Data Interpretation: Carbon balance in an Arctic Warming Manipulation

The blog posts linked below should help you understand the following vocabulary and concepts:

Vocabulary:
Permafrost
Thaw depth
Active layer
CO_2 flux
Photosynthesis
Respiration
Decomposition (microbial decomposition)
Net CO2 source
Seasonality (the seasonal cycles of an ecosystem that result from weather and physical controls, eg: light, temperature, rainfall patterns)
Control (in the context of doing experiments)

Concepts:
Arctic ecosystems
Permafrost – what is it, where can you find it, how is it changing with warming?
Ecosystem CO_2 exchange and carbon balance
Seasonality in Arctic ecosystems (eg: summer activity, winter dormancy)
Soil carbon
Photosynthesis
Respiration
Microbial decomposition

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Data Interpretation: Carbon balance in an Arctic warming manipulation

Background:

Experimental manipulations and ecosystem ecology:

Scientists use experimental manipulations to untangle the many complex ways in which entire ecosystems respond to change. Experiments help us to test our theories and hypotheses. Experiments cannot answer all our questions about change, nor can they capture all the interactions, but data from experiments give us a good idea of how quickly, and how much an ecosystem could change.

The Carbon in Permafrost Experimental Heating Research, CiPEHR for short, is an example of an Arctic warming manipulation. At CiPEHR we use snow fences in the winter to insulate and warm the soil. Snow accumulates at the snow fence and acts like a blanket, trapping heat, and warming the soil. We call this the SOIL WARMING TREATMENT and it simulates what might happen in the Arctic if the atmosphere keeps warming. An important part of every manipulative experiment is the CONTROL. In a control we do not apply any manipulation, but everything else is the same, this way we can isolate the effect of soil warming. A good control is crucial in every experiment.

Important note:

An important thing to remember about CiPEHR is that we are creating one potential climate change scenario by rapidly warming the soil. The warming that the experiment creates is happening alongside background Arctic warming, and we can use our results to understand how more rapid warming impacts ecosystem processes.

How does a snow fence work?
Snow depth data from the CiPEHR experiment

Every year, in spring, a shoveling crew arrives at the field site. We measure the snow on both sides of the snow fence with an avalanche probe – (a long ruler with a metal tip that is usually used to rescue people from avalanches). This tells us how much snow accumulated, and how much we have to shovel. A thick snow blanket contains a lot more water, and melts more slowly than a thin snow blanket. We remove the extra snow so that we do not create unintended effects, and can make sure the snow fence is only creating a soil warming effect. We shovel off the accumulated extra snow on the soil warming side until it reaches the same height as the control side. Then we let the snow on both sides melt at its' natural rate.

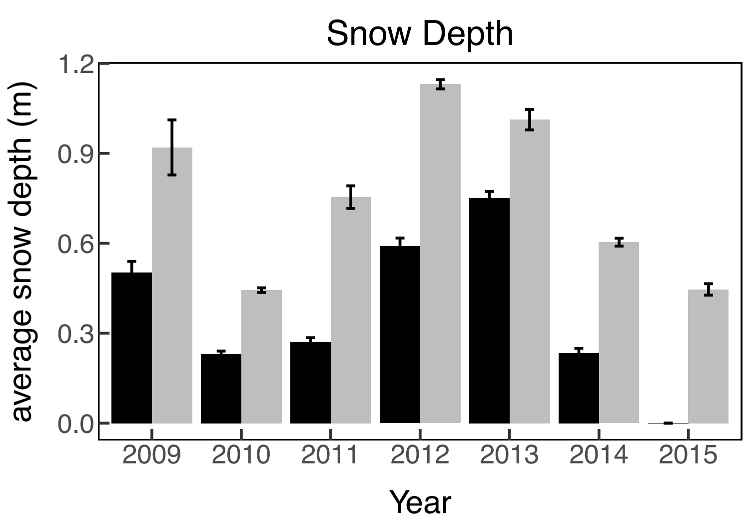
Check out these blogs by PolarTrec Teacher Tom Lane:

What's going on at the CiPEHR site?
https://www.polartrec.com/expeditions/carbon-balance-in-warming-and-drying-tundra-2013/journals/2013-04-08

Why all this shoveling?
https://www.polartrec.com/expeditions/carbon-balance-in-warming-and-drying-tundra-2013/journals/2013-04-08-0

Examine the graph below:

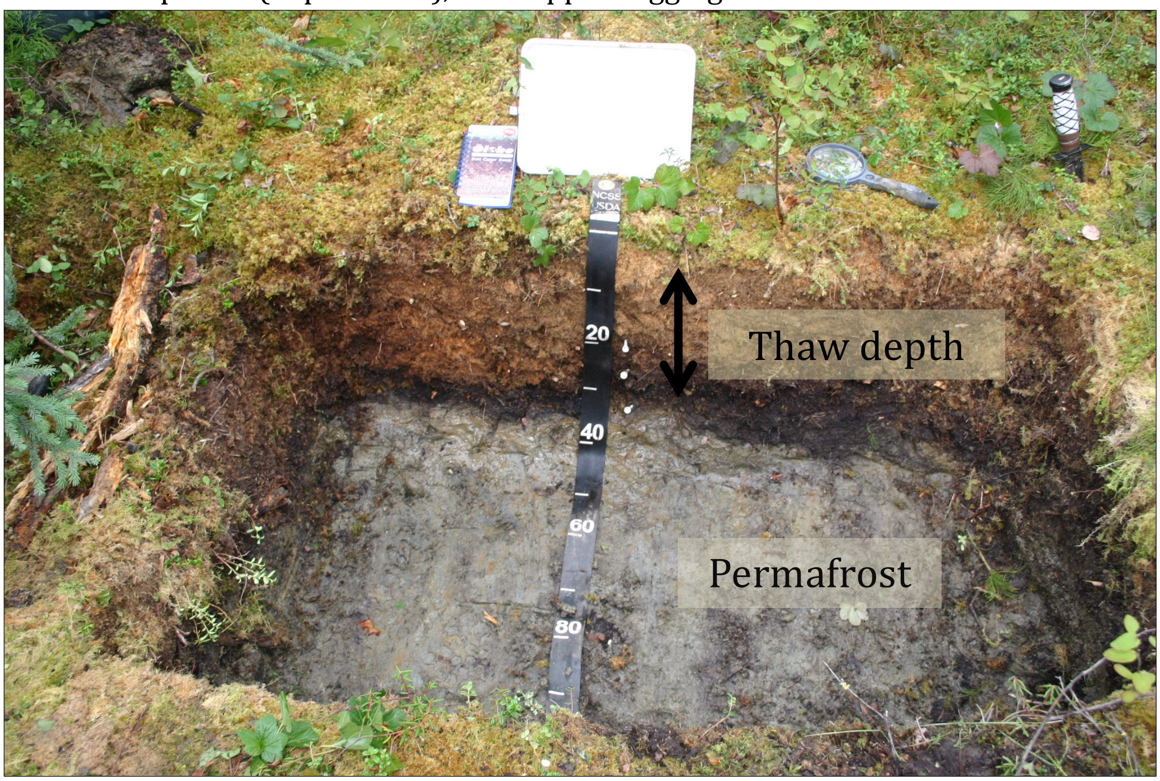
a. Create a legend for this graph. Which color bar represents the soil warmed side, and which bar represents the control?
b. What does the different height of the bars tell you about different winters?
c. Which year was the biggest snow year?
d. What happened in 2015?



What effect do the snow fences have on soil temperatures at CiPEHR?

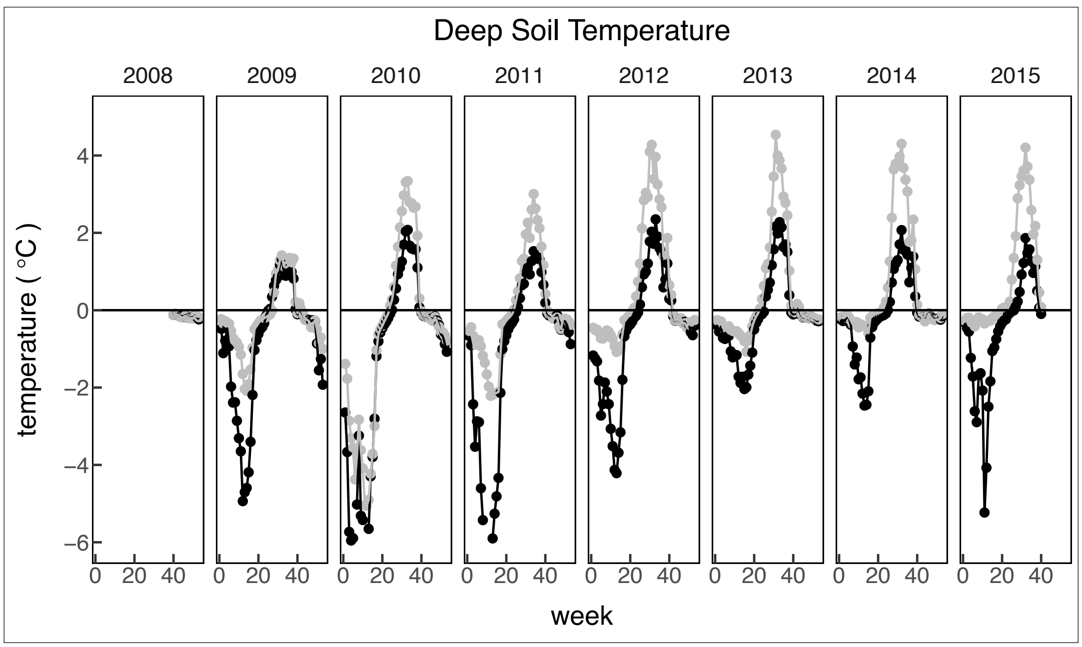
Soil temperatures are very important for the microbes that live there, and we generally expect that warmer temperatures will increase microbial decomposition of soil carbon. We monitor soil temperatures at 40cm depth because that gives us a good idea of how much the soil column has warmed with increased snow-depth. When we combine the soil temperature data with CO_2 flux data it helps us make predictions of how warmer soil temperatures could impact the CO_2 balance of tundra ecosystems.

Permafrost profile (depth in cm), we stopped digging when we reached solid ice:



Analyze the soil temperatures. Week 0 starts 1st Jan and week 51 ends 31st Dec.

a. Give the graph a legend. How can you tell which treatment the grey and black points came from?
b. How did the treatments affect soil temperatures in winter?
c. How did soil temperatures in the <u>soil warming treatment</u> change in summer?
d. Challenge Question: If you compare the snow depth and the soil temperature graphs, can you say how high and low snowfall years affect soil temperatures?
e. Fun side note: Look at maximum temperature of these soils in summer. The maximum temperatures are similar to the temperatures in a refrigerator. People across the Arctic have historically dug holes in the ground to store meat and other food. Warming in the Arctic threatens these natural refrigerators and makes it more difficult to safely use this traditional food storage method.



What effect do the snow fences have on permafrost at CiPEHR?

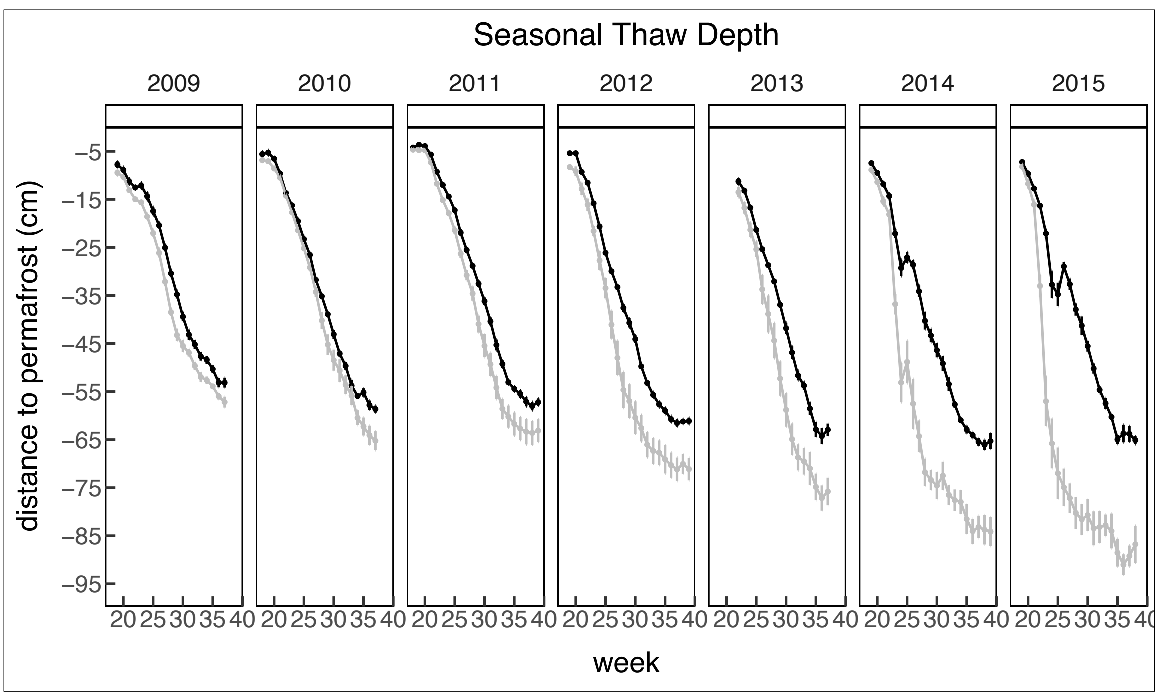
Once a week we measure thaw depth, the distance from the ground surface to solid ice. The maximum thaw depth is called the Active Layer, because plants, roots, and microbes can grow and are most active in this layer. Beyond the Active Layer is permafrost; it is frozen all year.

If it is cold enough the whole soil column refreezes each winter. This cycle happens every year.

Read this blog by Karen Temple-Beamish to understand more about thaw depth: *Depth to permafrost:*
https://www.polartrec.com/expeditions/carbon-balance-in-warming-and-drying-tundra-2016/journals/2016-07-28

Look at thaw depth data from 2009 to 2015.

a. Give the graph a legend. What color represents each treatment?
b. What happens to the thaw depth each year, as we move through the summer?
c. What has happened to the active layer thickness (maximum thaw depth) from 2009 to 2015?
d. How much has the active layer increased from 2009 to 2015?
   i. For Control?
   ii. For Soil warmed?



Part II:

Background:

CO_2 balance:

The global carbon balance is affected by how much carbon dioxide (CO_2) is stored and released by ecosystems all over the world. The main mechanism for CO_2 storage depends on plants. Plants use sunlight and CO_2 to produce energy in a process called photosynthesis. The plants use carbon from CO_2 to make wood, and roots, and long-lived leaves. This is carbon that can stay in the ecosystem for many years. When plants die microbes decompose plants and this creates soil organic matter and becomes carbon stored in the soil. Soil carbon can be stored for many more years than plant carbon. However, when microbes decompose the dead plant matter, they release CO_2 back to the atmosphere. If decomposition exceeds plant CO_2 uptake then an ecosystem looses CO_2 and is called a 'net CO_2 source'. Soil in the Arctic stores more carbon than the soil in any other ecosystem in the world. Very cold temperatures in Arctic permafrost soils have protected soil carbon from microbial decomposition for thousands of years. As the Arctic warms, scientists are concerned that the amount of CO_2 released from permafrost will increase because microbial decomposition is faster in warmer temperatures. However, scientists are not sure how much, or how quickly CO_2 will be lost from permafrost ecosystems.

At CiPEHR, we use the soil warming manipulation and CO_2 measurements to provide us with data that tell us how soil warming and permafrost thaw impact CO_2 storage in a tundra ecosystem. Scientists can combine measurements from experimental manipulations, observations on the ground and from satellites, and data from many different Arctic regions in the USA, Canada, Scandinavia, and Siberia to get a more accurate picture of how the Arctic is changing.

How do plants respond to air and soil warming?
Plant Greenness data from CiPEHR:

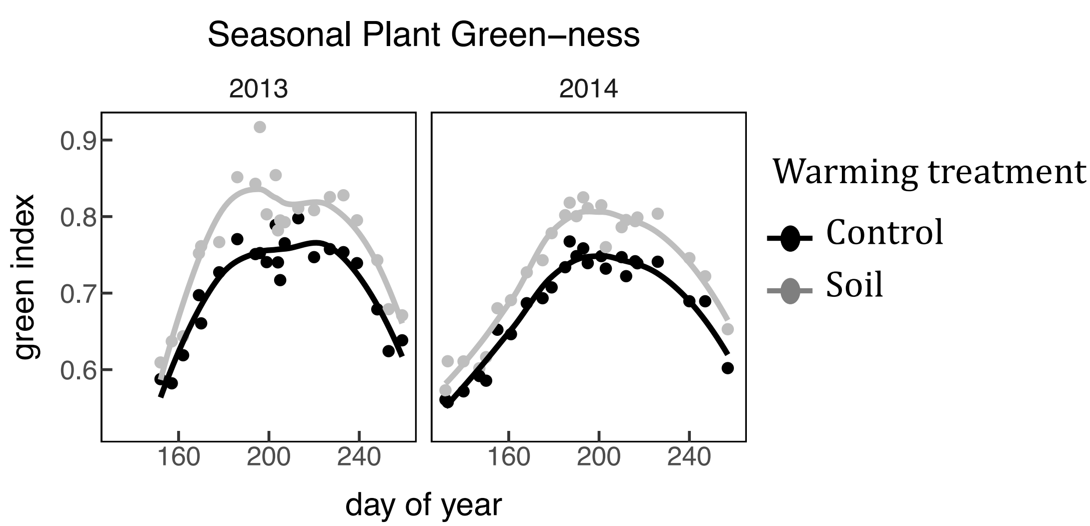
Plants are very important for the CO_2 balance, and increased plant growth could increase ecosystem CO_2 storage, if microbial respiration does not exceed plant CO_2 uptake. Arctic warming has two effects on plant growth: plants in cold climates grow better in slightly warmer temperatures, and permafrost releases nutrients, along with soil carbon, when it thaws. The combination of warmer temperatures and more nutrients could help plants grow, and we need to account for this in the carbon balance.

To keep track of what the plants are doing we measure plant greenness, and then we can compare this to CO_2 uptake.

These blogs by Karen Temple-Beamish explain the special camera used for measuring greenness and how permafrost thaw could affect plant growth:
Measuring Green:
https://www.polartrec.com/expeditions/carbon-balance-in-warming-and-drying-tundra-2016/journals/2016-08-04

Collecting plant greenness data can be time consuming so we do not have data from all years of the experiment. The figure below shows two summer seasons of plant greenness (1 May – 30 Aug)

a. Think back to the first graphs of sunlight and temperature. What does the plant greenness tell you about plant seasonality?
b. How did Soil warming affect plant greenness?
c. How does plant greenness help you understand summer CO_2 uptake in the previous section?



How does warming affect carbon dioxide uptake and release?

Photosynthesis is the process that allows plants to capture energy from the sun, and take CO_2 out of the atmosphere. Microbes cannot use energy from the sun, they use dead leaves and plant roots in the soil to get energy. When microbes use that energy they release CO_2 in a process called respiration. Almost all living things "breathe" out CO_2 when they use energy to survive. Every summer we use automatic chambers to measure CO_2 uptake and release. We use these data to see how soil warming and permafrost thaw affect CO_2 storage in the tundra. In the graphs below, you can see the effect of soil warming treatments and the seasonal pattern of CO_2 uptake and release from early summer (1 May) to the end of summer (30 Sep).

These blogs will help you understand what's going on:

Who's doing all the breathing out there? (Susan Steiner)
https://www.polartrec.com/expeditions/tundra-nutrient-seasonality/journals/2012-06-19

Moving Chambers (Karen Temple-Beamish)
https://www.polartrec.com/expeditions/carbon-balance-in-warming-and-drying-tundra-2016/journals/2016-07-29

Seasonal CO_2 flux:

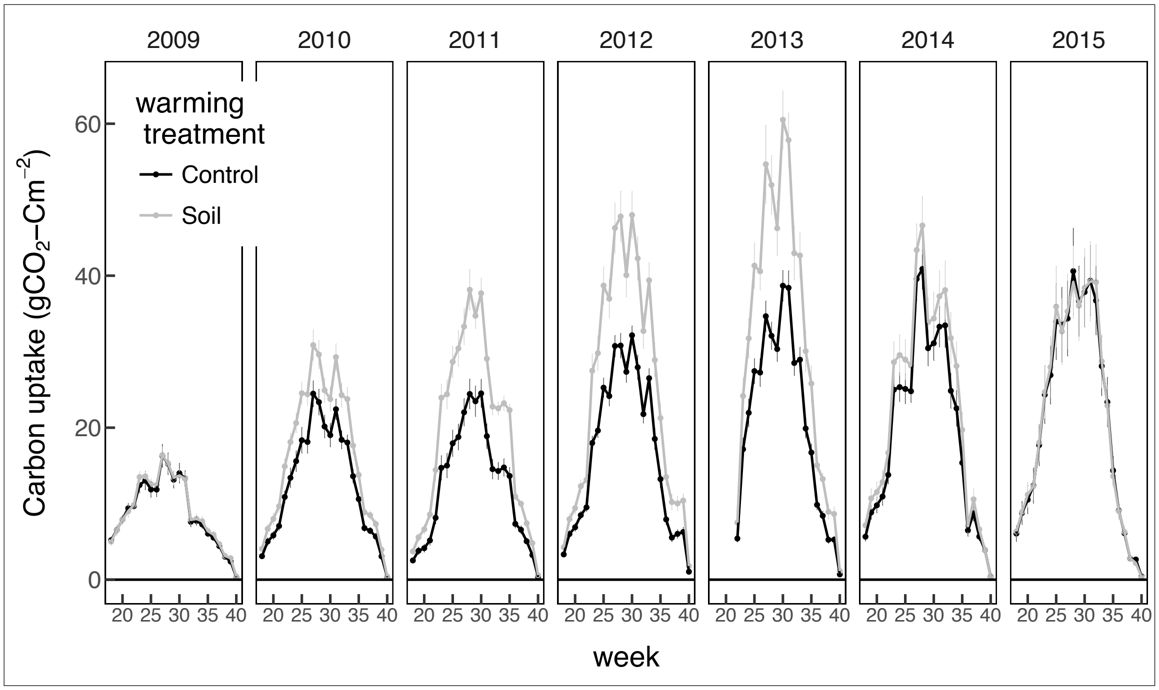
The two figures below show the seasonal cycle of CO_2 uptake and release. One shows CO_2 uptake, the other shows release. They are on the same page to make it easier to compare CO_2 uptake and release patterns.

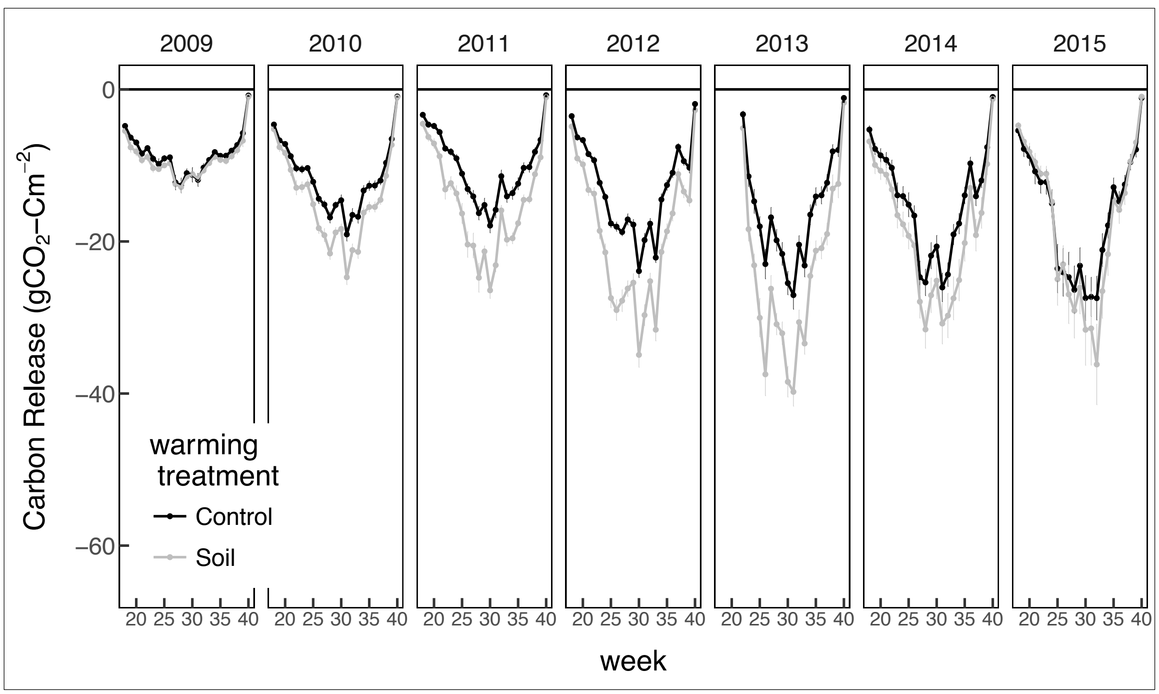
Look at the figure of CO_2 uptake:

a. Why does CO_2 uptake change from the beginning to the end of each season?
b. How does Soil warming affect CO_2 uptake?
c. Is the effect of Soil warming the same in each year?
d. When is the effect of Soil warming strongest?

Look at the figure of CO_2 release:

a. Where is the CO_2 coming from?
b. The patterns are very similar to CO_2 uptake. Why do you think this is the case?
c. Why would CO_2 uptake increase in the beginning of the growing season and then decrease again?
d. When is CO_2 release highest?
e. Why do you think CO_2 release is greater in Soil warming treatments?


2009
2010
2011
2012
2013
2014
2015
warming treatment
Control
Soil
Carbon uptake (gCO2–Cm−2)
60
40
20
0
20 25 30 35 40
week


2009
2010
2011
2012
2013
2014
2015
0
−20
−40
−60
Carbon Release (gCO2–Cm−2)
warming treatment
Control
Soil
20 25 30 35 40
week

How does warming at CiPEHR affect the tundra CO_2 balance?

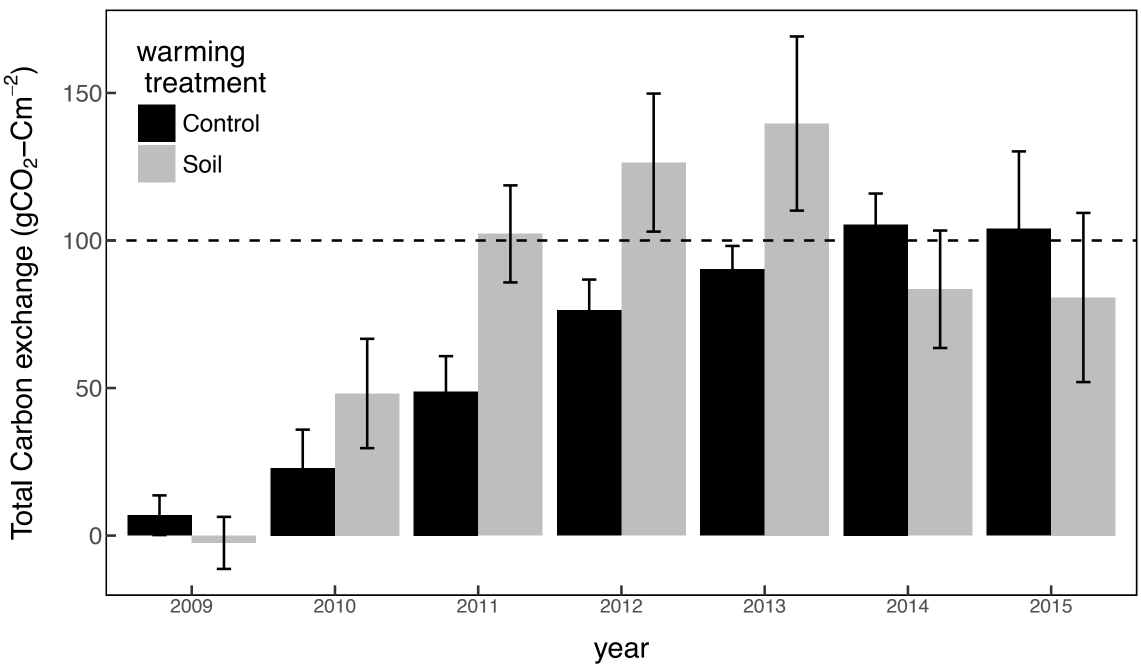
We use the summer CO_2 fluxes to calculate the total CO_2 storage. By adding up all the CO_2 storage and all the CO_2 release, we can determine the summer CO_2 balance of the tundra. We use this formula:

Total storage = CO_2 uptake – CO_2 release

The figure below shows total summer CO_2 storage.

a. In the summer does the tundra usually have more CO_2 uptake or more CO_2 release?
b. Was the effect of Soil warming the same in all the years?
c. How did Soil warming affect CO_2 storage from 2009-2013?
d. How did Soil warming affect CO_2 storage in 2014 and 2015?
e. Overall, how did Soil warming affect summer CO_2 storage?

<u>Total summer CO_2 exchange:</u>



<u>The effect of winter on CO_2 balance:</u>

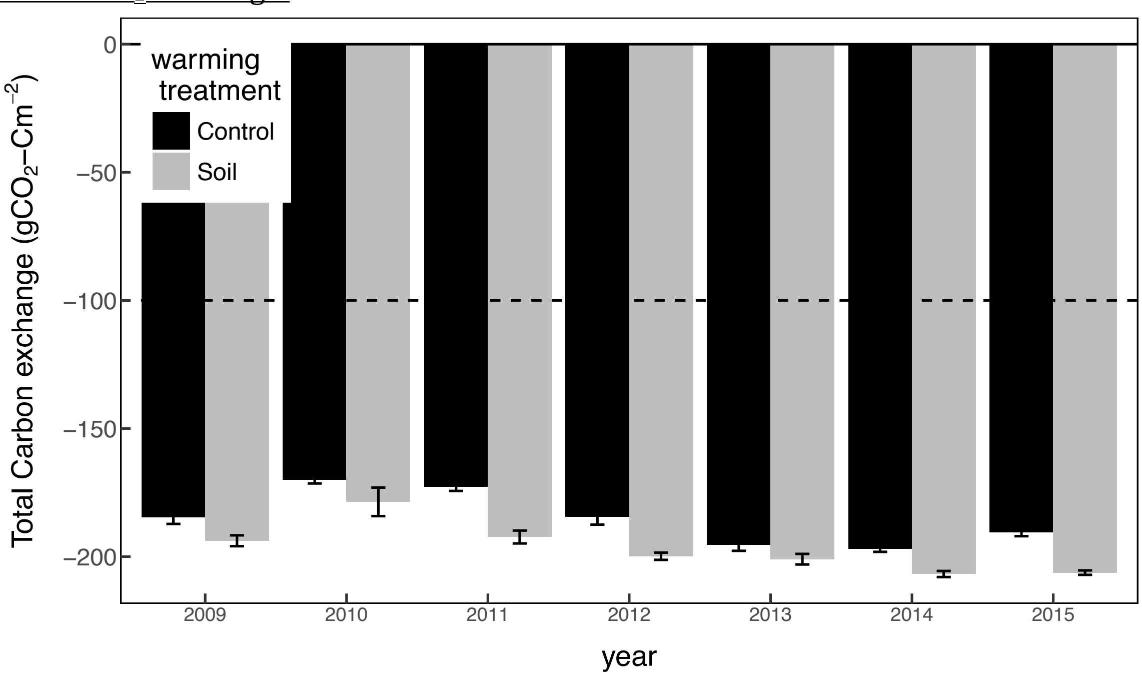
Scientists used to think Arctic winters are so cold that there is no microbial respiration and winter is not important for tundra CO_2 balance. Microbes are very hardy and have surprised scientists by being active in the winter, even when temperatures are colder than inside your freezer. In winter microbial activity is slow, but it adds up, and winter is actually a really important part of the CO_2 balance. The winter is also dark so plant photosynthesis does not balance out CO_2 release. Scientists and electronic equipment are less hardy than microbes so it is very difficult to get winter measurements. At CiPEHR, we have tried to measure winter CO_2 loss so that we can get a CO_2 budget for the whole year.

These blog posts from Tom Lane will show how we measure CO_2 flux in winter:
Update on CiPEHR:
https://www.polartrec.com/expeditions/carbon-balance-in-warming-and-drying-tundra-2013/journals/2013-06-01
The snow pits of CiPEHR;
https://www.polartrec.com/expeditions/carbon-balance-in-warming-and-drying-tundra-2013/journals/2013-04-16

The graph below shows winter CO_2 release from CiPEHR.

a. Why are all the numbers negative?
b. What is the effect of Soil warming on winter CO_2 release? Is it the same in all years?
c. Add winter CO_2 release to summer CO_2 storage (the dotted line will help). Is the tundra storing CO_2 or releasing CO_2?
d. What are the implications of warmer soil temperatures for tundra CO_2 storage?

<u>Winter CO_2 exchange:</u>



Reflection:

1. What surprised or interested you the most about the data that you analyzed?
2. Based on your analysis of the data, write a paragraph discussing why scientists should continue to study the carbon flux in the tundra ecosystem. Make sure to include EVIDENCE from the graphs that supports how this data help us understand how future atmospheric warming might influence the global carbon cycle?

Answer Key:

How does a snow fence work?
Snow depth data from the CiPEHR experiment

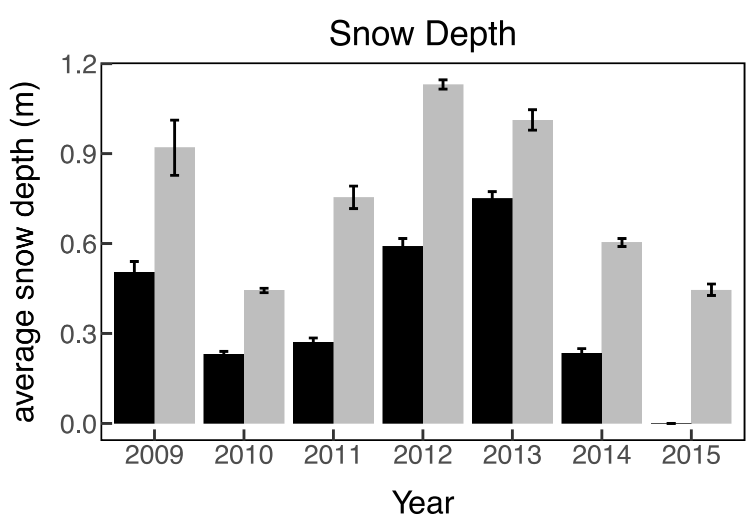
Examine the graph below:

e. Create a legend for this graph. Which color bar represents the soil warmed side, and which bar represents the control?
Black is 'Control' (no warming manipulation), Grey is 'Soil warming'

f. What does the different height of the bars tell you about different winters?
Depth of the snow cover. It shows a lot of variability from year to year. All the bars go up and down depending on how much it snowed that winter. But the soil warming always has deeper snow than the control.

g. Which year was the biggest snow year?
2013. Look at the black bars, that's the annual snow pack of that winter. The grey bars show how much extra snow was accumulated. 2012 was also a higher snow year and for some reason soil warming collected slightly more snow that year.

h. What happened in 2015?
There was very little snow on the tundra. The snow fences did accumulate snow, but on the control side there was no snow. Either the snow hardly accumulated on the tundra, or it all melted before we got out there with our measuring sticks.



What effect do the snow fences have on soil temperatures at CiPEHR?

Analyze the soil temperatures. Week 0 starts 1st Jan and week 51 ends 31st Dec.

f. Give the graph a legend. How can you tell which treatment the grey and black points came from?

Black is 'CONTROL', grey is 'SOILWARMING'. Grey has warmer soil temperatures in summer and winter.

g. How did the treatments affect soil temperatures in winter?

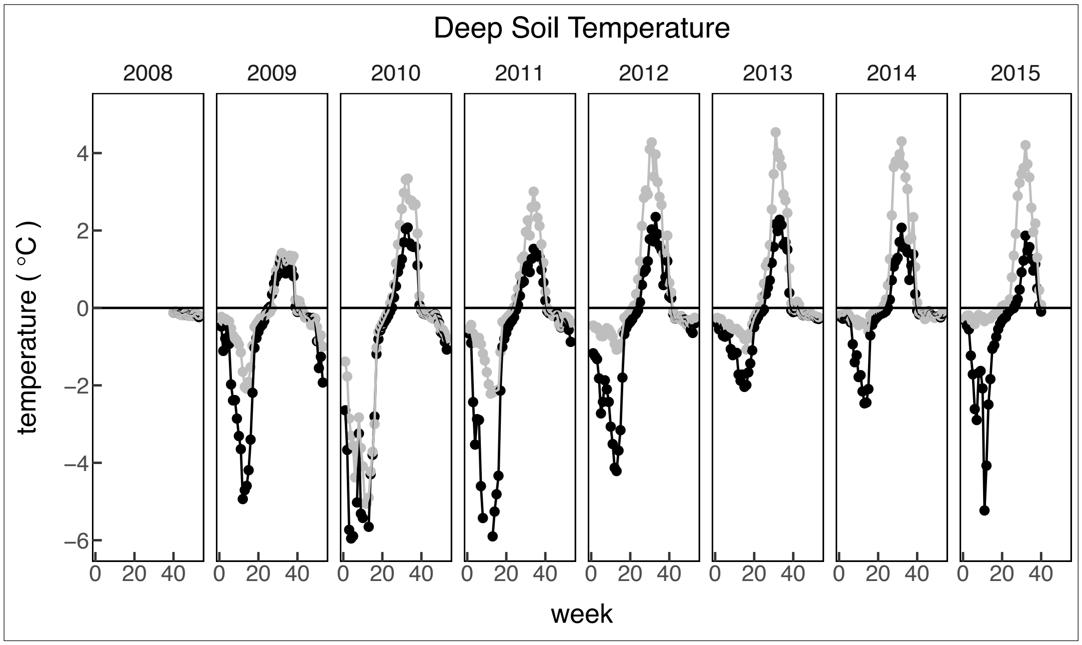
They were warmer. The effect was not the same in all years, the control was much more variable in winter because it is exposed to variable environmental conditions. The soil warming are buffered from cold air by the snow blanket and temperatures are therefore more constant. Over time the soil warming winter temperatures got warmer and in 2014 and 2015 they almost didn't freeze.

h. How did soil temperatures in the soil warming treatment change in summer?

They got warmer, but only after two winters of warming (in 2010). The summer temperatures are much more consistent between years than the winter temperatures. That's because summer conditions are a little less extreme than winter conditions, and winter (eg: snow fall, air temperatures) has a greater effect on soil temperature dynamics than summer.

i. If you compare the snow depth and the soil temperature graphs, can you say how high and low snowfall years affect soil temperatures?

The years with the deepest snow (2012 and 2013) had warmer soil conditions than years with lower snow (2010, 2011, 2015). 2014 is a bit tricky because it had low snow, but temperatures were warmer than 2010, 2011, 2015. This could be a lag effect, with more heat storage in the soil after high-snow winters two years in a row.


Deep Soil Temperature
2008
2009
2010
2011
2012
2013
2014
2015
temperature (°C)
4
2
0
−2
−4
−6
0 20 40
week

What effect do the snow fences have on permafrost at CiPEHR?

Look at thaw depth data from 2009 to 2015.

e. Give the graph a legend. What color represents each treatment?

Black for control, grey for soil warming.

f. What happens to the thaw depth each year, as we move through the summer?

Focus on the seasonal dynamic here, from week 18-40. Each summer the thaw depth increases gradually. This happens as sunlight and summer air temperatures increase.

g. What has happened to the active layer thickness (maximum thaw depth) from 2009 to 2015?

Focus on the last few data points in each year, they represents maximum thaw depth (active layer thickness). In general the active layer got thicker each year, in control and soil warming, but much more rapidly in soil warming. Each year the difference between control and soil warming is greater. **You might also notice the interesting jumps in 2014 and 2015; the thaw depth got deep really early in 2014 and 2015. This indicates that the soil column did not freeze completely. The gradual increase in thaw depth is typical, as air temperatures warm up and the soil thaws from the top down. In soil warming the surface soils froze, but that freezing front did not penetrate all the way to the permafrost layer, and we have created an unfrozen soil sandwich. As soon as the surface soils thaw, we hit that unfrozen layer and drop all the way down to the permafrost layer, that thaws a little more over the rest of the summer.**

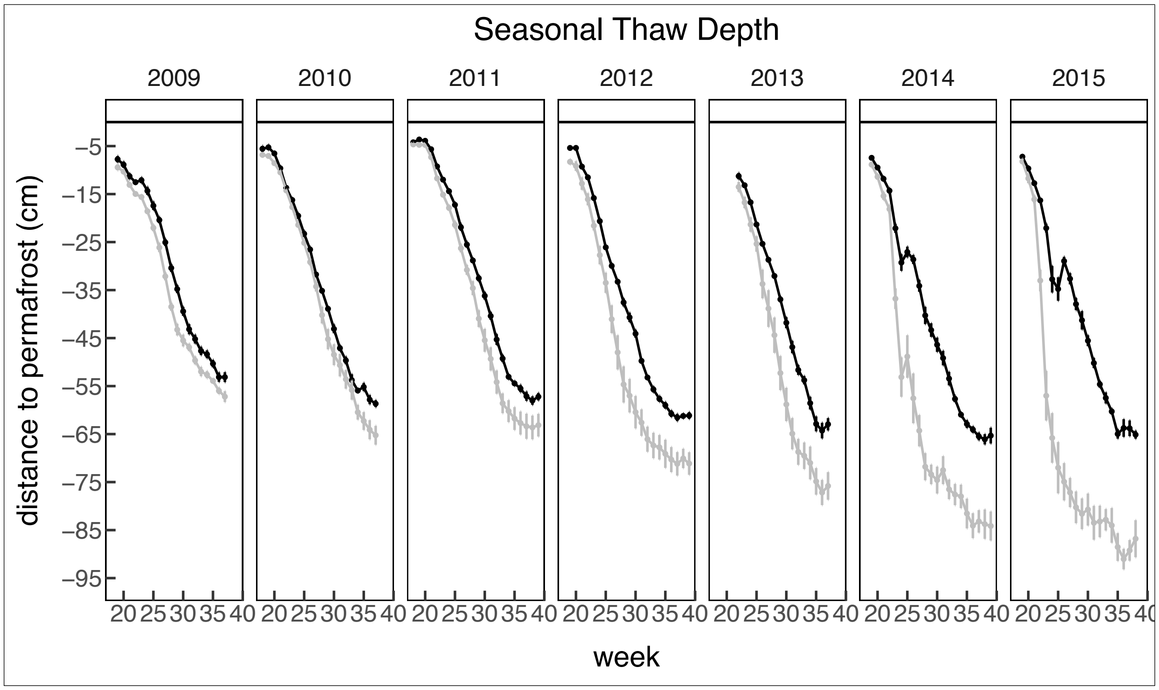
h. How much has the active layer increased from 2009 to 2015?

iii. For Control?

Approximately 10cm, from 45 to 55cm

iv. For Soil warmed?

Approximately 30-40cm from 45 to 85/95cm


Seasonal Thaw Depth
2009
2010
2011
2012
2013
2014
2015
distance to permafrost (cm)
−5
−15
−25
−35
−45
−55
−65
−75
−85
−95
20 25 30 35 40
week

How do plants respond to air and soil warming?
Plant Greenness data from CiPEHR:

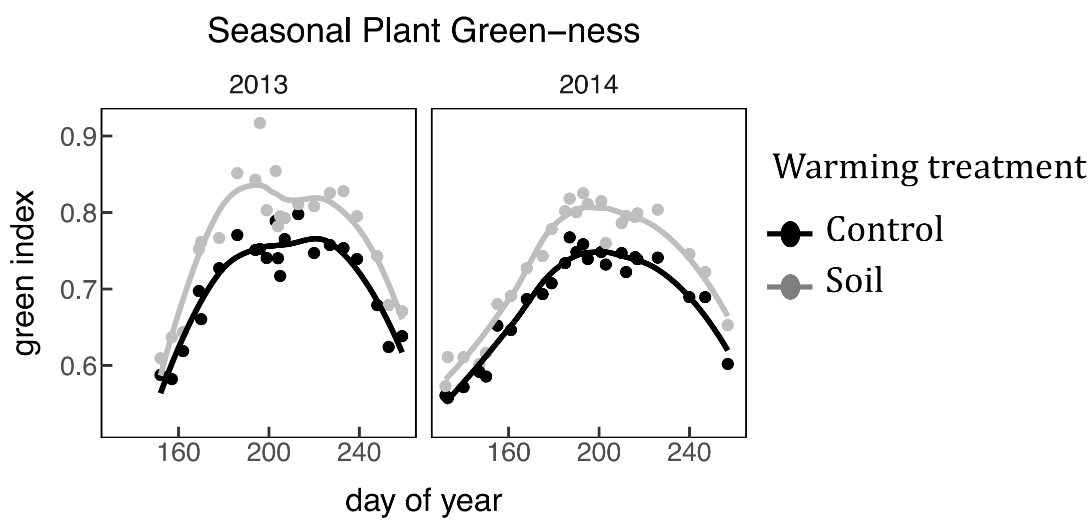
Collecting plant greenness data can be time consuming so we do not have data from all years of the experiment. The figure below shows two summer seasons of plant greenness (1 May – 30 Aug)

d. How did Soil warming affect plant greenness?

Increased plant greenness.

e. How does plant greenness help you understand summer CO_2 uptake in the previous section?

Relate to higher CO_2 uptake in the peak summer and how plant growth and microbial dynamics both contribute to the overall CO_2 balance of the ecosystem.



Part II:
How does warming affect carbon dioxide uptake and release?

Look at the figure of CO_2 uptake:

e. Why does CO_2 uptake change from the beginning to the end of each season?
Temperatures warm up, the plants become green and active and start taking up CO_2.

f. How does Soil warming affect CO_2 uptake?
From 2009-2013 CO_2 uptake in the peak of the summer increased each year. In 2014 and 2015 this peak CO_2 uptake declined. (If 'why?' comes up: Soil warming has caused permafrost thaw, and the loss of soil ice structures. Thaw and loss of soil ice causes the surface to slump in a process called 'thermokarst formation', and is comparable to sink-holes. Tundra is essentially a wetland ecosystem, and when the surface slumps you get patchy puddles (or ponds, at a bigger scale), plants can't grow very well in puddles, and wet conditions can suppress microbial activity a little bit because there is less oxygen in wet soil. As a result we see lower CO_2 uptake in the Soil warmed plots as physical changes in the soil warming experiment change in unexpected ways. What happened in the first 3-4 years may not reflect the changes over a longer time period, which is why long term experiments are important.)

g. Is the effect of Soil warming the same in each year?
No. The effect of soil warming increased each year from 2009-2013, but then decreased in 2014 and 2015. The Control also increased from 2009-2015, this is likely to be background warming in the region, and is also seen in the thaw depths of the Control.

h. When is the effect of Soil warming strongest?
In the peak of the growing season, and in 2013. The peak of the season is when plants are most active, 2013 was a very warm, dry year, and might represent very vigorous plant growth. The plants also grew in response to soil warming because of the extra nutrients released during permafrost thaw, 2013 might therefore represent the peak of plant growth, which leveled off in 2014 and 2015 as the plants reached a maximum size (plants can't keep growing indefinitely).

Look at the figure of CO_2 release:

f. Where is the CO_2 coming from?

Microbial soil decomposition. (Could go into: plant leaves and roots also respire and release CO_2 when they use the energy fixed by sunlight to grow. Some of the Co2 release therefore also comes from plants.)

g. The patterns are very similar to CO_2 uptake. Why do you think this is the case?

Microbes respond to experimental soil warming, and they also respond to warming in the summer each year. As air temperatures, and soil temperatures increase each season microbes become more active, as temperatures cool in the autumn microbial activity declines again. (Because plants also respire some of the seasonal and warming is likely also because there are more plant roots and more plant

activity that produces a little more CO_2. The CO_2 produced by plants is offset by the plant growth, but excess CO_2 from microbial decomposition is not offset and contributes to the ecosystem CO_2 source dynamics.)

h. Why would CO_2 uptake increase in the beginning of the growing season and then decrease again?

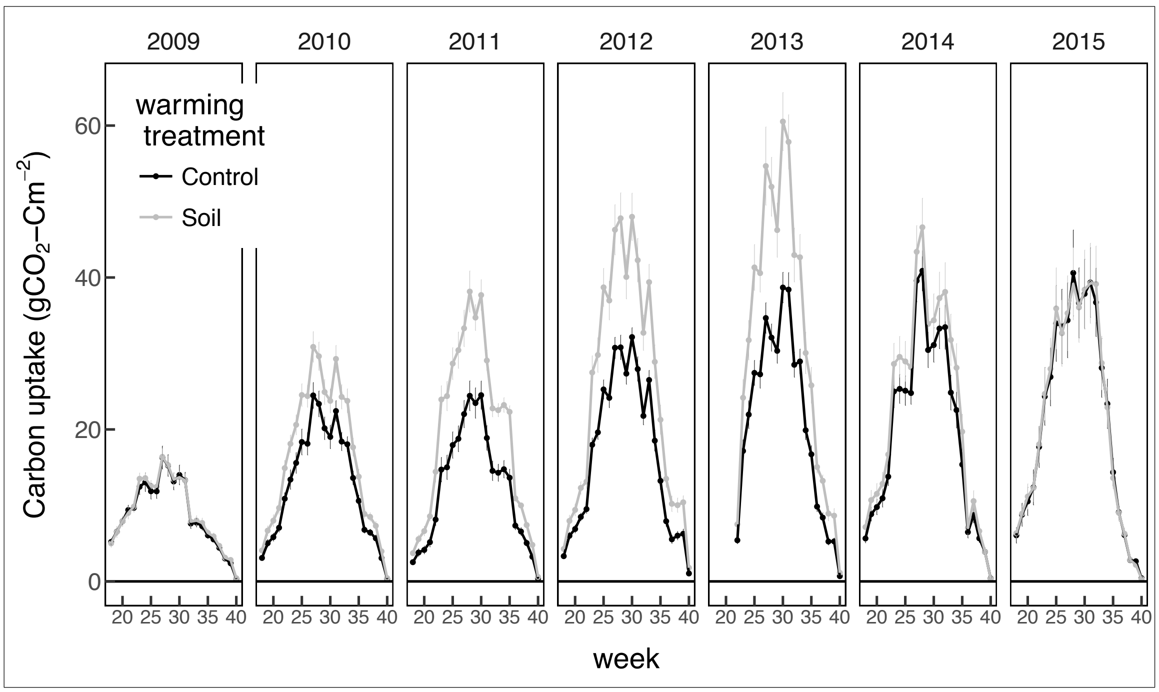
Because soil temperatures increase and then decrease each season, and microbes are sensitive to soil temperature. They are more active in warm soil.

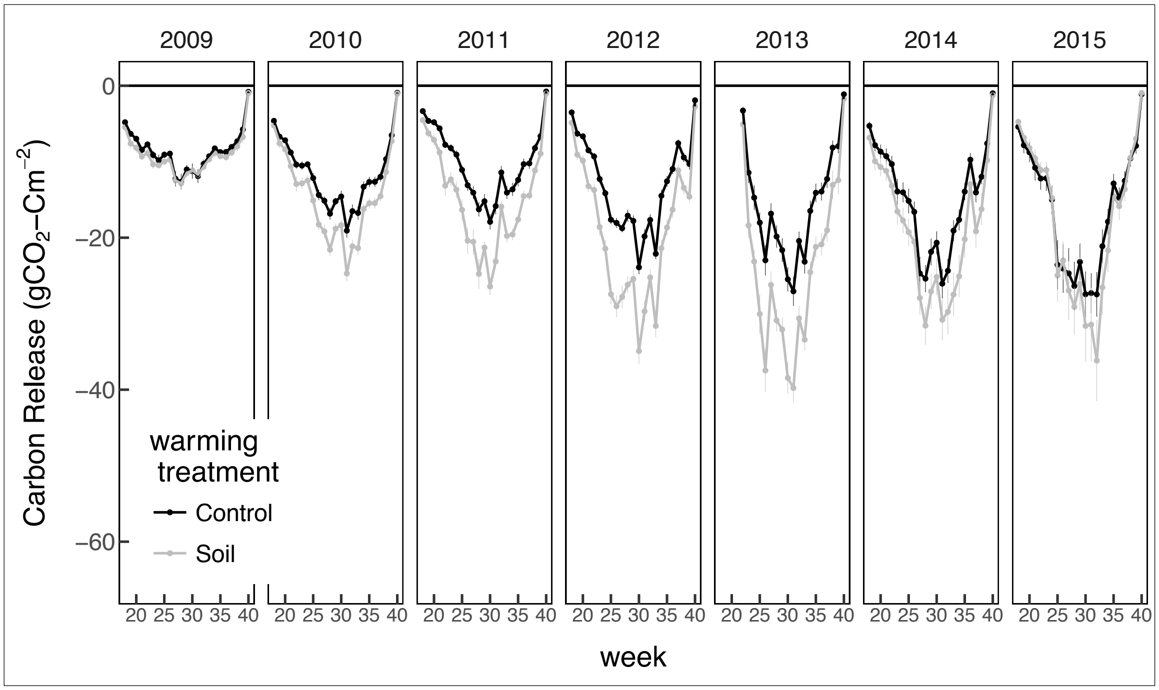
i. When is CO_2 release highest?

Peak growing season, and 2013. Soils are warmest in the peak of the summer. In 2014 and 2015 CO_2 release is lower than in 2013, but still higher in Soil warming compared to Control. Wet conditions can suppress microbial decomposition, but, it appears, not as much as wet conditions suppress plant growth.

j. Why do you think CO_2 release is greater in Soil warming treatments?

Microbes are more active in warm soils.




2009
2010
2011
2012
2013
2014
2015
0
−20
−40
−60
Carbon Release (gCO_2–Cm^{-2})
warming treatment
Control
Soil
20 25 30 35 40
week

How does warming at CiPEHR affect the tundra CO_2 balance?

We use the summer CO_2 fluxes to calculate the total CO_2 storage. By adding up all the CO_2 storage and all the CO_2 release, we can determine the summer CO_2 balance of the tundra. We use this formula:

Total storage = CO_2 uptake – CO_2 release

The figure below shows total summer CO_2 storage.

f. In the summer does the tundra usually have more CO_2 uptake or more CO_2 release?

In general the tundra stores more CO_2 in the summer. (+ve numbers mean net storage).

g. Was the effect of Soil warming the same in all the years?

No. The patterns are roughly similar to the peaks of the previous two seasonal graphs.

h. How did Soil warming affect CO_2 storage from 2009-2013?

CO_2 storage increased in control and soil warming, but soil warming caused greater CO_2 storage each year. This indicates more plant growth than soil respiration/microbial decomposition in response to soil warming.

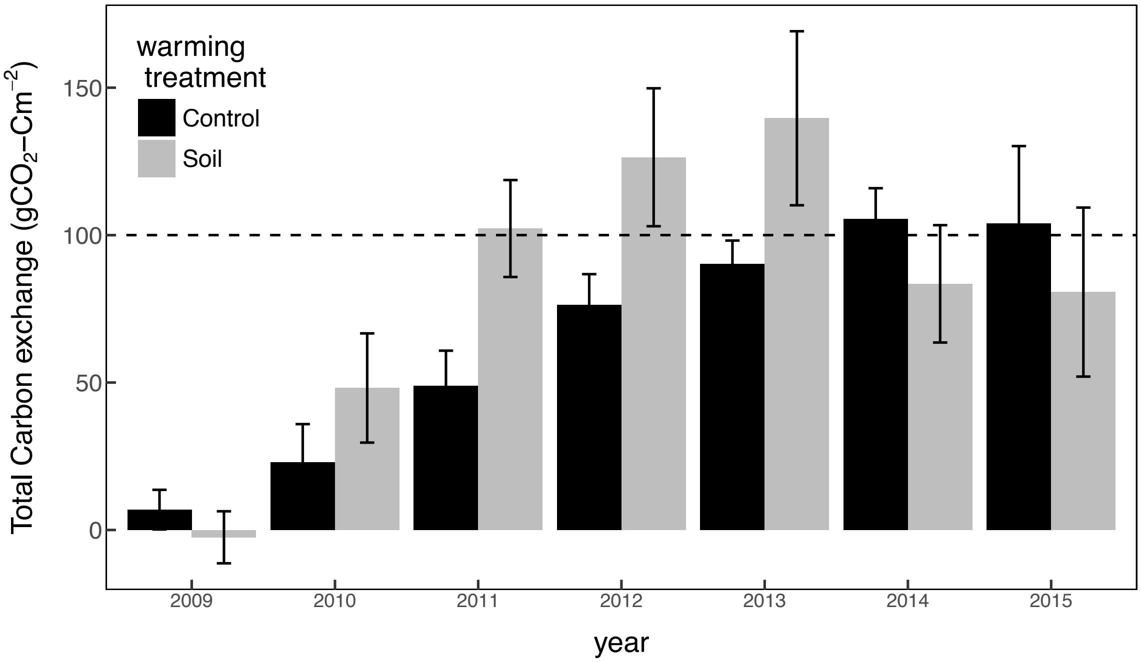
i. How did Soil warming affect CO_2 storage in 2014 and 2015?

In 2015 and 2014 the pattern of control vs soil warming reversed. Net CO_2 storage declined in soil warming. This indicates that there was less excess CO_2 uptake in the soil warming treatments.

j. Overall, how did Soil warming affect summer CO_2 storage?

Overall CO_2 uptake in summer still exceeds loss. Initially soil warming stimulated plant growth and CO_2 uptake, but in 2014-2015 the experiment may have reached a threshold where plant growth has slowed and soil warming treatments have less CO_2 storage than control.

Total summer CO_2 exchange:



The effect of winter on CO_2 balance:

The graph below shows winter CO_2 release from CiPEHR.

e. Why are all the numbers negative?

There is no CO_2 uptake in winter and the winter is a net CO_2 source.

f. What is the effect of Soil warming on winter CO_2 release? Is it the same in all years?

CO_2 release was greater in soil warming treatments in all years. The effect of soil warming is quite consistent each winter.

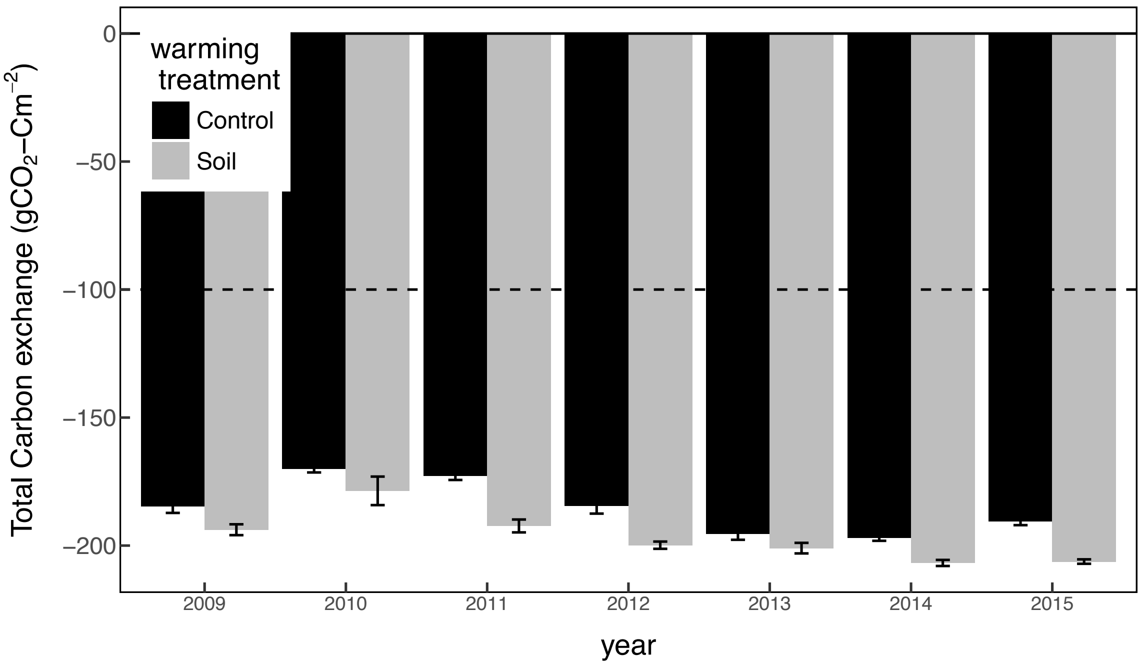
g. Add winter CO_2 release to summer CO_2 storage (the dotted line will help). Is the tundra storing CO_2 or releasing CO_2?

When summer and winter are added together the tundra is a net CO_2 SOURCE. Winter CO_2 loss exceeds storage. In 2012 and 2013 the Soil warming bars are above the dotted line, but only go to 150g CO_2 while every winter releases between 150-200g CO_2. In 2014 and 2015 the soil warming treatment took up less CO_2 than the control in the summer, and was therefore an even stronger sink.

h. What are the implications of warmer soil temperatures for tundra CO_2 storage?

If you look only at summer you might conclude that warming increases tundra CO_2 storage, but when we take into account the increased losses in the summer the tundra is a net CO_2 sink in all years, and in control. Higher CO_2 loss from warmer winter soils offsets the increased CO_2 uptake in the summer and the tundra is a net CO_2 source. Source strength is likely to increase with warming in winter, and summer, but the effects are not straight-forward because the first 5 years (2009-2013) show a very different pattern than 7 years (2009-2015). Continued monitoring will give us a better idea of short and long-term dynamics which can often be quite different.

Winter CO_2 exchange:



How do plants respond to air and soil warming?
Plant Greenness data from CiPEHR:

Collecting plant greenness data can be time consuming so we do not have data from all years of the experiment. The figure below shows two summer seasons of plant greenness (1 May – 30 Aug)

f. How did Soil warming affect plant greenness?

Increased plant greenness.

g. How does plant greenness help you understand summer CO_2 uptake in the previous section?

Relate to higher CO_2 uptake in the peak summer and how plant growth and microbial dynamics both contribute to the overall CO_2 balance of the ecosystem.