Influence of Winter Climate Change on Forest Biogeochemistry

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Boston University
Winter Air Temperatures Rising in New England

Station 1 at Hubbard Brook (December - February)
Snowpack Depth Decreasing in New England

Hubbard Brook

Max. Snow depth (cm)

- 560 m elevation
- 890 m elevation

US Forest Service
Help, the mountains are melting!
The case of the disappearing ski slopes

By NOAH SCHAEFER | November 7, 2012

CHRONICLE ONLINE

Nov. 10, 2010

In 100 years, maple sap will flow a month earlier

By Krishna Ramanujan

As the climate warms this century, maple syrup production in the Northeast is expected to slightly decline by 2100, and the window for tapping trees will move earlier by about a month, reports a Cornell study.

Currently, the best times to tap maple trees are within an eight-week window from late winter to early spring when temperatures cause freezing at night and thawing by day.

"By 2100, we can expect to begin tapping maples closer to Christmas in the Northeast," said Brian Chabot, professor of ecology and evolutionary biology and a co-author of a paper on climate changes and maple sugar production that appeared earlier this year in the journal Climate Change.

Sap flow is related to pressure changes in the trees' xylem, which are tubes beneath the bark that carry sap from the maple's roots up to the leaves. As maple trees freeze in winter, gases are pushed out of the xylem into surrounding tissues, and negative pressure is created within the xylem compared with atmospheric pressure. When the trees thaw, the gases expand and dissolve back into the sap.
Reduced Snow Pack Leads to Increased Soil Frost
Insulating Properties of Snow
Winter Climate Change in the Northeastern U.S. Over Next 100 Years

- 4 to 4.5 °C warmer
- Reduced winter snowpack
- Increased soil frost
Link Between Soil Frost and Nitrogen Leaching

Soil frost events?

NO$_3^-$ (µmol L$^{-1}$)


Hubbard Brook

US Forest Service
Why Care about Nitrogen Leaching?

- Release of $\text{N}_2\text{O}$
- Reduced forest productivity
- Acidification of stream water
- Eutrophication (algal blooms)
- Methemoglobinemia (blue baby syndrome)

$\text{NO}_3^-$ Leaching

Nitrogen
Why Does Reduced Snow Pack and Increased Soil Frost Lead to N Leaching?

- No changes in microbial N production
- Increased root mortality

Groffman et al. and Tierney et al. 2001; Cleavitt et al. 2008
Why Does Reduced Snow Pack and Increased Soil Frost Lead to N Leaching?

- No changes in microbial N production
- Increased root mortality

- Reduced plant N uptake?

Groffman et al. and Tierney et al. 2001; Cleavitt et al. 2008
Nitrogen Uptake by Trees

Snow previous winter
(no soil frost)
Nitrogen Uptake by Trees

Snow previous winter (no soil frost)

Little snow previous winter (soil frost)
Nitrogen Uptake by Trees

Snow previous winter (no soil frost)

Little snow previous winter (soil frost)

\[
\text{NH}_4^+ + \text{NO}_3^- \rightarrow \text{N}_2 \text{O} + \text{N}_2
\]
Why Does Reduced Snow Pack and Increased Soil Frost Lead to N Leaching?

- No changes in microbial N production
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Why Does Reduced Snow Pack and Increased Soil Frost Lead to N Leaching?

- No changes in microbial N production
- Increased root mortality

- Reduced plant N uptake?
- Reduced forest productivity?
- Reduced forest C uptake?

Groffman et al. 2001; Tierney et al. 2001; Cleavitt et al. 2008
Soil Frost and Canopy Uptake of CO₂

Little soil frost

Less canopy C uptake?

Increased soil frost
Hypotheses

Reduced snow pack and increased soil frost result in decreased:

- root health and nutrient uptake
- sap flow and canopy uptake of carbon
- aboveground productivity
Hubbard Brook
Harvard Forest

Sugar maple - American beech
Red maple - Red oak
Snow-Removal Experiments at Hubbard Brook and Harvard Forest

n = 4 reference and 4 treatment plots at Hubbard Brook
n = 3 reference and 3 treatment plots at Harvard Forest
Snow and Soil Frost Depth Measurements

Snow Depth

Frost tubes with methylene blue dye
Snow and Soil Frost Depth Measurements

Snow Depth

Frost tubes with methylene blue dye

clear = frozen
blue = unfrozen
**Snow and Soil Frost Depth**

![Graph showing snow and soil frost depth over time](graph)

- **Reference**
- **Snow Removal**

**Legend:**
- Snow-removal treatment ended

**Axes:**
- Y-axis: Depth (cm)
- X-axis: Dates from 10/31/2008 to 5/1/2009

**Graph Description:**
- The graph illustrates the depth of snow and soil frost over time for both reference and snow-removal treatments.
- Snow depth peaks and decreases over time, with a notable decline starting around 2/6/2009.
- Soil frost depth remains relatively constant with minor fluctuations throughout the period.
Soil Frost Results in Elevated NO$_3^-$ in Leachate
Soil Frost Results in Elevated NO$_3^-$ in Leachate

What explains elevated NO$_3^-$?

- Snow-Removal
- Reference

NO$_3^-$ (mg N L$^{-1}$)

2008
- Aug
- Oct
- Dec
- Feb
- Apr
- Jun
- Aug
- Oct
- Dec
- Feb

2009
- Jun
- Aug

2010
- Soil Frost

Soil Frost Results in Elevated NO$_3^-$ in Leachate
Hypotheses

Reduced snow pack and increased soil frost result in decreased:

• root health and nutrient uptake
• sap flow and canopy uptake of carbon
• aboveground productivity
Uptake of Nitrogen by Trees by Sugar Maple Trees

Socci and Templer (2011)
Plant Ecology and Diversity
Uptake of Nitrogen by Trees by Sugar Maple Trees

Net Uptake (µmol N g root\(^{-1}\) hr\(^{-1}\))

- Reference
- Snow removal

P < 0.05

Year 2009

April 22 April 30 May 6 May 13 May 21 May 27

Net Uptake (µmol N g root\(^{-1}\) hr\(^{-1}\))
Uptake of Nitrogen by Trees by Sugar Maple Trees

Net Uptake ($\mu$mol N g root$^{-1}$ hr$^{-1}$)

- **Reference**
- **Snow removal**

\[ P < 0.05 \]

36%
Soil Frost Induces Root Injury of Sugar Maple Trees

37% Increase in snow-removal plots

Commerford et al. (2013) Oecologia
Electrolyte Leakage

37% Increase in snow-removal plots

Below 50% threshold = tissue mortality

Commerford et al. (2013) Oecologia
Reduced snow pack and increased soil frost results in decreased:

- root health and nutrient uptake
- sap flow and canopy uptake of carbon
- aboveground productivity
Sap Flow and Net Canopy C Uptake

Measuring sap flow

Measuring leaf-level gas exchange
Soil Frost Reduces Sap Flow by Sugar Maple Trees

Sap Flux (L H₂O m² d⁻¹)

Reference
Snow Removal

Templer et al. *In prep*
Soil Frost Reduces Sap Flow by Sugar Maple Trees

Templer et al. In prep
Soil Frost Reduces Growth of Sugar Maple Leaves

Commerford et al. (2013) *Oecologia*
Soil Frost Reduces Sap Flow by Red Maple Trees

![Bar chart showing the effect of soil frost on sap flow for Red Oak and Red Maple trees. The chart indicates a 23% drop in sap flow for Red Maple trees compared to the reference condition. The statistical significance is marked with a p-value of 0.1.](attachment:image.png)
Soil Frost Reduces C Uptake by Red Maple Trees

Carbon Uptake

(µmol CO₂ m⁻² ground sec⁻¹)

Reference
Snow Removal

Red Oak
Red Maple

P = 0.06
23% drop

0 5 10 15 20 25 30 35 40

Carbon Uptake

(µmol CO₂ m⁻² ground sec⁻¹)
Hypotheses

Reduced snow pack and increased soil frost results in decreased:

- root health and nutrient uptake
- sap flow and canopy uptake of carbon
- aboveground productivity (litterfall and radial growth)
Soil Frost Does Not Affect Rates of Litterfall

Pre-Treatment

- Litterfall (g m⁻²)
- 2010: Reference: 80, Snow Removal: 60

Post-Treatment

- Litterfall (g m⁻²)
- 2010: Reference: 80, Snow Removal: 60

P-values:
- Pre-Treatment: P = 0.97
- Post-Treatment: P = 0.51
Soil Frost Does Not Affect Rates of Litterfall

![Graph showing litterfall rates before and after treatment comparison.](image)

- **Pre-Treatment**
  - Year: 2008
  - Litterfall (g m\(^{-2}\)): Reference - 160 ± 10, Snow Removal - 140 ± 10
  - Significance: \( P = 0.97 \)

- **Post-Treatment**
  - Year: 2009
  - Litterfall (g m\(^{-2}\)): Reference - 160 ± 10, Snow Removal - 160 ± 10
  - Significance: \( P = 0.51 \)

- Year: 2010
  - Litterfall (g m\(^{-2}\)): Reference - 160 ± 10, Snow Removal - 80 ± 10
  - Significance: \( P = 0.51 \)
Soil Frost Does Not Affect Basal Area Increment

Pre-Treatment

Post-Treatment

$P = 0.66$

$P = 0.56$
Soil Frost Does Not Affect Basal Area Increment

Pre-Treatment

Post-Treatment

$P = 0.66$

$P = 0.56$
Winter Climate Change Effects on Forest Ecosystems

Smaller winter snowpack and increased soil frost:
- increase NO$_3^-$ leaching due to diminished N uptake by trees
- decrease rates of water and C uptake by maple trees
- do not affect aboveground productivity in the short-term
Winter Climate Change Effects on Forest Ecosystems

Smaller winter snowpack and increased soil frost:
– increase NO$_3^-$ leaching due to diminished N uptake by trees
– decrease rates of water and C uptake by maple trees
– do not affect aboveground productivity in the short-term

Implications for biogeochemistry, water quality, and tree species composition of northern temperate forests.
**Acknowledgements**

**Undergraduate Students**
- Rebecca Antonoplos
- Komal Basra
- Angelica Carreon
- Keita DeCarlo
- Mary Farina
- Omar Gutierrez del Arroyo
- Adam Jacobs
- Brita Jessen
- Allyssa Kilanowski
- Stephanie Kubala
- Michael Mangiante
- Monika Mathur

**Ph.D. Graduate Students**
- Andy Reinmann
- Rebecca Sanders-Demott
- Annie Socci
- Patrick Sorensen

**Technicians**
- Eddie Brzostek
- Stephanie Juice
- Lindsay Scott
- Alex Webster
- Matt Ross
- Bethel Steele

**High School Students**
- Liz Cortesseli
- Vanessa Lee
- Ari Coopersmith

**Collaborators**
- John Campbell
- Dan Commerford
- Paul Schaberg
- Kimberly Wallin

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Andrew W. Mellon Foundation