Acid Rain Impacts on Calcium Nutrition and Forest Health

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PRESENTATION OF PAPER BY KELLI KEARNS
Outline

About the Paper
Background & Motivation
Previous Findings
Experimental Methods
Experimental Results
Synthesis & Overall Mechanism
Broader Implications for Forest Health
About this Paper

Somewhat of a review paper--synthesizes existing info and presents experimental data

Sections were divided by content, not by standard “intro, results, etc.”

Cited 250 times (source: Google Scholar)
Background

Acid precipitation contains $\text{H}^+$, $\text{SO}_4^{2-}$, $\text{NH}_4^+$, and $\text{NO}_3^-$

Public classically viewed acid deposition as a local issue, but is a global phenomenon

Nine years after the Clear Air Act amendments and a sulfur dioxide emission reduction, in Northeast U.S. did not seem to be improving – some areas still have pH <3.0

Inspired developments in measuring leaching, depletion, and cycling of calcium due to acid rain in forest soils

Cumulative soil Ca depletion estimates 50% over ~45 years

National Acid Precipitation Assessment Program (NAPAP) found that acid deposition could be linked to red spruce decline, but not yet proven
Picea *ruebens* (Red Spruce Tree)

Gymnosperm in the Pinaceae family

Perennial growth – helpful for collecting data

Photos from USDA.gov
Motivation

Effects of soil on ecosystem health have been mostly speculative

Red spruce decline synonymous with acid rain → significant freezing injury over 40 years coincides with the sulfur/nitrogen dioxide emissions over that time

Ultimately, a physiological explanation for red spruce decline is needed
Previous Findings: Overall

Proposed that aluminum is mobilized in soil by acid deposition and reduces storage/availability of calcium
◦ Reductions in Ca:Al ratios, sapwood area, and live crown volumes
◦ Leaves trees more vulnerable to secondary stresses like disease, pests, and freezing
Acid rain linked to “dark respiration” and reductions in net photosynthesis
Also proposed that elevated SO$_4^{2-}$ in acid rain may be altering the carbon metabolism of trees
◦ Leading to physiological impairment, increased vulnerability to secondary stresses
Previous Findings: Freezing Injury to Red Spruce

Established that red spruce winter-injury is caused by subfreezing temperatures

In-vitro data: freezing injury range is -37°C to -47°C (overestimate)

In-vivo data: freezing injury range is -30°C to -54°C

Table 1. Estimates of midwinter cold tolerance for current-year foliage of red spruce from northern US populations.

<table>
<thead>
<tr>
<th>Location</th>
<th>Date</th>
<th>Number of trees</th>
<th>Injury temperature (°C)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Whiteface Mountain, NY</td>
<td>January 1987</td>
<td>20</td>
<td>LT_{10} = -37^{b}</td>
<td>Sheppard et al. 1989</td>
</tr>
<tr>
<td>Nesowdnahunk Lake, ME</td>
<td>January 1990</td>
<td>10</td>
<td>T_c = -41^{b}</td>
<td>Hadley and Amundson 1992</td>
</tr>
<tr>
<td>Camel's Hump Mountain, VT</td>
<td>January 1992</td>
<td>5</td>
<td>LT_{20} = -46^{b}</td>
<td>Perkins et al. 1993</td>
</tr>
<tr>
<td>Mt. Mansfield, VT</td>
<td>January 1995</td>
<td>10</td>
<td>T_c = -47</td>
<td>Strimbeck et al. 1995</td>
</tr>
<tr>
<td>Mt. Mansfield, VT</td>
<td>January 1996</td>
<td>60</td>
<td>T_m = -42</td>
<td>Schaberg et al. in press a</td>
</tr>
</tbody>
</table>

{^a}LT_{10,20} is the temperature associated with 10% or 20% foliar freezing injury, T_c is the highest temperature at which statistically significant increase in freezing injury is detected, and T_m is the temperature associated with the increase in slope of the injury response curve.

{^b}Estimated from Sheppard et al. 1989.
Previous Findings: Freezing Injury to Red Spruce/Acid Rain and Cold Tolerance

During most winters, ambient temperatures approach the max. cold tolerance.

Acid rain exposure reduces freezing tolerance of red spruce trees by 3-10°C.

Figure 1
Previous Findings: Cold Tolerance Related to Foliage Calcium

Figure 2.
Previous Findings: Younger vs Older Needles

Results indicated that red spruce has the physiological capacity to develop greater cold tolerance over time.

Figure 3.
Experimental Methods: What are some possible routes of entry for acid rain into plants?
Experimental Methods

Misted trees with acid solutions prepared to resemble regional cloud chemistry

Measured foliar calcium leaching, total foliar calcium, mCa fluorescence, and cold tolerance under various conditions

Factorial Arrangement:

<table>
<thead>
<tr>
<th>pH</th>
<th>Calcium (µmol/L)</th>
<th>Aluminum (µmol/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3.0</td>
<td>25</td>
<td>200</td>
</tr>
<tr>
<td>3.0</td>
<td>75</td>
<td></td>
</tr>
<tr>
<td>3.0</td>
<td>225</td>
<td></td>
</tr>
<tr>
<td>5.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Experimental Results: Acid-induced foliar leaching and cold tolerance reductions

Calcium leaching concentrations were 2-10 times greater for an induced pH of 3.0 rather than 5.0.

In vitro partitioning experiment showed that about 85% of acid-leached calcium was from needles rather than stems.

In lab, 50% more acid-leached calcium was from current-year rather than year-old foliage, and pH 3.0 treatment assimilated 60 times more H+ than the pH 5.0 needles.

Significant membrane disruption and 4-10ºC reduction in freezing tolerance → indicates that the plasma membrane may be very important!
Experimental Results: Acid-induced foliar leaching and cold tolerance reductions

a – In vivo Ca leaching
b – Total foliar calcium
c – Membrane stability by electrolyte loss
d – Cold tolerance

Open bars: pH = 3.0
Full bars: pH = 5.0
Experimental Results: Acid-induced foliar leaching and cold tolerance reductions

Open bars = needles + twigs
Solid bars = needles alone

Figure 5.
Experimental Results: Importance of membrane-associated calcium

Majority of calcium in red spruce foliage is insoluble, extracellular calcium oxalate of little physiological importance

The more important calcium—membrane calcium (mCa)—is highly susceptible to leaching by acid

mCa is a small fraction of the total calcium, but strongly influences the response of the cell to changing conditions (like freezing temperatures!)

Changes in mCa are not seen in looking at total foliar calcium alone
Experimental Results: Importance of membrane-associated calcium

Figure 6. Relationship between total calcium and membrane-associated calcium (mCa) concentrations for current-year foliage of red spruce seedlings (DeHayes et al. 1997). Parameters are not significantly correlated ($r = -0.14, P = 0.34$).
Experimental Results: Importance of membrane-associated calcium

Membrane calcium is stored on the cell wall and then transported through the plasma membrane to produce freeze-shielding proteins

Figure 7.
Experimental Results: Importance of membrane-associated calcium

Figure 7.
Question:

Based on this proposed significance, why might older red spruce needles tolerate cold temperatures better than younger needles?
Experimental Results: Seasonal changes in mCa

Figure 8. Seasonal patterns of membrane-associated calcium (mCa) in current-year and year-old needles of red spruce seedlings. The decrease in mCa during a midwinter thaw is significant for current-year, but not year-old, needles (DeHayes et al. 1997).
Experimental Results: Perturbations to mCa versus total foliar calcium pools

Found that aluminum-induced changes in physiology appear direct and independent of calcium additions.

Soil treatments did not have any significant effects, but acid-mist treatment had profound effects → **3.0 pH mist led to significant calcium leaching**

- Any soil-induced changes likely resulted in leaching from extracellular calcium pools

“Acid mist-induced reductions in mesophyll cell and mCa were relatively minor in late summer but reached a maximum of 35% between mist treatments by midwinter, even though acid mist-treatments had been removed months earlier.”

- Similar pattern for cold effects
Experimental Results: Nature of calcium leaching and cold tolerance perturbations

Acid deposition can influence cation dynamics in foliage directly—indeed independent of belowground processes.

Because HCl was used in experimentation and $\text{SO}_4^{2-}$ was not introduced, acid mist-induced calcium leaching and cold tolerance reductions are most likely the results of $\text{H}^+$-driven cation exchange.
## Experimental Results: Data Table

### Table 2. Influence of soil calcium, soil aluminum, and acid mist treatments on current-year foliar calcium leaching and concentration, membrane-associated calcium (mCa), and cold tolerance in red spruce.\(^a,^b\)

<table>
<thead>
<tr>
<th>Treatments</th>
<th>Foliar calcium leaching (µg/L)</th>
<th>Total foliar calcium (mg/kg)</th>
<th>mCa fluorescence</th>
<th>Cold tolerance (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Jul '94 Aug '94 Sep '94</td>
<td>Jul '94 Sep '94 Nov '94 Feb '95</td>
<td>Sep '94 Nov '94 Jan '95</td>
<td>Nov '94 Jan '94 Feb '95</td>
</tr>
<tr>
<td>Soil calcium</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 µmol/L</td>
<td>249</td>
<td>172</td>
<td>84</td>
<td>0.21 **</td>
</tr>
<tr>
<td>225 µmol/L</td>
<td>373</td>
<td>150</td>
<td>106</td>
<td>2335</td>
</tr>
<tr>
<td>Soil aluminum</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 µmol/L</td>
<td>247</td>
<td>162</td>
<td>113</td>
<td>2417 **</td>
</tr>
<tr>
<td>200 µmol/L</td>
<td>328</td>
<td>133</td>
<td>96</td>
<td>1523</td>
</tr>
<tr>
<td>Acidic mist</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pH 3.0</td>
<td>526 **</td>
<td>233 **</td>
<td>148 **</td>
<td>1969</td>
</tr>
<tr>
<td>pH 5.0</td>
<td>66</td>
<td>64</td>
<td>60</td>
<td>1971</td>
</tr>
</tbody>
</table>

\(^a\)Schaberg et al. in press b.

\(^b\)Asterisks indicate cases in which soil calcium, soil aluminum, or acidic mist treatment means are significantly different at \(P \leq 0.05\) (*) or \(P \leq 0.01\) (***) within sample date based on analysis of variance.
Proposed Mechanism

Discredits former hypotheses regarding $\text{SO}_4^{2-}$ or aluminum driving detrimental effects from acid deposition.

These results correspond with the unique features of the red spruce tree freezing injury syndrome: old vs new foliage, persistence of freezing injury effects even after acid is removed.

Mechanism plausibly explains the indirect effects of acid deposition on red spruce tree decline.

Figure 9.
Larger Implications: Broader Forest Health

The small, environmentally sensitive mCa pool appears to serve an active role in stress-response over the insoluble tissue-based calcium.

Results not exclusive to just the red spruce tree and motivates further investigation of these processes in other plants.

Acid-induced soil calcium depletion could further exacerbate mCa deficiencies and cause larger-scale forest damage.

Table 3. Relative stability of cell membranes in the current-year foliage of red spruce and balsam fir seedlings following autumn (September–November 1997) application of pH 5.0 or pH 3.0 simulated cloud water treatments.4,b,c

<table>
<thead>
<tr>
<th>Species</th>
<th>Membrane stability (relative electrolyte leakage)</th>
<th>Change in membrane leakage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>pH 5.0</td>
<td>pH 3.0</td>
</tr>
<tr>
<td>Balsam fir</td>
<td>0.220</td>
<td>0.322**</td>
</tr>
<tr>
<td>Red spruce</td>
<td>0.254</td>
<td>0.338**</td>
</tr>
</tbody>
</table>

4Schaberg et al. in press b.
5Mist solutions equalized SO4^2- concentrations between pH treatments.
6Double asterisks (**) indicate pH treatment means within species are significantly different at P ≤ 0.01 based on analyses of variance.
Thank You!