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Evolution of Forest Cover and Soil Chemistry at 16 Swedish Forest Sites Following Future Deposition Scenarios

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Approved by

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Abstract

The high levels of atmospheric sulfate and nitrogen deposition due to human activities have had a visible impact on forest ecosystems in Sweden. Although these emissions are already being reduced as a result of the introduction of transboundary air pollution protocols, the recovery of forest ecosystems may take a long time. This study describes the development of 16 forest ecosystems in Sweden during and after the emissions peaks. It is found that most of the sites are recovering from the acidification effects, but that the recovery process is very slow. The recovery is found to be slower in southern sites with richer soil than in northern sites. This is probably due to the higher buffering capacity of the southern soil.

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About the Author

Salim Belyazid holds a Bachelors degree in General Engineering with a major in Instrumentation and a minor in Mathematics from the Al Akhawayn University in Ifrane, Morocco. In December 2000, he graduated from the Masters Program in Environmental Sciences at Lund University, Sweden. Salim is currently a Ph.D. student at the Chemical Engineering Department at the Technical University of Lund, Sweden. His research focuses on the biogeochemical cycles in forest ecosystems and the impacts of different environmental factors on forests. Modeling is at the center of this work's methodology. Salim participated in the development of an entire forest ecosystem model, the first version of which was completed in March 2004. The model is currently used to run scenarios of forest ecosystem responses to different environmental and management scenarios. In this context, he participated in IIASA's 2004 Young Scientists Summer Program (YSSP), where he worked with the Forestry Program on this paper. Salim intends to complete his Ph.D. studies in March 2006.

Evolution of Forest Cover and Soil Chemistry at 16 Swedish Forest Sites Following Future Deposition Scenarios

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1 Introduction

The importance of being able to do forecasting is emphasized by the increasingly changing environmental conditions. In order to achieve a reasonably accurate picture of the future, dynamic models are needed due to their ability to explain process responses to changes in conditions. These changes, however, can vary considerably on a geographical scale. For this reason, the present paper attempts to look at the dynamics over time of 16 study sites distributed over Sweden in order to obtain a more regional rather than local image of the possible future picture of forests and forest soils in Sweden.

2 ForSAFE

ForSAFE (Figure 1) is a mechanistic model that focuses on the dynamics of a boreal forest ecosystem with limited empirical dependencies in order to be able to capture, to the largest extent possible, the dynamic responses of the studied forest ecosystem to environmental changes.

The model brings together three basic material and energy cycles: the biological cycle, the biochemical cycle, and the geochemical cycle (Kimmins, 1997). ForSAFE combines the engines of three established models: the tree growth model PnET (Aber and Federer, 1992), the soil chemistry model SAFE (Alveteg, 1998), and the decomposition model Decomp (Walse *et al.*, 1998).

2.1 The Biological Cycle in ForSAFE

The processes of tree growth are represented in this cycle.

To calculate photosynthesis, the tree canopy is stratified into 50 layers of equal thickness. In each layer, gross photosynthesis is calculated as a function of Leaf Area Index (LAI) (Aber and Federer 1992):

$$GrossPhotosyn_i = DW_i \times f(N) \times LightEff_i$$

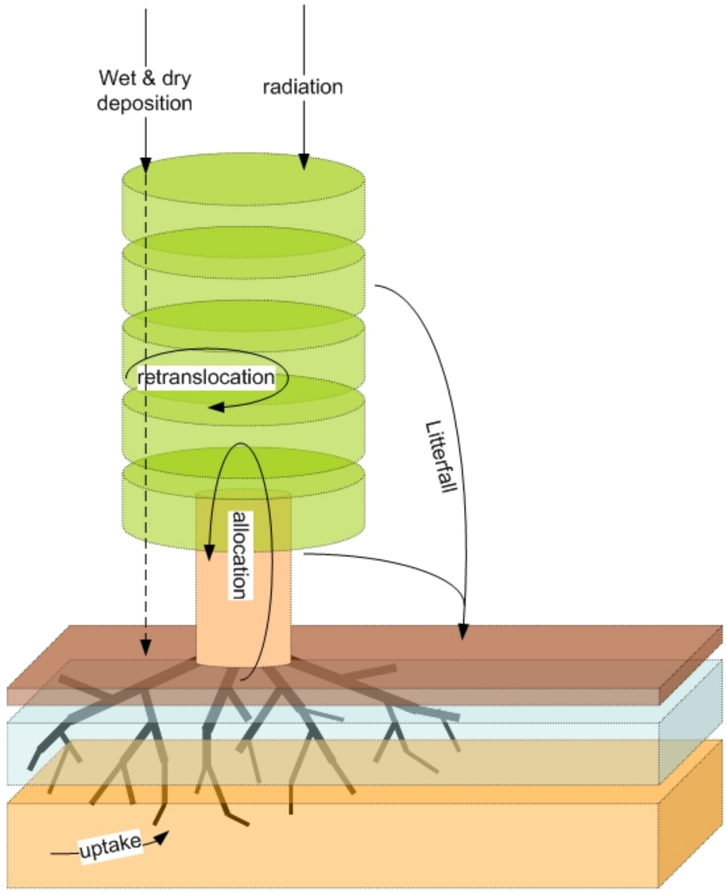

Figure 1: ForSAFE closes the material flow loops between vegetation, detritus and soil.

where DW_i is the specific Dry Weight of layer *I*; *f(N)* is the sum of the effect of foliage N concentration (*FolNConc*) on photosynthesis and base foliage respiration (*BaseFolResp*), and is given by (Aber and Federer 1992):

$$f(N) = (a + b \times FolNConc) + BaseFol\mathrm{Re}sp$$

$LightEff_i$ is the light efficiency at canopy layer I and is given by (Aber and Federer 1992):

$$LightEff_i = 1 - e^{-LightInt_i \times \log(2) / HalfSat}$$

$LightInt_i$ is defined as the intensity of the Photosynthetically Active Radiation (PAR) at layer i. $LightInt_i$ is a function of the downwelling shortwave radiation (Rad) and the Specific Leaf Weight of layer I (SLW_i) and is given by (Aber and Federer 1992):

$$LighInt_i = Rad \times e^{-k \times \sum_{j=1}^{layer_i} 1/SLW_j \times CrownDW/50}$$

The total gross photosynthesis of the tree is the sum of the individual gross photosynthesis of the individual canopy layers.

Photosynthesis replenishes the plant carbon pool, which is consequently used for carbohydrate allocation to the different tree parts. Allocation takes place on two different time scales; shoot allocation is a yearly event; and root and wood allocation is a monthly event. The allocated carbon to the different parts of the tree is directed towards maintenance respiration, growth, and growth respiration successively. The change in biomass following growth and litter (explained below) is used to calculate the nutrient requirement of each part of the tree, and nutrients are allocated accordingly.

Litter fall is calculated separately for the different parts of the tree. Foliage turnover depends on empirical parameterization of needle or foliage retention of the tree species under a specific climate. The wood turnover rate is derived directly from a user input rate of wood dieback. Finally, root turnover is derived from the net *N* mineralization of the previous year.

Coupled with litter formation is nutrient retranslocation, which takes place before the litter is shed, and the retranslocated nutrients are turned back into the tree's main nutrients pool from where they are allocated in later events.

2.2 The Biogeochemical Cycle

The biogeochemical cycle is the link between the remaining two cycles considered in the model. This part of the model comprises the processes of uptake, litter decomposition, and soil nutrient dynamics with a short time scale.

The nutrient uptake is driven by a tree's nutrient requirement. The potential nutrient uptake is first calculated as the difference between the empirically-defined optimal tree nutrient content in the tree nutrient pool and the actual nutrient content. The actual uptake is then the correction of the potential uptake following nutrient availability in the soil.

Soil nutrient availability, in turn, is calculated from the soil chemistry equilibrium (Figure 2). Soil nutrients are in balance between the soil solution and adsorption. Nutrients in the soil solution are available for uptake.

The biogeochemical cycle also includes the downward flow of matter from vegetation to soil through litter decomposition and litter nutrients mineralization. The decomposition module (Walse *et al.*, 1998) considers four different classes of decomposable organic matter, namely, easily decomposable compounds, lignin, holocellulose, and resistant compounds. The four different classes are set apart for each soil layer. Depending on the decomposability of the different organic classes, the decomposition process is altered by temperature, moisture, and soil pH and Aluminum content. The effects of these three factors are assumed to be multiplicative. For each decomposable class, we can summarize the decomposition rate as the mass loss rate that follows:

$$\frac{dMi}{dt} = -ri = kpoti * Mi * fi(T) * gi(\theta) * \Phi i(pH, Al)$$

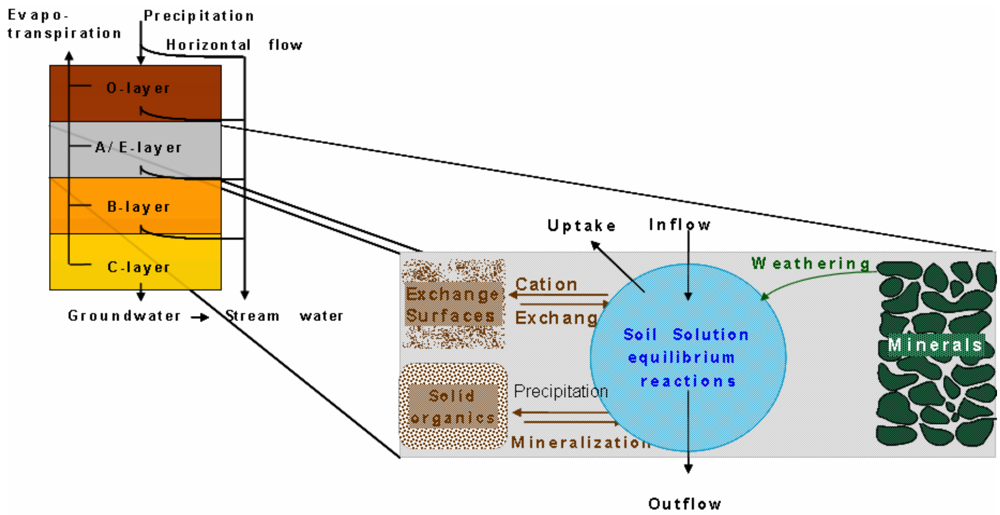

Figure 2: The soil model consists of a pile of similar, but not identical, soil layers with individual properties. Within each soil layer, the same processes of nutrient mass balances hold with different proportions.

where *i* stands for easily decomposable, lignin, holocellulose, and recalcitrant (resistant compounds); *M* is the mass of the *i* compound; *kpoti* is an empirical constant for the compound *I*; and *f*, *g*, and Φ are functions of the temperature, moisture, and pH-Aluminum effects, respectively, on the decomposition rate.

2.3 The Geochemical Cycle

Because of the largeness of the temporal and special scale of the geochemical cycle compared to the other two cycles included in the model, the former is only included as input to the model.

3 The Sites

The 16 sites are distributed over Sweden as part of the ICP FOREST LEVEL II monitoring program (International Cooperative Program on Assessment and Monitoring of Pollution Effects on Forests, see http://www.icp-forests.org).

The latitudinal distribution of the sites provides a relatively wide range of climatic factors and deposition magnitudes. The average annual temperature varies between 0°C and 7°C, decreasing from south to north. The mineral deposition also shows large gradient decreases with latitude, falling from 27 kg/ha/yr to 1.5 kg/ha/yr for nitrogen (N), and from 12 kg/ha/yr to 1.3 kg/ha/yr for Sulfur (S).

The sites in Figure 3 have been the subject of a prior study focusing on soil dynamics (Martinson *et al.*, 2005) using the SAFE model (Alveteg, 1998). This study provided the grounds for the soil data used here, but it lacked the continual feedback between the forest cover and the soil.

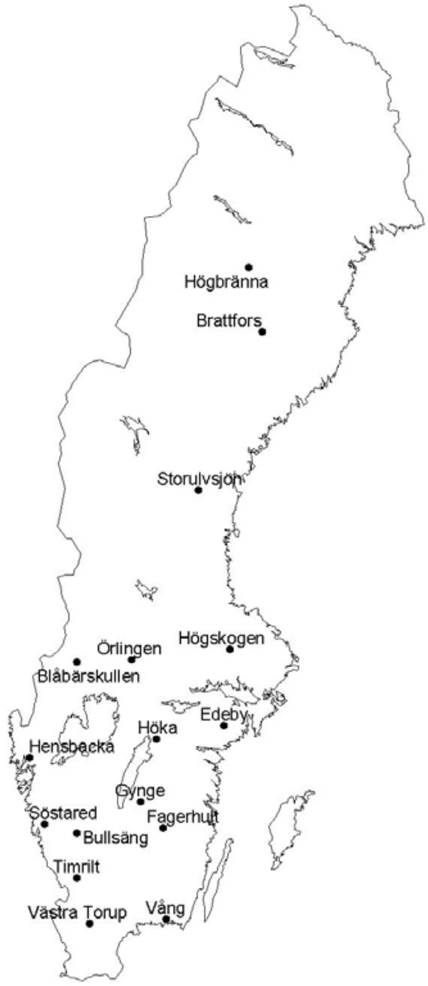

Figure 3: 16 forest sites, distributed throughout Sweden, were studied to evaluate the effects of the Gothenburg Protocol on emission reductions on forest soil health.

3.1 Input Data

The soil input data for all of the study sites, including soil types, mineralogy, and physical properties of the soils, was derived from the study by Martinson *et al*. (2005). The parametric vegetation data was selected for pine and spruce — the two species present at the sites — from Aber *et al*. (1995; 1997). For sites where both or a third species were present, the forest was parameterized according to the dominant tree. Data for the decomposition parameters were taken from the parameterization carried out by Walse *et al*. (1998) and Wallman *et al*. (2005). The time series of climate input data for temperature and precipitation were extracted from the SWECLIM database through the Swedish Environmental Research Institute (IVL). The time series for solar radiation were derived from cloud cover data from the Climate Research Unit at the University of East Anglia, Norwich, UK, according to the method described in Rivington *et al*. (2002). Deposition data were derived from the study by Martinson *et al*. (2005).

Deposition trends were based on the 1999 UN ECE LRTAP Gothenburg Protocol (Schopp *et al.*, 2003).

4 Results and Discussion

This section presents an overview of the model's simulation output over the 16 study sites and a discussion about possible explanations for the model's behavior.

4.1 Vegetation Results

Model outputs for vegetation biomass are shown in Figure 4, which shows modeled against measured stem biomass data.

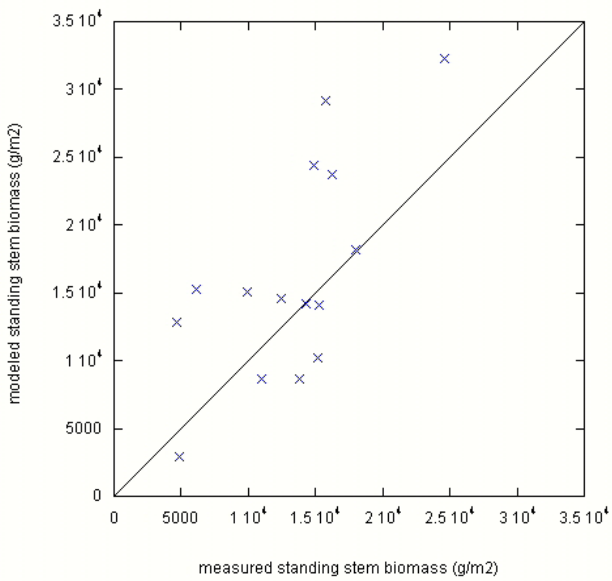

Figure 4: Modeled versus measured stem biomass over the 16 study sites.

The discrepancies between the measured and modeled values can be explained by process modeling causes as well as data inconsistencies. The trend of over estimating biomass at high measured biomass values and underestimating it at low measured biomass values can be related to the parameterization of the vegetation module in the model (Wallman *et al.*, 2005). The leaf retention period is kept constant throughout the sites that contain similar tree species. However, because the sites are distributed over a wide climatic spectrum, the leaf retention period was not, in reality, expected to be similar but, instead, would increase with a decrease in favorable climatic conditions. The northern sites should therefore have larger leaf retention periods than the southern sites. This is supported by the fact that the results show a trend where the model over estimates the biomass at low latitudes where growth conditions are more favorable, while it under estimates it at higher latitudes where growth conditions are less favorable (Figure 5).

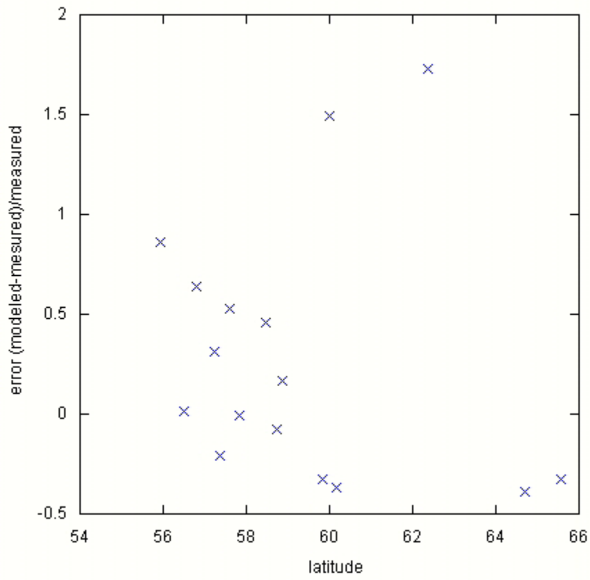

Figure 5: The error between the modeled and the measured stem biomass shows a declining trend with increasing latitude with the exception of two sites where the modeled biomass is very much higher than the reported measurements.

Other factors of tree physiology would also probably change with the latitudinal transect of the sites, and not evaluating these parameters for each site can be a substantial source for the differences observed in Figures 4 and 5. However, the lack of data from each site does not allow the calibration of the physiological variables of the trees at the different sites.

A further possible cause behind the differences between measured and modeled biomass is possible lacunas in management history of the study sites. The frequency and intensity of prescribed thinning obviously has a direct effect on the standing biomass, as does the management practices in use regarding the harvest of the whole tree or only the stem. This is even more important considering the effect of management practices on litter production and litter composition. This, in turn, influences the nutrient availability for the trees and therefore the standing biomass.

4.2 Soil Chemistry Results

To illustrate the changes occurring in the soil, we focus on the base cations to aluminum ratio (BC/Al) as an indicator of soil health. The BC/Al was elected for its good representation of soil nutritional status and soil pH. Acidification of the soil following NO3-, NH4+, and SO42- principally results in a release of adsorbed Al into the soil solution. A direct result of this increase in soil solution Al is the decline of the BC/Al. The acidification process also causes the release of base cations, thus promoting growth in the short term but depleting the soil adsorbed BC stores. The released BC are taken up by the trees or, in some cases, are primarily leached. With acidification then, a decrease in the BC/Al is expected, and not only in the short term. Figure 6 shows the changes in the BC/Al in the upper layer for the 16 study sites over time and latitude.

The ratios presented in Figure 6 are weighed against the BC/Al value for 1900. The graph shows the changes relative to the reference values of BC/Al at the stated year. Differences between the sites can thus not be seen. However, an interesting behavior appears from the graph. The weighed BC/Al shows an overall decreasing trend with increasing latitude, most notably towards the middle period of the simulation (late 1900s). This suggests that the northern sites are, and probably will, experience more loss of base cations and a further increase in soil solution Al than southern sites.

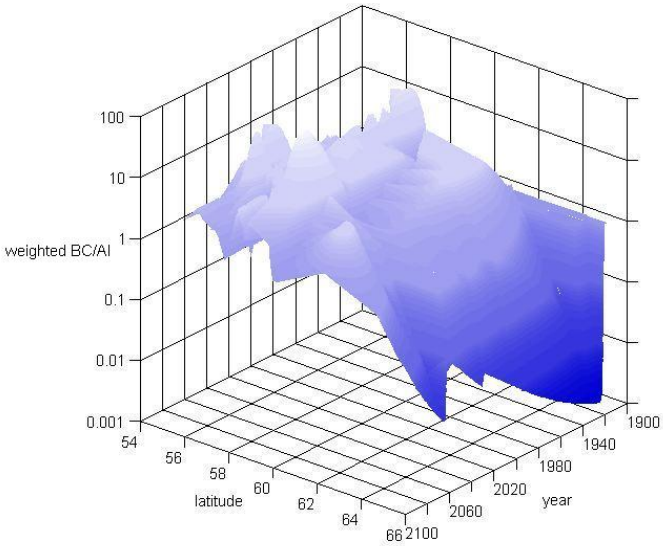

Figure 6: The weighted BC to Al ratio in the upper soil layer (0 to 5 cm) shows a decreasing trend with increasing latitude, while the behavior over time varies considerably between the study sites.

Another trend that appears is that southern sites show first an increase of BC/Al until the beginning of the 2000s then start declining. Northern sites, on the other hand, show a less pronounced increase of BC/Al in the short term, and a delayed start of decline of the ratio.

Since Figure 6 shows the BC/Al for the upper layer, the explanation for the displayed behavior has to be looked for mainly in the deposition and decomposition information, which form the main, if not exclusive, source of BC in the upper soil layer. Both deposition and decomposition are of further interest considering the positive effect of soil nitrogen content on soil Al. The initial increase in the BC/Al for the southern sites can be explained by the build-up of biomass and consequently litter. The increase in biomass is primarily due to an increase in N deposition, driving an increase in photosynthesis. The higher litter fall implies a higher BC mineralization rate, and the increased biomass production causes an increase in N uptake (as most of the study sites are N limited), thus reducing Al solubility in the soil. Together, these two processes can explain the initial increase of BC/Al at the southern sites. In the northern sites, however, increased N deposition could have a stronger effect than decomposition, thus dampening the process described above. On the other hand, the unfavorable climatic conditions in the northern sites also mean a reduced increase in growth, and thus a lower increase in litter.

The dynamics of the BC/Al also need to be seen in the light of changing base saturation (BS) of the soil. Figure 7 shows the changes over time and latitude of the BS for the organics soil layer.

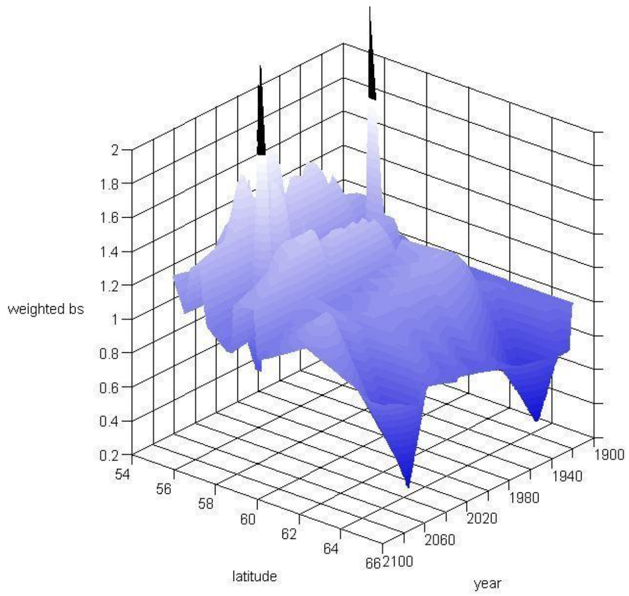

Figure 7: Changes over time and latitudes of the base saturation at the 16 study sites.

As for the BC/Al, the sites' BS also shows a decreasing trend with altitude. The incidental extreme peaks are due to clear cutting and planting events. The negative tendency observed over latitudes partially explains the previously described decrease in the BC/Al. However, it is important to keep in mind the effect of litter fall and decomposition as well as deposition on the formation of BS in the organic layer. In fact, weathering does not contribute to the BC pool of this layer. Thus, the decreasing trend of BS can be explained by the declining deposition of BC over increasing latitudes. In addition, the contribution of litter to the BS can also be seen in this trend. Considering the higher net primary production (NPP) in the southern sites, a higher litter fall occurs at lower latitudes. The litter content of BC reflects the biomass BC content, which in turn is replenished from the different soil layers. The trees can be seen as BC pumps that drive the cations up from the lower soil layer where weathering takes place, and places them into the upper organic soil layer through litter fall.

Within the individual sites, BS shows a similar common behavior. The BS increases from the 1900 level, stabilizes for a certain period, then starts declining back to 1900 levels. The rise and decline happens at different time intervals, with a tendency that the changes occur earlier at the southern sites than at the northern ones. The common behavior is probably due to the management practices applied to the sites. All the stands have been planted early in the 1900s. The effect of this practice is the original increase in BS, due to the gradually increasing uptake and litter fall following a growing biomass. Later on, as the forest matures and the major disturbance is thinning, the BS increase slows down. The thinning causes relatively large periodical increases in the litter, thus replenishing the BC pool of the upper layer. Moreover, as the litter formed from thinning has not undergone any retranslocation, the nutrient content of this litter is high. As a consequence, more nutrients are immobilized in the soil organic matter, and released gradually with time through decomposition and mineralization. These pulses of nutrient-rich litter could compensate for the continuously increasing uptake. In the latter period of the simulation, however, no thinning is applied and the maturing forest, mostly newly planted, will steadily deplete the BC pool in the soil until the stage where litter fall and uptake equalize and cancel out the effects of each other. This can be observed in Figure 7 at the southern most sites.

The slower dynamics of the northern sites are primarily due to the unfavorable growth and decomposition conditions prevailing in the north. As the biomass increment is small in the north due to limited photosynthesis following mainly low temperatures, both the uptake of BS and litter formation are slow, thus causing the time lag in the curves from the south to the north as observed in Figure 7.

Because of the complex involvement of deposition, litter fall, and decomposition in influencing the chemistry of the soil organic layer, a deeper look into the soil should be taken to see the long term effects of the past, current and future deposition rates on soil chemistry.

Figure 8 shows the deviation in BC/Al from the 1900 values. At the 15 centimeter (cm) depth of the soil, the drastic effects of forest management practices can still clearly be seen. The occasional fluctuations, both peaks and depressions on the graph surface, are direct results of thinning and clear cutting events. As the assumption was that stem-only harvests were carried out, every cutting activity produces a substantial fresh litter that is rich in nutrients. The consequent decomposition increases the soil BS content and with that the BC/Al. Yet it is important to note that these events are only short lived. After the leaching or uptake of the mineralized nutrients, the BC/Al drops nearly as fast as it increased. This behavior is dampened in the northern sites due to the considerably lower decomposition and mineralization rates.

Probably the most notable behavior appearing in Figure 8 is the decreasing trend of the BC/Al in all but one of the sites throughout the 1900s. This behavior agrees with the hypothesis that acidification would result in a decreased BC/Al. A difference also appears in the rate of BC/Al decline between the southern and the northern sites. The ratio declines slightly faster in the northern sites. This is unexpected considering the much higher deposition in the south. However, the larger cation exchange capacity (CEC) in the richer southern soils could be behind a larger buffering capacity of these soils, thus slowing down the decline on the BC/Al.

The impact of CEC can also be seen during the recovery phase during the 2000s, after emissions reduction. During this period, the CEC has the reverse effect as it slows recovery. In fact, it can be seen that the northern sites recover faster than the southern ones. The CEC then works as a two-way buffer, preventing the fast decline of the BC/Al as well as a fast recovery.

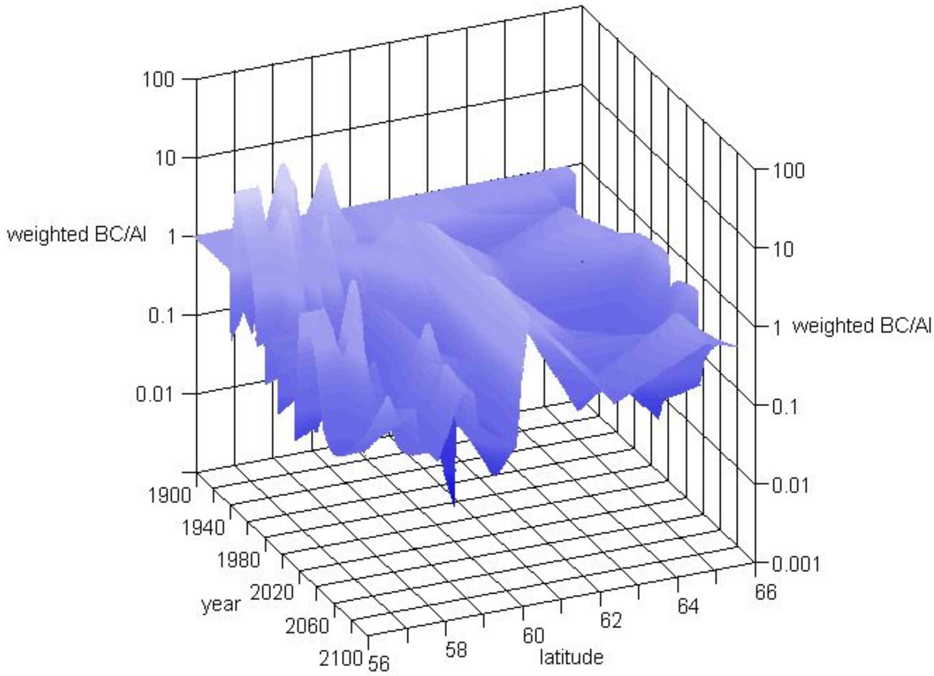

Figure 8: The BC/Al shows a declining rate from the 1900 level for nearly all of the study sites. The elevated values correspond to thinning and clear cutting events.

5 Conclusions

It is obvious that the forest soils have, to different degrees, been disturbed by the increased atmospheric deposition. It is probable that the soils will recover; however, this will probably take a long time. While this does not seem to represent any strong negative effects on the forest crops today, it may be a serious limitation in the future. Although the levels of N deposition have decreased from the 1900's peak, they are still higher than the historical magnitudes. This could imply a shift of the limiting factor for forest growth against the evolutionary adaptation of the Swedish forests. A higher supply of N will mean a faster depletion of BC, and as the major source of these consists in the slow process of weathering, the rate of depletion may well be beyond the rate of replacement.

Thus, the recovery from acidification observed above should not be a safety signal, but rather an indicator for the slow response (and, in the case of damage, recovery) time of forest ecosystems in the south and their fragility in the north.

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