

Forest and Terrestrial Systems

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What I am going to be talking about this afternoon has been touched on in some of the other talks. I am going to be giving a little bit more detail, and I am also going to try to highlight some of the scientific progress, since 1990.

That was brought up earlier this morning, and scientists do feel that we have made quite a bit of progress since 1990, the last big NAPAP assessment, particularly in terms of understanding the extent of effects.

We have that better defined now, and also in terms of understanding the processes that have been affected by acid rain. That is extremely important in terms of evaluating the potential for recovery.

The topic is a little more narrow than shown in the handouts. I am going to specifically be talking about forests, soils and trees. This is where the majority of the terrestrial effects research has been done.

If we use 1990 as our baseline, we can say, since then, that we have developed a much better understanding of soil processes and how changes in soils are linked to changes in surface waters.

In 1990, there had not been good documentation of changes occurring in soils as a result of acid rain, something that had been suspected since the 1970s, but by 1990, still really hadn't been proven.

Also, in the 1990 assessment, the only tree effect that they talked about was high elevation red spruce, which was felt was clearly the result of acid rain, but the mechanisms weren't all that well understood at that time.

I will jump right in first with the soil side of things. You can look at the effects of acid rain on soil, really, in terms of three primary changes.

Again, these have already been touched on earlier today. The first one is depletion of calcium from the soil. This is very important in terms of evaluating recovery potential. I will get into that a little bit more. It is something we weren't aware of in 1990.

The second change – mobilization of inorganic aluminum is something we actually were aware of as early as 1980, but how that mobilization of

aluminum interacts with calcium in the soils is something we have a little better handle on today.

I need to make sure that I am clear on the distinction of why I am referring to it as inorganic aluminum.

As was mentioned earlier, aluminum is very common in most soils, but if it is not mobilized, it is not harmful. In some cases, it can be naturally mobilized by organic acids, but what you form is organic aluminum, and that form generally is not toxic to aquatic life and doesn't cause a problem for tree growth.

Now the third change, accumulation of sulfur and nitrogen. In 1990 the widely held view was that deposition of sulfur – I am referring to northeastern soils that don't have the absorption capacity that the southeastern soils have, that Art Bulger mentioned earlier – the sulfur coming in as sulfuric acid basically passes through the soils and goes right into the streams.

It was also felt that the nitrogen being deposited, in terms of its effects on surface waters, was a similar direct effect, primarily the result of nitric acid building up in the snow pack in the spring, and then being released quickly as the snow melted, causing acidification episodes.

We know now that in both the cases of sulfur and nitrogen, that the system is quite a bit more complicated than that, and I will talk a little bit more about that as well.

I would like to go over why calcium is important in natural ecosystems, particularly terrestrial ecosystems.

Calcium is essential for wood formation in trees. Trees have a very high demand for calcium. If they don't have enough calcium, they don't grow at as fast a rate.

Calcium in the soil also is very important. It is the primary element that neutralizes acidity, whether the acidity was generated through natural organic acids in soil or by acid rain. If there is sufficient calcium in the soil, the acidity will be fully buffered.

Also, something that hasn't been touched on

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much, calcium is an essential nutrient for aquatic plants and animals.

We talk about the effects of acid rain on aquatic ecosystems in terms of toxicity and so forth, but related to the issue of recovery, we have less and less calcium going into our aquatic systems, and that is undoubtedly having a more subtle effect on the productivity of these systems.

Now, I mentioned that we suspected a problem with acid rain effects on soils as early as the 1970s, and some of you are probably wondering after more than 20 years, why didn't you figure it all out sooner.

The biggest reason was a lack of historical data. Soil science in this country is a fairly new science, and there really was no pre-acid rain data that we could compare to.

This was changed by a study done out of the University of Pennsylvania. They were able to repeat the sampling of one of the earliest forest soil studies in the country, which was conducted in the Adirondack Mountains.

They determined, using the original laboratory methods, that there was about this much calcium, referred to as acid-extractable calcium, in the Adirondack soils between 1930 and 1932 (Figure 1).

That individual point right there represents a large number of sites, over 50 sites scattered throughout the Adirondacks.

The group at the University of Pennsylvania went back and re-sampled these sites, duplicated the original methods and came up with the 1984 value.

You can see a drop from about 80 to 50, indicating fairly strong evidence that there is less calcium in the Adirondack soils than there was in the 1930's.

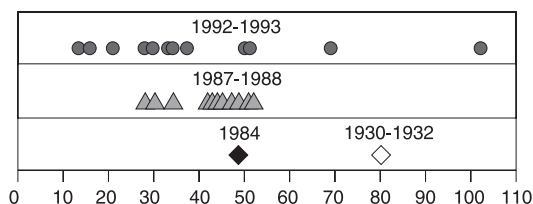


Figure 1. Acid-extractable calcium in millimoles per kilogram.

Also shown on this figure is a study up on the top bar, that was done in the 1990s to evaluate what the range in calcium concentrations was throughout the northeast.

The sites were specifically selected to see how broad a range we had. You can see that the value in the Adirondacks falls pretty much in the middle of the range. So, that Pennsylvania study wasn't presenting data that was atypical to the northeast. Results of an additional study are also presented there in the third bar.

That really is the closest thing we have to being able to evaluate what soils look like before acid rain in this country.

Even though we don't have much historical data in the United States, we have been getting a better handle on the processes involved, how these soils may be changing and how the calcium in different horizons relate to each other.

This particular graph shows data collected at those same spruce sites that were selected over the northeast to determine the range in soil variability (Figure 2).

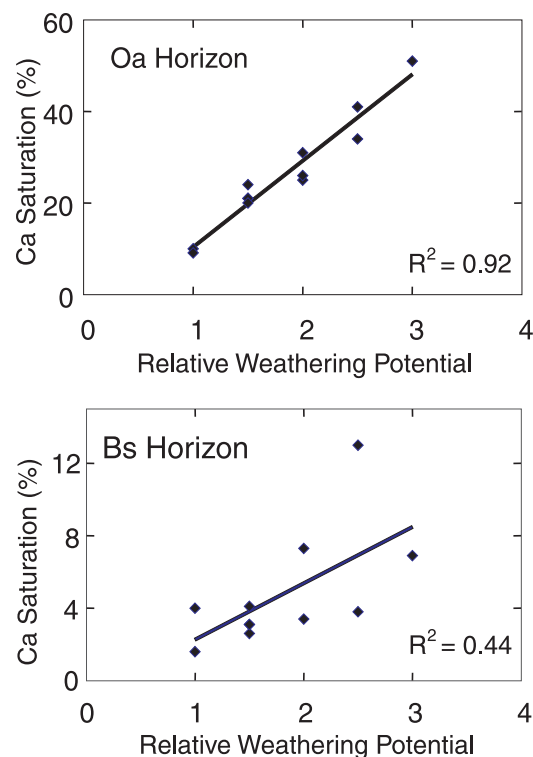


Figure 2. Oa and Bs horizon of Northeastern spruce tree sites.

This is the amount of calcium in the soil plotted versus relative weathering potential. I think most of you are familiar with the fact that differences in mineralogy affect the availability of calcium.

Certain types of rocks produce calcium that is available for plants and for leaching into surface waters, at higher rates than others.

The weathering potential, or the calcium availability, was plotted versus the amount of calcium. This is in the O horizon, the top surface horizon that is formed by organic materials, leaves and branches falling down and so forth.

The calcium that you see here was actually taken up by roots into the biomass and then deposited to form this OA horizon.

You can see that the amount of calcium is very, very strongly related to the weathering potential, how much calcium can be released from the rocks at this site. This is what you would expect, although this is an organic horizon.

In the mineral horizon directly below it, which is the ultimate source of this calcium, you would expect to see a very similar relationship, but actually you don't.

There is a correlation there, a positive correlation, but it is much weaker than it is for the upper organic layer.

This is getting into the details a little bit further, but basically what this suggests is that the calcium in this mineral horizon, in the B horizon, has been depleted to a level where the mineralogy is no longer as clearly reflected.

As you lower the calcium to a certain level you begin to mobilize aluminum.

The aluminum starts to control the chemistry and basically the aluminum buffers any further decreases in calcium. So, you get into that range where aluminum is mobilized and you lose the signal between the calcium and the type of parent material that is there.

The reason this happens in the mineral soil rather than the organic layer above, is that the organic layer is where there is very, very intense root activity, a recycling of the calcium.

These sites are all pretty low in calcium, so as soon as the plant material decomposes and releases some calcium, there are plenty of roots there to

grab it, and that prevents it from leaching out of the soil.

In the deeper soil, this recycling by roots is not nearly as strong. Therefore, we end up with the differences between the two horizons.

I am going to get a little bit more technical here and talk about aluminum mobilization. So, as we are depleting the calcium, we get to a point where the pH of the soil decreases and aluminum enters soil solution.

Basically, this can be looked at in terms of the difference between the base cations and the acid anions. Among the base cations, calcium is typically the most abundant. So, we usually talk about base cations in terms of calcium. Magnesium is also important, particularly for tree growth, but it is not as abundant, potassium as well. In a situation that is well buffered, the sum of the base cations are much higher than the acid anions and aluminum just stays put and doesn't cause a problem. As you get closer and closer between these two amounts, that is when you begin to see aluminum appearing in the soil solution.

This is the sort of result you get in terms of aluminum to calcium ratios. Quite a bit of work has been done in the laboratory to evaluate the effects of aluminum to calcium ratios on growth of various tree species. It has been difficult to do *in situ* studies because of the nature of trees being large and growing so slowly, but the greenhouse experiments pretty clearly show that if you get an aluminum to calcium ratio of greater than one, you are going to be impairing the growth of the tree.

Here are average values for all those northeastern spruce sites. In the OA horizon we have a range from 0.1, which is very healthy, to 2.2, which is not (Table 1).

Then you look at the B horizon, and, as I said, the B horizon has been affected to a greater extent, and you see that even the lowest number is still over that threshold of 1.

I want to look at it in terms of what happens to the soil water when it moves into the streams. You heard about how aluminum is toxic to fish.

As this difference between the base cations and acid anions decreases from high numbers down toward zero, the inorganic aluminum concentra-

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Table 1. Aluminum to calcium ratio (mol/mol).

	<u>Oa Horizon</u>	<u>B Horizon</u>
<u>Spruce Stands</u>		
Soil Solution	0.1 - 2.2	2.3 - 12
Exchange sites	0.1 - 3.8	3.0 - 35
<u>Hubbard Brook</u>		
Exchange sites	0.3	5.7
<u>Winnisook</u>		
Exchange sites	1.9	24

tion increases abruptly and you cross this toxic threshold.

This is the threshold for brook trout, which is one of the most acid tolerant species. So, once you get across that line, you are really going to have problems with your fish populations.

Now I would just like to shift to the third item I had listed in terms of soil changes, the effects of acid rain on sulfur and nitrogen in forest soils.

We knew that sulfate could accumulate in the southern forests through absorption, but it was really not well understood that sulfur could accumulate in soils of the northeastern region.

Most of the attempts at doing sulfur balances through the 1980s showed that the sulfur in, more or less balanced the sulfur out.

This graph shows that the total sulfur in soil versus the atmospheric deposition is actually very strongly correlated (Figure 3).

There does seem to be a mechanism for accumulation of sulfur within the soil, but the sulfur doesn't necessarily stay there indefinitely. It does seem to be gradually working its way out, particularly in situations where you have an extended dry period followed by some rain. That seems to release some of this sulfur and, every time it does, you get a very severe acidification episode.

We look at nitrogen. Nitrogen is a little bit different. Under pristine conditions, it is the growth limiting nutrient in forest ecosystems.

It also is accumulating in forest soils to the point where some of these forests do not seem to be very effective at retaining nitrogen, or at least not as effective as they used to be, in which case it behaves similarly to sulfur. You get a dry period followed by a wetting up and you can release a lot

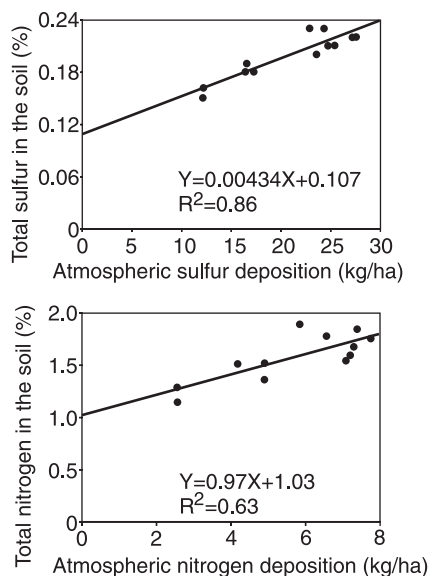


Figure 3. Soil chemistry in spruce forests (NY, VT, NH, ME).

of nitrate as nitric acid, and you get your acid episodes in stream water. These can occur any time of the year, and they still do occur during spring snowmelt as well.

Just to summarize the current status of the watershed budgets for sulfur and nitrogen, because they do look a little different than we used to think they did, the outputs of sulfur are currently exceeding the inputs.

That means if we shut off any inputs of sulfur and acid rain tomorrow, we would still be losing some sulfur into the surface waters as sulfuric acid. As we are doing that, we are continuing to put a drain on the base cations.

The same thing with the nitrogen situation. As the nitric acid is formed and leaches into the surface waters, it is contributing to the calcium depletion problem.

If we want to think about recovery in terms of soils, we need to put this information into context. It is a difficult concept to define because we really don't know what the situation was prior to acid rain, but we are getting a pretty good understanding of the changes in soils that have occurred.

In regard to the magnitude of the changes, there is still a fair amount of uncertainty. The timing of the changes, did they happen quickly or

did they happen over a 50-year time period, is also quite uncertain.

We do know that the changes have occurred, and we do have some understanding of the mechanism. As a result, the models currently, such as the one that Dr. Driscoll presented this morning, present a much lower level of uncertainty than the models did back in 1990.

In 1990, the models did not assume changes in soils. Now they are incorporating these changes in soil, so we are making progress.

That is not to say that with Dr. Driscoll's model, all the uncertainty is gone. There is still a fair amount of uncertainty but there has clearly been progress.

This third item here, how much change has occurred through natural processes or land management, non acid rain issues. We know these are also factors.

Early on in acid rain research, it was felt that soils really didn't change much and that changes would occur typically over centuries, not decades.

We know that is not the case and that factors other than acid rain can change soils very significantly over decadal time scales. That also plays into any sort of assessment to determine recovery potential.

Now I will switch to tree responses. I am really going to limit it to just two trees. Work has continued on red spruce, as you heard, and sugar maple, but it really hasn't expanded beyond that point. So, we really can't talk about forest ecosystem effects, but we can talk about two very important tree species in the forest.

This plot shows, in the top box, the incidence of winter injury, reported winter injury in the northeast (Figure 4). Extremely cold temperatures end up killing the current year needles of the red spruce trees.

Some pretty conclusive evidence has demonstrated that this is the result of acid rain, through interactions of the needles with acidic mist and fog and so forth.

We also can say with a fairly high level of confidence that the changes in soils that I have been talking about have also reduced the stress tolerance of red spruce trees and contributed to some of this.

We have a good record of the fact that the red

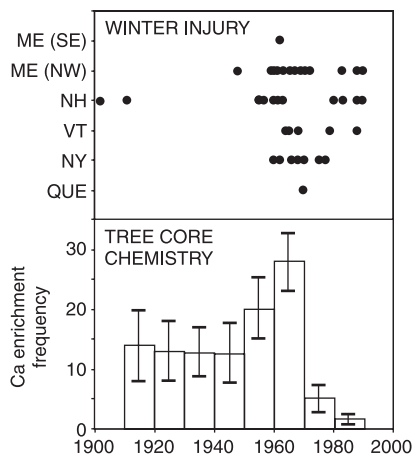


Figure 4. Relationship between tree core chemistry and winter injury in red spruce trees (NY, VT, NH, ME).

spruce trees have responded physiologically to changes in soils. That is what is shown in this lower panel.

Without getting into the complexities of this vertical axis, it is basically an indication of the amount of calcium retained within the wood as the tree grows.

This is a summary of 300 to 400 trees collected over the northeast, looking at the calcium incorporation over these different decades.

You can see that things run along pretty consistently right up until 1940, and then we see a big jump for a couple of decades, and then a big drop.

At the early stages of acid rain, calcium actually was more available. The hydrogen ion was actually freeing up the calcium in the soil, making it easier for the tree roots to take it up. So, the higher calcium availability was reflected in the calcium in the tree tissue.

As the acids continued to be deposited on the soils, the calcium continued to be leached out at a higher rate than it was being added through the breakdown of the rocks and minerals. You end up getting lower levels of available calcium. This is a pretty strong indication that these trees have been growing in soils that have been changing.

The situation in Pennsylvania is that the trees need a certain level of calcium or magnesium. If they don't get enough, they are much more susceptible to stresses. In this case, defoliation from

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native insects is a big stress. Studies conducted by the U.S. Forest Service have shown a strong link among concentrations of calcium and magnesium in the soil and leaves, and unusually high mortality of sugar maple trees. This relationship appears to be confined to ridge tops, where soil base concentrations tend to be lowest.

If there is sufficient magnesium, or at least higher levels of magnesium in the foliage, trees can recover from the defoliation. If they have extremely low levels, that is where you get the dead sugar maples. So, acid rain doesn't kill the trees directly, but it reduces their ability to deal with stresses.

I just want to show one graph (Figure 5). The scientists from the U.S. Forest Service have developed a way to measure stress in trees before they die, which is actually a very important tool.

These are results from northeastern red spruce stands. The concentration of putrescine is related to the ratio of Al to Ca in the soil, the higher the ratio, the higher the putrescine concentration. A value of this ratio of greater than 1.0 has been shown in laboratory studies to stress red spruce seedlings. This figure presents evidence from the field that this ratio is also linked to stress in mature trees.

Going from a low slope position to a ridge top, this is typically where we see the worst effects. The ridge tops have the least amount of calcium. They probably had the least amount of calcium before acid rain. Therefore, they are the most sensitive.

It is clear that the trees are under the greatest amount of stress in these soils. Also, I would like to point out that there is some data there for YB,

which stands for yellow birch. So, we are beginning to take a look at a new tree species.

Just to summarize, then, before I stop – and you have heard some of this already – 20 to 50 percent of the canopy spruce have died in high elevation sites in the Adirondack, Green and White Mountains, but the spruce die back is not limited to high elevations. Pretty much throughout its range we can find it.

It is partially the result of acid fog, partially the result of calcium depletion in soils and, as I just got done saying, the sugar maple die back is also linked to insufficient calcium in the soil. Thank you.

QUESTIONS

AUDIENCE: I wonder if you have any data as to acid death mortality rates versus acid deposition rates?

MR. LAWRENCE: Mortality rates for trees?

AUDIENCE: Correct.

MR. LAWRENCE: Yes, that is part of any study to evaluate unusual causes of mortality. I can throw this up (Figure 6). This is just a very crude way to get at that.

This is a healthy sugar maple stand in Pennsylvania. There will be a certain percentage of trees that are dead through natural processes, with not a lot of light coming through the canopy and a situation where things look pretty green.

In these situations where you have the sugar maple die back – this was shown earlier – you end

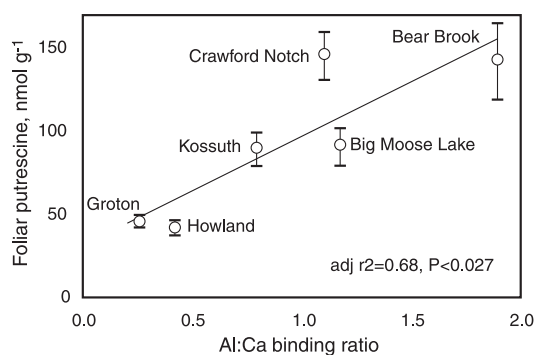


Figure 5.



Figure 6.

up losing 50 to 100 percent of the sugar maple trees and there is no regeneration going on.

AUDIENCE: Could you elaborate on that? I have information that says they are dying at the rate of 160 percent, and the absolute rate is 50 percent.

MR. LAWRENCE: I guess I would have to look at that. The numbers, I don't really understand the numbers. Forests don't die at a 50 percent rate.

AUDIENCE: Over 100 years they don't. [Remainder of question off microphone.]

MR. LAWRENCE: The trees in the forest will not reach the same age they used to; is that what you are saying?

I am not familiar with any studies to directly look at that. It is a very interesting question. One thing I could comment a little bit about, and I am more of a soil chemist, but my forest colleagues feel that, for example, with the spruce situation, the spruce that have died tend to be of a certain size rather than of a certain age.

This was part of the controversy early on. They said, well, maybe the spruce are all reaching their natural life span, but that really wasn't the case. It was more a matter of size and the fact that these trees grew to a large size under certain soil chemistry and the conditions changed too quickly for them to adapt.

That explains why, if you go to these sites that have had extensive spruce die back, you will see spruce regeneration.

Those trees probably won't ever achieve the growth rates of their parents and how long they end up growing is a little hard to say right now. I think it is probably safe to say that that site is not as productive. There is still a lot of work that needs to be done with trees.

AUDIENCE: Along those lines, I am under the impression that the calcium requirement in a small spruce is the same per square inch as a larger tree. [Remainder off microphone.]

In view of the calcium requirement, do you think these trees will grow very – you say slowly, but will they have a chance of really replacing the trees on those sites?

MR. LAWRENCE: That is a very good point. If my Forest Service colleague was here, Walter Shortle he could give you more details.

That is exactly what he says, and that is what they use to explain why these large spruce trees died, because all of a sudden they couldn't get enough calcium. On the basis of that, we probably wouldn't expect to see a spruce forest replace the ones that died of the same vigor, size, stand density, et cetera.

MS. MC KENNA: Mary McKenna from Howard University. I know you said you were not looking at the forest ecosystem as a whole, but how much evidence is there that the understory layer is playing a role here, and perhaps not allowing more calcium to be held in, for example. [Portion off microphone.]

MR. LAWRENCE: I don't have any direct knowledge of understory studies to specifically look at that. The understory is certainly important and there are other factors, particularly in the northeast, that are coming into play, things like deer browsing, that is also stressing the understory and the regeneration of these trees.

Studies have been done to exclude the deer and they are still having trouble regenerating. In terms of the herbs themselves, I am not sure – I am not aware of any studies but there is certainly potential for interaction there.

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