Forests, Acidification and the Socio-economic Cost

— Modeling damage- and mitigation cost of forest soil acidification

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The ongoing acidification of forest soils, believed to cause a severe impact on the ecosystem, is one of Sweden's major environmental problems. The objective of this study is to elucidate if mitigate a future impact of acidification is economically worthwhile. The total economic value of resources affected by forest soil acidification is estimated. The impact of acidification on different values is also analysed. Furthermore, the amount of forested area, acidified due to anthropogenic activities, is explored. Finally, a model is developed to analyse how a future impact may affect the timber production in a forest stand. The results of this study show that the total economic value of resources affected by forest soil acidification amounts to 65 billion SEK annually. The total forest area in southern Sweden, acidified due to anthropogenic activities, is estimated to 5 million hectares. The abatement cost, if liming is undertaken, is estimated to at least 7.5 billion SEK with a lasting time of 20-40 years. The model suggests that a minor decrease in forest production would result in a significant loss of value. The overall conclusion suggests that there is a significant risk of a future cost, many times higher than the present cost of mitigating the acidification.

Introduction

Humans use forests in many ways, such as timber production, game hunt, picking berries and other recreational activities. Forests are also a vital habitat for many plant and animal species. The continuing soil acidification within forests in Sweden is a serious longterm threat to the longevity of these utilities (Johansson et al. 1999) and may therefore result in loss of values contributing to our common welfare.

Acidification of the soil leads to leaching of plant nutrients, such as potassium, calcium, and magnesium, which in time may cause nutrient deficiencies, and thereby threaten the productivity of forest (Sverdrup et al. 1994). The process of acidification also results in increased concentrations of aluminium and other toxic metals in the soils, ground- and surface waters (Tuvander and Oskarsson 1997). The biodiversity of lakes and rivers is drastically impoverished in areas affected by surface water acidification (Johansson et al. 1999). Furthermore, acidified ground water can cause problems, for instance by corroding pipe-work (Bertills et al. 1989), but also by creating health risks as the acidification increases the mobility of various harmful metals, such as aluminium, mercury, copper, zinc, cadmium, and lead (Bjertness and Alexander 1997; Gerhardsson and Skerfving 1997).

The purpose of this paper is to explore possibilities and drawbacks of using economic valuation to lay base for carrying out measures to mitigate a future environmental impact on a natural resource. The cost of mitigating a possible future negative impact in acidified forest soils is studied and evaluated from a socio-economic perspective. The expected cost of not undertaking measures to mitigate forest soil acidification is compared with the option to mitigate the effects by liming forest soils.

Ecology and Economics

The interest in studying the causality between economy and ecology has increased after it has been identified that human resource use often results in negative environmental effects. The gross national product (GNP) is commonly used as an indicator of a nation's wealth. If the GNP increases, the society's general welfare is believed to increase (Figure 1).

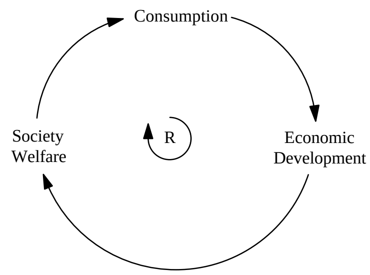

Figure 1. The general perception of development seems to be regarded as a continuous reinforcing loop. By stimulating the consumption, the economic development increases. An increased economic development increases the total welfare.

Although exceptions are known it is fair to conclude that with increased economic development, a general environmental degradation occurs due to increased emissions of pollutants and/or loss of natural habitats. The polluted or degraded environment is reducing the society's welfare but is not always affecting the economical activity (Figure 2). One reason is that many values connected to the environment, contributing to our welfare, is not incorporated in the GNP. An increase of economic activities is usually regarded as positive for the total welfare. An economic activity that leads to a reduced value of an environmental asset will, if neglected, give an overestimated depiction of increased wealth. Placing an economic value on degradation of natural resources is therefore of immense importance when quantifying our welfare by economic means.

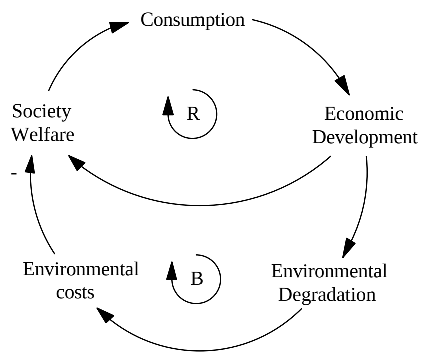

Figure 2. Economic development is often connected with an increased environmental degradation that, in time, causes a cost for the society and thereby reduces its welfare. Thus, the environmental resilience, function and quality balance the reinforcing system.

A socio-economic measure can be regarded worthwhile if the investment increases or preserves the total national welfare when carried out. To consider an activity worthwhile, the total economic value of receiving improved environmental quality has to be equal to or higher than the abatement cost (Turner et al. 1994). A delicate problem here is how we should estimate the economic value of an improved environmental quality. Furthermore, even if it would be possible to elucidate that mitigating forest soil acidification would be socio-economic worthwhile, it is not sure that this will hold true when including the discount rate. The main reason being that a future cost is depreciated with a given interest rate over time.

A natural resource can be said to represent a certain *total economic value* (TEV). Woodland is for example, used in various ways by different stakeholders. It has therefore many values, and as many of these as possible should be considered when estimating the TEV.

TEV can be divided in two broad categories*;* *use value* and *non-use value*. The use value can further be divided into *current use* (e.g. for forestry, recreation, carbon fixing, etc.) or *optional use* value (e.g. establishing a natural reserve). The non-use value is usually defined as the *existence value*, reflecting people's allocation of value to the knowledge that a specific resource exists even if they never will use it for themselves (Wibe 1994). The value of biodiversity is often referred to as a *non-use existence value.*

Different methods have been developed to measure the economic value of non-marketed goods and services. The most frequently used are; travel cost method (TCM), hedonic pricing method (HPM) and contingent valuation method (CVM) (Wibe 1994).

By signing the Agenda 21 document in Rio de Janeiro 1992, Sweden is committed to develop environmental accounts to improve the connection between economic activities and environmental degradation (SOU 1991). Environmental accounting will have a major impact on the net national product (NNP), since degradation of resources are included and may therefore be a better indicator of welfare than the gross national product (GNP). The process to establish an environmental accounting system in Sweden is carried out by three governmental institutions (SCB 1997); National Institute of Economic Research (Konjukturinstitutet, KI), Statistics Sweden (SCB) and the Swedish Environmental Protection Agency (SEPA).

Estimating the economic value of utilities affected by forest-soil acidification

Within the forest ecosystem, there are, basically, four values that could be affected by acidification; forest production, recreational value, biological diversity and ecological services. The economic impact is not, however, clearly visible since we have not experienced or identified a reduced timber production or quantified the value of lost biodiversity.

Hultkrantz (1991) estimated that the total value derived from forests in 1987 amounted to 22 thousand million SEK, which was 4 thousand million more than the amount included in the national accounts. Including the economic value of berry/mushroom production and forest growth as a carbon sink derived the higher value. It should be noted that the recreation value was not included in this study. The annual forest production[1] has today a net value of 30 thousand million SEK[2,3] (Forest statistics 1998).

To estimate the recreation value of forests, a number of studies using CVM have been carried out. According to Jämttjärn (1997), approximately 373 million visits are made in Swedish forests annually. The total recreational value is estimated at 19 thousand million SEK annum^{-1}. The annual willingness to pay (WTP) to mitigate forest acidification in Sweden is estimated to be 380 SEK person^{-1}.

The total economic value of forests can be estimated to approximately 55 thousand million SEK annum^{-1}. This figure is derived when adding the annual value of produced forest timber (30 thousand million SEK), the estimated recreational value (19 thousand million SEK) and the value of berries, mushrooms, game meat and carbon sink which contributed with 19% of the total timber value in Hultkrantz estimates from 1991.

Forest soils are leaching acid water to adjacent watercourses. Eventually, the run-off water ends up in lakes with an increased acidity as a result. In 1985, a national survey was carried out where it was estimated that 21 500 of Sweden's 85 000 lakes were damaged to a level where many organisms were unable to survive (Monitor 1991). The impact on lakes has an effect on recreational fishing that is an important leisure activity in Sweden. The economic value of recreational fishing in Sweden is estimated to approximately 10 thousand million SEK annually (Ahnér and Brann 1996). To mitigate the problem of acidified lakes the government granted 1.6 thousand million SEK to a Swedish liming programme during the period 1976 and 1995 (Svenson et al. 1995).

Acidity in forest soils is proceeding downwards as long as acidification continues. Eventually acidified water reaches the ground water. Bertills *et al.* (1989) estimated the annual cost for increased corrosion of water-pipes to 200 million SEK. Acidified drinking water may also lead to health effects (Bjertness and Alexander 1997) although convincing evidence is lacking. The concentration of acid metal ions in water increases with lower pH values, especially aluminium, iron, cadmium and manganese (Johansson et al. 1999). In 1989, the total number of 65 000 wells in southern Sweden were estimated to have water quality below a recommended standard (Bertills et al. 1989). Dangerous to health or not, people are worried about elevated concentrations of heavy metals in their drinking water and the total WTP for the adult population to maintain a healthy drinking water is estimated to 2 thousand million SEK annum^{-1} (Silvander 1991).

It can be argued that the forest soil acidification will lead to secondary effects on surface and ground water (including wells). Although presumably a few numbers of wells is located in forests it is relevant to include the effects of acidification on these values when estimating the cost of forest soil acidification. Liming of forest soils has been shown to enhance the conditions for both adjacent surface- and ground water (Nyström et al. 1995; Norrström and Jacks 1993). Restoring the pH in lakes will also

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[1] Includes only the total value derived from selling timber on the open market. Management or harvesting costs are not considered. Refinement undertaken after harvest increases the value of the timber. However this value enrichment is not considered here since it would be possible to buy timber from other countries and still increase the value from refinement in Sweden.

[2] US$ 1 ≈ 10 SEK.

[3] No correction to present value (year 2001) has been made since it had only a marginal impact.

improve the conditions for many species (Lingdell and Engblom 1995) although the recovery period may be considerable (Appelberg et al. 1993).

We can conclude that forest soil acidification have a potential of affecting many values that resides within the forest ecosystem. In addition, values that are found outside what we usually refer to as forests are also affected by soil acidification that takes place within the forests. Thus, we may regard forest soils as a polluting source, affecting surface- and ground water negatively. The TEV of the utilities with a possibility to be affected sums up to 65 thousand million SEK annually. This is a considerable value that needs to be considered when judging if a mitigation measure is economically worthwhile.

Area Affected by Acidification

The economic cost of a future negative impact on forest production is dependent on the area affected. A significant area is, and will be, affected by acidification (Monitor 1991). According to Sverdrup and Warfvinge (1995), 80% of Sweden's forest soils are exceeding the critical load of acidity. When these areas reach their new steady state equilibrium, they will have a lower pH and a lower concentration of base cations (BC). The critical load concept in these calculations is defined as the maximum amount of sulphur and nitrogen deposition that will not cause long-term damage to ecosystem structure and function. The critical limit is the most unfavourable value that the chemical criteria may attain without long-term harmful effects on ecosystem structure and function (Barkman 1998). For forest soils, a BC/Aluminium ratio=1 is used as one critical limit (Sverdrup and Warfvinge 1995). If the ratio falls below this level, growth reduction of trees is expected.

Data from the national forest survey were used to calculate how much forestland that falls in specific pH intervals. The pH measurement in the B-horizon performed by the national forest survey was used for analysis in this study. The reason for selecting this layer is that the upper layers are more variable and dependent on stand age (Tamm and Hallbäcken 1986). Although the B-horizon may be affected by stand cycle variations it is less pronounced than layers closer to the surface. In the national forest survey the upper level of the B-horizon is sampled for pH analysis (Figure 3). The natural (unaffected by human activities) pH level in the B-horizon is believed to be somewhere between 5.0 and 5.5 (Nihlgård et al. 1996).

In the national forest survey each plot has a corresponding weight factor. This weight factor should be interpreted as area around the plot that has similar conditions. In this way a specific plot is represented by a certain area size.

The resulting 897 plots are assumed to correspond to the total forested relative area, which amounts to 8.2 million hectares in the studied region (Götaland and Svealand). Thus, the sum of the weight factors for all the studied plots represents 100% of the forested area. By dividing the plots into 16 pH intervals, ranging from <4 to >=6.8, the total relative area is subdivided into these pH intervals.

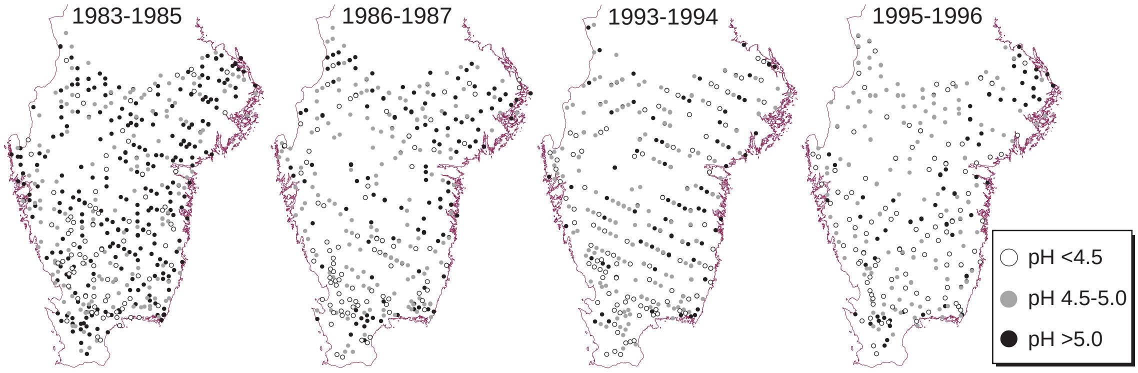

Figure 3. The maps illustrate pH in the upper B-horizon between the years 1983 and 1996 made in southern Sweden by the National Forest Survey.

Calculating the mean cumulative value of each interval for the sampled period 1983-1987 and 1993, 1995, indicates that approximately 60% (5 million hectares) of the total forested area in southern Sweden has a pH below 5.0 in the B-horizon (Figure 4).

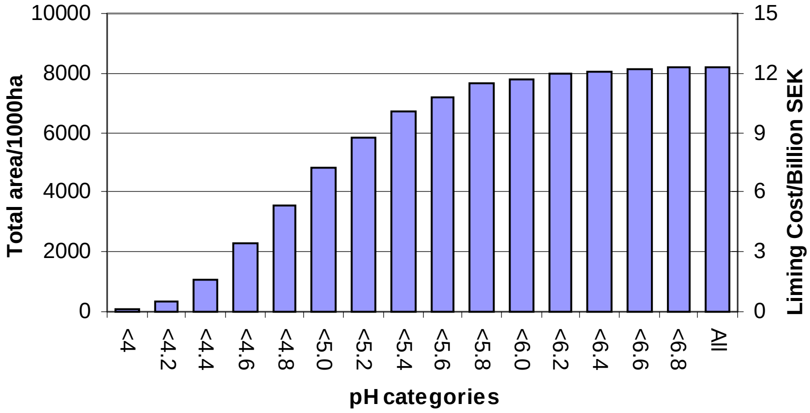

Figure 4. Chart showing the area of forestland in southern Sweden that is represented below a specific pH value. Approximately 5 million hectares (or 60% of the total area) have a pH below 5.0 in the upper B-horizon.

To determine if a variation exists between the years, individual calculations of the sampled years were made. The PROFILE model (Sverdrup and Warfvinge 1993) was used to estimate pH levels in the year 1840, and when steady state equilibrium is reached[4].

The mean value of the relative area in each pH interval between 1983-1985, 1986-1987 and 1993-1995 was calculated. The result from the calculations, and the values modelled with PROFILE is presented in Figure 5.

[4] At steady state the pH is maintained at the same level by balancing processes in the soil.

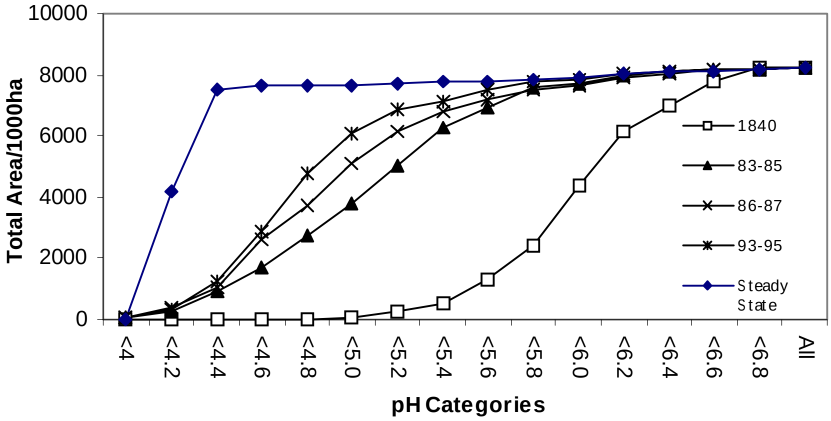

Figure 5. The pH in 1840 and when reached steady state was modelled with the PROFILE model. Mean values were calculated for 1983-1985, 1986-1987 and 1993-1995. The chart illustrates a continuous trend toward a lower pH in forest soils of southern Sweden.

The results indicate a rapid increase of areas with a pH below 5.0. According to the PROFILE model, the area below pH 5.0 was 65 000 hectares, in 1840. In 1983-1985 this figure reached 3.8 million hectares, and increased to 6 million hectares in 1993-95. When steady state equilibrium is reached, 7.6 million hectares is predicted to be acidified (93% of total). The time perspective for the system to reach steady state is dependent on factors such as; soil characteristics, acid precipitation, biomass harvest, weathering, etc.

If we were to restore the acidified area to a natural pH level this cost would be termed restoration cost. Assume that the proposed liming methods proposed by the national forest authority (NFA) would bring us back to a more natural state of the soils acidity. The cost of acidification can then be calculated by multiplying the area defined as acidified (below pH 5) with the liming cost per hectare, estimated to 1500 SEK hectare^{-1} by NFA. Thus, the total restoration cost for acidified soils in southern Sweden amounts to 7.5 thousand million SEK. It should be pointed out that this cost is calculated from the average of all the sampled years. A comparison with area classified as acidified in 1983 and 1995 is, by using the same calculations, 5.25 and 9.75 thousand million SEK, respectively. The difference in cost implies that there is a rapid increase of the cost over time. The annual increase of the restoration cost can therefore be calculated to (9.75-5.25)/12 = 375 million SEK.

Modelling a Future Growth Decline

A future decline in forest growth will lead to a cost for the society. The magnitude of this cost is dependent on the total impact on forest production. In spite of the uncertainties, it is interesting to make simulate how a future impact would affect the growth of a tree stand. With help of best guesses and Monte Carlo analysis, it is possible to simulate a likely response of a growth decline initiated by acidification. A dynamic computer model was developed with the aim to simulate the impact on stand growth and its effect on the final volume of biomass and subsequent economic cost. The model is focused on the response of a forest stand affected by a growth decline.

The growth pattern of a forest stand can be described with a logistic function. Over the life span, the annual increment in biomass (volume) increases to a maximum and then declines to zero. The cumulative growth pattern of a forest stand has been described with an equation presented by Hägglund[5] (SOU 1978).

$$Volume = 164.16\left(1 - 6.3692^{-\frac{year}{CT}}\right)^{2.8967} \quad (1)$$

Equation 1 estimates the volume of biomass at a given relative age. The culmination time (CT) differs with tree species and determines the time when annual growth culminates. The annual growth is also dependent on the Site Productivity Class (SPC). The SPC describes the growth capacity for a given location, i.e. yield.

The economic value is not proportional to the total biomass volume. The value per hectare is dependent on species, volume, price and quality. There are generally three different markets for tree products; timber, pulp and biofuel. The highest price per m^3 is paid for timber.

The total impact on produced biomass is dependent on variables such as area affected, magnitude of the growth decline, at what time in the life cycle the effect will be apparent, duration of the growth reduction, and to what level the growth will be restored.

By testing different scenarios a better understanding on how these factors interrelate is gained. The factors affecting growth reduction can be described with a function:

$$R = f(a, m, t, p, r) \quad (2)$$

Let R be the total impact on biomass production, which is a function of area (a), magnitude of the growth reduction (m), time before the growth reduction occurs (t), prolongation of the growth reduction (p) and resilience (r) that determines the level to which growth is restored after the impact. In the model, these variables can be adjusted independently to study the effect of different hypotheses (Figure 6). Table 1 describes the parameters and their function.

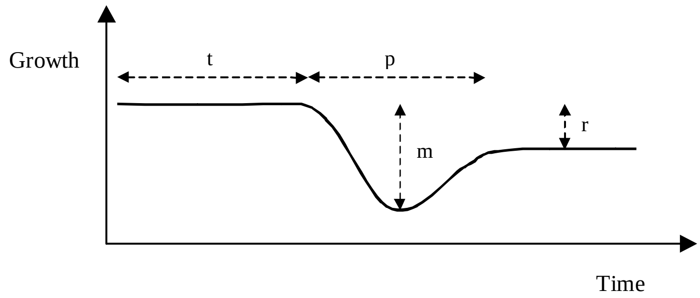

Figure 6. Figure illustrating the different factors that determine the total loss of production. An estimate of all these variables is needed to approximate the total effect of production decline. (t) is the time when the expected decline will occur, (m) is the magnitude of the expected decline, (p) is the time by which the decline will continue and, (r) is the level to which the growth will be restored to after the impact.

[5] The equation has been modified slightly in the model.

Table 1. Parameters that determine the impact of a future growth reduction.

Growth Reduction	*Description*	*Unit*
Time before impact	The time when reduction will occur	Year
Magnitude	Reduction level of annual growth	Per cent
Prolongation	Number of years the reduction persists	Year
Resilience	Level of reduction that will persist	Per cent

Running the Model

An arbitrary forest stand of one hectare with the culmination time of 75 years and a mean annual increment of 10 m^3 $year^{-1}$ was selected (CT=75, SPC=10). The figures correspond with a spruce stand with an annual average productivity of 10 m^3 per hectare. A simulated growth reduction of 10% was included after 30 years of growth. The reduction prolongs for 20 years before going back to normal. The figures are here selected only to simulate an arbitrary growth reduction. Figure 7 shows the impact on annual growth and final volume.

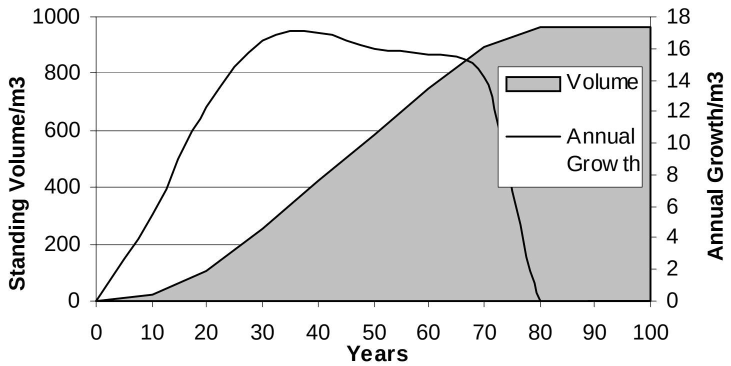

Figure 7. Introducing a growth reduction of 10% after 30 years, which prolongs for 20 years, result in a lost volume. The effect is clearly visible in the annual growth pattern, but hardly noticeable in the cumulative volume increment.

The estimated volume for the stand is 1000 m^3. Due to the introduced growth reduction, the actual volume when felled was 965 m^3. Thus, in this simulation 35 m^3 was lost due to the introduced reduction. Note that thinning, that normally occurs two or three times during a stand cycle, is not included in this model. The final volume is therefore overestimated.

Sensitivity Analysis and Salvage Felling

A sensitivity analysis on the *t* variable shows no significant differences. At maximum, a difference of 10 m^3 lost volume is dependent of the time the impact occurs. The *p* factor showed a more pronounced effect. That is, the duration of the growth reduction had a larger impact than at what time the impact occurred. An analysis on the magnitude indicates that its effect on the final volume was similar to the prolongation factor.

During the analysis, the magnitude had its maximum at 20% (t=20, p=30, r=0), which is comparable to the lost volume if felled 10 years earlier.

The reduction was restored to zero and a (salvage) felling was introduced 10 years earlier than expected. This time the final volume was 856 m^3 and the lost volume amounted to 144 m^3. Thus, the impact of felling the stand 10 years earlier had a higher impact than reducing the growth for a few years. In fact, it will have a greater impact than a reduced growth of 10% during the whole life span (100 m^3 lost).

Monte Carlo Simulation

A Monte Carlo analysis on the variables affecting reduction was made. This method uses a numerical sequence of random numbers sampled from a chosen probability function, e.g. a normal distribution function. In this way, the best guess can be tested with an included uncertainty. In the model, only normal distributions, one- or two-sided, are used. The purpose with a Monte Carlo simulation is here to test the stability of the model.

For each variable, a normal distribution was used. The assumed mean values and the corresponding standard deviations (also assumed) are given in table 2.

Table 2. Assumed mean value and standard deviation for the different variables that constitutes the total reduction impact. These values were used as input to the Monte Carlo simulation.

Variables	*Mean*	*SD*	*Distribution*
Time, t	50	14	Two sided
Magnitude, m	0	8	One sided
Prolongation, p	35	10	Two sided
Resilience, r	0	3	One sided

The values where assumed according to following reasoning. The impact on growth is likely to be apparent during years when the annual growth rate is high. The demand for nutrients is relatively higher during these years (30-100). Furthermore as the stand grows, nutrients are depleted from the soil.

The magnitude is selected with a mean value of 0 i.e. no impact at all, but with a one sided distribution and a standard deviation of 8. The randomised sequence had a maximum magnitude of 18 per cent. It is estimated that the future annual growth reduction will be between 2-19%, depending on future abatement scenarios (Sverdrup and Warfvinge 1993). The assumption to use a mean value of zero may therefore be too conservative.

The prolongation period is difficult to even guess. It is likely that it will be very long due to the slow regeneration rate of acidified soils experienced in the Gårdsjö roofing project (Hultberg and Skeffington 1998). Resilience is also a complicated parameter to guess. This is mainly included in the model to enhance the long-term effects connected with prolongation.

The variables *culmination time* and *SPC* were also normally distributed. These were then included in the Monte Carlo Simulation to receive a mean value of the lost volume for all tree species and with different SPC. The mean value of the culmination time was set to 90 years with a SD at 13. The mean SPC for Svealand and Götaland is estimated to 6.2 and 8.7 respectively (Forest statistics 1998). The mean SPC was in the model set at 8 (SD=3).

The salvage felling, defined as a felling that occurs earlier than expected, was also introduced in the model. The felling distribution was selected from a one-sided, normal distribution function with a mean value of 0 and a SD of 7. The mean value of CT was adjusted to 88 (SD10).

The result of running the simulation for 100 iterations is presented in table 3.

Table 3. Results from running the Monte Carlo simulation with salvage felling included.

	Estimated Vol. (m^3/ha)	Actual Volume (m^3/ha)	Loss (m^3/ha)	Cost (SEK)*
Mean	719	663	57	18527
SD	299	258	42	13605
Min	47	47	0	0
Max	1533	1296	237	77262

*The cost is calculated by multiplying the lost volume with 326 SEK.

Analysis and Conclusions

From running the sensitivity analysis, we can draw four conclusions. First; a moderate growth reduction will be difficult to detect. The introduced growth decline was not visible on the cumulative growth. Out in the field it would be even more difficult due to the various factors affecting growth such as rainfall, temperature, length of growing season, management, etc. Secondly; the time when the impact will be apparent may not be as important as the magnitude. However, the magnitude of growth decline may be dependent on growth rate and the highest growth reduction is likely when the need for nutrients is at maximum. Third; the prolongation of the growth decline is important for the final volume. It is reasonable to believe that a growth decline continues until the stand is felled if initiated during the period of high annual growth. Forth; if a stand is felled premature (salvage felling), this will have a major impact on final volume. Salvage felling has not been considered in earlier studies of the impact of acidification and it would be interesting to study if it occurs more frequently in Sweden nowadays. Sverdrup *et al.* (1994) states that tree mortality will increase as a result of exceeding the critical limit. This will have similar effects as the salvage felling studied in this paper since it is assumed that the forester fells the stand if the risk for die-off increases.

A rough validation of the model is derived when dividing the estimated volume per hectare with 88, which is the mean life span. This gives us the simulated annual growth for southern Sweden. By multiplying with forested area in southern Sweden (8.2 million hectare) the mean production in biomass is derived. This calculation implies an annual growth of 67 million m^3, or 70% of the total annual growth in Sweden. The mean annual growth in southern Sweden between 1992 and 1996 is calculated to 55 million m^3 (60% of total) (Forest statistics 1998). One reason for this mismatch may be that the CT is overestimated in the model.

The results from the Monte Carlo simulation can give us a hint of a total future cost in southern Sweden. Sverdrup and Warfvinge (1995) estimate that 80% of Sweden's forests are within the risk of being negatively affected. No time frame is, given, however. For southern Sweden, this figure is 100%, which amounts to 8.2 million hectares. If we use the results from the Monte Carlo simulation a possible future cost in decreased production can be calculated by multiplying the 8.2 million hectares with the simulated mean loss per hectare and the mean price per m^3. This equation results in a total cost of 153 thousand million SEK. Dividing the total cost with the mean culmination time - when the stand is felled - gives us the mean annual cost of 1.7 thousand million SEK (6% of the annual timber net (raw) value). This is of course very speculative since we have few indications of when, where and how much of the growth that will be affected. It is noteworthy however that even a minor change in annual production will render a significant cost.

Liming the total acidified area (5 million ha) with 3-4 tonnes dolomitic lime/woodash per hectare will cost approximately 7.5 thousand million SEK. If liming eliminates the impact for more than 7 years, it will be worth to carry out the project. To what extent the proposed liming measures will mitigate a negative impact is not shown.

Assuming a similar effect on the Total Economic Value (i.e. loss of recreation value, berries, water, etc.) the total loss may be estimated. The total economic value of utilities affected by acidification is in this study estimated to 65 thousand million SEK $annum^{-1}$. How much of the TEV that should be placed on southern Sweden is difficult to say. Since a large part of the Swedes resides in the south it is quite possible that a major part of this value is derived in this region. Anyway, a reduction of 6 per cent annually would, if realised, render a considerable cost regardless if we assume that 50, 70 or 90 per cent is found in southern Sweden.

We could turn the question the other way around - how many per cent growth reduction is economically acceptable before liming is cost efficient? The annual lost value (c) is dependent on the estimated annual value (v) and per cent reduction (p); $c = vp100^{-1}$. Let us assume that a specific measure mitigates a future growth reduction for t number of years. The total value derived under this period can be written T = vt. However, the future revenue is discounted with a given rate (r), resulting in a total value lower than T. When including the discount rate, the equation should be written;

$$T = \sum_{t}^{1} v(1+r)^{-t} \tag{3}$$

The lost value (c) can with the same reasoning be written;

$$c = \frac{p}{100} \sum_{t}^{1} v(1+r)^{-t} \tag{4}$$

Mitigating growth reduction is economically worthwhile until the point where the mitigation cost (m) equals the discounted lost value;

$$m = c = \frac{p}{100} \sum_{t}^{1} v(1+r)^{-t} \tag{5}$$

Let us analyse how investing in a mitigation measure is dependent on the time mitigating effect will persist (i.e. how many years a growth decline will be avoided). Assume that liming would eliminate a future growth decline for t number of years. The cost of liming is 1500 SEK ha^{-1} and the annual produced volume per hectare has, under normal conditions[6], a value of 2200 SEK. Equation (5) can be rewritten to;

$$p = \frac{100m}{\sum_{t}^{1} v(1+r)^{-t}} \qquad (6)$$

where p indicates per cent growth decline required before a mitigation measure is economically worthwhile. Figure 8 illustrates that cost efficiency is dependent on the number of years that liming will mitigate the effect. A discount rate of 3 per cent is used in this example (r = 0.03). If the cost of liming is 1500 SEK ha^{-1} and the annual value of the produced volume is 2200 SEK it implies that a growth decline of 68% is required if the effects of liming only persists for one year. If it persists for 20 years, a 4 per cent decline is enough for the measure to be carried out (Figure 8).

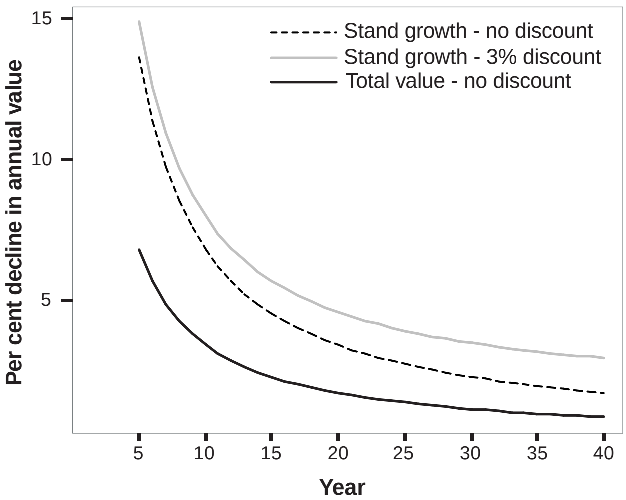

Figure 8. The number of years that a given mitigation measure will prevail will determine how much decline in a value that is justifiable to prevent given a certain cost and a certain annual value.

Since the cost of mitigating acidification with lime (and wood ash) is fairly low (1500 per hectare) the operation is worthwhile if the positive effects on tree growth will persist for a longer period (20-40 years). A decline in forest growth of less than 5 per cent will make mitigation measures worthwhile independent of using the discount rate or not.

A sensitivity analysis shows that the discount rate does not affect the pattern significantly. Furthermore, if the positive effects of liming will persist for a longer period (20-40 years), the other two variables (liming cost and produced timber value) will not cause a major impact on the output. Thus, it seems fair to conclude that liming is economically worthwhile if liming mitigates a future growth decline of 2-5 per cent, and if the effect would persist for more than 20 years. The same result would apply to a similar reduction of the total economic value (TEV).

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[6] This value is derived when multiplying the average annual growth (6.2-8 m^3 ha^{-1}) with mean price (326 SEK).

Discussion

The amount of area that in this report is defined as acidified amounts to 5 million hectare. The annual increase of acidified area seems very rapid to judge by the results. It is assumed that the frequency distribution used is a relative representation of the total area. It is questionable to what extent this assumption correlates with reality. Soil pH is heterogeneous and varies significantly within a given area. If the result is due to variation within the material, it is reasonable to assume that the result would have been a random variation between the years. In this material, however, a clear trend toward more sites having a lower pH is visible. To some extent the decrease in pH may be explained by the fact that the mean age of forest stands is becoming older (Forest statistics 1998). Tamm and Hallbäcken (1986) concluded that stand age had no effect on the lower soil horizons. It is therefore questionable if aging is the only factor contributing to the rapid decrease of pH over such large area at this soil depth. Harvest and deposition is most probably contributing to the rapid increase of acidified area.

The total cost of mitigating the impact on these areas amount to 7.5 thousand million SEK if liming with 3 tonnes hectare^{-1} is used. How long this measure will persist is difficult to say. Probably at least between 20 to 40 years. It should be noted that liming eventually result in preliminary negative side effects that also should be considered and cost estimated.

The effects of acidification are slow, making them difficult to identify. Due to the various variables affecting growth in forestry, it is difficult to detect a growth decline. The model used in this study implies that a decline will be very difficult to detect in the field if the magnitude of the impact is moderate. However, even a small decrease in produced timber may render in a significant cost.

It is taken for granted that a reduced growth will inflict a loss of value. It also possible that a slow growth rate increase the quality of the timber, and thus the price paid per m^3. It is therefore a theoretical possibility that net revenue loss will be less significant. However, the dominating part of the annual harvest is sold to the pulp industry where the price is less dependent on wood quality.

Increased mortality has not been considered in the model. This may also affect the value. It is important to realise, however, that the total growth of the stand may be different from the individual growth. If one tree suffers from a disease or anything that may affect the growth rate or vitality, other trees in the surrounding may benefit.

Going towards sustainability requires that we monitor changes in the surrounding environment. In this way, we may give predictions for the future. These predictions are very difficult to perform since many uncertainties are involved. Despite the drawbacks of defining an economic value on non-marketed goods and services it may be of importance since it diverts the focus away from only accounting marketed goods and services. We all agree that these utilities are important values contributing to the common welfare in Sweden. How these values should be quantified is a matter of discussion. The economic valuations seem to many people a crude way of valuing the invaluable. Indeed this is right. The methodologies have been criticised by many authors and the uncertainties are significant. These values are also affected by various factors such as environmental accidents, information, education, etc. Nevertheless, the problem remains, to estimate and justify the amount of money being worthwhile to spend when mitigating the impact of forest soil acidification.

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