

# Acid Rain and Sugar Maple Decline

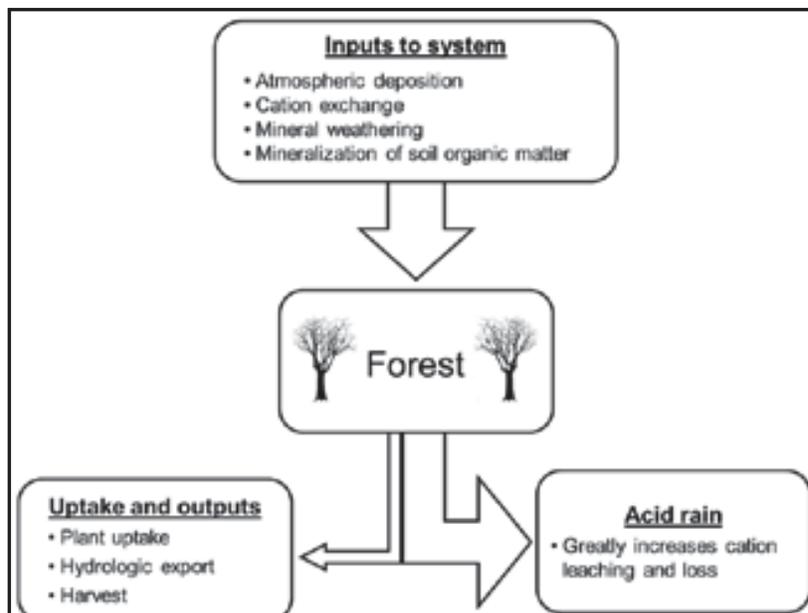
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## Acid Rain and Cation Depletion

Through the increased combustion of fossil fuels, humans have dramatically increased pollutant additions of sulfur and nitrogen into the atmosphere where it combines with water to form sulfuric and nitric acids, creating acid rain (Driscoll et al. 2001). Incoming acid rain has various impacts on human and natural systems, including the accelerated degradation of built infrastructure (e.g., buildings, bridges and monuments). However, the most pervasive influence of acid rain is that it disrupts nutrient cycling within ecosystems, speeding the loss of beneficial cations (positively charged elements like calcium (Ca), magnesium (Mg) and potassium (K)) and mobilizing potentially toxic ones like aluminum (Al). In forests, nutrient levels reflect the balance of inputs to the system (e.g., through atmospheric deposition, soil cation

exchange, and mineral weathering of underlying rock) and plant uptake and nutrient exports (e.g., via leaching loss and harvesting).

Inputs of acid deposition disrupt this natural balance and leads to a net loss of cations through acid-induced leaching (Figure 1). Although this increased leaching removes many cations, losses of most plant-essential cations (e.g., Mg and K) are limited because they can be reabsorbed back into stems before leaf senescence in the fall. In contrast, Ca is not mobile in the phloem and cannot be reabsorbed into stems, so all foliar Ca is lost when leaves are shed and this Ca is vulnerable to leaching loss as leaves decay (Schaberg et al. 2010). Protracted Ca leaching from soils and litter can lead to the net Ca depletion and the development of tree Ca deficiencies (Schaberg et al. 2010).



**Figure 1.** Diagram of how acid rain can increase the leaching export of base cations (especially Ca) from forests so that natural nutrient cycling is disrupted and net Ca depletion occurs.

## Calcium Depletion as a Unique Threat

Not only is Ca more vulnerable to leaching loss and soil depletion, Ca deficiencies are particularly damaging to trees because Ca-dependent physiology is so crucial to maintaining tree health and productivity. There are two basic functions of Ca in plants: 1) to enhance structural integrity (of cell walls and membranes) and 2) as a signaling agent that helps cells regulate carbon metabolism and stress response.

It is this second function that acid rain-induced Ca depletion likely disrupts the most. Deficiencies of Ca impair cellular stress response systems and make trees more vulnerable to damage and decline following exposure to stresses that would otherwise not have been consequential (Schaberg et al. 2001). The combined action of acid rain-induced Ca deficiencies that impair stress response (a predisposing factor) followed by exposure to environmental stress (e.g., drought or insect defoliation-inciting factors) then result in exaggerated tree injury and decline (Schaberg et al. 2001, 2010). Evidence that Ca depletion predisposes trees to decline following exposure to other environmental stresses comes from studies of numerous species in locations around the world where acid rain has become a modern threat (Schaberg et al. 2010). However, one of the best-studied examples of this is the decline of sugar maple (*Acer saccharum* Marsh.) trees in northeastern North America.

### Sugar Maple Decline as a Case Study

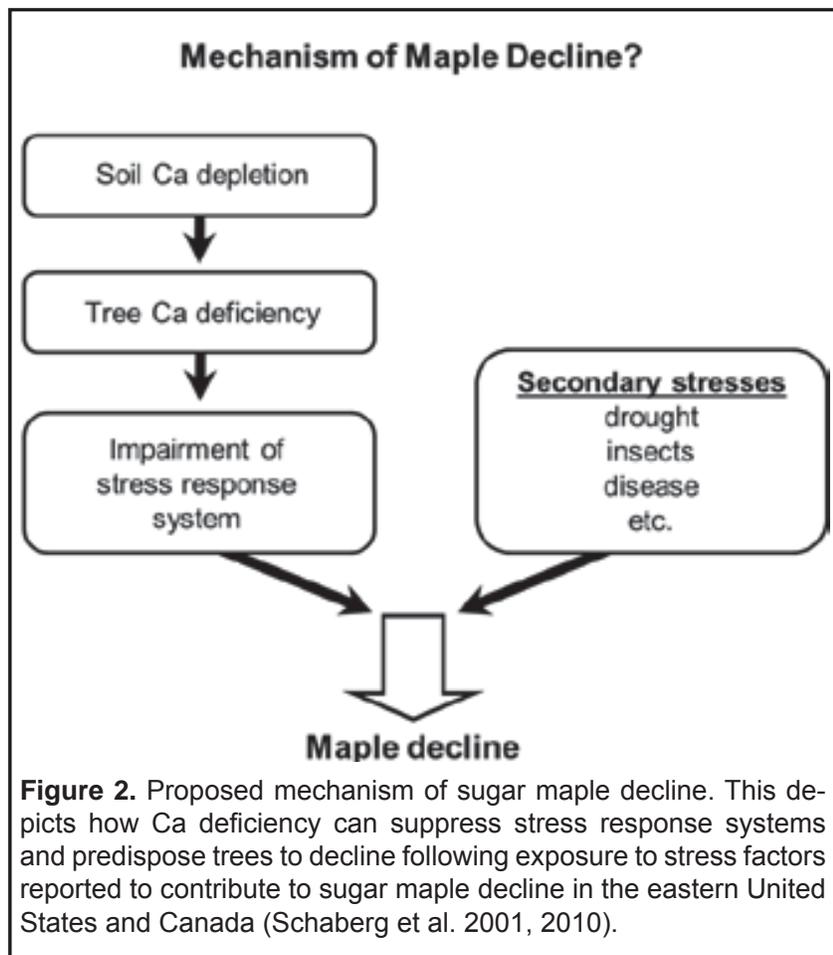
Sugar maple decline has been documented throughout parts of the northeastern United States and adjacent Canada over many recent decades (Schaberg et al. 2010). This decline has been characterized by two primary symptoms: crown dieback and woody growth declines. This decline is consistently associated with both cation (most

notably Ca) deficiencies and with an array of secondary environmental stresses (e.g., freezing injury, drought and insect defoliation – depending on the year and location) (e.g., Horsley et al. 2002, Long et al. 2009). This integration of predisposing and inciting factors forms an overall model of the causes of sugar maple decline (Figure 2), and established a testable hypothesis that has been used to evaluate the consistency of decline factors across the landscape and design experiments to evaluate if Ca addition could reverse decline.

### Evidence from Native Stands and Experiments

Numerous studies have shown that declining sugar maple stands are characterized by having reduced foliar Ca nutrition (e.g., see reviews in Schaberg

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**Figure 2.** Proposed mechanism of sugar maple decline. This depicts how Ca deficiency can suppress stress response systems and predispose trees to decline following exposure to stress factors reported to contribute to sugar maple decline in the eastern United States and Canada (Schaberg et al. 2001, 2010).

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et al. 2001, 2010). However, because declining trees are also expected to have reduced transpiration (the source of Ca to leaves), then it becomes unclear whether foliar Ca deficiency is a likely cause or unintended consequence of maple decline. To better distinguish foliar Ca deficiency as a cause or consequence of decline, Schaberg et al. (2006) sampled soil and foliar nutrition, and crown health and woody growth of sugar maple trees in 14 stands in Vermont that were predicted to have differing soil Ca levels based on the chemical composition of the bedrock geology that is the foundation for soil development (Schaberg et al. 2006). Sites were chosen based on predicted Ca status with no prior information on levels of sugar maple decline. Sites predicted to have diminished Ca status were indeed low in Ca, and they

exhibited poorer crown condition and reduced woody growth relative to sites where Ca was more available (Schaberg et al. 2006). Although this experiment showed that Ca deficiency was more likely a cause rather than a side-effect of sugar maple decline, more convincing demonstration of the causative influence of Ca depletion on sugar maple decline involved manipulation experiments in which decline symptoms were reversed following the addition of Ca lost through acid rain-induced leaching.

Several experiments have shown that treating soils with dolomitic lime (that adds Ca and Mg) can improve crown health and increase woody growth among declining sugar maples (e.g., Long et al. 1997). However, a more focused test of the influence of improved Ca nutrition can be achieved if only Ca

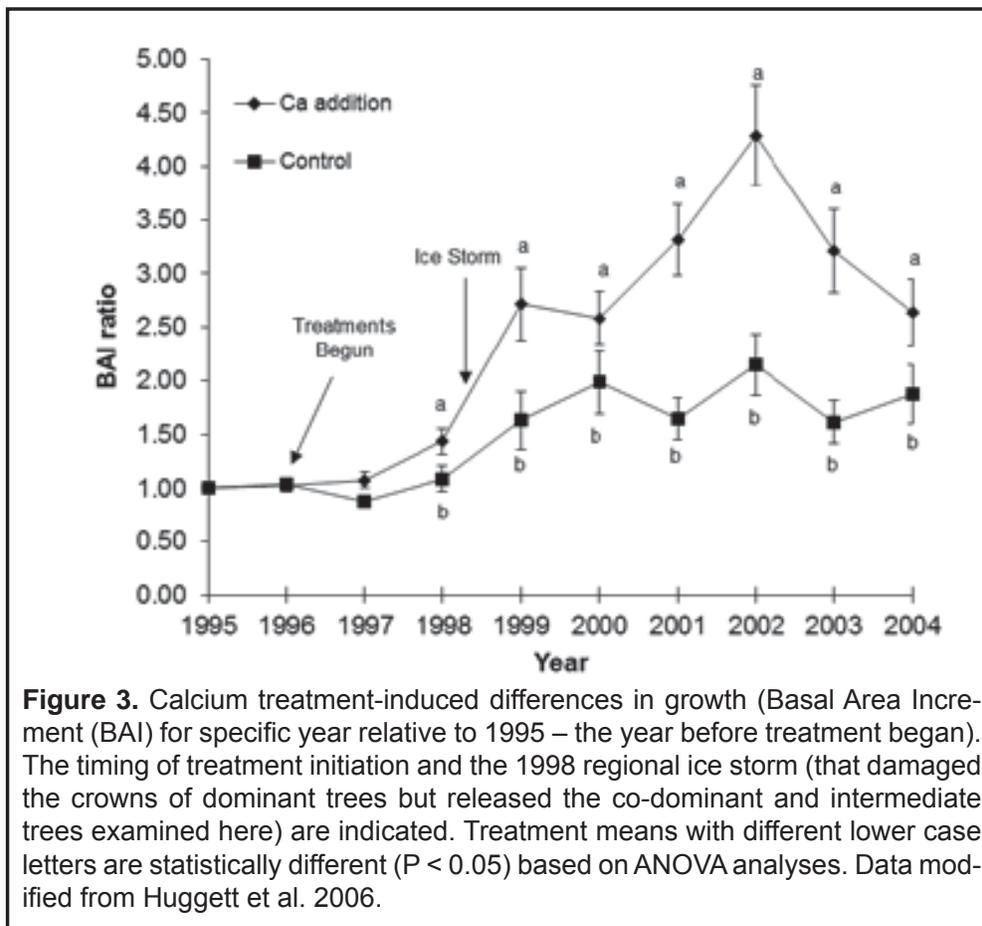
(and not Mg) is added to soils. Specific Ca-addition studies have been conducted at the Hubbard Brook Experimental Forest in New Hampshire at two spatial scales: 1) a plot-based study where Ca was added to a series of 40 m x 40 m forest patches, and 2) a large-scale study where Ca was added to an entire 11.8 ha watershed. For both experiments, Ca was added primarily as pelletized wollastonite (CaSiO<sub>3</sub>) at a level calculated to replace the Ca lost through decades of acid rain exposure. Comparative controls were adjacent to untreated forests at either a plot- or watershed-level for which Ca depletion from acid deposition was well documented. At the plot level, Ca addition improved a wide-range of factors relative to trees on control plots, which included increased foliar Ca, greater foliar protection (i.e., antioxidant activity), improved crown health, improved reproduction (more flowers, seed, and better germination), increased stem woody growth and improved stress response (Huggett et al. 2007, Halman et al. 2013). These last two factors are depicted in Figure 3. Here, Ca addition was associated with an increase in stem woody growth – but primarily only after the

regional 1998 ice storm damaged the crowns of overtopping dominant trees and released the co-dominant and intermediate sugar maple trees measured (Huggett et al. 2007). Even the trees on untreated control plots showed some release following the ice storm, but the full growth potential for crown release was only recorded when trees also received supplemental Ca (Figure 3). Similar results were seen at the watershed scale where Ca addition was followed by increased foliar Ca, increased leaf area, improved crown health, greater wood production, reduced fine root biomass, and a shift in biomass from below to aboveground tissues (Battles et al. 2014, Fahey et al. 2016).

### The Broader Landscape and your Sugarbush

Studies like the ones described above

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have helped define how acid rain-induced Ca depletion predisposes sugar maple trees to decline. But not all sites are expected to be equally vulnerable to soil Ca depletion and tree decline. Sites that have Ca-poor soils and experience elevated inputs of acid rain are the most vulnerable to reductions in tree health and productivity. But how does one determine whether any particular forest site is at risk of acid rain-induced Ca depletion and tree decline? At least two methods are available and are used at different scales: 1) computer modeling of cation cycling relative to acid rain inputs to evaluate locations and patterns of risk over broad landscapes, and 2) nutritional assessment of smaller forest parcels to evaluate site-specific needs.

One solution to providing a more broadly applicable and spatially explicit estimate of the vulnerability of sites to acid deposition-induced Ca depletion is through the use of critical load exceedance models and associated maps. The critical load with respect to acid rain-induced Ca leaching is a quantitative estimate of the amount of pollution deposition below which there is no harmful effect (e.g., net Ca depletion; Schaberg et al. 2010). When a site's threshold for pollution loading (critical load) is subtracted from the estimated amount of incoming acid rain at that site, the exceedance of the critical load is determined. Sites with positive exceedance values are predicted to be vulnerable to pollution-induced reductions in health and productivity as Ca reserves are depleted over time. Although several specific critical load exceedance models exist, this general approach for identifying areas where acid deposition likely induces net Ca depletion and tree decline has been successfully tested for conifer and hardwood systems (Oui-

met et al. 2001) including sugar maple stands (Watmough 2002).

If concerns exist about possible Ca depletion within individual forests, then site-specific nutritional assessments can be conducted. These assessments can range from the use of indicator plants as a qualitative guide of site fertility, to more quantitative measures of soil and foliar nutrition that are typically conducted by local agricultural testing laboratories (Wilmot and Perkins 2004).

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