The Study

It's Cold Down Here!

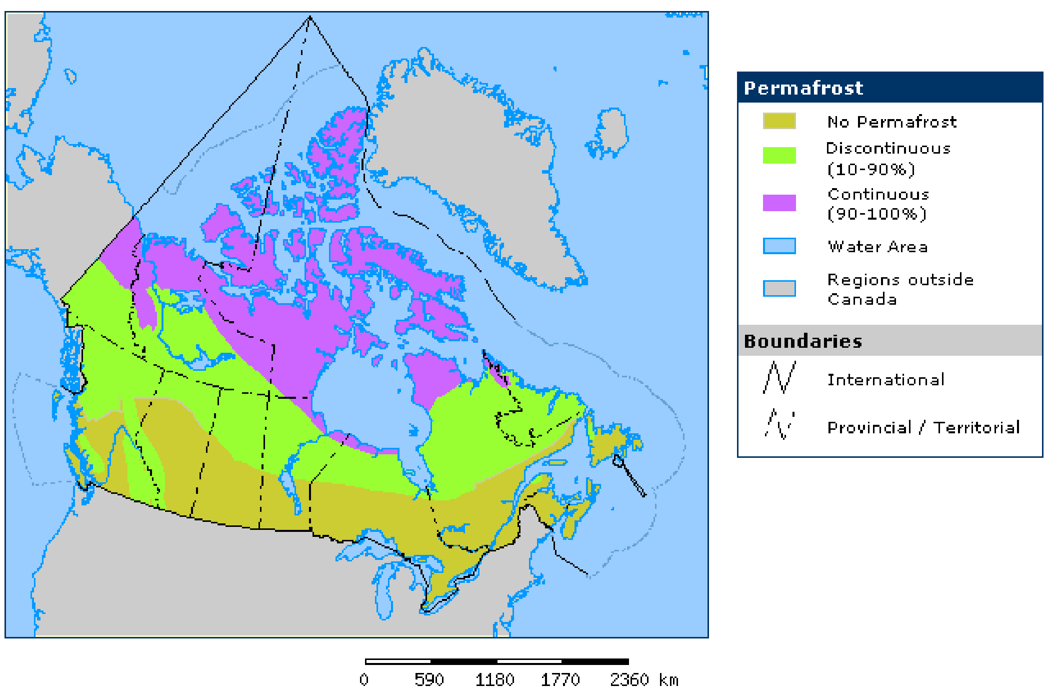
Examining surface controls on permafrost and active-layer development

Learning Objectives

- Define permafrost and the active layer
- Define heat capacity and thermal conductivity
- Describe the effect of surface vegetation on the soil thermal regime
- Assess the impact of a vegetation layer on active-layer development

The story behind the study

Permafrost regions are characterized by ground which remains frozen for two or more consecutive years. By definition, permafrost is not determined by the moisture content in the soil, only by its temperature. This means that permafrost environments may have high or low moisture contents. Globally, permafrost is present in extreme northern and southern environments. Permafrost is continuous across the most extreme landscapes and discontinuous (patchy) across more southerly regions.



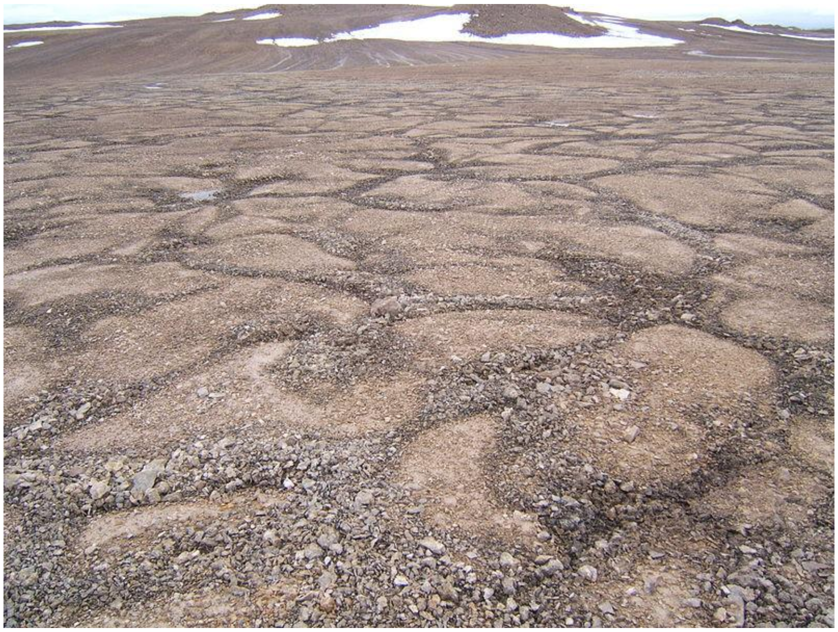
Distribution of permafrost in Canada; percent values in bracket refer to the proportion of the terrestrial surface underlain by permafrost. (This map has been adapted from: http://atlas.nrcan.gc.ca/site/english/maps/environment/land/permafrost)

Ms. Sandy's Notes – It's Cold Down Here!

Permafrost environments are very sensitive to climate change and present special challenges to northern resource development in Canada. Permafrost plays an important role in the global climate system. About half of all the global soil organic carbon is located in permafrost regions. With warming of the soils in these regions, this carbon may be released to the atmosphere as carbon dioxide and methane, potent greenhouse gases and act as a positive feedback accelerating climatic change (see "**The Arctic Has Gas**" another research study featured on this website for more information on the impacts climate change may have on carbon storage in the Arctic). Permafrost degradation can also have devastating impacts on buildings, roads, and gas pipelines in northern communities all of which rely on the structure of frozen ground for stability.

As permafrost is a thermal condition of the ground, it is important to understand the factors that influence ground temperature. Ground temperature is primarily governed by climatic characteristics (such as air temperature and precipitation) and soil characteristics (such as organic matter content and moisture content). This relationship is further moderated by topography and other surface properties that result in local microclimates – relatively small areas that have different conditions such as near-surface air and soil temperature, humidity, etc than the surrounding area. These microclimates form due to differences in the way energy is exchanged between the atmosphere and the surface. In many cases the presence of a surface organic layer may diminish temperature extremes in the soil below due to its insulating effects. The role of surface vegetation is of particular importance in lower latitude (discontinuous) permafrost regions. Here, permafrost is typically found in areas with organic soils such as peatlands.

Permafrost regions are also characterized by the active layer – the upper most layer of ground that experiences seasonal freeze-thaw activity. The process of active-layer development begins once enough energy arrives at the surface in the spring and continues into the fall when the ground begins to refreeze. Downward heat transfer occurs primarily by conduction. Two soil properties fundamentally control the depth of annual thaw, these are: (**1**) heat capacity and (**2**) thermal conductivity. Heat capacity – the amount of heat required to cause a change in temperature – and thermal conductivity – the ability of the soil to conduct heat – are dependent on the portions of soil constituents (air, water, organic material, and mineral component) as all of these elements have different individual heat capacities. These two factors in turn influence the rate and depth of thaw.

Evidence of Permafrost Scientists can often tell where permafrost is located without digging simply by looking at the ground surface. Unique patterns, such as this "patterned ground", and landforms are shaped by the presence of permafrost. Photo from Wikimedia Commons by Anthonares	
Peatlands Permafrost is often found below peatlands due to the insulating effect of the thick vegetation. Palsa peatland near Whapmagoostui-Kuujjuarapik, northern Quebec. Photo by Luc Pelletier	
Human Settlements Permafrost can affect buildings and other structures due to localized thawing. These houses in Inuvik are built on stilts to prevent heat transfer into the ground. Note also that the pipes are installed above ground instead of buried below ground in the permafrost. Photo from Wikimedia	

Commons by Phil Morin (http://inuvikphotos.ca)	
Human Settlements When houses or other structures are built directly on or in permafrost, the permafrost will begin to thaw causing instability. This traditional home in Siberia was built directly on the ground. Photo from Wikimedia Commons by Adam Jones adamjones.freeservers.com.	

Research summary

On a global scale, the degradation of permafrost may have an important impact on carbon storage and climate change; on a local level, it will impact human habitation and resource development. Previous studies in the continuous zone of permafrost have shown that the degradation or removal of surface organic matter tends to increase active-layer depths and thus results in a degradation of near-surface permafrost (Smith 1975; Mackay 1995). Degradation of the surface organic layer may result from natural events, such as forest fires, or from anthropogenic activities such as land use change and resource development.

In this study, the effects of surface vegetation on near-surface ground temperature and active-layer depths were examined at sites in the discontinuous permafrost region of the central Yukon Territory (**Figure 1**). Discontinuous permafrost is characteristically warm (near 0°C) and the local occurrence of permafrost is governed by microclimatic differences arising from variations in topography, soil conditions, vegetation, and snow cover. Here, permafrost is typically found in forested soils with thick organic layers. Tree cover prevents much of the insulating snow from reaching the ground surface allowing the soil to cool in winter while surface organic matter reduces the amount of warming in summer.

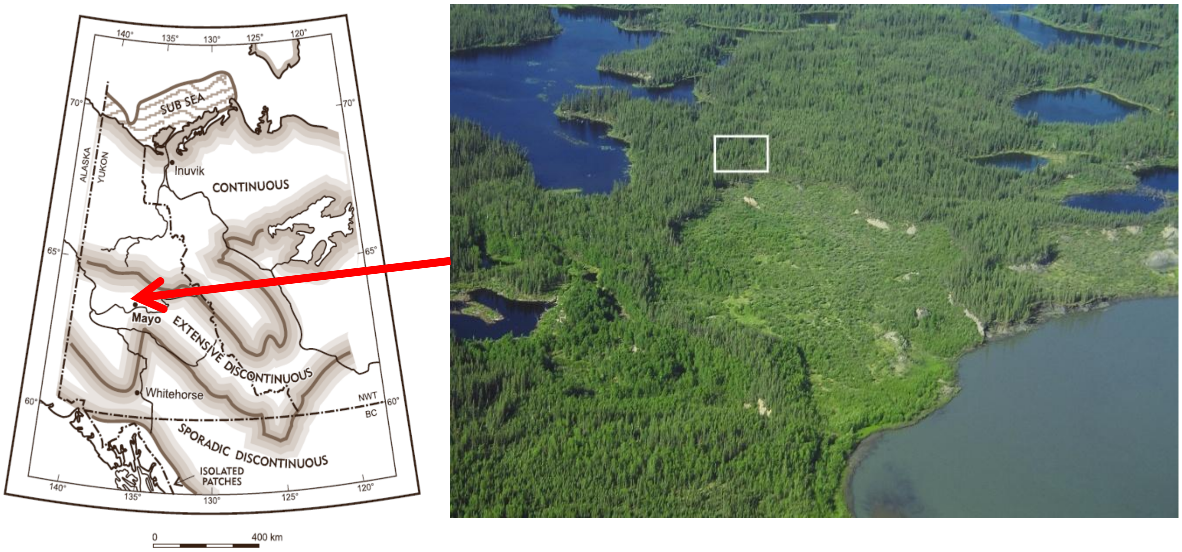


Figure 1. Left: Permafrost map of the Yukon Territory (Burn, 2000), Right: Overview of study area, white box indicates sites.

Two sets of paired sites were selected, in order to assess the importance of surface vegetation and organic matter on permafrost characteristics. Surface vegetation was removed from one site in each pair, exposing the mineral soil (**Figure 2**). Ground temperature was monitored at each site for a period of three years. While surface disturbance did not result in changes to the mean annual ground temperature, the active-layer depth increased by approximately 20 cm in disturbed sites and the annual temperature range (difference between maximum and minimum temperatures) was greater by nearly 10°C. These findings suggest that, in the central Yukon Territory, forest cover and surface organic matter are critical to the presence and stability of permafrost.

Figure 2. Contrast between the undisturbed site (left) and the disturbed site (right). Photos taken by Dr. C.R. Burn, Carleton University, Ottawa, Ontario.

Student Activities

1) *Exploring Permafrost*

Learn more about permafrost at these useful links.

- **National Snow and Ice Data Centre:** A wide range of resources about the physical and social sciences related to frozen ground. http://nsidc.org/frozenground/climate.html
- **International Permafrost Association**: An organization that fosters permafrost research worldwide. http://ipa.arcticportal.org/resources/what-is-permafrost
- **Soil Landscapes of Canada:** Follow links to view examples of permafrost affected soils in Northern Canada. http://sis.agr.gc.ca/cansis/nsdb/slc/intro.html
- **The Atlas of Canada:** An interactive website that allows you to explore Canada's permafrost regions. http://atlas.nrcan.gc.ca/site/english/maps/environment/land/permafrost
- **National Geographic:** Amazing photograph of permafrost landscapes. http://ngm.nationalgeographic.com/2007/12/permafrost/edmaler-photography

2) *Permafrost and Physical Characteristics*

- **Exercise 1** (see end of this document)– Assess the impact of vegetative cover on soil thermal properties.
- **Exercise 2** (see end of this document) – Determine the effect of surface disturbance on soil temperature ranges and active-layer depth.
- **How Permanent is Permafrost**? A classroom activity that explores the relationship between surface air temperature and permafrost. http://nsidc.org/frozenground/classroom/permanent_permafrost.html
- Earth Exploration Toolbox: This site will enable users to examine possible relationships between changes in surface air temperature and changes in permafrost temperature and coverage. http://serc.carleton.edu/eet/permafrost/teaching_notes.html

3) *Permafrost and Human Activities*

- **Newton's Apple Permafrost Activity:** Try this activity to see how structures can thaw the permafrost around them. A supplementary activity (Permafrost Try Its) simulates ice wedging in soil. http://www.newtonsapple.tv/TeacherGuide.php?id=1174
- **Permawhat?** Create your own permafrost and see what happens when you place a structure upon it. http://www.pbs.org/edens/denali/permawht.htm

Definitions

Permafrost: Ground that is frozen (< 0^{o}C) for two or more years. Permafrost can be continuous (covering a whole area) or it can occur in discontinuous patches throughout a region.

Heat conduction: A mode of transfer of energy within and between bodies of matter, due to a temperature gradient. Heat spontaneously tends to flow from a body at a higher temperature to a body at a lower temperature, until they reach thermal equilibrium. Conduction is due to the collisions of molecules during their random motion.

Heat capacity: The amount of heat required to cause a change in temperature a unit volume by 1 degree Celsius.

Thermal conductivity: A material's ability to conduct heat.

Microclimate: Any climatic condition concentrated within a relatively small area that differs from the surrounding climate. Microclimates typically develop in areas with specific topography, vegetation, or other characteristics that differ from the surrounding area.

Active layer: The top layer of ground that experiences seasonal freeze-thaw activity.

Explorers

Dr. Elyn Humphreys, Associate Professor, Department of Geography and Environmental Studies, Carleton University

Graham Gilbert, Undergraduate Student, Department of Geography and Environmental Studies, Carleton University

References

Burn CR. 2000. The thermal regime of a retrogressive thaw slump near Mayo, Yukon Territory. *Canadian Journal of Earth Sciences*, **37**, 967-981.

Mackay JR. 1995. Active layer changes (1968-1993) following the forest-tundra fire near Inuvik, N.W.T., Canada. *Arctic and Alpine Research,* **27 (4)**, 323-336.

Smith MW. 1977. Microclimatic influences on ground temperatures and permafrost distribution, Mackenzie Delta, Northwest Territories. *Canadian Journal of Earth Sciences*, **12**, 1421-1438.

Exercise 1:

Objective

Assess the impact of vegetative cover on soil thermal properties.

Testable Hypothesis

Does an insulating layer influence the rate of soil temperature change in two identical sandy soils?

Methods

Have two medium sized containers filled with dry sand. In one container place a thin (1 cm thick) sheet of Styrofoam (*alternatively use a layer of moss or other type of ground cover*). Insert a thermometer to a depth of 2 cm (or more) in the center of each container and record the soil temperatures. Set an incandescent bulb 40 cm above the surface of each container. After 10 min, measure the soil temperature as before. Return the containers to the lights (switch positions to ensure there is no bias in heating). After another 20 and 30 min, measure the temperature of the soils' temperature.

Exercise 2:

Objective

Determine the effect of surface disturbance on annual and monthly temperature ranges as well as active-layer depth. Data is provided in Table 1 and Table 2..

Abstract and Data Set

10 cm ground temperatures were obtained for two sites within the Stewart River Valley in the central Yukon Territory from July 2008 to June 2009 (Table 1). Active-layer depth was measured in 2007, 2008, and 2009 (Table 2). Surface vegetation and organic material was removed from one site (Figure 3). This activity is intended to emphasize the linkage between vegetation cover, near-surface temperature fluctuations, and active-layer depth.

Table 1. 10 cm ground temperatures at disturbed and undisturbed locations in the Stewart River Valley, Yukon from July 2008 to June 2009.

	Disturbed Site			Undisturbed Site		
Month	Average Temp (°C)	Maximum Temp (°C)	Minimum Temp (°C)	Average Temp (°C)	Maximum Temp (°C)	Minimum Temp (°C)
2008						
July	10.0	11.2	8.5	5.3	5.7	4.4
August	8.6	9.6	6.1	5.7	6.3	4.9
September	4.3	5.7	0.5	3.5	4.6	1.3
October	-0.3	0.4	-0.6	0.6	1.3	0.3
November	-0.7	-0.6	-1.1	0.3	0.3	0.3
December	-1.5	-0.6	-2.4	-0.1	0.3	-0.6
2009						
January	-3.2	-1.6	-4.5	-1.1	-0.3	-1.7
February	-3.6	-3.4	-4.0	-1.7	-1.4	-2.0
March	-3.9	-3.6	-4.3	-2.4	-2.1	-2.5
April	-2.6	-1.1	-3.5	-1.4	-0.2	-2.2
May	0.6	4.2	-0.9	0.6	0.7	0.0
June	8.2	9.9	4.2	2.3	3.2	0.7

Table 2. Active-layer depths at disturbed and undisturbed locations in the Stewart River Valley, Yukon. The depth of the active layer was determined by measuring the depth at which water was thawed in a 2 m long water-filled tube drilled into the permafrost at each site. This measurement is made at the end of august.

Year	**Disturbed Site** Active-layer depth (cm)	**Undisturbed Site** Active-layer depth (cm)
2007	85	68
2008	89	76
2009	93	64

Activities

i) For each month, calculate the range in temperature at the disturbed and undisturbed sites using the data provided in Table 1.

When compared to air temperatures, temperature in the ground exhibits less variation at diurnal (daily), monthly, and annual time scales. Compare the impact of surface vegetation on soil temperatures by following the steps below.

- Calculate the temperature range as the difference between maximum and minimum temperatures for each month and each site in Table 1.
- Plot these values as two lines on a line graph with temperature range (°C) on the y axis and Month on the x-axis.
- Compared to the other months, what factors might explain the reduced temperature range during February and March? Consider parameters which are subject to variation over the course of the year.
- Determine the annual temperature range by calculating the difference between the maximum and minimum annual temperatures in each data set. What is the impact of denudation on the annual temperature amplitude?

ii) Using the active-layer depths supplied in Table 2 run a paired t-test in Excel (or other statistics software) to test the null hypothesis that disturbance involving vegetation removal does not increase active layer depth and the alternate hypothesis that disturbance does increase active layer depth.

At sites experiencing the same air temperatures, active-layer development is principally controlled by the surface energy balance. The absence of surface organic matter and exposure of darker mineral soil tends to reduce reflectance and increase the amount of solar radiation absorbed by the surface. This energy heats the soil surface and drives evaporation. As a result, near-surface mineral soil may be slightly drier which then reduces the amount of energy required to raise the soil temperature. Finally, heat can flow by conduction from the warm surface down into the soil more readily in mineral soil vs. organic soil because of less air space and better contact between the mineral soil particles. Consequently, disturbed sites are able to thaw deeper each season.