon in the ecosystem, it is useful for detecting the contribution of old carbon that has previously been frozen in permafrost and isolated from the modern carbon cycle. The best application of radiocarbon might be as a monitoring tool where measurements of ecosystem carbon losses could be made through time at observation locations. The impact of thawing permafrost on carbon cycling should be reflected in these loss pathways appearing more depleted in radiocarbon as inputs of old carbon increase. These data could be monitored for trends through time and in relation to climatic fluctuations to detect significant change.

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