

**Effect of a soil calcium addition on the extension and radial growth rates of
American beech (*Fagus grandifolia*) saplings**

Suk-Ann Yee

Abstract Since the industrial revolution, acid rain has caused the leaching of nutrients such as calcium from forest soils, resulting in declines in the health and biomass production of northern US hardwood forests (Likens 2004). To reverse the effects of calcium loss, scientists added 50 tons of wollastonite (CaSiO_3) to the soils of a small watershed in Hubbard Brook Valley, NH in 1999. In July and August 2005, 100 American Beech (*Fagus gradinfolia*) saplings were harvested, 25 from each of four sites: upper control, lower control, upper calcium and lower calcium. I recorded the age, height, and diameter for each sapling, and determined the yearly extension and radial growth rates for the last 15-20 years. Due to the occurrence of a winter ice storm at the upper elevations in January 1998, saplings in these sections (upper control and upper calcium), had significantly higher radial and extension growth rates as compared to saplings in the lower sections of the watersheds. Although increased calcium concentrations in leaf samples show that soil calcium is being taken up by the saplings, any impact of the calcium on growth rates is being drowned out by other local environmental factors (climate, site-to-site differences).

Introduction

Acid rain from anthropogenic sources has impacted the ecosystems of northeastern United States since the mid- 20th century (Likens and Bormann 1974). The acidity is the result of a reaction between sulfates and nitrates, released through the burning of fossil fuels, and water in the atmosphere. Acid rain has resulted in the degradation of buildings, health problems such as asthma and bronchitis, and decreases in air visibility (EPA 2005). Acid rain also affects forest ecosystems by causing nutrients to be leached from watershed soils into streams, and by releasing toxins, such as aluminum, into forest soils (Likens et al. 1998). Likens et al. (1998) found that the amount of calcium sequestered in the soils of Hubbard Brook Valley, a northeastern forest ecosystem, decreased by four-fold between 1965 and 1969, from 202 to 54 mol/hectares due to acid rain.

The intensity of soil calcium depletion is dependent upon the buffering capacity of local soils. Areas with high base nutrient content (Calcium, Magnesium, and Potassium) may show few effects from acid rain, because these ions buffer the effect of the leaching. However areas with lower base nutrient content are highly affected by acid rain because tree growth is limited by the amount of available Ca, Mg and/or K (EPA 2005). Because of the dependency on soil nutrient content, the effects of acid rain often take decades to show up in forest vegetation.

At my study site, the Hubbard Brook Experimental Forest in Campton, New Hampshire, the results of acid rain was not visibly noticeable until the 1980's. Through the 1960's and 1970's, Likens, et al. (1998) found that the rate of biomass accumulation in the Hubbard Brook valley was 4.85 Mg/ha-yr, but the accumulation rate slowed considerably after 1989 to 0.89 Mg/ha-yr, presumably due to soil calcium depletion. Although the enactment of the Clean Air Act in 1970 has diminished the intensity of acid rain, the effects of the leaching will take decades to reverse, as the replenishment of soil calcium through natural weathering sources will take a considerable amount of time (Tomlinson 2003).

Although acid rain is detrimental to forest ecosystems as a whole, some species are more susceptible than others. For example, sugar maple (*Acer saccharum*), a co-dominant species in the northern hardwood forest, has experienced decline in the health of mature trees, as well as a marked decrease in seedling survival rate due to acid rain (Hogan 1998). Less is known, however, about sugar maple's primary competitor, American beech (*Fagus grandifolia*).

Mature beech trees experienced high mortality due to an invasive insect-fungal disease complex first introduced in the mid-20th century. As a stress response to the disease, many of the trees began to put out root sprouts (Houston 1997). These root sprouts grew vigorously and now dominate the understories of many northern hardwood forests. Siccama (1997) found that the density of beech saplings in the 2-9 cm dbh (diameter at breast height) category increased five-fold between 1965 and 1997 in the Hubbard Brook valley. This cohort of root sprouts is a phenomenon that has been little studied. In 2002, Kobe et al. completed a study on the effect of calcium addition to tree seedlings and found that calcium has a significant impact on rates of sugar maple growth, but found no significant increase in growth rates of American beech. However, Kobe's study focused on beech seedlings, rather than saplings, which have deeper, more well-established roots. Because of its high frequency of occurrence in the understory, and its competitive interaction with the more frequently studied sugar maple, American beech is an ideal study species.

Scientists at the Hubbard Brook Ecosystem Study chose to address the issue of calcium depletion on the large scale by conducting a watershed soil calcium addition experiment. An amount of calcium comparable to twice the amount lost over the last 50 years, was added back to forest soils in the form of wollastonite ($\text{Ca}[\text{SiO}_3]$) in October 1999 (Likens 2004). The calcium was dropped via helicopter onto forest soils in the form of small white time-release capsules. It has now been seven years since the addition and we hypothesize that there should be detectable responses in forest growth and vigor. In this experiment, I assess the impacts of the calcium soil addition on the growth rates of American beech saplings. Growth rates tend to reflect environmental factors including large-scale, long term climatic events such as droughts, as well as local conditions such as the opening of a light gap in the canopy (Phipps 1985, Messier and Nikinmaa 2000). Because extension growth is more sensitive to local light variability than radial growth, I hypothesize that any effect the soil calcium addition has on beech health will be more apparent in radial than extension growth. The response of extension growth to local factors such as light availability will likely outweigh any response to the soil calcium addition. The creation of large canopy gaps, due to a winter ice storm in January of 1998, is the largest confounding factor in this study. The gaps are predicted to produce higher rates of growth in the upper elevations, which were particularly hard hit by the storm.

Methods

Study site: Field work was conducted at the Hubbard Brook Experimental Forest (HBEF), a deciduous second-growth forest located in the White Mountain National Forest in central New Hampshire. Last logged in 1917 (Bormann et al. 1994), the forest is even-aged and composed predominately of hardwoods, interspersed with conifer stands at higher elevations. Dominant hardwood species include American beech (*Fagus grandifolia*), sugar maple (*Acer saccharum*), and yellow birch (*Betula alleghaniensis*) at lower elevations, and white birch (*Betula papyrifera*), in the upper elevations. Conifer stands are dominated by red spruce (*Picea rubens*), and balsam fir (*Abies balsamea*). Between 1965 and 1997, the density of beech in the understory has increased fivefold due to root sprouting of mature beech trees. There has been a corresponding decline in sugar maple and red maple saplings (Hane 2003). The HBEF offers a unique research opportunity due to the availability of an extensive amount of forest composition and nutrient cycling data collected over the last half-century.

Sapling collection: In July and August 2005, 100 beech saplings were collected from two watersheds located in the HBEF. Fifty saplings were collected in a reference area, west of Watershed 6 (W6), and 50 saplings were collected from Watershed 1 (W1), to which calcium had been added in the form of wollastonite in October 1999 (Fig. 1). Saplings were chosen at 25 m intervals along a series of transects as the nearest healthy sapling between 1 and 4.5 cm dbh. In W1, the 50 collection points correspond to an already established, 25x25m plot grid. In each watershed, the 50 trees were divided into two groups--upper watershed and lower watershed--in order to control for the effect of an ice storm that occurred in January 1998. The storm caused high mortality and breakage at upper elevations, creating large canopy gaps. This partitioning of sapling collection sites should aid in separating the effect of increased light from any calcium effect on beech sapling growth rates. An effort was made to avoid taking saplings from under rare instances of intact canopy at upper elevations, as well as saplings from under rare large canopy gaps at lower elevations.

Saplings were stripped of branches while in the field, leaving the longest branch for extension growth assessment. Once removed from the field, sapling boles were cut into sections roughly 137 cm in length to facilitate handling, extension growth was measured, and two cross-sectional “cookies” were taken, one from the base of the sapling and one at breast height (137

cm). The sapling sections were bundled and are being stored at the Hubbard Brook facilities in the event they are needed for chemical analysis or further assessment.

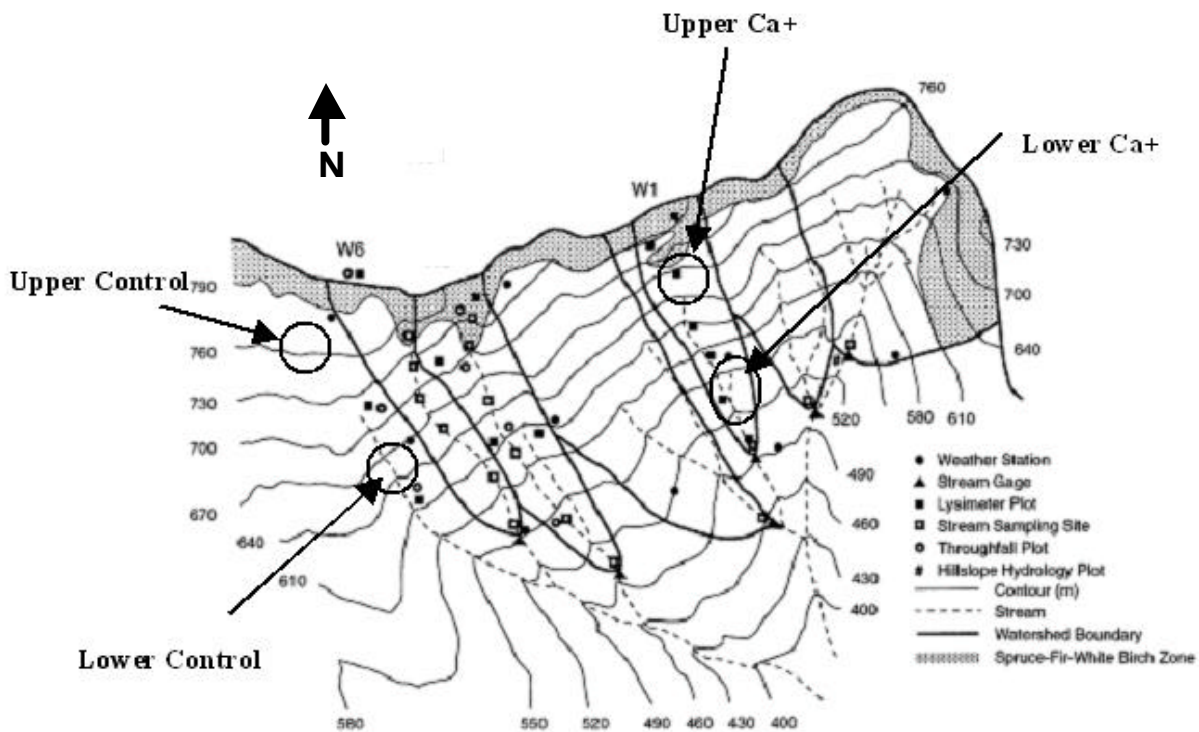


Figure 1. South-facing watersheds of the Hubbard Brook Experimental Forest, where the saplings were harvested. W1 is the calcium addition watershed. West of W6 is the control watershed.

Extension growth The amount of vertical growth experienced by the longest leader, or branch, of a sapling each year is referred to as extension growth. The beginning of a year of growth is denoted by the presence of bud scars that encircle the circumference of the branches or bole of a sapling. Extension growth can be read anywhere from 7 to 30 years back from the harvest date depending on rates of growth; the more rapid the growth rate, the more difficult it is to read older scars. Scars were read with the naked eye, or with the aid of a magnifying glass.

Radial Growth Tree rings are a result of the alteration between wide earlywood cells, produced at the start of the growing season, and shorter latewood cells, produced near the end of the growing season. The age of the sapling was determined by counting the number of rings in a cross-sectional cookie taken from the base of the sapling. Although accurate for aging purposes, rings measured at the basal cross-sectional cookie can vary in width depending on the height at which the cookie was taken. Therefore, the widths of the rings in a cross-section taken at breast height were measured and used to assess the environmental conditions under which the saplings

grew. Because the cross-sections tend not to be perfectly symmetrical, I choose to take measurements on a radial line that was the average of the longest and shortest radii in length.

Results

Sapling Statistics Harvested trees were primarily grouped between 1.5-3.5 cm in diameter at breast height (dbh), although about a quarter lie out of this range (Fig. 2a). The outer bounds are 1.0 and 4.2 cm in dbh. As the harvested trees were chosen by dbh size, there is little variation in sapling diameter and the distribution is a regular one. Much more variable was sapling height, with the harvested trees falling anywhere between 2.67 and 8.93 meters in height, although most trees are considerably shorter than the upper limit (Fig 2b). There was also a high amount of variation in the age of the saplings which ranged from 13 to 58 years old. Over 50% of the saplings were between 30 and 40 years old, and most of the rest were younger than 30 years (Fig 2c).

Because the harvested saplings were

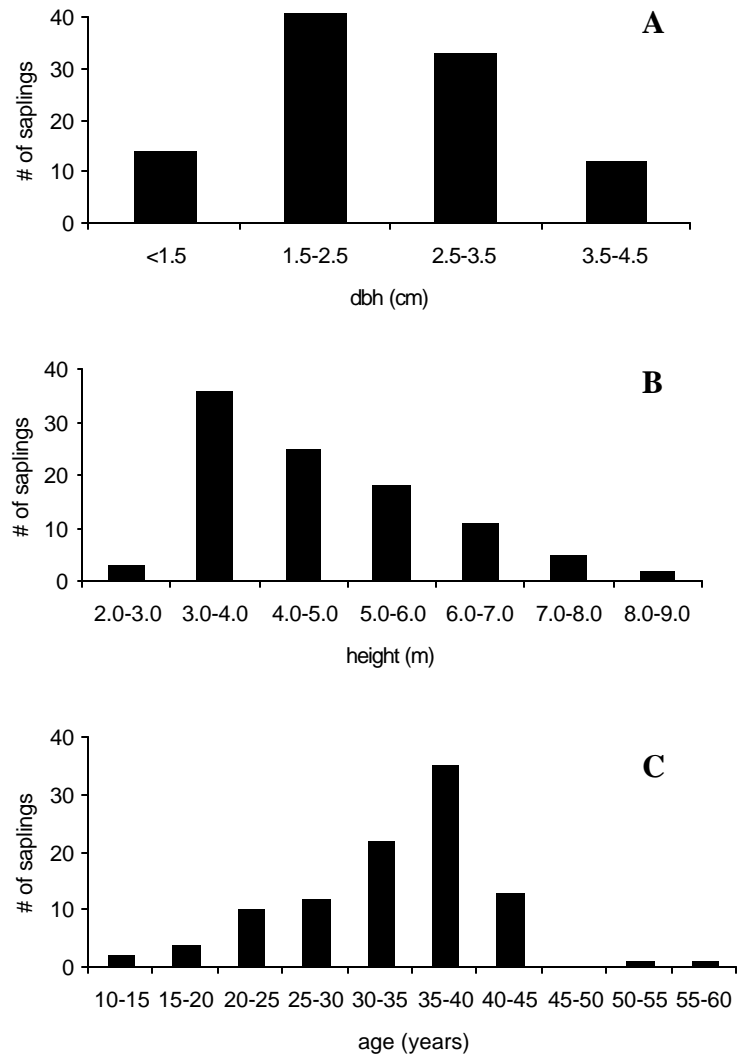


Figure 2. Diameter (A), height (B) and age (C) distributions of the 100 saplings harvested from the two watersheds.

Table 1: the average dbh, height and age (with standard errors) of the saplings in each of the 4 harvesting

Watershed	Average DBH (cm)	Average Height (m)	Average Age (yrs)
Upper Control	2.5 ? 0.16	5.54 ? 0.26	34 ? 1.98
Upper Calcium	2.36 ? 0.17	4.33 ? 0.21	31.6 ? 1.62
Lower Control	2.44 ? 0.17	4.5 ? 0.33	33.5 ? 1.11
Lower Calcium	2.32 ? 0.14	4.76 ? 0.24	36.2 ? 1.05

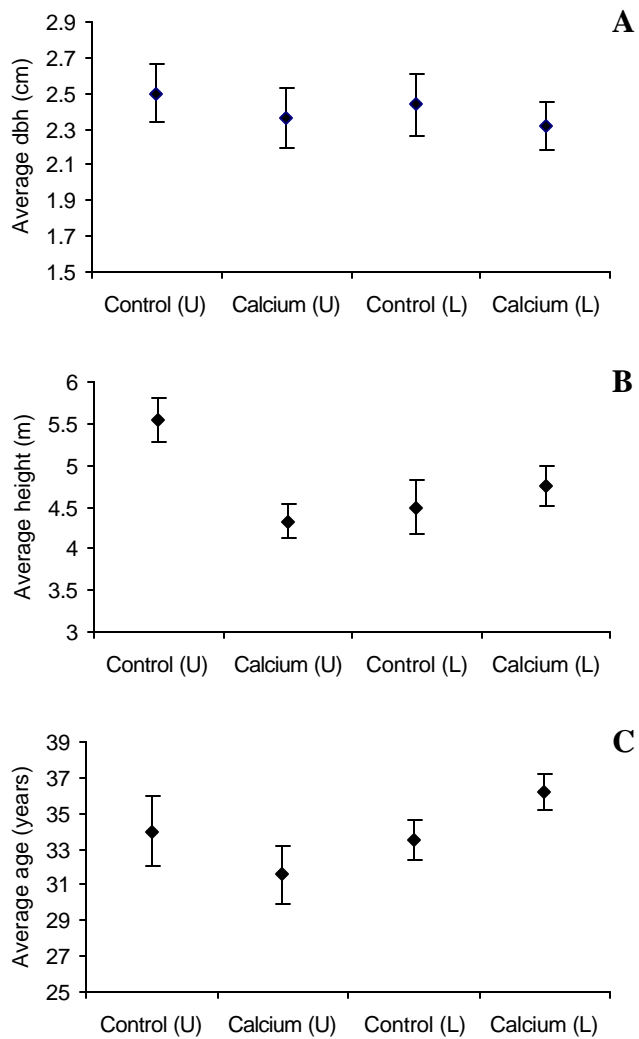


Figure 3. The average dbh, height and age of the saplings in each of the harvest areas.

selected by dbh, the average dbh for each harvest area was comparable across harvest sites. (Table 1, Fig 3a.) There was more variation in the average height and age of the harvested saplings in each area (Fig 3b and 3c), with the trees in the lower calcium addition watershed being about 2 –5 years older than the other trees on average. Although the average height of the harvested trees in each of the four areas were in the 4-6 meter range, the average height of the upper control site is higher than all of the others by ¾ of a meter (Fig 3b).

Height and age of each sapling were plotted against the dbh to determine what type of correlation, if any, exists between these variables (Fig. 4). On average, a one cm increase in diameter corresponds to approximately 1.36 meters of growth in height and about 4.6 years in age. The correlation between dbh and height was

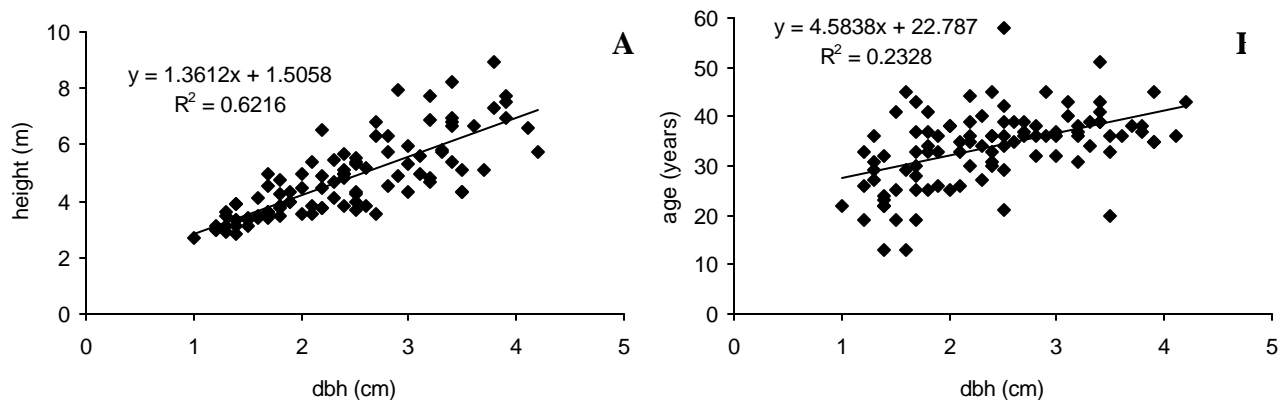


Figure 4. correlation between dbh and height, and age and height in harvested saplings.

strongest ($R^2=0.62$) with the points from individual trees being closely clustered for the lower values (smaller, shorter saplings) but fanning out for larger values of height and dbh (Fig 4a). The correlation between dbh and age ($R^2=0.23$) is less than the correlation between dbh and height (Fig. 4b). There are several outliers which indicate the presences of some very old, but relatively skinny trees (2.5 cm dbh, 58 years), as well as the occurrence of very young trees of the same size (2.5 cm dbh, 21 years).

Figures 5-7 show the average yearly radial growth rates of the harvested saplings over the last 20 years. Prior to the calcium addition and the ice storm, average rates range from 0.2-0.6 mm per year. After the disturbances, growth rates increase to up to nearly 1 mm of width per year. Focusing on the radial growth rates prior to the ice storm, it is evident that, though there is some site to site variation, rates tend to be relatively constant, and similar across all four harvest sites. After the winter ice storm of 1998, growth rates in the upper watersheds increase noticeably (Fig. 5). T-tests show that there is a significant difference in the average radial growth rates between the upper and lower watersheds after the 1998 ice storm, when prior to the storm, there is no significantly detectable difference. Post-ice storm, growth rates in the upper

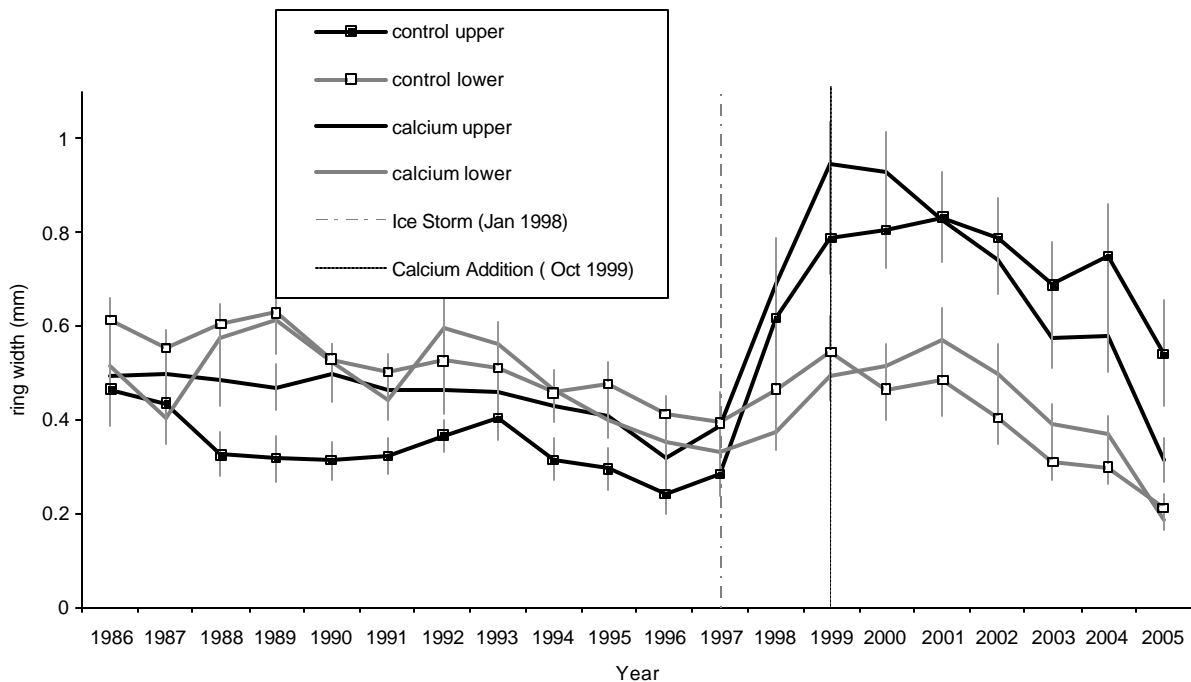


Figure 5: Average radial growth rates and standard errors in each of the four harvest sites

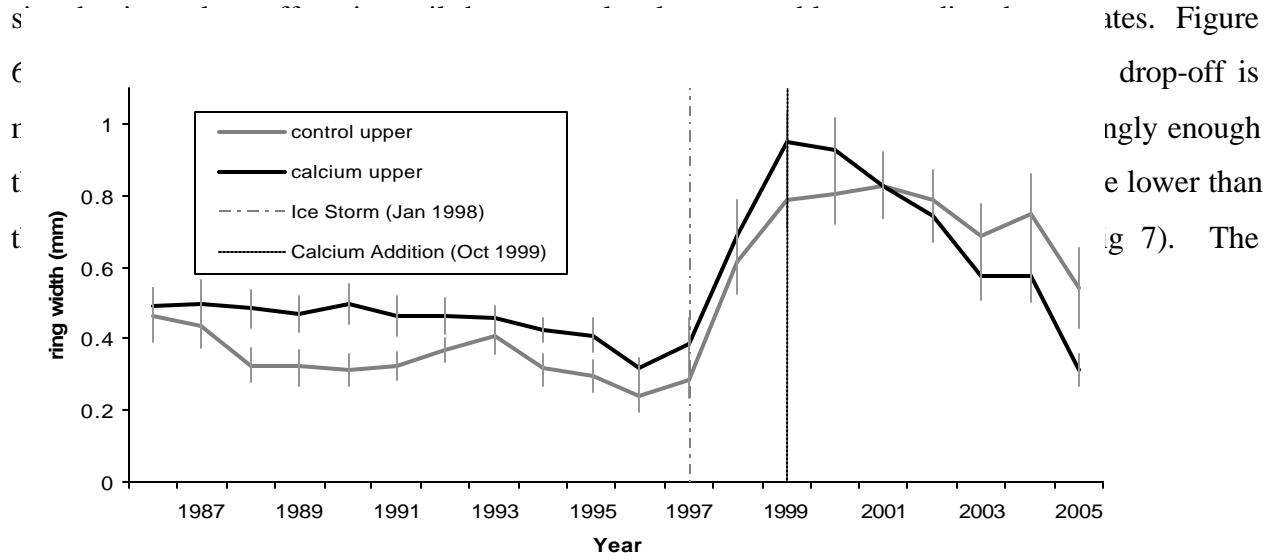


Figure 6: Average yearly radial growth rates in the upper section of the watersheds.

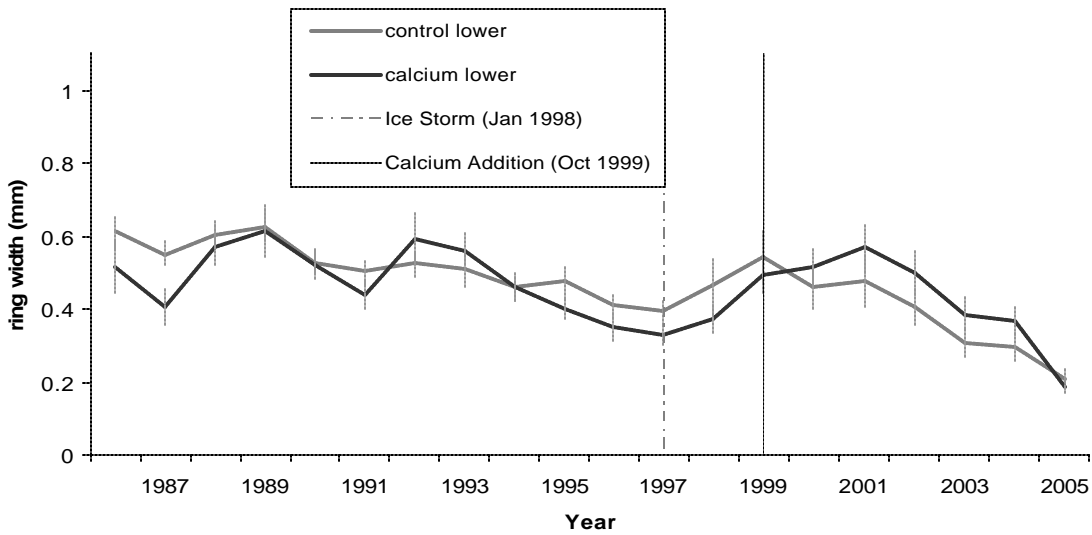


Figure 7: Average yearly radial growth rates in the lower section of the watersheds.

radial growth rates of the lower sites also appear more variable from year to year than the growth rates in the upper sites. The results of the calcium addition are not readily detectable by eye in either graph, especially in the lower sites where the calcium addition line crosses the control line several times.

The extension growth rates over the past 15 years exhibit a similar trend to the radial rates, but the results are less clear (Fig 8-10). Average yearly growth rates range from 10 cm to 24 cm, with just as much variation occurring before the storm as after. Prior to the ice storm, there appears to be some site to site variation, but general trends are similar across sites. There is a general downward trend in the pre-disturbance timeframe between 1990 and 1998, most clearly shown in the lower watersheds in Figure 10. Post-ice storm, the growth rates of the upper watersheds separate themselves from the growth trends of the lower watersheds, but are not significantly higher than pre-disturbance rates. Whereas there was a drop off in radial growth rates after the initial increase post-ice storm, extension growth rates in the upper watersheds remain relatively level after 1999 (Fig 9). Figures 9 and 10 show the high level of variation between the calcium and control sites in the upper and lower areas of the watersheds.

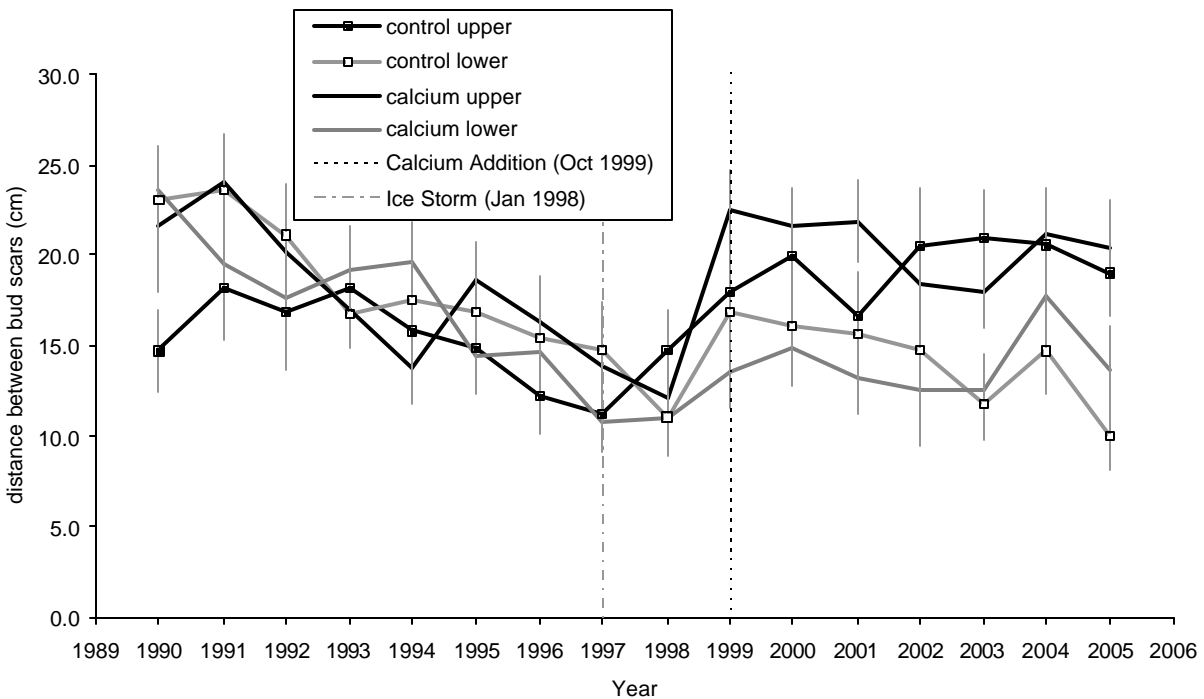


Figure 8: Average yearly extension growth rates and standard errors in each of the four harvest areas.

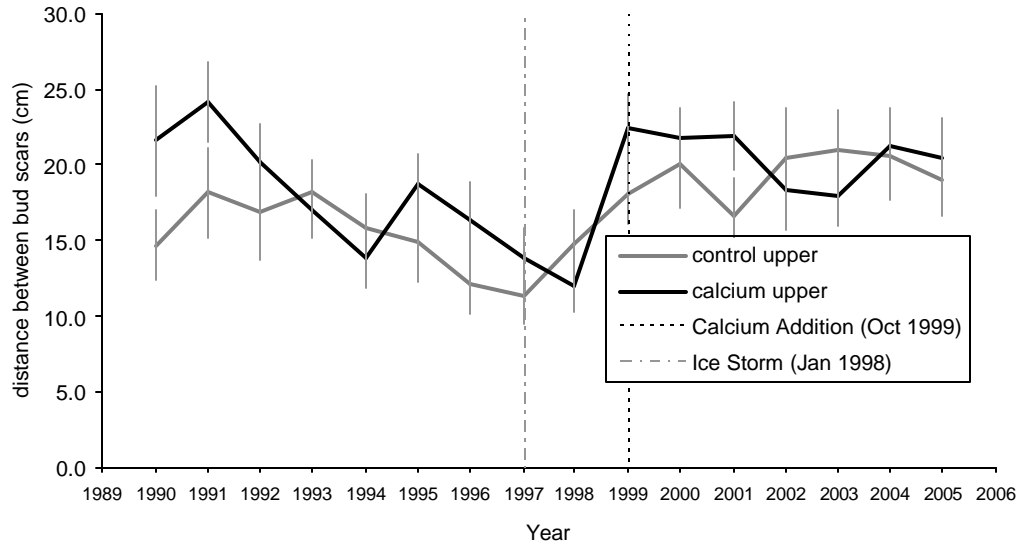


Figure 9: Average yearly extension growth in the upper section of the watersheds

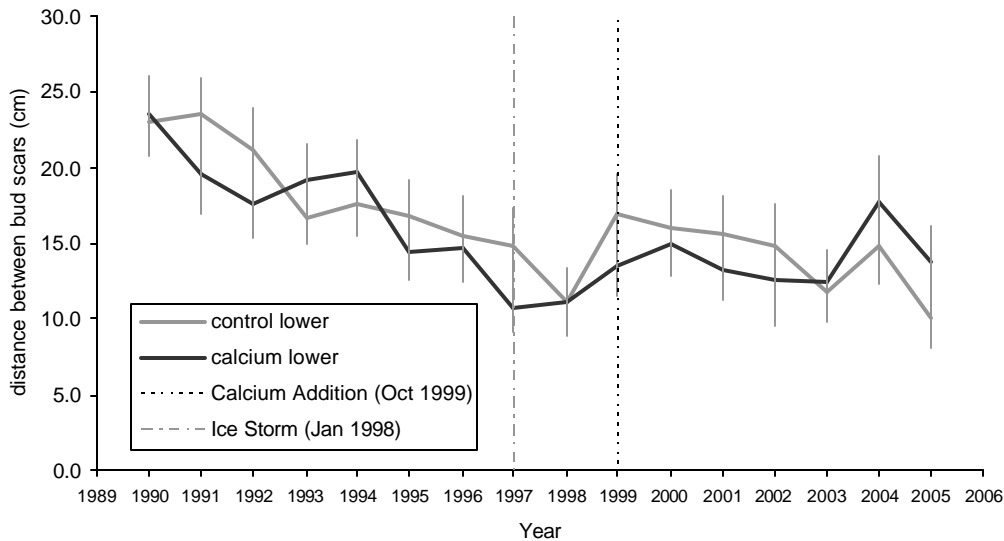


Figure 10: Average yearly extension growth in the lower section of the watersheds

Discussion

Because this experiment could not be conducted using two identical watersheds, I begin with a discussion of some of the differences between the four harvesting sites. The control watershed had a sapling density of 2913 stems/hectare in 1998 whereas the calcium addition watershed had a sapling density of 2198 stems/hectare (saplings in this case are defined as trees between 2-9 cm

dbh) (Siccama and Denny 2004). Because denser forests create more competition in the understory for scarce light resources, the trees in the control watershed tend to be taller and skinnier than those in the ca+ watershed. Also of note is the origin of these trees. Most are root sprouts which grew as a stress response by dying mature beech trees to an invasive insect-fungal complex called beech bark disease. As a result the saplings all tend to be roughly the same age (between 30-40 years) and form an unusually dense understory (Houston 1979).

As expected, the height of a tree is quite closely correlated with its diameter at breast height since trees tend to grow wider as they grow taller (Figure 4a). The correlation is tighter in the smaller saplings because they tend to be younger and less affected by site to site variations in light and nutrient availability. As the trees grow older, environmental factors can create tall skinny trees as well as short, wide ones. There is less of a correlation between age and dbh because of the plastic growing characteristics of American beech saplings. In a dense understory, saplings may remain stunted for many years, growing sideways in search of light (Messier and Nikinmaa 2000). Once the canopy opens though (through the mortality of a canopy tree), growth levels can increase quite suddenly and dramatically as saplings take advantage of the light availability. The outliers in Figure 4b suggest that some of the saplings may have been taken from resource rich environments where a 21 year old sapling has a dbh of 2.5 cm, the same dbh as another of the outliers which was 58 years in age and probably stunted by lack of light availability or access to other resources.

Although there is a good deal of individual sapling growth rate variation from year to year, an average of these growth rates per sapling area can be used to compare differences in growth rates in each sampling site. The difference that is most apparent is that of the ice storm, which occurred in January 1998. During the storm, ice crystallized on the canopy of the forest at a specific elevation band (the upper sapling area, in this study). Due to high winds, many canopy trees fell, leaving large gaps in the canopy at the upper elevations. In response, understory saplings immediately took advantage of the high light availability and growth rates increased rapidly (Figures 5 and 8). The radial increase was immediately apparent in the 1998 growth season, whereas the increase in extension growth did not appear until the 1999 growth season. This discrepancy can be explained by the inability of buds to take advantage of sudden changes in light availability because they are set at the end of the previous growth season (Denny, pers comm.). Another hypothesis is that the buds were damaged during the ice storm, so that the

increase in light availability was not taken advantage of until the next year. The effect of the ice storm is much more prevalent in the upper watersheds because this is where much of the tree mortality occurred. The trees harvested from the lower section of the watersheds were relatively unaffected. The increase in radial growth rates due to the ice storm is much more apparent in the radial growth than the extension growth. Because of the high mortality of canopy trees from the ice storm, understory trees gained access to unexpectedly high levels of light. Since extension rates represent the beech trees search for light for photosynthesis, it is not surprising that given this access to light, they no longer need to put much energy into extension growth rates as the light requirement is saturated. More resources are allocated to radial growth and thus the increase is more apparent in the radial growth rates than the extension rates.

The decrease in radial growth rates after the ice storm is likely a result of the growing in of the canopy by beech saplings slightly larger and taller than those harvested for this study (Figure 7). As light levels dropped off, growth rates dropped as well. This drop is particularly steep in the calcium addition watershed where the canopy is visually growing in much more quickly than that of the control watershed. The upper sections of the control watershed is also experiencing high rates of paper birch, *Betula papyrifera*, mortality, which may account for the more open canopy. The corresponding lack of a drop off in extension growth rates is probably due to the fact that light levels have not decreased to a level that is affecting branch length or photosynthesis rates so that the saplings are forced to re-allocate resources away from extension growth rates.

Figure 8 shows extension growth rates starting up high, at about 24 cm/year and then dropping to 10 cm before the ice storm. Rather than attributing this decrease to environmental factors, I would suggest that this drop is in fact partly due to human error and the limitations of this analysis. Bud scars tend to become harder and harder to read as one moves backwards along the bole of a tree. It is likely that 10-15 years back along the trunk, some bud scars weren't readily apparent and were skipped and unread, resulting in longer sections of growth than might otherwise be found if the scars were more concrete. Large scale climatic trends may contribute to this downward trend, but more than likely it is largely a result of human error and the constraints of reading bud scars. The first 10 years of growth though, tend to be highly accurate, and the response to the ice storm in extension growth is unmistakable.

The differences in local environment, as well as the occurrence of local disturbance events, such as the ice storm, make it difficult to accurately assess the effect of the calcium addition on the sapling growth rates. Calcium from the soils is being absorbed by the beech saplings as evidenced by increase calcium concentration in beech sapling leaves (Siccama, pers. comm.) However any effect on growth rate proves difficult to identify concretely. However, it is a known fact that beech trees are much less sensitive to calcium concentrations than the other dominant tree in the northern hardwood forest- sugar maple, *Acer saccharum*. In response to the soil calcium addition in 1999, the health and vigor of the sugar maple canopy has increased, and there has been a larger number of sugar maple seedlings and saplings found in the understory of the calcium addition site. Further analysis needs to be completed to study the interaction between sugar maple and American beech in these unique conditions. This coming summer, further research will be conducted to quantify light availability at each of the individual harvest sites in order to account for some of the site to site variation. Perhaps this study, repeated several years down the line, with a larger sample size, might also yield clearer results. Nevertheless, this study shows the sensitivity of American beech trees to local environmental conditions and helps quantify the characteristics of this unique cohort of beech saplings.

References

- Denny, E. and T.G. Siccama. 1996. Beech Hell in a Nut Shell. The ingrowth and upgrowth of a thicket understory of Beech (*Fagus grandifolia*) in the Northern Hardwood forest at Hubbard Brook. Unpublished article.
- Environmental Protection Agency. January 2005. Acid Rain. <http://www.epa.gov/acidrain>
- Forrester, J.A., and J.R. Runkle. 2000. Mortality and replacement patterns of an old-growth Acer-Fagus woods in the Holden Arboretum, northeastern Ohio. *Naturalist* 144:227-242.
- Griffin J.M., G.M. Lovett, M.A. Arthur, and K.C. Weathers. 2003. The distribution and severity of beech bark disease in the Catskill Mountains, NY. *Canadian Journal of Forest Research* 33:1754–1760.
- Hane, E.N. 2003. Indirect effects of beech bark disease on sugar maple seedling survival. *Canadian Journal of Forest Research* 33:807-813.
- Hogan, G. D. 1998. Effect of simulated acid rain on physiology, growth and foliar nutrient concentrations of sugar maple. *Chemosphere* 36:633-638.
- Houston, D.R. 1997. Beech bark disease. USDA Forest Service, Hamden, CT. (<http://www.invasive.org/symposium/houston.html>)

- Hubbard Brook Long Term Ecological Research Site. 2001. Research and Data: Overview. (<http://www.hubbardbrook.org/research/overview/hbguidebook.html>).
- Kobe, R.K., G.E. Likens, and C Eager. 2002. Tree seedling growth and mortality responses to manipulations of calcium and aluminum in a northern hardwood forest. *Canadian Journal of Forest Research* 32: 954-966.
- Latty E.F., C.D. Canham, and P.L. Marks. 2003. Beech bark disease in northern hardwood forests: the importance of nitrogen dynamics and forest history for disease severity. *Canadian Journal of Forest Research* 33:257-268.
- Likens, G. E. 2004. Some perspectives on long-term biogeochemical research from the hubbard brook ecosystem study. *Ecology (Washington D C)* 85:2355-2362.
- Likens, G. E., and F. H. Bormann. 1974. Acid rain - A serious regional environmental problem. *Science* 184:1176-1176.
- Likens, G. E., C. T. Driscoll, D. C. Buso, T. G. Siccama, C. E. Johnson, G. M. Lovett, T. J. Fahey, W. A. Reiners, D. F. Ryan, C. W. Martin, and S. W. Bailey. 1998. The biogeochemistry of calcium at Hubbard Brook. *Biogeochemistry (Dordrecht)* 41:89-173.
- McGee, G.G., D.J. Leopold, and R.D. Nyland. 1999, Structural characteristics of old-growth, maturing, and partially cut northern hardwood forests: *Ecological Applications* 9:1316–1329
- Messier, C., and E. Nikinmaa. 2000. Effects of light availability and sapling size on the growth, biomass allocation, and crown morphology of understory sugar maple, yellow birch, and beech. *Ecoscience* 7:345-356.
- Phipps, R. L. 1985. Collecting, preparing, crossdating, and measuring tree increment cores. U.S. Dept. of the Interior, Geological Survey. *Water-Resources Investigations Report* **85-4148**.
- Rhoads, A.G., S. P. Hamburg, T.J. Fahey, T.G. Siccama, E. N. Hane, J.J. Battles, C. Cogbill, J. Randall, and G. Wilson. 2002. Effects of an intense ice storm on the structure of a Northern hardwood forest. *Canadian journal of Forest Research* 32 (10): 1763-1775.
- Siccama, T.G. and Denny, E. 2004. Interactive Biomass Program. <http://www.hubbardbrook.org/yale/watersheds/w6/biomass-stop/biomassw6.htm>
- Tomlinson, G. H. 2003. Acidic deposition, nutrient leaching and forest growth. *Biogeochemistry (Dordrecht)* 65:51-81.