Regional Nutrient Budgets in Forest Soils in a Policy Perspective

Akselsson, Cecilia

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CECILIA AKSELSSON

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LUND INSTITUTE OF TECHNOLOGY
Lund University

DEPARTMENT OF CHEMICAL ENGINEERING
LUND UNIVERSITY

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ABSTRACT

Sweden's forests are one of its most important natural resources, as well as being important from ecological and social perspectives. Nutrient sustainability is essential to maintain the production capacity and reduce the effects of acidification and eutrophication. Nutrient sustainability is strongly affected by anthropogenic influences such as air pollution and forestry practices. Regional assessments of the nutrient sustainability with different deposition and harvesting scenarios are thus required in policy-making. This thesis deals with the nutrient sustainability regarding nitrogen, calcium, magnesium and potassium on a regional scale in Swedish forests, and the potential effects of forests on carbon sequestration. It includes method development of regional weathering rate modelling, regional budget calculations for Sweden, and a discussion of the results in a policy context.

Estimates of base cation budgets showed that the pools of exchangeable base cations are decreasing and that the stores are being depleted at rates that could lead to negative effects within the period of one forest rotation. The whole-tree harvesting scenario indicated substantially higher base cation losses than the stem harvesting scenario in spruce forests, while the losses were significantly lower in pine forests. The nitrogen budget calculations indicated a risk of nitrogen leaching in southern Sweden and increased nitrogen shortage in northern Sweden. Consequently, policies affecting the supply of nitrogen must take into account regional differences if they are to be effective. Calculations showed that carbon sequestration in Swedish forest soils is not an effective way of decreasing national net carbon dioxide emissions, since the long-term capacity is low and involves the accumulation of nitrogen, increasing the risk of acidification and eutrophication of aquatic and terrestrial ecosystems. Whole-tree harvesting, combined with the use of branches, tops and needles as biofuel to replace fossil fuels, would substantially decrease the present carbon dioxide emissions from fossil fuels.

The results highlight several conflicts, not only between production goals and environmental objectives, but also between environmental objectives regarding acidification, eutrophication and emissions of greenhouse gases. The methods of calculating nutrient and carbon budgets are considered suitable for decision support in policy-making, but should preferably be combined with other types of methods, for example, dynamic modelling.

Keywords: Nutrient budget, acidification, eutrophication, carbon sequestration, deposition, forestry, regional scale, policy-making

Contents

Appendices

The thesis is based on the following seven papers:

I. Akselsson, C., Holmqvist, J., Kurz, D. and Sverdrup, H.:
Relations between bedrock mineralogy, till mineralogy and elemental content in till in southern Sweden
Submitted for publication

II. Akselsson, C., Holmqvist, J., Alveteg, M., Kurz, D. and Sverdrup, H., 2004:
Scaling and mapping regional calculations of soil chemical weathering rates in Sweden
Water, Air, and Soil Pollution: Focus[1] **4**: 671-681

III. Akselsson, C., Sverdrup, H. and Holmqvist, J.:
Estimating weathering rates of Swedish forest soils in different scales, using the PROFILE model and affiliated databases
Accepted for publication in Journal of Sustainable Forestry[2]

IV. Akselsson, C., Westling, O. and Örlander, G., 2004:
Regional mapping of nitrogen leaching from clearcuts in southern Sweden
Forest Ecology and Management[3] **202**: 235-243

V. Akselsson, C., Sverdrup, H., Westling, O., Holmqvist, J., Thelin, G., Uggla, E. and Malm, G.:
Impact of harvest intensity on long-term base cation budgets in Swedish forest soils
Manuscript

VI. Akselsson, C. and Westling, O., 2005:
Regionalized nitrogen budgets in forest soils for different deposition and forestry scenarios in Sweden
Global Ecology and Biogeography[4] **14**: 85-95

VII. Akselsson, C., Berg, B., Gundersen, P. and Westling, O.:
Comparing two methods to calculate terrestrial carbon sequestration rates in forest soils on a regional level
Submitted for publication

Related papers

The author has also been involved in the following related papers:

1. Akselsson, C., Ardö, J. and Sverdrup, H., 2004:
   Critical loads of acidity for forest soils and relationship to forest decline in the northern Czech Republic
   Environmental Monitoring and Assessment **98**: 363-379

2. Akselsson, C., Berg, B., Meentemeyer, V. and Westling, O.:
   Carbon sequestration rates in organic layers of boreal and temperate forest soils – Sweden as a case study
   Global Ecology and Biogeography **14**: 77-84

1 Introduction

Air pollution together with forest management have greatly changed the conditions in European forests during the past century. Acidifying deposition, mainly consisting of sulphates, nitrates and ammonium, reached a peak during the 1980s (Schöpp et al., 2003) and has led to acid soils and surface water with high aluminium (Al) concentrations, causing the loss of the important tree nutrients calcium (Ca), magnesium (Mg) and potassium (K) (Haynes and Swift, 1986). Although acid deposition has decreased, soils are still acidified in large areas of Europe and the recovery process will, according to model calculations, proceed slowly (Martinson, 2004).

Apart from the acidifying effect of nitrate and ammonium, the increased nitrogen (N) availability in soils has led to changes in biodiversity (Nordin et al., 2005) and increased N leaching in many northern forest ecosystems which have traditionally been considered to be N-limited (Aber et al., 1989; Gundersen et al., 1998). On a wider scale N leaching causes aquatic eutrophication.

When considering the effects of acidity and nutrient availability on forest ecosystems, it is also relevant to discuss the role of forests in one of the world's most debated environmental issues, namely climate change. Carbon (C) storage in forests is an integral part of the global C cycle as forest soils and trees are both potential sinks and sources of C (von Arnold, 2004). Another perspective of C related to forests is that branches, tops and needles (slash) can contribute to more sustainable energy production by replacing fossil fuels.

Sweden is covered by 23 million hectares of productive forest, which corresponds to 55% of the total land area, according to data from the Swedish National Forest Inventory (data from 1997-2001). Forestry products constitute 13% of Sweden's total exports (National Board of Forestry, 2004) and a continued high production level is thus important from an economic perspective. Apart from economical interests, the forests are also important from ecological and social points of view (Sverdrup and Svensson, 2002). Maintained biodiversity and good quality of the runoff water are important ecological issues, while from a social point of view forests are important for recreation. During the second half of the 20th century an increase in forest growth was observed in Swedish forest inventories. This increase can largely be explained by changes in forest management (Elfving and Tegnhammar, 1996). The actual increase in growth has probably been supplemented by the increased N deposition (Näsholm et al., 2000). The increased intensity in forestry, with increased growth and harvesting of stems, has led to losses of important nutrients. By the end of the previous century whole-tree harvesting had become more common (Gustafsson et al., 2002) and nutrient losses have thus increased.

The conflicting interests associated with forests, together with the environmental problems that have arisen, can cause goal conflicts in forestry. Compromises and new management methods are required in order to achieve acceptable solutions. Since different authorities are responsible for different goals, this requires negotiations on a political level between the different authorities. Decision support should be provided on a regional scale, where the goal conflicts are illuminated and different alternatives are analysed and evaluated from different perspectives.

2 Objectives and scope

This thesis deals with conflicting goals in forestry from a sustainability point of view with respect to nutrient resources. It focuses on regional base cation and N budgets and on how they are affected by different deposition and forestry scenarios (Papers V and VI). Phosphorus and trace elements are not considered. During the calculation of N budgets the work was extended to include C, due to its close connection with the N budget and the increasing interest in C sequestration in forest ecosystems connected to climate change (Paper VII). The overall objective was to provide improved information regarding the biogeochemical aspects of base cation, N and C budgets on a regional scale, suitable for decision support on a regional and national level, in certain environmental issues regarding sustainable forestry and air pollution, namely acidification, eutrophication and C sequestration. The economical, social and biodiversity aspects were not included.

The work included evaluation of existing monitoring and inventory data as a basis for regional biogeochemical calculations. Method development studies were required to improve the resolution and accuracy of the data. In Paper I one of the most important parameters for modelling weathering, the mineralogical composition, is addressed. Spatial variation of the elemental content and mineralogical composition of the soil and bedrock are compared in an area in southern Sweden, in order to evaluate the possibility of estimating the mineralogical composition based on elemental content and bedrock mineralogy. In Papers II and III the scaling-up of weathering calculations is described, results are presented and the issue of weathering rates on different scales is discussed. The results from these studies were used, with some modifications, in the study described in Paper V on base cation budgets. Paper IV presents N leaching from clearcuts on a regional scale, and the results were used in the study described in Paper VI on N budgets. A schematic picture of the outline is presented in Figure 1.

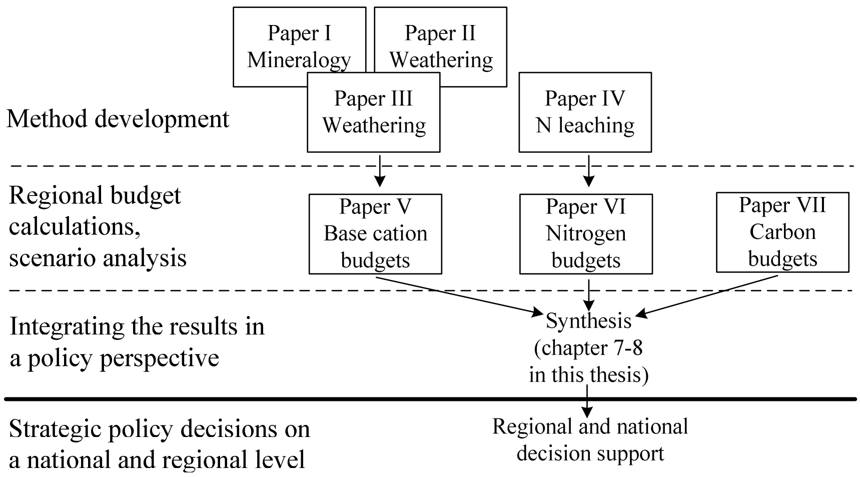


Figure 1. *Schematic outline of the thesis and how it is related to policy assessments. The bold line separates the thesis (above the line) from policy assessments (below the line).*

3 Background

3.1 Sustainability in forest ecosystems

Sustainability is a broad concept used in many different contexts. Sustainable development is, according to the Brundtland Report, defined as "...development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission of Environment and Development, 1987). More specific definitions are required within specific fields.

Sustainability in forest ecosystems can be divided into three parts: natural sustainability, economic sustainability and social sustainability (Sverdrup and Svensson, 2002). This thesis focuses on part of the natural sustainability, i.e. nutrient sustainability. Nutrient sustainability means that no long-term depletion of nutrients takes place, implying a balance between input and output (Sverdrup and Svensson, 2002). In a situation of nutrient sustainability the internal net production capacity of the forest ecosystem is maintained. The nutrient sustainability concept is central when discussing acidification, eutrophication and C sequestration.

3.2 Present policies in Swedish forestry

Forestry in Sweden is regulated mainly by the Swedish Forestry Act. In addition to this, 15 objectives for environmental quality have been established by the Swedish Parliament, with the overall aim of the present generation being able to hand over a society to the next generation where the major environmental problems have been solved (Swedish Environmental Protection Agency, 2000). Many of the objectives are connected to forests and forestry in one way or another, and for some of them forestry is central. The Swedish Forestry Act, the environmental objectives and scientific material are used by authorities in different fields to formulate recommendations.

3.2.1 The Swedish Forestry Act

The first paragraph in the Swedish Forestry Act (1979:429) states the philosophy of Swedish forestry policy:

"The forest is a national resource. It shall be managed in such a way as to provide a valuable yield and at the same time preserve biodiversity. Forest management shall also take into account other public interests."

It places equal emphasis on two goals: productivity and protection of the environment. The production goal states that forests and forest soils should be used effectively, resulting in long-term high yields. There are many paragraphs in the Forestry Act describing how this goal should be reached, e.g. by planting new forests (or taking measures for natural regeneration) after regeneration felling and performing cleaning and thinning in young forests to encourage forest development. The environmental goal deals with maintaining the natural production capacity, preserving biodiversity, and protecting the cultural heritage. Special environmental care is required to reach this goal, for example avoiding large felling areas, leaving older trees standing on felling sites, leaving protective buffer zones adjacent to water, retaining some deciduous trees in coniferous forests and avoiding damage to sensitive habitats and valuable historical sites. Moreover, all forest owners must present reports on their forest and its environmental status. The Swedish Forestry Act is formulated in such a way that it gives great freedom to individual forest owners.

3.2.2 Objectives for environmental quality

The environmental objectives contain descriptions of the environmental characteristics required to achieve natural sustainability. Different authorities are responsible for different objectives. Below follows a description of some of the objectives concerned with nutrient sustainability, acidification, eutrophication and C sequestration.

The **"Sustainable forests"** objective states that: *"The forest and forest land's value for biological production must be protected at the same time as biological diversity and cultural heritage values and social values are protected".* This objective deals mainly with biodiversity issues, but also includes preservation of the natural production capacity of forest soils, recreation, and preservation of cultural remains.

The objective "**Natural acidification only**" is formulated as follows: *"The acidifying effects of acid deposition and land use must not exceed limits that can be tolerated by land and water. In addition, deposition of acidifying substances must not accelerate the corrosion of technical materials of cultural artefacts and buildings."* This objective concerns both soil and water. The natural production capacity and the biodiversity should, according to the objective, not be affected by anthropogenic acidification, and the critical loads of acidity should not be exceeded. Acidification effects on technical materials through corrosion are also included.

The "**No eutrophication**" objective reads: *"Nutrient levels in soil and water must not cause adverse effects on human health, the pre-requisites for biological diversity of versatile land and water use"*. This objective aims at combating the effects of eutrophication, resulting from deposition and land use, on the nutrient status and biodiversity in aquatic and terrestrial ecosystems.

The "**Limited influence on climate**" objective states that: "*Levels of greenhouse gases in the atmosphere must, in accordance with the UN Framework Convention on Climate Change, be stabilised at a level at which human impact will not have a harmful effect on climate systems. This objective is to be attained in such a way and at such a rate as to protect biological diversity, assure food protection and not jeopardise other sustainable development goals. Together with other countries, Sweden is responsible for achieving this global objective."* This implies that the concentrations of carbon dioxide (CO_2) in the atmosphere must be kept at an acceptable level and that other greenhouse gases may not increase. Forestry is interesting in this objective due to its great impact on the C cycle.

3.3 Acidification and base cation losses

Acidification was identified as a serious environmental threat in Scandinavia in the late 1960s (Odén, 1968), but acidification has been going on since the start of industrialization in the 19th century. Deposition of sulphate (SO_4^{2-}), originating mainly from the burning of fossil fuels and from industrial processes, and nitrate (NO_3^-) from combustion, leads to the addition of acidity to the soil, as sulphuric acid and nitric acid. NO_3^- is, however, only directly acidifying if it is not taken up, since uptake leads to the release of a negatively charged ion, usually OH^- or HCO_3^-. Deposition of ammonium (NH_4^+), originating mainly from manure, does not have a direct acidifying effect. However, N accumulation forms a reservoir of potential acidity that can be released when the N retention capacity of the forest soil is reached (Galloway, 1995).

Forest growth naturally leads to soil acidification since trees take up more positive than negative ions and thus release H^+ ions in exchange. The acidification persists if biomass is harvested, as this leads to removal of base cations from the system. Slash removal causes increased soil acidification. The long-term sensitivity to acidification is highly dependent on the weathering of the soil. Soils with easily weathered minerals can neutralize more acid deposition than soils with slowly weathered minerals.

The short-term resistance to acidification depends on the base saturation, i.e. the fraction of base cations on the exchange positions of the soil particles. As a result of acid deposition, H^+ ions replace the base cations Ca, Mg, K and Na on the soil particles, and base cations are thus lost from the soil by leaching. This causes lower base saturation and decreased resistance to further acidification. Acidified soil leads to acidified runoff water and thus acidification of streams and lakes. The losses of the important nutrients Ca, Mg and K may lead to deficiencies in trees. Ca is needed to form calcium pectate, which is an important component of the cell wall, while Mg and K are needed for photosynthesis. Shortage of these nutrients can lead to long-term negative effects on soil fertility, tree growth and tree vitality (Rosengren-Brinck et al., 1998; Thelin et al., 1998). Acidification also leads to reactions involving Al compounds, leading to increased amounts of inorganic Al dissolved in soil water and adsorbed onto soil particles. High concentrations of Al are toxic to roots (Cronan et al., 1989). Furthermore, Al can bind the important nutrient phosphorus, which may lead to phosphorus deficiencies in plants.

3.4 Eutrophication

N loads to the sea have increased substantially during the 20th century. The main anthropogenic sources from land areas in Sweden are agricultural land (54%) and sewage treatment plants (24%) (Bergstrand et al., 2002; Brandt and Ejhed, 2003). N is often the limiting factor for algae in the marine environment, and increased amounts of N commonly lead to increased biological production (Sedin, 2003). The decomposition of dead plant material after algal blooming requires high amounts of oxygen, leading to a deficiency in the sea-bed water. Many marine organisms including fish are dependent on the spawning areas of especially shallow bottoms, and eutrophication thus changes the marine ecosystem. Phosphorous (P) is generally the limiting factor in lakes, but in areas with high P availability N can be limiting and N addition can thus cause eutrophication.

In northern forest ecosystems N is often considered to be the limiting factor for growth (Tamm, 1991), and N leaching from growing forests is thus generally very low. From a forest production point of view the problem associated with N is thus considered to be the possible shortage which limits growth. For this reason N fertilization is common practice to increase forest production. The high N deposition, culminating at the end of the 20th century (Westling and Lövblad, 2000; Schöpp et al., 2003), may lead to terrestrial eutrophication, leading to negative effects on other species and on biodiversity (Brunet et al., 1998; Strengbom, 2002; Strengbom et al., 2002; Nordin et al., 2005). Furthermore, with a high N supply other factors can become limiting for growth, and the excess N may then be leached out of the soil causing marine eutrophication. There are many examples of this from areas with high N loads (Aber et al., 1989; Gundersen et al., 1998). Knowledge regarding the increased deposition of N in the southern part of Sweden has restricted fertilization to the northern part of the country (National Board of Forestry, 1991).

Although N leaching from growing forest in Sweden is generally small, there are indications of markedly increased leaching at several sites in the southwestern part of Sweden during the recent decades, which cannot be explained by forest damage or other disturbances (Hallgren Larsson et al., 1995; Nohrstedt et al., 1996; Nilsson et al., 1998). Conditions on clearcuts are completely different from those in growing forests, since net mineralization continues at the same or an even higher rate, while there is no uptake by trees. This causes increased N leaching from clearcuts, as has been shown in several studies in Europe (Adamson and Hornung, 1990; Wiklander et al., 1991; Ahtiainen, 1992; Rosén et al., 1996; Ahtiainen and Huttunen, 1999) and in the United States (Dahlgren and Driscoll, 1994; Pardo et al., 1995; Hermann et al., 2001). In a study of clearcuts in southern Sweden, N concentrations in soil water were found to be positively related to N deposition (Löfgren and Westling, 2002). The relation can be explained by greater net mineralization in forest soils with high amounts of N.

The C/N ratio in the organic layer is a measure often used to link the N status of a forest soil with the risk of increased N leaching. According to empirical studies by Gundersen et al. (1998), a ratio of less than 25 indicates an increased risk of substantial N leaching. Data from the National Forest Inventory (Hägglund, 1985) on C/N ratios in humus show ratios between less than 25 in southwestern Sweden and above 35 in the north. A special study of 32 coniferous stands in the southernmost part of Sweden showed that 45% of them had a C/N ratio of less than 25 (Jönsson et al., 2003). Such low C/N ratios indicate that there is a risk of increased N leaching from growing forests, especially in old stands with less N uptake than young stands.

3.5 Climate change

The global average surface temperature has increased by 0.6ºC during the past century, according to Watson et al. (2001). Temporal climatic variation is normal, but there is general agreement among researchers that this increase is caused by the emissions of greenhouse gases, which affect the radiation balance. Water vapour and CO_2, which occur naturally in the atmosphere, do not affect the incoming short-wave radiation from the sun, but they absorb a large amount of the outgoing thermal radiation. This means that much of the heat is stored in the atmosphere. Emissions of CO_2 and other greenhouse gases with the same absorbing effect lead to an increased greenhouse effect and thus increased temperatures. CO_2, mainly from burning of fossil fuels, is the most significant greenhouse gas. Methane, different chloro-fluoro compounds and nitrous oxides are other examples of significant greenhouse gases. Scenario analyses indicate that the average temperature at sea level will increase by 1.4-5.8ºC from 1990 to 2100 (Watson et al., 2001). Furthermore, precipitation is expected to increase and there are also indications that the frequency of extreme weather events will increase.

Forest ecosystems have been proposed as potential C sinks that can counteract the release of CO_2 to the atmosphere and thus global warming (IPCC, 1995). By increasing the standing stock, the C sequestration in both biomass and soil can increase. This leads to decreased net emissions of CO_2, defined as the difference between emissions to, and removal from, the atmosphere (UN, 1997). Renewable fuel, such as biomass, is normally not included in the estimations of net emissions, since the CO_2 emissions are balanced by the CO_2 fixation. Thus, replacing fossil fuels by slash from thinning and regeneration felling decreases the net emissions of CO_2. This requires an intensive forestry with whole-tree harvesting.

3.6 Forestry, climate and geology in Sweden

Sweden is situated between the latitudes 55ºN and 69ºN, and the climate thus varies considerably throughout the country, the transition from temperate to boreal climate being at around 60ºN. In most parts of Sweden, precipitation ranges from 600 to 900 mm y^{-1} (Raab and Vedin, 1995). In southern Sweden it is as high as 1300 mm in certain parts of the western coastal region, whereas in areas at the same latitude along the eastern coast it is on average 600 mm a year. The precipitation is greatest in the mountains in the northwest, where it can be as high as 2000 mm. The geographical variation in mean temperature in Sweden is high. The mean temperature in the winter varies between 0ºC in the south and -16ºC in the north. The corresponding figures in the summer are 16 and 8ºC (Raab and Vedin, 1995).

The bedrock in Sweden consists largely of different kinds of igneous rocks, such as granite. Gneisses are common in the southwestern parts of Sweden and sedimentary bedrock is found mainly along the mountain range in the northwest, in other parts of northern Sweden, in the southernmost part of Sweden, and on the islands Öland and Gotland. Small areas of acid, intermediate, and basic vulcanites are sparse. The dominant type of soil is podzol (according to the FAO/UNESCO soil classification system), and the most common soil texture is sandy till. Ditched organic forest soil accounts for 7% of the managed forest area (Hånell, 1990).

The coniferous species Norway Spruce (*Picea abies* (L.) H. Karst.) and Scots Pine (*Pinus sylvestris* L.) are dominant, covering 30% and 36% of the forested area respectively (National Board of Forestry, 2000). Spruce is the dominant coniferous species in southern Sweden, whereas pine is more common than spruce in northern Sweden. Birch is the most common deciduous species

(*Betula pubescens* Ehrh. and *Betula pendula* Roth), while European beech (*Fagus sylvatica* L.), trembling aspen *(Populus tremula L.)* and pedunculate oak (*Quercus robur* L.) cover smaller areas. The dominant method for regeneration felling is clearcutting (Stokland et al., 2003). Traditional forestry in Sweden involves the harvest of stems only, however, during recent decades whole-tree harvesting, in which branches, tops and needles are removed, has become more common (Gustafsson et al., 2002). In 2002, branches, tops and needles were removed from 20% of the harvested area, the corresponding figure for southern Sweden being 40% (National Board of Forestry, 2003). Sweden faces changes in the energy supply system through conversion from fossil fuels to other energy sources, biofuels being an important alternative (Swedish Energy Agency, 2003).

4 Theory

4.1 System analysis

The system analysis approach is useful in analysing and illustrating system behaviour (Haraldsson, 2005). System analysis involves the mapping of system structure, identification of system components, identification of causal links and investigation of system behaviour, and also helps in the creation of mathematical models. Regionalization studies require the simplification of complex systems and for this system analysis is an effective methodology (Haraldsson and Sverdrup, 2004). Causal loop diagrams (CLDs) are useful for illustrating system behaviour. A cause-effect relationship is illustrated by an arrow from the cause to the effect. A plus sign indicates a positive relation, i.e. an increase in the causal parameter leads to an increase in the affected parameter, and a decrease leads to a decrease. A minus sign, on the other hand, denotes a negative relation, i.e. an increase in the causal parameter leads to a decrease in the affected parameter, and a decrease leads to an increase. Feedback is often involved, as exemplified in the CLDs and the corresponding reference behaviour patterns in Figure 2.

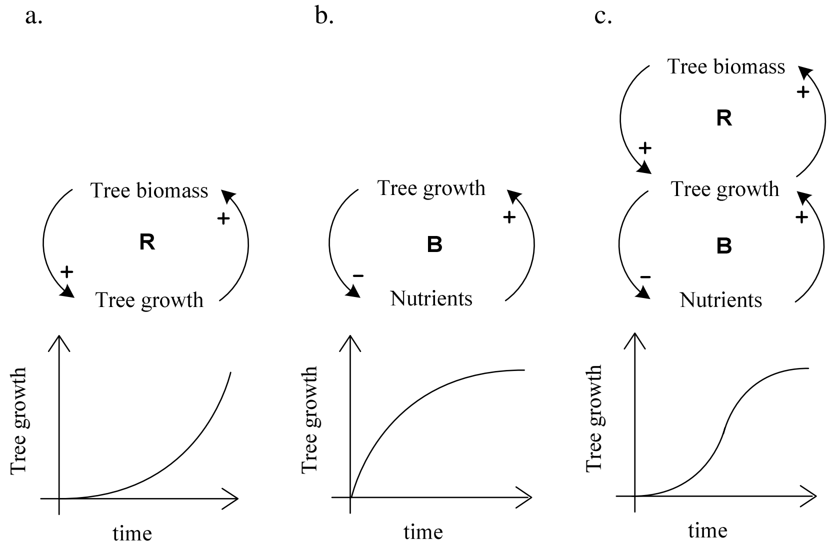


Figure 2. *The reinforcing (R) loop between tree biomass and tree growth and the corresponding reference behaviour are shown in (a). More tree biomass leads to more growth and more growth leads to more tree biomass, as can be seen in the increasing tree growth in the reference behaviour pattern. The balancing (B) loop between tree growth and nutrients and the corresponding reference behaviour pattern are illustrated in (b). More nutrients lead to more tree growth, but more tree growth leads to less nutrients, which leads to a flattening-out of the reference behaviour pattern. The combination of the two loops and the corresponding reference behaviour pattern are shown in (c). More tree biomass will lead to more tree growth, which will increase tree biomass, but at the same time decrease the amount of nutrients, which in turn affects tree growth negatively. This may lead to a reference behaviour curve that first increases and then flattens out.*

4.2 Nutrient and carbon cycling in forest soils

The cycles of the base cations, N and C in forest soils are closely linked and interdependent and are related to the environmental issues of acidification of soil and water, eutrophication and net emissions of greenhouse gases (Figure 3). To improve readability, the CLD in Figure 3 is greatly simplified and several factors, such as photosynthesis and factors affecting weathering and decomposition, are not included. The anthropogenic factors affecting acidification, eutrophication, net emissions of greenhouse gases and production are summarized in Table 1.

N addition may lead to increased growth and thus increased C sequestration in the forest/soil system, as long as the trees are N limited. However, N accumulation in the soil increases the risk of N leaching and eutrophication of terrestrial and aquatic environments. N accumulation also implies a potential acidifying effect (Section 3.3), this is however not included in Figure 3 for reasons of clarity. N also acidifies the soils indirectly as increased growth leads to a greater uptake of base cations.

The anthropogenic deposition of S together with forest growth imply decreased acid neutralizing capacity (ANC). ANC in the soil solution is derived from a soil water charge balance and can be expressed as:

$$[ANC] = [NH_4^+] + 2[Ca^{2+}] + 2[Mg^{2+}] + [K^+] + [Na^+] – 2[SO4^{2-}] – [NO_3^-] – [Cl^-] \quad (1)$$

or as:

$$[ANC] = [HCO_3^-] + 2[CO_3^{2-}] + [OH^-] + [R^-] - [H^+] - \sum_{n=1}^{3} n \left[Al(OH)_{3-n}^{n+} \right] \quad (2)$$

In a short term, however, this decrease in ANC may be counteracted by cation exchange, which leads to a decrease in base saturation. When the base saturation decreases the potential of base cation release through ion exchange decreases. This leads to acidified soil water with high concentrations of H ions and inorganic Al, and low concentrations of base cations. This may affect growth negatively and lead to acidification of ground- and surface water.

Harvesting of biomass (removal of stems and sometimes also branches, tops and needles) is another important anthropogenic driving force. The more intense the harvest, the more base cations are removed from the system, thus increasing the risk of acidification. The N availability and the risk of N leaching, on the other hand, decrease at high harvest intensity since N is also removed from the system. Although high harvest intensity provides economic benefits in the short term, the nutrient losses can lead to negative effects on production in the long term. Another aspect of the harvest intensity concern the C sequestration. The C sequestration in forest biomass and forest soils can be increased by increasing the standing biomass.

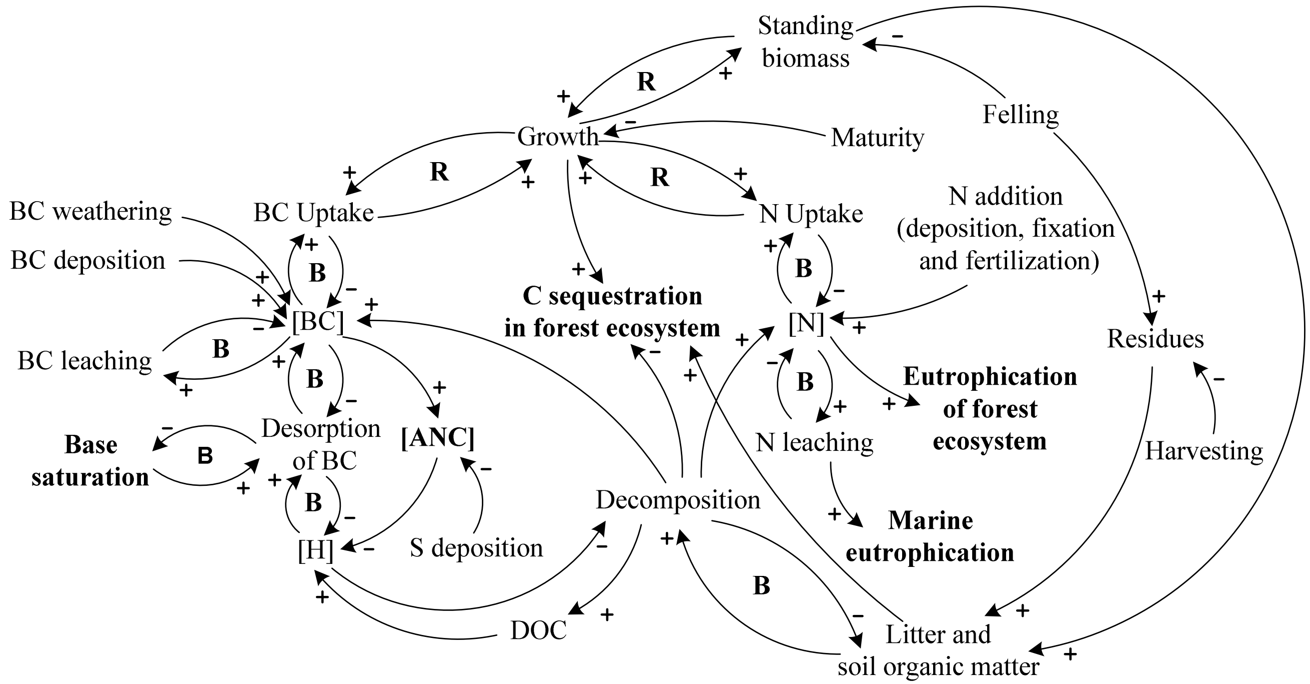


Figure 3. *Simplified CLD of the nutrient cycles in forest soils in relation to the environmental issues of acidification of soil and water, eutrophication and net emissions of greenhouse gases (associated with C sequestration). DOC = dissolved organic carbon, BC = base cations and the elements in brackets are concentrations in the soil solution.*

Table 1. *Effects of deposition and forestry on eutrophication, acidification, net emissions of greenhouse gases and production/economy. Plus (+) indicates an increase and minus (–) a decrease. Only the most obvious relations are included in the table.*

	Eutrophication	Acidification	Net emissions of greenhouse gases	Production/ Economy
N deposition/N fertilization	+	+	– (+)[1]	+ (–)[1]
S deposition		+	+	–
Increase of standing biomass	–		–	–[2]
Whole-tree harvesting	–	+	+/–[3]	+

[1] The sign in brackets refers to the situation when the N retention is exceeded and tree growth is reduced.

[2] The decrease in production/economy is valid if the increase in standing biomass is obtained by decreased harvesting.

[3] Less C is sequestered in the forest ecosystem, but if the slash is used as biofuel, replacing fossil fuel, the net CO_2 emissions will decrease.

Regional-scale calculations require breaking down of the system described in in Figure 3 to smaller, more manageable compartments. Thus, base cations, N and C were treated separately in the present study. More detailed descriptions of base cation cycling and N cycling are presented below, followed by descriptions of the base cation, N and C budgets employed in Papers V-VII.

4.2.1 Base cation cycling

The input of base cations to the system occurs through deposition and weathering, as shown in Figure 4. Weathering rates are highly dependent on the soil water chemistry. High concentrations of H ions increase the weathering rate while high base cation and Al concentrations inhibit it. Weathering rates are also controlled by the physical, mineralogical and hydrological properties of the soil (Sverdrup and Warfvinge, 1995) as discussed in Section 4.3.2 (not included in Figure 4). Desorption and adsorption of base cations in the soil occur naturally through the ion exchange process. The desorption process is accelerated by acidification, leading to decreased base saturation. The base cations are removed from the soil through uptake and leaching. The leached base cations are permanently lost, while the base cations taken up goes through an internal circulation and is returned to the soil solution through canopy exchange, litterfall and decomposition. At harvesting, however, base cations are removed from the system and the acidification becomes persistent. Other nutrients, soil properties and climatic factors that affect e.g. decomposition, have been left out for clarity.

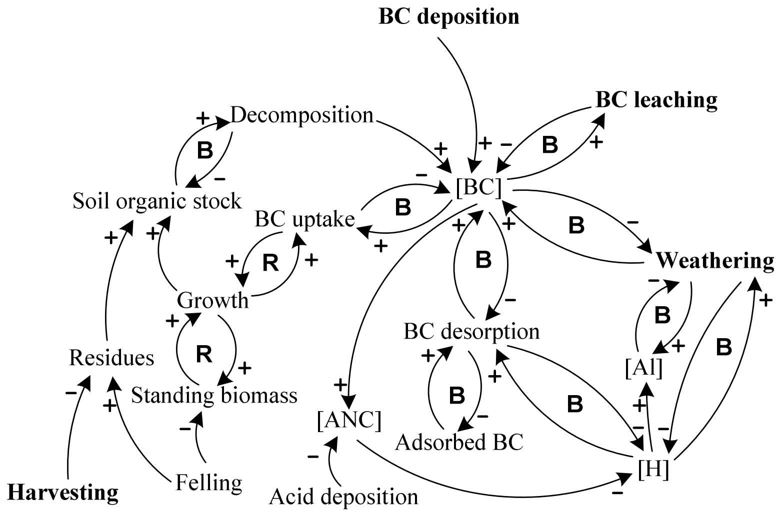


Figure 4. *Simplified CLD of base cation cycling in a forest ecosystem. The bold type marks the inflow and outflow terms used in the budget calculations (Section 4.3.1).*

4.2.2 Nitrogen cycling

The input of N occurs through deposition and fixation and the losses through harvesting, leaching and denitrification (Figure 5). An increase in N deposition enriches the soil in N which leads to an increased N uptake in trees and thus increased growth, as long as the trees are N limited. The N taken up goes through an internal circulation and is returned to the soil solution through canopy exchange, litterfall and decomposition, and net losses from the internal circulation with uptake and litterfall are restricted to the harvest losses. As long as the trees are N limited, the N losses through leaching are low. Other nutrients, soil properties and climatic factors that affect e.g. decomposition, are left out for clarity.

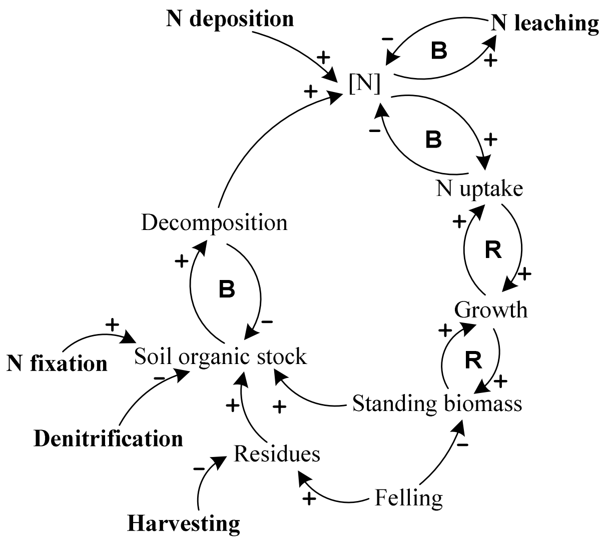


Figure 5. *Simplified CLD of N cycling in a forest ecosystem. The bold type marks the inflow and outflow terms used in the N budget calculations (Section 4.3.3).*

4.3 Budget calculations

Budget calculations, also referred to as mass balance calculations, are often used to estimate the nutrient status in an ecosystem. The calculations are based on the general equation of continuity:

$$\text{inflow} + \text{production} = \text{outflow} + \text{accumulation} \quad (3)$$

The degree of net accumulation or net loss (Δ) can thus be estimated as:

$$\Delta = \text{inflow} + \text{production} - \text{outflow} \quad (4)$$

A positive value of Δ indicates net accumulation and a negative value indicates net loss. Net changes in either direction occur in natural ecosystems, but normally at low rates. Accumulation and net losses at high rates may indicate a risk of adverse environmental effects.

The budget calculations in the present study are based on static mass balances, i.e. the mass balance terms are assumed to be constant over time. The results give indications of the nutrient sustainability of a system. If the budget is negative it can be concluded that one or more of the mass balance terms will eventually change since the output cannot be larger than the input in the long term. When this happens depends on the nutrient store in the soil and thus measures of soil stocks are required in combination with the mass balance estimates. The same reasoning applies to positive mass balances.

The input data demand for static mass balance calculations is limited, something which is necessary to allow regionalization. The results are robust and easy to interpret as long as the assumptions are kept in mind, which makes budget calculations useful as decision support. The potential of using static budget calculations for future projections is, however, limited since the dynamics of nature are not included.

4.3.1 Base cation budgets

Deposition, mostly as sea salt, industrial discharge and soil particles transported by the wind over a range of different distances, constitutes the input of base cations to the forest ecosystem together with weathering of soil minerals. The outflow of base cations from the forest ecosystem consists of harvested biomass and leaching. If reprecipitation of base cations into new minerals is neglected and if only vertical percolation is considered the nutrient budgets for base cations can be calculated as:

$$\Delta = \text{Deposition} + \text{Weathering} - \text{Harvesting} - \text{Leaching} \quad (5)$$

where Δ = accumulation (+) or loss (–).

The accumulation/loss is the change in the pool of exchangeable cations in soil and, in case of increasing or decreasing humus layer thickness, the change in the pool of base cations bound to soil organic matter. Only the fluxes into or out of the soil are included in the calculations, not the processes within the soil (Figure 4). The soil properties and climate drivers are assumed to be constant over time within each site. Whereas current rates, or approximations of current rates, can be used for the deposition, weathering and leaching terms, the harvesting term must be regarded in the perspective of a whole forest rotation. Thus, the results of the calculations give the yearly net change as an average for a forest rotation, provided that the other terms are constant over time.

4.3.2 Modelling weathering rates with the PROFILE model

The PROFILE model (Sverdrup and Warfvinge, 1993; 1995) was used in the present study for calculation of the weathering rates. The model has been used in earlier studies for scaling up weathering rates to a regional level (Holmqvist, 2001; Warfvinge and Sverdrup, 1995). PROFILE is a biogeochemical model originally developed to calculate the effect of acid rain on soil chemistry. PROFILE includes process-oriented descriptions of chemical weathering of minerals, leaching and accumulation of dissolved chemical components, and solution equilibrium reactions. The PROFILE model calculates the weathering rates at steady state, i.e. the situation when no state variables in the forest ecosystem change over time.

The transition state theory, stating that the rate of a chemical reaction is controlled by the decomposition of an activated complex, is applied to the weathering calculations (Sverdrup, 1990; Sverdrup and Warfvinge, 1995). The soil profile can be divided into layers with different properties, preferably corresponding to the naturally occurring soil stratification.

In PROFILE the dissolution rate (r) of a mineral (j) is calculated as the sum of the dissolution rates of four reactions: reactions with the hydrogen ions (H^+), water hydrolysis, reactions with CO_2 molecules and reactions with organic acid ligands:

$$r_j = r_{H^+} + r_{H_2O} + r_{CO_2} + r_{org} \tag{6}$$

The weathering rate in the entire soil profile is then calculated as (Sverdrup and Warfvinge, 1995):

$$R_w = \sum_i^{layers} \sum_j^{minerals} r_{ij} \cdot A_{ij} \cdot \theta_i \cdot z_i \tag{7}$$

where:

R_w = The total weathering rate for the whole soil profile
r_{ij} = The reaction rate of mineral j in layer i
A_{ij} = Exposed surface area of mineral j in layer i
θ_i = Soil moisture saturation in layer i
z_i = Soil layer thickness of layer i

The dissolution rates of different minerals vary widely and the mineralogical composition of the soil is thus decisive for the weathering rates. Other important input data are exposed mineral surface area, soil moisture saturation, temperature and concentrations of hydrogen ions, base cations and organic acids. From a tree perspective, only the weathering occurring in the soil layers accessible by the tree roots is of interest. Root depths for different tree species are thus important input data.

4.3.3 Nitrogen budgets

Deposition and fixation constitute the inflows of N to the system, while harvested biomass and leaching account for the losses. If only vertical percolation is considered the nutrient budgets for N can be calculated as:

$$\Delta = \text{Deposition} + \text{Fixation} - \text{Harvesting} - \text{Leaching} - \text{Denitrification} \tag{8}$$

where Δ = accumulation (+) or loss (–).

Only the fluxes into or out of the soil are included in the calculations, not the processes within the soil (Figure 5). Soil properties and climate drivers are assumed to be constant. As in the case of the base cation budget the static N balance calculations give the yearly net losses as an average for a forest rotation, provided that the budget terms are constant over time.

4.3.4 Carbon budgets and carbon-nitrogen interactions

Net C fixation through net photosynthesis constitutes the input of C to the system while the outputs are soil respiration losses, leaching of DOC (dissolved organic carbon) and losses through harvesting of biomass:

$$\Delta = \text{Net fixation} - \text{Soil Respiration} - \text{Harvesting} - \text{Leaching} \qquad (9)$$

where Δ = accumulation (+) or loss (–).

C fixation and soil respiration are difficult to quantify. Since the N budget is easier to calculate, and since the C and N cycles are closely linked in organic matter, the N accumulation can be used to approximate C sequestration (Gundersen, 2002). In a N-limited forest ecosystem, increased input of N, e.g. as deposition, may lead to increased tree biomass. More C and N are thus bound to the growing biomass and more C and N will be added to the soil as above- and below ground litter. The net result of increased N deposition is thus increased C and N sequestration, in both trees and soil. If the C/N ratio in soil, as an average for a forest rotation, is assumed to be constant, the C sequestration rate in the soil (ΔC) can be approximated from the N accumulation data (ΔN):

$$\Delta C = \Delta N \cdot \frac{C}{N} \qquad (10)$$

Although it is likely that the C/N ratio decreases at high N loads, the decrease is probably small and the approximation is thus considered sufficiently reliable.

4.4 Regionalization

Site level modelling is a powerful tool for understanding natural processes in detail, and for predicting future effects of different actions on site level. However, for policy decisions on the national level scaling-up from site level to regional level is required. The large amount of input data needed for detailed single-site modelling is often not available at the regional level, and thus simplifications have to be made, e.g. by using budget calculations (Section 4.3). Mass balance calculations on a regional level involve combining different data layers in order to obtain new information. This can be done by overlay operations in a Geographical Information System (GIS) (Figure 6).

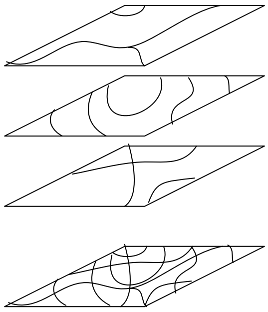


Figure 6. *Overlay operation where different input data layers are combined in a GIS to derive new data.*

In environmental science, regionalization must often be performed based on site-level data from different kinds of monitoring networks or experiments. Geostatistical analyses can be used to optimize the regionalization process. A central concept in geostatistics is "spatial autocorrelation", which means that sites close to each other tend to have similar values, while sites further apart differ more. The spatial autocorrelation for a parameter can be described with geostatistics, and this information can then be used to optimize the interpolation process. The semivariance is often used when describing autocorrelation. The semivariance $\gamma(\mathbf{h})$ is half of the variance between values at points separated by the lag vector **h**, but since the variance in this case applies to pairs of points the semivariance is the variance per point (Webster and Oliver, 2001). An estimation of $\gamma(\mathbf{h})$ is obtained by using equation 11:

$$\hat{\gamma}(\mathbf{h}) = \frac{1}{2m(\mathbf{h})} \sum_{i=1}^{m(\mathbf{h})} \{z(\mathbf{x}_i) - z(\mathbf{x}_i + \mathbf{h})\}^2 \qquad (11)$$

where:

$\hat{\gamma}(\mathbf{h})$ = estimated semivariance
$m(\mathbf{h})$ = number of pairs of data points seperated by the vector **h**
$z(\mathbf{x}_i)$ and $z(\mathbf{x}_i + \mathbf{h})$ = the values of a property at the locations $(\mathbf{x}_i)$ and $(\mathbf{x}_i + \mathbf{h})$

The spatial autocorrelation can be described in variograms for different directions. Assuming isotropic variations, equation 11 can be used by substituting **h** with h=|**h**|. Figure 7 shows a typical variogram, including one part with spatial autocorrelation (to the left) and one part without spatial autocorrelation (to the right).

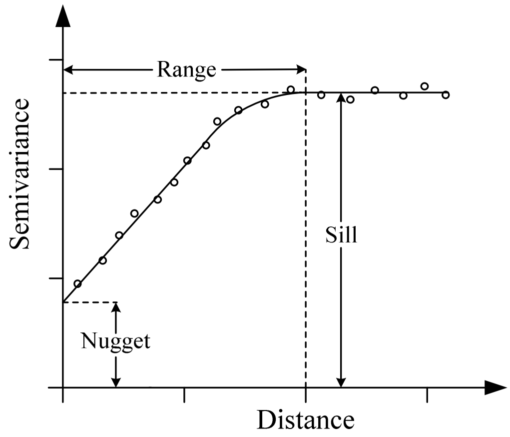


Figure 7. *The variogram. The range is the distance within which there is spatial autocorrelation. The sill is the semivariance at distances longer than the range. The nugget is the spatially uncorrelated variation.*

Kriging is an interpolation method that uses the variogram model together with available point data to estimate values at unsampled places. Estimation of a property at a point by means of ordinary kriging requires the calculation of a weighted average of the data:

$$\hat{Z}(\mathbf{x}_0) = \sum_{i=1}^{N} \lambda_i z(\mathbf{x}_i) \qquad (12)$$

where:

$\hat{Z}(\mathbf{x}_0)$ = the estimated value of a property at location $\mathbf{x}_0$
N = the number of sampling sites
λ_i = the kriging weights
$z(\mathbf{x}_i)$ = the value of the property at location $\mathbf{x}_i$

The kriging weights depend on the variogram model and the configuration of the sampling points. Close-lying points are assigned higher weights than distant points, and clustered points are assigned less weight individually than isolated ones at the same distance. The use of geostatistical information from the variogram model in the interpolation process distinguishes kriging from other interpolation methods. The geostatistical methods are described thoroughly by Webster and Oliver (2001).

5 Methods

Three methodologies were central in the studies described in this thesis:

- GIS-based nutrient budget calculations
- Geostatistics and regionalization
- Scenario analysis

Nutrient budget calculations (Section 4.3) were performed on a GIS platform with raster data (i.e. grid based) in a 5·5 km grid. For each grid cell the required mass balance terms were estimated, modelled, or derived from available sources. Geostatistics (Section 4.4) were used in the regionalization of several parameters in order to transform the point data to the raster data format. Scenario analysis was applied and scenarios were developed in collaboration with authority representatives and experts in different fields. The system analysis approach (Section 4.1) was applied throughout the studies. The budget calculations, the methods of estimating C sequestration, the different method development studies, and the national databases used are described briefly below. The budget calculations are not valid for ditched organic forest soils, corresponding to 7 % of the managed forest area (Hånell, 1990), since no data were available for such conditions.

5.1 Estimation of the base cation budget

5.1.1 Budget calculations for base cations

Base cation budget calculations (Section 4.3.1) were performed for the plant-active base cations Ca, Mg and K. Base cation deposition from 1998 was derived from the MATCH model (Langner et al., 1996), and base cation weathering rates were modelled with the PROFILE model (Section 4.3.2). Base cation loss through harvesting was based on growth data from the Swedish National Forest Inventory (Hägglund, 1985) and base cation concentrations in different tree parts for different tree species (Jacobson and Mattson, 1998; Egnell et al., 1998; Swedish Pulp and Paper Institute, 2003). It was assumed that the net growth was equal to the harvest, i.e. no change in standing biomass. This assumption is suitable when considering the nutrient balance in the root zone in areas where clearcutting is the harvesting method applied. Leaching was estimated based on soil water concentrations from the Throughfall Monitoring Network (Hallgren et al., 1995) and runoff data from the Swedish Meteorological and Hydrological Institute (SMHI) (Raab and Vedin, 1995).

Two scenarios were investigated for spruce and pine separately: a stem harvesting scenario and a whole-tree harvesting scenario. Whole-tree harvesting was defined as harvesting of 75% of the branches in thinning and in regeneration felling. Furthermore it was assumed that 75% of the needles accompanied the branches when they were removed. The fraction for branches was based on an “intensive harvest” scenario (National Board of Forestry, 2000), the fraction for needles being based on a study of needle loss in slash removal (S. Jacobson, pers. comm.). The root depth of spruce was assumed to be 40 cm, and that of pine 50 cm (organic layer included), based on data compiled by Rosengren and Stjernquist (2004). The budget calculations are described thoroughly in Paper V. The regionalization of the weathering rates is however, described in more detail below.

5.1.2 Development of method for estimating mineralogical composition

The mineralogical composition of the soil is decisive for the primary conditions for weathering. In Sweden, where the soils are mainly glacial tills, the local and regional variation of soil mineralogical composition is large. Regional weathering estimations thus require high-resolution estimates of the mineralogical composition. In Paper I, two indirect methods of estimating mineralogical composition on a regional basis, i.e. normative modelling based on soil elemental concentrations and relating soil mineralogical composition to underlying bedrock, are evaluated. Two areas in southern Sweden, which differ greatly in soil elemental composition according to the national soil geochemical mapping (Figure 8), were compared with respect to elemental content, mineralogical composition and bedrock mineralogy. Samples were taken from ten sites in each of the two areas. Elemental contents were analysed and the mineralogical composition was optically determined. The mineralogical composition of the bedrock underlying the sites was derived from databases from the Swedish Geological Survey (Persson, 1985; Wikman, 1998).

Normative modelling was performed with the Bern model (SAEFL, 1998) in a three-step process. Firstly the soil chemistry was transformed into base compounds, i.e. a set of normative, stoichiometrically ideal compounds from which real mineral stoichiometries can be formed as linear combinations. Secondly, the base compounds were transformed into real primary minerals using specified mass balance formulae, i.e. linear combinations, based on prior knowledge of expected mineralogy and mineral stoichiometry in the area. Thirdly, the resulting minerals, together with the remainder of the base compounds, were used to calculate the amount of secondary minerals formed by weathering.

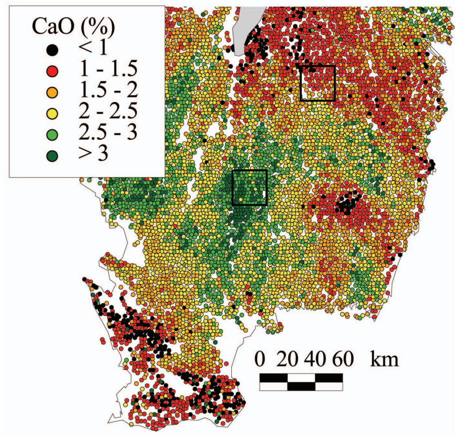


Figure 8. *The total content of Ca, measured as CaO, in and around the two investigated areas in southern Sweden, based on soil geochemical mapping (Lax and Selenius, In press).*

5.1.3 Development of method for regional weathering modelling

PROFILE was used for weathering calculations on a regional level. The basis for the study was data on elemental contents in glacial till (Section 5.4.1). Normative modelling (Section 5.1.2) of the elemental contents was applied to the sites to estimate the mineralogical composition. No measurements for the sites were available for other input parameters required, and thus data in raster or vector format from other national databases were used. The point databases were managed geostatistically and kriging interpolated. The point-based mineralogy data were then combined with the raster- or vector-based data in overlay operations to achieve a point database with all the required data for site-level PROFILE modelling (Figure 9). The estimations are valid for glacial tills, the highly dominant soil type in Sweden.

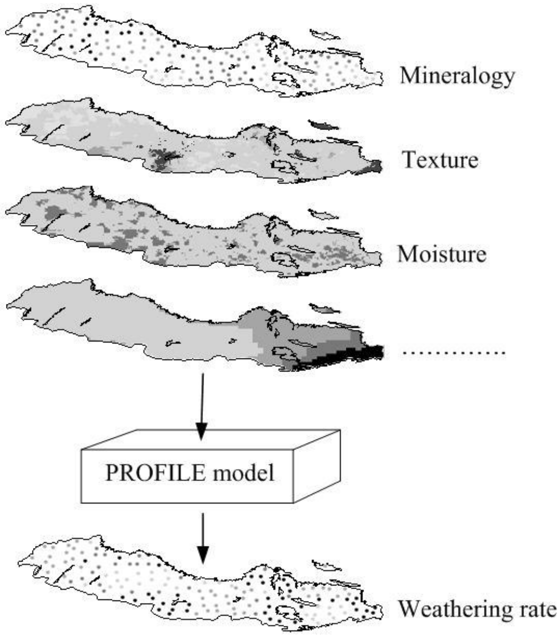


Figure 9. *Combining site-level data (mineralogical composition) with area covering maps (for example maps of texture and moisture) for site-level weathering modelling with the PROFILE model (Paper II).*

The methodology and the data acquisition are further described in Paper II and the application of the regional database to different scales is demonstrated and discussed in Paper III. Improvements to the PROFILE input data are made continuously, and the weathering rate data applied in the base cation budget calculations (Paper V) were thus improved in various respects compared with the results in Paper II. For example, a fraction of blocks and stones of 30% was introduced, based on an average value obtained from ten soil texture distribution curves from sandy tills (T. Påsse, pers. comm.). The weathering of blocks and stones can be neglected and thus the fraction of blocks and stones should be considered in the calculations of the amount of soil exposed to weathering. Further improvements are described in Paper V.

5.2 Estimation of nitrogen accumulation rates

5.2.1 Budget calculations for nitrogen

The N accumulation rates were estimated by means of budget calculations (Section 4.3.3). In contrast to the base cation budget calculations, the N in the increasing standing biomass, according to data from the 1990s (National Board of Forestry, 2000), was subtracted from the estimated total N accumulation, in order to differentiate it from the N accumulation in soil. The reason for this was that the purposes for the N calculations and the base cation calculations were somewhat different: The N calculations were aimed at estimating the risk of N leaching from the grid cells, by quantifying the N accumulation in the grid cells as an average for all forest types. The base cation calculations were aimed at estimating the nutrient sustainability, by determining the base cation accumulation/loss in managed spruce and pine forests in the grid cells. On a grid cell level the accumulation of N in the increasing biomass is substantial since the harvesting is currently less than the net growth, while in a specific spruce or pine stand almost all trees are normally harvested.

Modelled deposition data from 1998 (nitrate and ammonium) were derived from the MATCH model (Langner et al., 1996). N fixation was set to a constant value of 1.5 kg ha^{-1} y^{-1} based on a study in northern Scandinavia and Finland by DeLuca et al. (2002), where a N-fixing symbiosis between a cyanobacterium (*Nostoc* sp.) and the feather moss *Pleurozium schreberi* was found to fix between 1.5 and 2 kg ha^{-1} y^{-1}. N loss through harvesting and net N accumulation in biomass was estimated based on growth data from the National Forest Inventory in Sweden (Hägglund, 1985), province-based harvest/growth ratios from the 1990s (National Board of Forestry, 2000), and N concentrations in different tree parts for different tree species (Jacobson and Mattson, 1998; Egnell et al., 1998; Swedish Pulp and Paper Institute, 2003). Denitrification was neglected since it occurs mainly under wet conditions and can be assumed to be very small in most well-drained Swedish forest soils (Nohrstedt et al., 1994). Leaching was based on runoff and N concentration in soil water (Löfgren and Westling, 2002; Bergstrand et al., 2002; Brandt and Ejhed, 2003). Leaching from clearcuts in southern Sweden was estimated separately, as described in Section 5.2.2 and Paper IV.

Four scenarios were investigated:

- Base scenario: N deposition of 1998, stem harvesting only
- Whole-tree harvesting scenario: N deposition of 1998, whole-tree harvesting
- Decreased N deposition scenario: a 30% decrease in deposition from the 1998 level by 2010, stem harvesting only
- Whole-tree harvesting and decreased deposition scenario: a 30% decrease in N deposition from the 1998 level by 2010, whole-tree harvesting

The harvesting scenarios were defined according to Section 5.1.1. The deposition scenario with a 30% decrease in N deposition by 2010 was based on the 1999 Gothenburg Protocol (UN/ECE, 1999), assuming that the targets of the protocol are reached. The methods are described thoroughly in Paper VI.

5.2.2 Method for estimating nitrogen leaching from clearcuts

A linear relationship was assumed between N deposition and concentration in soil water on clearcuts in southern Sweden (Section 3.4; Löfgren and Westling, 2002). The relationship was assumed to be valid for the deposition interval in southern Sweden and was used, with slight modifications due to new available data (Figure 10), to calculate N leaching from clearcuts on a municipality level in southern Sweden (Paper IV). Deposition for 1998 calculated with the MATCH model (Langner et al., 1996) was used as input data, together with runoff data from the SMHI, and clearcut areas for the municipalities based on planned regeneration fellings reported to the National Board of Forestry. The N retention downstream the clearcut was not included in the calculations which means that the estimated leaching is the gross leaching, i.e. a measure of the N leaving the clearcut rather than a measure of how much is added to the surface water.

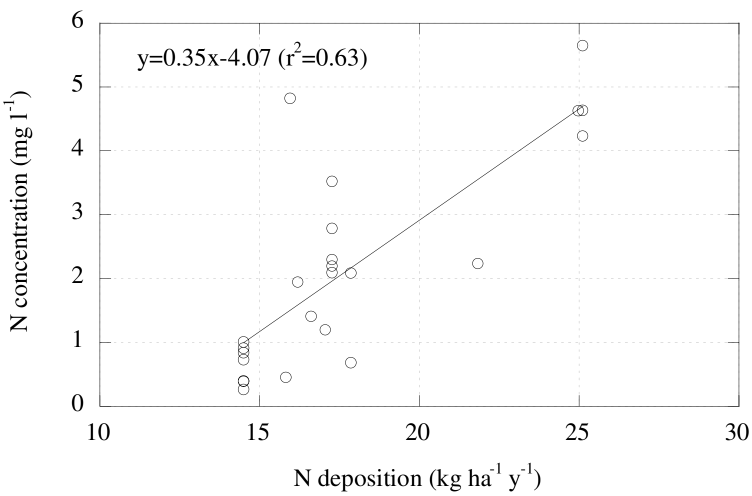


Figure 10. *N concentration at clearcuts in southern Sweden with different N deposition, based on soil water measurements compiled in Löfgren and Westling (2002).*

The linear relationship in Figure 10 is only an approximation for the specific deposition interval. The concentration can obviously not increase continuously in a linear way, and there are other factors involved that strongly affect the concentration, e.g. ground vegetation type, soil properties and forest management methods. The linear relationship is thus not applicable for site-level predictions, but gives an indication of the direction of the correlation between N deposition and N concentration, which can be used to make approximate estimates of the N leaching from clearcuts on a regional level.

5.3 Estimation of carbon sequestration in soil

The European programme CNTER (Carbon-nitrogen interactions in forest ecosystems) uses two different methods for calculating C sequestration in the soil, one based on N balance calculations, which are often easier to perform than C balance calculations, and one based on litterfall data and empirical data on how much litter remains as a recalcitrant fraction. These methods were applied on a regional scale to Sweden.

5.3.1 The N balance method

The C sequestration rate calculated using the "N balance method" (Equation 10; Gundersen, 2002), was estimated by grid-level multiplication of the N accumulation in the base scenario (Sections 5.2.1 and 6.3), and the C/N ratio in the organic layer (O horizon) (Figure 11) from the National Forest Inventory. The C/N ratio was a regional average, thus excluding variations within a forest rotation. It was assumed that the soil C/N ratio is constant over time. The results are presented and discussed in Section 6.4 and in Paper VII.

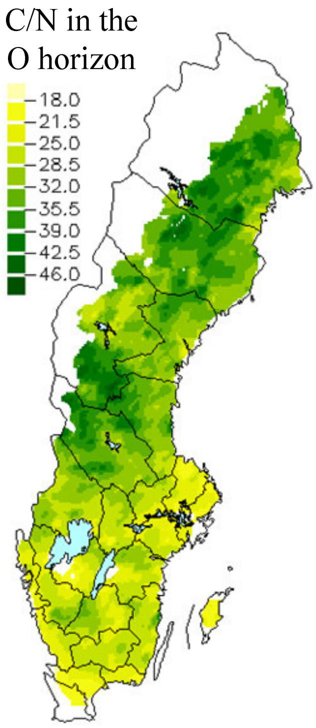


Figure 11. *C/N ratio in the organic layer from kriging interpolation (Swedish University of Agricultural Sciences, 2003), based on data from the National Forest Inventory (1983-1987) (Hägglund, 1985).*

5.3.2 The Limit value method

The "Limit value method" (Berg and McClaugherty, 2003) was used for regional-scale estimation of the C sequestration rates in the organic layer in mature forests (Paper VII, Akselsson et al., 2005). In the "Limit value method" the accumulation of organic matter from above-ground litter is estimated from litterfall data and data on the recalcitrant fraction after decomposition of soil organic matter (SOM) (Berg et al., 1996; 2001). The C sequestration rate can then be estimated by multiplying the accumulation of organic matter by the C concentration in SOM.

Litterfall was mapped on a regional scale based on observed tree-species-specific relations between a climatic parameter, actual evapotranspiration (AET) and litterfall (Berg and Meentemeyer, 2001; Meentemeyer et al., 1982). AET was modelled with the WATBUG model (Sharpe and Prowse, 1983). The recalcitrant fraction was derived from litter mass loss experiments from all over Sweden (Berg, 1998). The recalcitrant fraction was multiplied by litterfall to give the annual SOM build-up (Berg et al., 2001; Berg and McClaugherty, 2003) for different groups of tree species.

5.4 National databases used

A substantial part in the present study involved finding and preparing input data for the calculations. Two input databases were created, a weathering database with site level data (more than 25 000 sites) for weathering modelling, and a grid database (created in cooperation with IVL Swedish Environmental Research Institute) with a resolution of 5·5 km as the basis for the mass balance calculations. These two databases were based on several existing national databases. Some of most important data in the thesis are described below.

5.4.1 The mineralogical composition

The mineralogical composition is one of the most important inputs required for weathering calculations. The site level mineralogy database was based on 26 754 sites with elemental analyses of soil (total concentrations of elements). It included elemental analyses on the fraction <0.06 mm from a depth of about 1 metre on 22940 glacial till sites, supplied by the Swedish Geological Survey (SGU) (Lax and Selenius, In press), elemental analyses (fraction <2mm, depth 40-60 cm) from 1897 sites from the National Forest Inventory (Hägglund, 1985), and elemental analyses (fraction <0.125 mm, depth about 1 metre) from 1917 sites from the mining company Terra Mining. The results of the elemental analyses were transformed into normative mineralogy according to the methods described in Section 5.1.2.

5.4.2 Deposition

Deposition data were required for the mass balance calculations, for the weathering rate calculations and for the estimation of N leaching from clearcuts. Modelled data from the Swedish dispersion model, MATCH (Langner et al., 1996) were used. The model deals with the transport of emitted substances, wet deposition and dry deposition in coniferous and deciduous forest and on arable land. Modelled deposition data for 1998 were employed. The deposition was modelled at a resolution of 20·20 km, and was then refined to the 5·5 km resolution based on land use information. Modelled deposition within 5·5 km grid cells provided the framework and resolution of the grid database employed for mass balance calculations.

5.4.3 Tree species composition and forest properties

Information on tree species composition and forest properties was used for calculations of net growth and harvest and for the deposition estimations which are tree species dependent. The fraction of different forest types in the 5·5 km grid cells was based on satellite image (IRS WIFS) interpretation, performed for the purpose of the present study, where four forest classes were employed: coniferous forest, deciduous forest, mixed forest and clearcuts (Mahlander et al., 2004). Data on forest properties such as the dry weight of different tree parts, volume and growth, were obtained from the National Forest Inventory in Sweden (Hägglund, 1985). Data on the tree species composition (e.g. the fraction of spruce and pine in coniferous forests) were obtained from the same source. Kriging interpolation was performed for the different forest parameters to the 5·5 km grid.

5.4.4 Runoff

Runoff information was gathered in order to estimate the leaching of N and base cations for the mass balance calculations. The data on runoff were derived from a vector map obtained from SMHI (Raab and Vedin, 1995) showing the annual mean runoff (1961-1990). Nine intervals were included in the map; <6, 6-8, 8-10, 10-12, 12-16, 16-20, 20-30, 30-40 and >40 $l\ s^{-1}\ km^{-2}$. The vector map was transferred to a grid map with a 5·5 km resolution, each grid cell being assigned the average value for the interval in question.

5.4.5 Concentrations of base cations and nitrogen in soil water

Concentrations of base cations and N in soil water, required for leaching estimations, were based on data from the Throughfall Monitoring Network (Hallgren Larsson *et al.*, 1995). Soil water analysis of suction lysimeter samples from the depth of 50 cm is performed three times a year at about 100 sites in Sweden. The first measurements started in 1985.

6 Results and Discussion

6.1 Results from method development

6.1.1 Evaluating methods for estimating mineralogical composition

The differences observed in the soil geochemical mapping (Lax and Selenius, In press), between elemental contents in the two areas investigated (Figure 8), were also found in the analyses presented in Paper I. The southwestern area showed higher contents of Ca, Mg and Fe but lower values of K. This was reflected in the optically determined soil mineralogical composition of the till, with significantly higher amounts of biotite, amphibole and epidote, and significantly lower values of K-feldspar in the southwestern area. The differences were not, however, reflected in the bedrock information from the area, and information on bedrock mineralogy is thus not sufficient for estimating the mineralogical composition in these parts of the country, which can partly be explained by the till having not only local sources.

The normative and the optically determined mineralogical compositions showed great similarities, especially for the dark minerals which are decisive for the weathering rate (Figure 12). This indicates that normative modelling is an appropriate method of estimating the mineralogical composition. Biotite was not included in the normative model since earlier Swedish mineralogy datasets showed little evidence for its frequent occurrence, but the optical analysis showed that it appeared at significant amounts. This led to an overestimation of other minerals in the normative mineralogical composition, mainly amphibole. The effect of this on the total weathering rate modelled by PROFILE is probably small, but not negligible, and biotite should thus be included in the normative model to improve the performance.

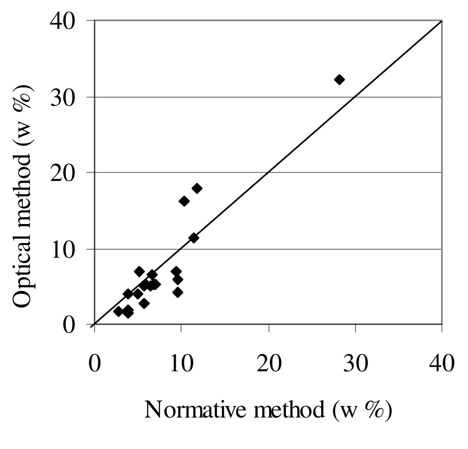


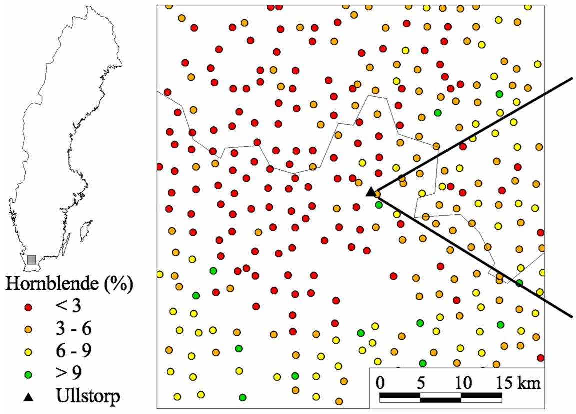
Figure 12. *Optically determined content of the mafic minerals (amphibole, biotite, epidote, pyroxene and chlorite) plotted against the normative content. The line shows a 1:1 relation.*

6.1.2 Weathering rates on different scales

The high-resolution geochemical database of Sweden is a good basis for PROFILE weathering calculations on different scales. The national scale resolution, which is described in Paper II, can be used as input for work in the convention on long-range transboundary air pollution (CLRTAP) (UN/ECE, 2005), as well as for following up national environmental objectives, e.g. in base cation budget calculations, as in Paper V. Although the modelling was performed on site level, it is important to keep in mind that only the mineralogy data are valid for a specific site, while the other data originate from various generalizations. The results should thus not be interpreted on a site level, but rather on a regional level.

In Paper III weathering estimations on different scales are described and discussed. The required resolution of the input data depends on the desired resolution in the output, which is closely connected to the aim of the calculations. In a special study of the county of Halland (Akselsson and Westling, 2004), aimed towards a regional follow-up of environmental objectives, a thorough investigation on available regional resolution data for the county was performed and the input database was updated with the best regional data currently available. The Swedish geochemical database is also suitable for use on a local scale. In large parts of Swedish forests there are sampling sites for soil geochemistry at approximately every two kilometres (Figure 8) and there is a clear autocorrelation for the soil geochemistry. This spatial autocorrelation means that it is possible to assess the approximate mineralogical composition of a forest stand based on surrounding sites.

Estimates for several individual forest stands have been made in Sweden and a fully developed method for assessing weathering rates in a forest stand exists. The coordinates of each stand are needed as well as information about forest type and soil properties such as the approximate texture and the moisture conditions. These data, together with data from the nearest geochemistry sampling point (Figure 13), can be used to run PROFILE and derive weathering rates. Other input data needed, such as deposition data, can be derived from the national databases. The variation in soil geochemistry in the area gives information about the uncertainties in the assumed soil mineralogical composition. In many areas the local variation is low, and the mineralogy data can be regarded as reliable. In some areas, however, there are large local variations, often caused by a locally varying geology, and the uncertainties are then larger. Site-specific data from the forest stand will naturally improve the accuracy.



Mineral	Fraction (%)
K-feldspar	13.6
Plagioclase	24.5
Hornblende	4.9
Illite	13.0
Epidote	2.6
Vermiculite	4.7
Apatite	0.8

Figure.13. *A scale-down of the national weathering assessment input database, here represented by the mineral hornblende (Paper III). The triangle represents the Ullstorp site where weathering rates have been estimated by Sverdrup et al. (In press). The distance from Ullstorp to the nearest sampling site was 700 m and the data from that site were used in nutrient sustainability assessments (values on the right).*

6.1.3 Nitrogen leaching from clearcuts

The estimated gross leaching from clearcuts showed a clear gradient from east (less than 5 kg ha^{-1} y^{-1}) to west (up to 35 kg ha^{-1} y^{-1}) (Figure 14), in accordance with the deposition gradient. The leaching gradient was reinforced by the higher runoff in the west. The results indicated that, in southwestern Sweden, with the highest N deposition, up to 40% of the total N leaching from forest soils originates from clearcuts. The major part of this increased leaching seems to be due to the high N loads.

In the counties in southern Sweden, 1-11% of the total gross leaching from land use (forestry and agricultural land) arises from clearcuts, according to the calculations. The increased N leaching from clearcuts in the areas with the highest N deposition shows that the N leaching from forest soils is not negligible, although it is a rather small fraction of the current total N leaching from forestry and agricultural land. Forestry methods counteracting this leaching are thus important. Shelterwood (about 150 stems ha^{-1}) reduce leaching substantially compared with total clearfelling (Örlander, 2000). The results from the study presented in paper IV was used in the N budget calculations in paper VI.

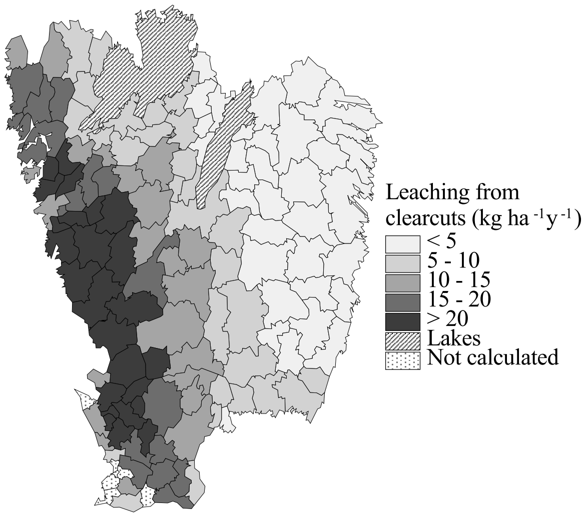


Figure 14. *Estimated leaching from clearcuts in the municipalities in southern Sweden (Paper IV).*

6.2 Will deposition and harvesting deplete the base cation pool?

The nutrient budgets showed net losses of Ca and Mg in almost the whole country in the two harvesting scenarios in both spruce and pine forests (Paper V). For K the balances were mainly positive for pine but negative for spruce. Leaching was a decisive term in the mass balances, especially for Ca and Mg, and leaching alone led to negative mass balances for Ca and Mg in most parts of the country, implying that there is presently no scope for sustainable harvesting. The difference between spruce and pine was striking, with substantially lower net losses for pine than for spruce due to a lower uptake of nutrients and deeper root systems, meaning that more weathering products are available to pine. Whole-tree harvesting increased the harvest losses by about 100% in spruce forests, and thus led to substantially higher net losses, especially of K and Ca, than stem harvesting (Figure 15). The effects of whole-tree harvesting in pine forests were smaller.

It is striking that there were no obvious geographical gradients in the results, despite the markedly higher historical and present acid deposition in south-western Sweden. This can partly be explained by the higher base cation deposition along the west coast, and also higher weathering rates in these areas due to more easily weathered soils. The current growth of the organic layer, which has been observed in the National Forest Inventory (Jernbäcker, 2003), indicate that the net losses from the mineral soil may be somewhat higher than the estimates.

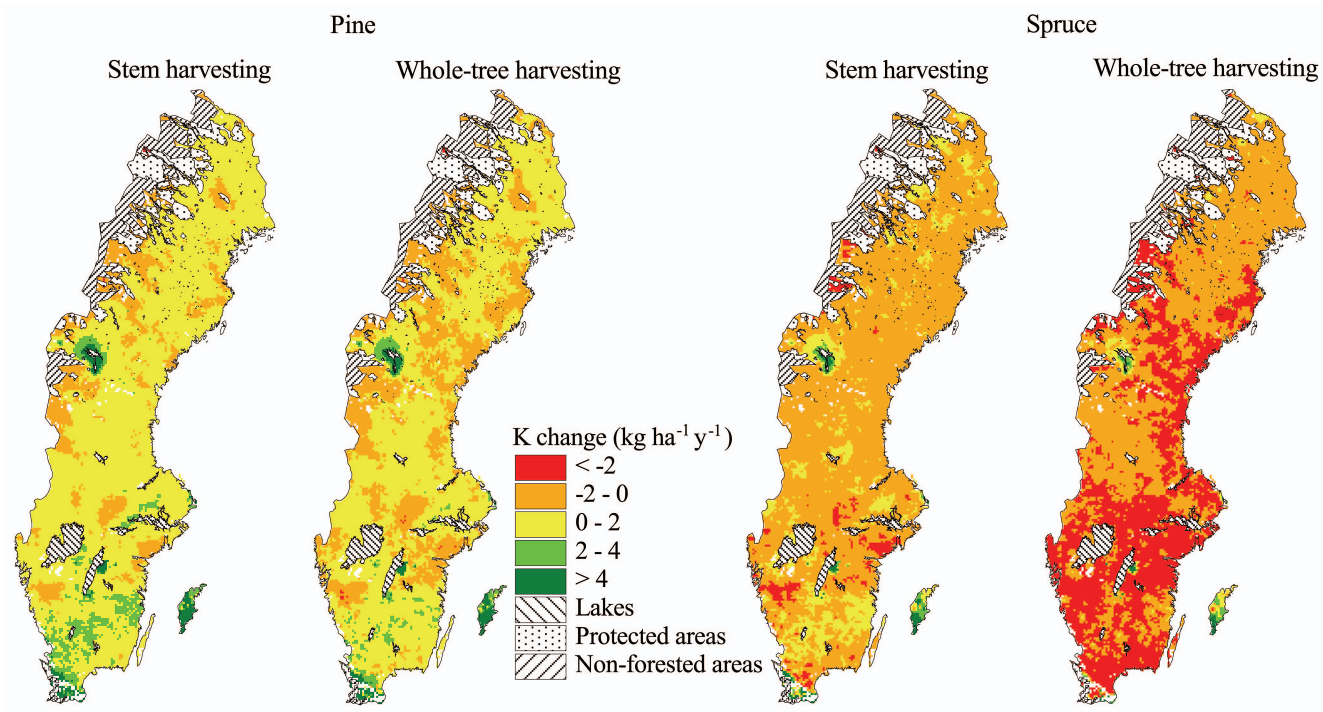


Figure 15. *Accumulation/loss of K in the stem harvesting and the whole-tree harvesting scenarios in spruce and pine forests, according to regional budget calculations.*

The pools of exchangeable base cations at 1625 sites, based on data from the 1990s from the National Forest Inventory in Sweden, showed substantial local variations, but some regional patterns could be discerned (Figure 16). The largest pools were found in the eastern part of southern-central Sweden. The frequency of sites with small pools was highest in the southwestern parts of Sweden, the western part of central Sweden and the northernmost parts. This pattern can be explained by different geological conditions, different acidification histories, and different land use and vegetation histories.

On 25% of the analysed sites the yearly losses of Ca, Mg and K corresponded to at least 3%, 6% and 1% of the pools of exchangeable base cations, respectively in the scenario of stem harvesting in spruce forests. If losses of this size continue, the depletion of the soil base cation pool may lead to negative effects on soil fertility, runoff water quality, tree vitality and tree growth within the time span of a forest rotation in parts of Sweden. Whole-tree harvesting increased the depletion rate significantly, and the corresponding figures were 5%, 8% and 3% for Ca, Mg and K respectively. Thus, avoiding whole-tree harvesting reduces the depletion rates substantially, but the net losses of Ca and Mg will still be large.

The high estimated base cation depletion rates caused by whole-tree harvesting are in accordance with results from experiments by Staaf and Olsson (1991) and Olsson et al. (1996). Data from the National Forest Inventory show no significant difference in the base saturation between the inventory in the 1980s and the inventory ten years later in the 1990s (Bertills, 2003). However, the short time span between the inventories, and the fact that the soil sampling was not performed at exactly the same sites in the two different inventories, mean that changes are difficult to detect.

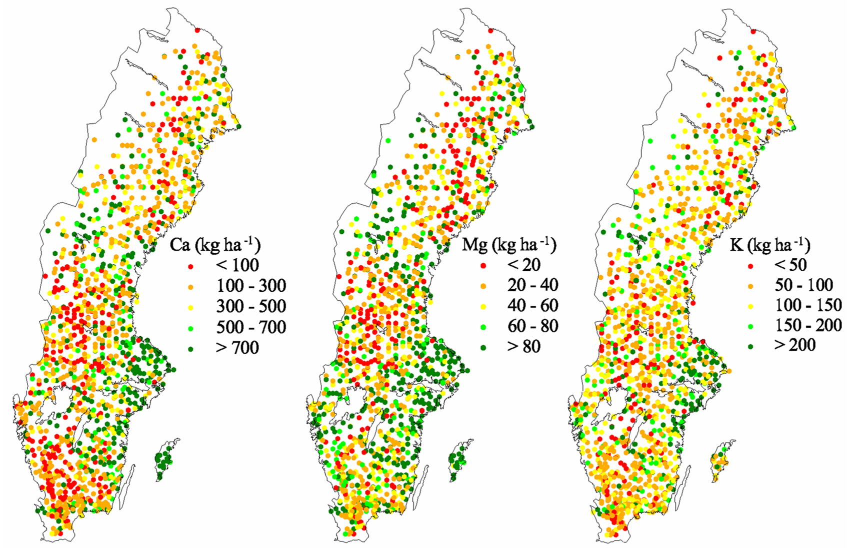


Figure 16. *Pools of exchangeable base cations. Data on concentrations in different soil horizons from the National Forest Inventory were applied, together with densities from Karltun (1995) and a constant fraction of blocks and stones of 30%, in accordance with the weathering calculations presented in Paper V.*

Net losses lead to depletion of the pool of exchangeable base cations and can be explained by excess soil acidity, i.e. acidity from deposition and base cation uptake that is not neutralized by weathering:

$$EA = D(S + N + Cl - Ca - Mg - Na - K) + U(Ca + Mg + K) - U(N) - W \quad (13)$$

where:

EA = excess acidity
D = deposition
U = net uptake (i.e. harvesting)
W = weathering

This excess acidity can lead to cation exchange releasing base cations but decreasing the base saturation and/or leaching of acidity from the system, causing acidified runoff water. Initially, in a non-acidified system, much of the excess acidity causes ion exchange, release of base cations and higher base cation leaching. However, together with the depletion of the soil pool, the ion exchange decreases, and thus also the base cation leaching. At this stage the excess acidity mainly leads to acidified runoff water.

The results from the budget calculations indicate that the situation in Swedish forests is not sustainable. This is in agreement with results from previous regional studies in Sweden (Olsson et al., 1993; Sverdrup and Rosén, 1998) and Finland (Joki-Heiskala et al., 2003). The net losses are largely due to the high degree of leaching, but the harvesting intensity (i.e. stem harvesting or whole-tree harvesting) and the choice of tree species also have substantial effects on the nutrient budgets. It can be concluded from the results that if the present acid deposition and harvesting intensity are maintained, continued net losses will lead to effects on leaching and/or tree growth. The temporal aspect can be included to some extent, through comparisons with the pools of exchangeable base cations, but to achieve a high temporal resolution, dynamic models such as ForSAFE (Wallman et al., 2005) or MAGIC (Cosby et al., 2001) have to be employed.

Further work is required to decrease the uncertainties in the budget calculations and thus increase their usefulness in policy assessments. The uncertainties are described thoroughly in Paper V and the main uncertainties are compiled in Table 2. Leaching is assumed to contribute most to the uncertainties and is thus of the highest priority. A sensitivity analysis showed, however, that even if leaching were to be reduced by as much as 50%, there would still be substantial losses of base cations from soils in managed forests in Sweden.

Table 2. *Main uncertainties in the base cation balance calculations.*

Term	Main uncertainties
Deposition	Probable underestimation of dry deposition since the monitoring equipment used to measure air quality does not monitor large particles[1].
Weathering	Low resolution of some important input data, mainly texture, blockiness and moisture. Uncertainties in the root depth.
Stem harvesting	Constant, species-specific concentrations in stems were used, although they are known to vary widely, since no data are available supporting a distinction between grid cells. Growth rates were interpolated from data with weak spatial autocorrelation.
Harvesting of branches	Constant, species-specific concentrations in branches and needles were used, although they are known to vary widely, since no data are available supporting a distinction between grid cells. The amounts of branches and needles on trees, estimated within the framework of the National Forest Inventory using standard methods, are associated with substantial uncertainties.
Leaching	The runoff data applied represent all existing land use classes, and may thus be overestimated for forests. The small number of soil water measurements (ca 100 sites in Sweden) increases the uncertainties.

[1] Christer Persson, pers. comm.

Bearing these uncertainties in mind, the interpretation of the results should be more on a relative basis, i.e. the effect of whole-tree harvesting and the differences between spruce and pine, than on the absolute values.

6.3 Nitrogen in forest soils – deficiency or excess?

The mass balance calculations for N (Paper VI), showed a clear decreasing gradient of N accumulation in the soil from the southwestern to the northern part of Sweden (Figure 17). In the base scenario there was a net accumulation for the country as a whole, except for certain rather small areas in the central and northern parts of the country, whereas net losses were dominant in the scenario involving both decreased deposition and whole-tree harvesting. The levels in the scenario involving whole-tree harvesting and that involving decreased deposition were somewhere in between. Throughout the country, deposition represented the major input of N and harvesting was generally the major output, although in northern Sweden leaching was of the same magnitude as stem harvest. Deposition was the dominant factor, except in the decreased deposition and whole-tree harvesting scenario, where N deposition and N loss through harvesting were of the same magnitude. The gradients of N deposition and N loss through harvesting were the same in terms of direction.

The large variation of N accumulation in Sweden indicates that the issue of N must be treated differently in different parts of the country. N deposition and harvesting intensity are of equal importance in the assessment of future effects. Long-term accumulation, as in southwestern Sweden, may lead to more growth and thus more biomass to harvest, but only as long as N is the limiting factor for growth. When N ceases to be limiting, leaching will increase (Stevens et al., 1993). In southwestern Sweden, the risk of N accumulation will persist even if the deposition is decreased and whole-tree harvesting is applied. Net losses of N in areas with low N availability may, on the other hand, lead to negative effects on growth. In northern Sweden the accumulation is very low with today's deposition and stem harvesting. Decreased deposition and/or whole-tree harvesting may lead to substantial net losses in these parts of the country.

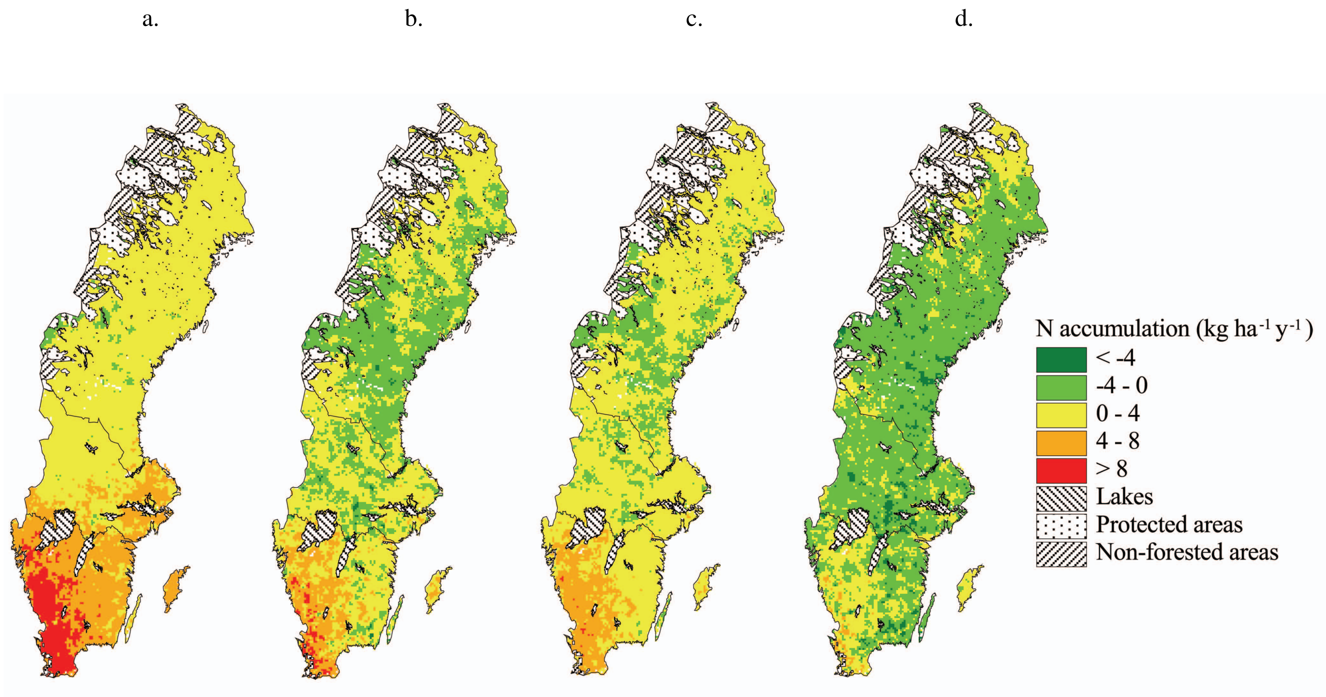


Figure 17. *N accumulation according to four scenarios: (a) deposition of 1998 and stem harvesting, (b) deposition of 1998 and whole-tree harvesting, (c) decreased deposition and stem harvesting and (d) decreased deposition and whole-tree harvesting.*

The results of the mass balance calculations should be seen from the perspective of the amounts of N in soil since the risks associated with net losses and net accumulation depend on the N availability in the soil. The total N store down to a depth of one metre is large, the median for 1293 sites over the whole of Sweden from the National Forest Inventory was estimated to be 5.2 metric tons per hectare, using soil densities from Karltun (1995) and a constant fraction of blocks and stones of 30%, in accordance with the weathering calculations (Section 5.1.3). The variation between sites is large: the 25-percentile and the 75-percentile were estimated to 3.3 and 7.9 metric tons per hectare, respectively. However, this N is bound in organic material with different strengths and the absolute amount of N does not give a clear indication of the N availability in soil solution. The C/N ratio of the soil organic matter may be a more useful measure of the N availability. The C/N ratio in the southern part of Sweden is often around 25 (Figure 11) which indicates an increased risk of N leaching according to Gundersen et al. (1998) (Section 3.4).

Also, the risk of net losses is highly dependent on the amount of N accumulated in the soil. Net losses in northern Sweden, with a history of low N deposition, are more likely to lead to negative growth effects than net losses in areas in southeastern Sweden, where the N deposition has been rather high in a historical perspective. Although it can be concluded whether there is accumulation or deficit, it is not possible with the present methodology to predict when effects such as increased leaching or decreased growth will appear. Dynamic modelling is thus being applied in an on-going project, in order to include the time aspects (Section 10.3).

N deposition is the decisive factor in the southern parts of Sweden, and uncertainties in this term probably contribute most to the overall uncertainty, at least in this region. In northern and central Sweden the uncertainties in the deposition and in the harvesting can be of equal importance. The differences between the results of the scenarios give an indication of the sensitivity to uncertainties in the deposition and harvesting terms. The main uncertainties in the calculation are compiled in Table 3 and discussed more thoroughly in Paper VI.

Table 3. *Main uncertainties in the N balance calculations.*

Term	Main uncertainties
Deposition	The total uncertainty is the combined effect of uncertainties in meteorological data, model formulations, emission data and data on atmospheric chemistry[1]. Deposition of organic N was not included.
Fixation	Based on a single study. Probable overestimation in southern Sweden since studies have shown that fixation decreases with increasing N availability[2].
Stem harvesting	Constant, species-specific concentrations in stems were used, although they are known to vary widely, since no data are available supporting a distinction between grid cells. Growth rates were interpolated from data with weak spatial autocorrelation.
Harvesting of branches	Constant, species-specific concentrations in branches and needles were used, although they are known to vary widely, since no data are available supporting a distinction between grid cells. The amounts of branches and needles on trees, estimated within the framework of the National Forest Inventory using standard methods, are associated with significant uncertainties.
Leaching	This is a small term in relation to the others and the contribution of uncertainties is thus small. The runoff data applied represent all existing land use classes, and may thus be overestimated for forests.

[1] Persson et al. (2004).
[2] Liengen and Olsen (1997) obtained a positive correlation between N fixing by cyanobacteria and C/N ratios.

6.4 The forest soil - a potential carbon sink?

The geographical gradients of C sequestration rates in forest soils, calculated using the “N balance method” and the “Limit value method” (Sections 5.3.1 and 5.3.2) showed the same trends, with highest C sequestration rates in southwestern Sweden (Paper VII). There are two conceptual differences between the methods, regarding the time perspective and the layers included. The estimates obtained with the “N balance method” can be regarded as averages of C sequestration rates on the timescale of a rotation, since all forest stages are included, while the estimates obtained with the “Limit value method” are valid for mature forests only. Furthermore, the “N balance method” includes all soil layers, while the “Limit value method” only includes the C sequestration based on the above-ground litter in the organic layer. Thus, the methods may be used for different purposes, e.g. organic layer vs. the whole soil profile, and for the decadal scale vs. the scale of a rotation. The results from the “N balance method” are used in the discussions below since this method was considered to be more suitable than the “Limit value method” in policy-oriented discussions about the total C sequestration potential of forest soils on the timescale of a forest rotation.

The C sequestration rates estimated with the "N balance method" ranged from -60 to 360 kg ha^{-1} y^{-1} (Figure 18). The rates were highest in the southwestern part of Sweden. In the northern half of Sweden it was generally less than 100 kg ha^{-1} y^{-1}. The total annual C sequestration for the whole country was 2.2 million metric tons C per year. This is within the interval of earlier estimations of C sequestration in the humus layer, 1.9 - 4.9 million metric tons C per year, based on observations of the increase of the humus layer in the National Forest Inventory (Jernbäcker, 2003). The yearly C sequestration can be compared with the yearly Swedish CO_2 emissions, carrying 15 million metric tons C per year (Jernbäcker, 2003; data from 2001).

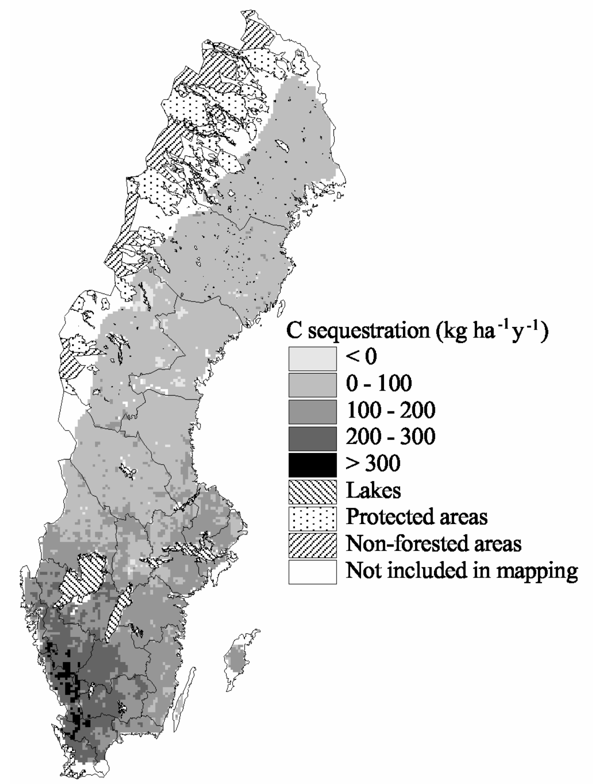


Figure 18. *C sequestration in forest soils in Sweden calculated with the "N balance method".*

The overall uncertainty in the C sequestration calculations using the "N balance method" is the result of the uncertainties in the N balance calculations (Section 6.3) and the assumption of a constant C/N ratio over time. Although the close connection between C and N in organic matter implies that large and rapid changes in the C/N ratios are unlikely, the "N balance method" gives a highest estimate for two reasons. Firstly it is likely that the C/N ratio decreases as the N deposition increases. Secondly, some of the C is accumulated in the mineral soil, which has lower C/N ratios.

A rough approximation of the uncertainty in the N accumulation of ±2 kg ha^{-1} y^{-1} gives a range in calculated C sequestration rates of ±40 kg ha^{-1} y^{-1} in areas with low C/N ratios and ±80 kg ha^{-1} y^{-1} in areas with high C/N ratios. In the areas with low C sequestration rates or with small estimated net losses, these uncertainties mean that it is difficult to conclude whether the balance is positive or negative, but the uncertainties are still small compared with the broad variation in results from other studies as discussed in Paper VII. Thus, although the assumption of constant C/N ratios is rough, the results can be considered to give a relatively reliable estimate. The calculations are not valid for ditched organic forest soils, corresponding to 7 % of the managed forest area (Hånell, 1990). This means that the total annual C sequestration in Sweden may be somewhat overestimated, since ditched organic forest soils often act as sources rather than as sinks (von Arnold, 2004).

7 The nutrient budgets in a policy perspective

7.1 Forestry, air pollution and environmental objectives

The effects of air pollution and increased biomass utilization on forest ecosystems and runoff water quality are diverse and several environmental objectives are affected. In this chapter the effects of air pollution and increased harvesting intensity on forest ecosystems from a nutrient sustainability perspective are described in the context of the environmental objectives "Sustainable forestry", "Natural acidification only", "No eutrophication" and "Limited influence on climate" (Section 3.2.2).

7.1.1 Sustainable forestry

The "Sustainable forestry" objective is the overarching forest objective, dealing with natural, economical and social sustainability. The issues of base cation and N sustainability included in this thesis are, however, considered more explicitly in the environmental objectives "Natural acidification only" and "No eutrophication" and are discussed in Sections 7.1.2 and 7.1.3.

7.1.2 Natural acidification only

Anthropogenic acidification is the combined effect of acid deposition and harvesting. In Paper V base cation budgets were used as a measure of acidification. A negative budget means that the base saturation, and thus the soil buffering capacity, decreases, which eventually leads to negative effects on the quality of soil water and runoff water. Thus, net losses lead to decreased buffering capacity, and are not consistent with the environmental objective of "Natural acidification only".

The results showed substantial losses of base cations in almost the whole country for all cases studied, except that of K in pine forests, indicating excess acidity from acid deposition and harvesting. The estimated net losses indicate that the pools are being reduced at a rate that may lead to negative effects on the timescale of one forest rotation in spruce forests. The results suggest that sustainable harvesting is not possible unless nutrients are added, that whole-tree harvesting accelerates the net losses of Ca and K substantially, and that further reductions of acidifying emissions are required to reach the environmental objective of "Natural acidification only". The substantially higher net losses for spruce than for pine show that the base cation budget is an important aspect that should be considered in site-specific recommendations on compensatory fertilization, harvest intensity and choice of tree species.

7.1.3 No eutrophication

The present anthropogenic contribution from forest soils to N eutrophication of marine environments is restricted to the N leaching from clearcuts (Paper IV) since the N retention in growing forests is generally high. In the counties in the southernmost part of Sweden, where the leaching from clearcuts is greatest, 1-11% of the total leaching from forest soils and agricultural land originates from clearcuts. Although the contribution from clearcuts is low, it is not negligible and it may increase if soil N accumulation continues. Thus, efforts should be made to minimize clearcut leaching by the choice of suitable forestry practices, e.g. leaving shelterwood (Örlander, 2000).

There are several indications that growing forests in southwestern Sweden may be close to their retention capacities, namely the increased frequency of leaching events at monitoring sites (Hallgren Larsson et al., 1995; Nilsson et al., 1998; Uggla et al., 2004), high N deposition for many decades, and low C/N ratios in the soil organic matter (Figure 11). The results of the N budget calculations in the study presented in Paper VI showed that in the southwestern parts of Sweden the N accumulation rates were up to 14 kg ha^{-1} y^{-1} according to the base scenario assuming the deposition of 1998 and stem harvesting only. Continued accumulation of this magnitude must be regarded as an obvious risk of future N leaching on a more regular basis also from growing forests. In southeastern Sweden, with N accumulation rates of 4-8 kg ha^{-1} y^{-1} assuming the deposition of 1998 and stem harvesting, there is also a significant risk of N leaching, while the risk of deposition-induced N leaching in central and northern Sweden must be considered small based on the N budget calculations.

The results show that reductions of N deposition are important if the objective of "No eutrophication" is to be fulfilled. Even if the N emissions in Europe decrease according to the 1999 Gothenburg protocol, i.e. the NO_x emissions are cut by 41% and ammonia emissions by 17% from the 1990 level by the year 2010 (UN/ECE, 1999), N accumulation rates will still be between 4 and 8 kg ha^{-1} y^{-1} in southwestern Sweden, and thus further reductions are required. Whole-tree harvesting decreases the N accumulation significantly, which can be positive from a eutrophication point of view. Whole-tree harvesting, however, also leads to losses of other nutrients, which is discussed in Section 7.2.

As regards eutrophication effects on ground vegetation and biodiversity, Nordin et al. (2005) showed that changes in key ecosystem components occur even at N deposition levels lower than 10 kg ha^{-1} y^{-1}, generally not regarded as harmful. Studies in boreal ecosystems in northern Sweden have shown that the understorey dominant *Vaccinium myrtillus* (blueberries) decreases at the expense of the grass *Deschampsia flexuosa* if N is added (Strengbom, 2002; Strengbom et al., 2002), largely due to the increase in attack of a parasitic fungus on *Vaccinium myrtillus*, and the recovery has been shown to be slow (Strengbom et al., 2001).

N fertilization has a long tradition in Sweden due to its potential economical benefits. It has decreased during recent decades (Sedin, 2003) but the present demand for high production may increase its use. The National Board of Forestry, together with the Swedish Environmental Protection Agency, has published recommendations as to where, when and how N fertilization should be applied in order to prevent acidification and eutrophication of aquatic and terrestrial ecosystems (National Board of Forestry, 1991). In the southernmost part of Sweden N fertilization is not recommended at all, in central areas the maximum recommended amount is 300 kg ha^{-1} during a rotation period and in the northern parts the corresponding figure is 600 kg ha^{-1} (Figure 19). The division of Sweden into three regions is based on the N status in forest ecosystems in different parts of Sweden.

These general recommendations are further refined based on other aspects on the stand level such as soil type, productivity class, soil depth and biodiversity values. An update of the recommendations is planned in the immediate future by the National Board of Forestry (H. Samuelsson, pers. comm.) and the results of the study of N budgets (Paper VI) constitute one of several important inputs in the new recommendations. Results on research on the effects of high N load on vegetation, other nutrient budgets and sensitivity to pathogens due to changes in nutrient availability (Tainter and Baker, 1996) are other important aspects that should be considered.

a. b.

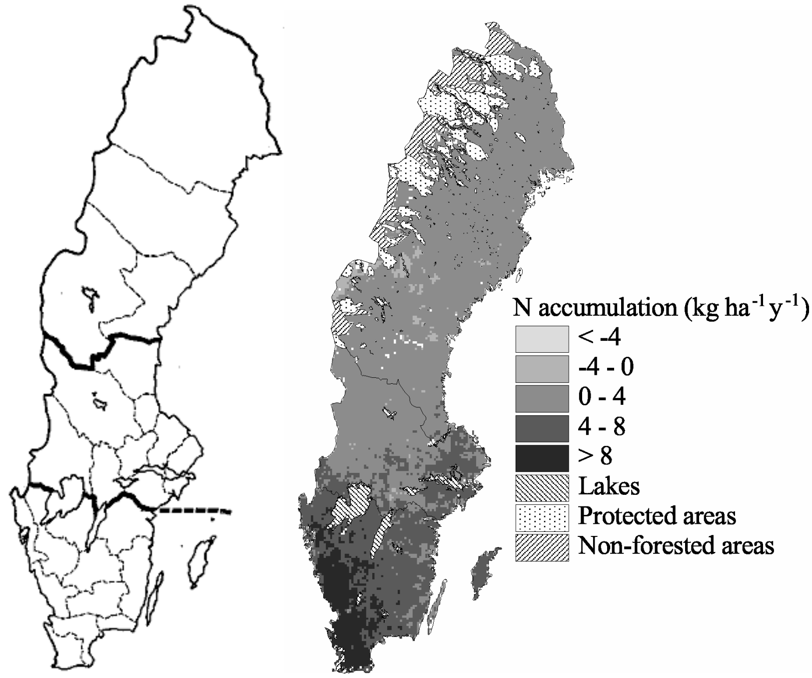


Figure 19. *(a) Division of Sweden into three parts with different recommendations regarding N fertilization (National Board of Forestry, 1991). (b) N accumulation in forest soils according to the base scenario (Paper VI).*

Rough geographical divisions, such as those in Figure 19a, are always controversial but are often required for practical reasons in policy-making situations. The results of the study presented in paper VI suggest that the differences between southwestern Sweden and southeastern Sweden are large (Figure 19b), and such a division should thus be made. It is important when formulating recommendations not only to consider the estimated accumulation/net loss, but also to consider the historical deposition. In southeastern Sweden, with high historical deposition, a great deal of N has accumulated in the soil, and even if the accumulation were to cease, N fertilization may lead to a risk of N leaching since the soil N stores are large.

7.1.4 Limited influence on climate

Forests can contribute to C sequestration through prolonged forest rotation periods and thus increased standing biomass. This will not only lead to more C being bound in the trees, but also to more C being bound in the soil. A continuous increase in C sequestration requires a continuous increase in standing biomass. High sequestration rates require limited harvesting and high N inputs to the ecosystem, which also means that soil accumulation of C occurs together with a substantial accumulation of N in the soil organic matter.

The total C sequestration rate in Swedish forest soil was, according to calculations with the "N balance method", 2.2 million metric tons per year (Section 6.4; Paper VII). If harvest statistics from the 1990s are applied (National Board of Forestry, 2000), the C sequestration in increasing standing biomass can be estimated to be 3-4 times higher than the C sequestration in the soil. C sequestration in forest ecosystems only leads to a temporary reduction in national net CO_2 emissions, and cannot be seen as a sustainable solution, but rather as a method of delaying emissions.

The C in harvested wood and slash will eventually be returned to the atmosphere as CO_2, and when this occurs depends on how the wood is used. Wood used for furniture, building material and other products, will lead to CO_2 emissions on the long term, whereas burning of slash and waste from sawmills causes CO_2 emissions on the short term. However, if the burning of slash is used to replace fossil fuels, this will decrease the net emissions of CO_2.

Biofuel (slash) from whole-tree harvesting, according to the scenario used in Papers V and VI, can substitute 3.6 million metric tons of oil per year. Combustion of this amount of oil leads to emissions of 11 million metric tons of CO_2. This can be compared with the total annual CO_2 emissions in Sweden, 56 million metric tons (data from 2001; Jernbäcker, 2003). Presently 10-20% of the biofuel potential associated with slash is used in Sweden, according to calculations based on the results from the present study and data in Gustafsson et al. (2002). By employing whole-tree harvesting the amount of branch and needle litter is decreased, which has a negative impact on the C sequestration in soil, and thus partly counteracts the decrease in net emissions resulting from the replacement of fossil fuel.

7.2 Conflicts in sustainable forestry

Several conflicts arise regarding nutrient sustainability, not only between production goals and environmental objectives, but also between environmental objectives on acidification, eutrophication and net emissions of greenhouse gases. Some positive and negative effects, regarding nutrient sustainability, of different actions associated with deposition policies and forestry methods are listed below.

1. Decreased deposition of S and N, beyond the agreements of the Gothenburg Protocol, will have positive effects on both acidification and eutrophication but:
    a. new pollution reduction negotiations will be required,
    b. decreased N availability can lead to decreased production in areas with low N load, and places restrictions on biomass utilization in these areas if N losses are not compensated for,
    c. decreased N availability may mean that N fertilization is required to maintain high growth rates.

2. N fertilization in an N-limited system implies increased growth, which is beneficial regarding both economy and increased C sequestration, but leads to a risk of:
    a. N leaching and acidification if the N addition exceeds the N retention capacity,
    b. deficiencies of other nutrients for trees, increased risk of pathogens and changes in the conditions governing biodiversity.

3. Whole-tree harvesting exports N from the system and thus decreases the risk of eutrophication and allows the possibility of replacing fossil fuels with biofuels, but leads to risks associated with:
    a. acidified soil, decreased base saturation and nutrient deficiencies in trees,
    b. decreased production potential,
    c. decreased soil C sequestration.

4. High C sequestration in the forest ecosystem decreases the net CO_2 emissions but:
    a. limits biomass utilization,
    b. implies N accumulation in the system leading to risks of N leaching, eutrophication, acidification and changes in conditions for biodiversity,
    c. reduces the possibility of using biofuels instead of fossil fuels.

While reduced sulphate emissions have led to continually decreasing deposition (Westling and Lövblad, 2000; Schöpp et al., 2003), it has proven to be more difficult to cut N emissions. Anthropogenic activities such as N emissions, N fertilization and harvesting are decisive in the outcome of efforts to achieve the objectives of "No eutrophication" and "Natural acidification only". Decreased N deposition may lead to the requirement of more extensive N fertilization to maintain the production capacity in some parts of Sweden, but this is no reason for reducing efforts to cut down N emissions. N deposition affects all ecosystems, most of them negatively on the long term regarding both eutrophication and acidification, whereas N fertilization should be restricted to only areas where it is needed, which minimizes the risk of negative effects.

The potential negative effects of N fertilization, i.e. the risk of N leaching, deficiencies of other nutrients, increased sensitivity to pathogens and negative biodiversity effects, should be evaluated thoroughly before employing N fertilization. Forestry methods can be optimized and whole-tree harvesting can be applied to decrease the risk of N leaching (Section 7.1.3). Compensatory fertilization of other nutrients may be required to prevent negative effects associated with nutrient deficiencies caused by harvesting and acid deposition. Fertilization should be preceded by extensive investigations in order to avoid negative effects such as increased nitrification and negative effects on ground vegetation.

C sequestration in increasing standing biomass in Sweden has low long-term potential and is in conflict with the production goal. The potential of C sequestration in forest soils is smaller on a yearly basis, but the C is sequestered on a longer term. However, C sequestration in soil involves corresponding N accumulation, which is in conflict with the objectives of "No eutrophication" and "Natural acidification only". Replacing fossil fuels with biofuels from slash decreases the emissions from fossil fuels. It is a more sustainable strategy than C sequestration in forest ecosystems, provided that the environmental risks associated with slash removal can be prevented.

7.3 Alternative methods of following up environmental objectives

In forestry policy, acidification has been dealt with through the critical loads approach. The critical load is defined by Nilsson and Grennfelt (1988) as "a quantative estimate of an exposure to one or more pollutants below which significant harmful effects on specified elements do not occur according to present knowledge".

In this approach a chemical criterion is chosen to predict the risk of damage using a biological indicator. A critical limit is set, i.e. "the most unfavourable value it can get, without long-term harmful effects on the ecosystem function and structure" (Sverdrup and Warfvinge, 1993). For the forested terrestrial ecosystem the tree is generally selected as the indicator. An often used chemical criterion is the molar ratio between base cations and inorganic Al, BC/Al, and a critical limit of 1 is commonly employed. However, this threshold is set with tree vitality in mind, and allows the base saturation to stabilize at a very low level, which may lead to highly acidified runoff water. Thus, a complete follow-up of the objective "Natural acidification only" requires complementary criteria.

The base cation budget calculations, presented in Paper V, focus on the base saturation. Negative base cation budgets mean that the base saturation decreases and thus that the soil buffering capacity through base cation exchange decreases. This gives a more complete evaluation of the environmental objective "Natural acidification only", but some pieces of the puzzle are still missing. The base cation release through ion exchange decreases together with the decrease in the base saturation, and this will lead to lowered base cation leaching and more acidified runoff water. Thus, a balanced budget at a late stage in the acidification process might imply highly acidified runoff water. The excess acidity (Section 6.2) can be used to complete the picture. Acid input, i.e. acid deposition and acidity added through base cation uptake by trees, that exceeds the neutralizing capacity of base cation weathering, will lead to excess acidity, which will decrease the base saturation and/or decrease the ANC in runoff. A critical load adapted to the "Natural acidification only" objective can thus be formulated as:

$$CL(Acidity) = W(Ca,Mg,K,Na) – U(Ca,Mg,K) + U(N) \quad (14)$$

The exceedance can then be calculated as:

$$Exc(Acidity) = D(S+N+Cl–Ca–Mg–Na–K) – CL(Acidity) \quad (15)$$

where:

CL = Critical load
Exc = Exceedance
D = Deposition
U = Net uptake (i.e. harvest)
W = Weathering

If this concept is used, exceedance of the critical load of acidity means decreasing ANC and/or decreasing base saturation. Generally, acidification is defined as decreasing ANC, but by including decreasing base saturation another aspect of acidification is included. The same basic concept was used by Joki-Heiskala et al. (2003) who used a simplified acidity balance on a regional scale in Finland. They made a number of assumptions, one of them that the acidifying effect of N leaching is negligible in Finland. Future risks of acidification due to N levels exceeding the N retention capacity of the forest were thus not considered.

In excess acidity calculations according to Equations 14-15, all deposited N that is not removed through net uptake is considered to be acidifying. This leads to an overestimation of the excess acidity, since N immobilization acts as a sink for acidity, as long as the retention capacity is not exceeded. In Sweden the immobilization has been modelled as a kinetic process, dependent on pH and temperature (Staaf et al., 2002). This approach involves large uncertainties, since it is difficult to estimate the long-term immobilization potential. The fate of the deposited N is crucial for the future acidification situation in forest soils.

The critical load concepts discussed above do not consider the recovery phase. When critical loads are no longer exceeded damaged ecosystems will remain which require remedial measures. Dynamic modelling can be an important tool in this process (Grennfelt et al., 2001).

8 Integrating science and policy

Applied research aimed at decision support must fulfil specific demands. The results must be easy to understand and interpret and it must be possible to translate them into authority recommendations or laws. In order to satisfy these demands a suitable method must be found for investigating the issue in question, there must be continuous communication between representatives of all the parties involved, and, finally, the results must be presented in an easily understandable way.

8.1 Choice of method and the process of data collection

The policy perspective must be addressed already when choosing the method, and the usefulness of the results should be decisive in the choice of method. The critical load concept (Section 7.3) is an example of a concept that has linked research and science successfully in studying acidification (Bäckstrand, 2001; Lidskog and Sundqvist, 2002). The advantages of the concept are that the calculations are easy to perform, and it is also easy to transform the results into air pollution abatement strategies.

In the present study mass balance calculations played an important part. Mass balance calculations are intuitive and the results are reliable and easy to understand. Several assumptions and limitations are associated with mass balance calculations, but they are easy to survey, which simplifies the interpretation. Another advantage is that the calculations require limited amounts of data, which makes them suitable for regionalization. The main disadvantage is the lack of dynamics, and thus the limited possibility of future extrapolation.

In order to cope with the wide geographical scale of the study, GIS was used to handle the data and to present the results. Maps produced in this way give a good overview of the regional variations on a national scale. The ability to perform regional mapping depends on the availability of geographical databases. Sweden is well-supplied with environmental datasets compared to many other countries. Some of these data are freely available for research, while others must be purchased at a high cost. Limited access to data prevents progress in environmental research.

8.2 Cooperation and communication

Continuous communication with authority representatives increases the probability that the research will be useful. In the present study representatives from the Swedish Environmental Protection Agency, the National Board of Forestry and the Swedish Energy Agency were involved. These authorities are responsible for the environmental objectives in question. Scenario analysis is a good platform for this kind of cooperation, since it has the potential of connecting policies with effects, and research with decision-making. In the present study, scenarios were formulated through a dialogue between researchers and authority representatives. The basis for cooperation was regular meetings. It was also important to consult experts in different fields, e.g. representatives from the forest sector, to ensure the relevance of the scenarios and the reliability of the input data. This was done continuously, not in the form of scheduled meetings.

Based on the experience obtained in the present study, an improved procedure consisting of a number of meetings with different participants is suggested (Table 4). The procedure is based on the same main concept as that proposed by Alcamo (2001).

Table 4. *Suggested procedure for policy-oriented research.*

Meeting	Participants	Activities
1	Researchers and authority representatives.	Establishing a common view of the problem, brainstorming about scenarios, identification of knowledge gaps, planning a workshop.
2 (Workshop)	Researchers, authority representatives, experts, politicians, nature conservation organizations and industrial representatives.	Presentation of the problem, the knowledge gaps and results from a number of scenario analyses. Discussions.
3	Researchers and authority representatives.	Compilation of the results from the workshop, decisions about scenarios.
4	Researchers, authority representatives, experts, politicians, nature conservation organisations, industrial representatives.	Presentation of the results, discussions of future work.

The four meetings outlined in Table 4 should be regarded as a general outline, and the number of meetings should be adapted to the nature and complexity of the problem. The first meeting, involving only the researchers and the authority representatives, is essential in order to create a common definition of the problem and a common objective. An important task at this meeting is to decide who to invite to the second meeting, a workshop involving discussions with a broader circle of interested parties, e.g. experts in the fields where knowledge is missing, politicians and representatives from organizations or companies who may be affected by new policies. The likelihood that new policies will be accepted on a broad scale will increase if all the interested parties are involved at an early stage. Some preliminary results from scenario analyses can be presented at the workshop, in order to initiate a discussion. The results of the discussion can be compiled and presented at a third meeting. Decisions should then be made about which scenarios should be studied, and how the knowledge gaps should be filled. At the fourth meeting, the results should be presented to the broader audience from the workshop.

By performing the process in this way the participation of interested parties, and thus also confidence in the policies, will increase. Continuous communication between the meetings, with short reports on how the work is progressing, keeps the parties informed, increasing their motivation and the effectiveness of the meetings. Group work involving researchers and stakeholders is thoroughly discussed in Haraldsson (2005).

8.3 Presentation of maps for policy applications

Is a researcher responsible for the results being interpreted in the correct way? The results are often presented as diagrams or maps, without the assumptions, explanations and discussions associated with the figures. From a scientific point of view the most important issues is that the results are published in a scientific paper. From a policy point of view, however, it is important that the results used for decision support give a clear picture.

Maps are a very useful means of presenting results. Maps are often seen as reality, no matter how well and thoroughly the uncertainties have been pointed out. Simple things, like the choice of colours, can affect the interpretation of maps, even if the intervals in the legend are the same. The cell size of the grid in this study, 5·5 km, was determined by the input data with the highest resolution. The reason for this was not to lose available information. Moreover, it is easier to complement the calculations with data with improved resolution if a smaller grid cell size is used. A disadvantage, however, is that the results can give the impression that they are more detailed than they actually are. No matter how small the grid cell size is, the output data can never be more accurate than the input data. In some cases, it may be more instructional to present isoline maps than grid maps. People are more used to isoline maps, and they know that there are no actual lines in nature. If grid maps are chosen for the presentation of results it is important to make them as clear as possible, regarding intervals, colours and figure text. It is also important to point out, in all contexts, that the purpose is not to analyse single grid cells, but to illustrate the gradients.

9 Conclusions

In this study regional-scale budget calculations have been performed with the aim of providing improved scientific data on which decisions can be based. Scenario analysis provided a good platform, since it has the potential of connecting policies with effects, and research with decision-making. The study led to the following main conclusions:

- Data on elemental contents in the soil at 22940 sites, from the Swedish soil geochemistry database managed by the Swedish Geological Survey (SGU), have increased the possibility of providing reliable estimates of base cation weathering rates on local and regional scales, which are essential inputs in base cation budget calculations.
- The results of the base cation budget calculations indicate that the present pools of exchangeable base cations will decrease even when stem-harvesting is employed, and that the losses of calcium and potassium will increase substantially with whole-tree harvesting. The results indicate that the stores will be depleted at rates that could lead to negative effects on trees and runoff water quality within one forest rotation.
- The current contribution from forest soils to the anthropogenically induced nitrogen leaching from land areas to the sea is restricted to nitrogen leaching from clearcuts. Although this fraction is small, it is not negligible and it may increase together with increased soil nitrogen availability arising from continuously high nitrogen deposition.
- The issue of nitrogen must be treated differently in different parts of the country, due to large variations in nitrogen availability. The nitrogen budget study indicates that there is an obvious risk of more frequent nitrogen leaching from growing forests in southern Sweden, even if the deposition were to decrease according to the agreements of the Gothenburg protocol. In central and northern Sweden, however, there is a risk of increased nitrogen shortage. The risk will increase as the deposition decreases.
- Carbon sequestration in Swedish forest soils is not an effective or sustainable way to decrease the net carbon dioxide emissions. The long-term capacity is low, the utilization of biomass must be limited and a high accumulation of nitrogen is required, increasing the risk of eutrophication and acidification.

- Large-scale whole-tree harvesting has the potential to substantially decrease the present carbon dioxide emissions from fossil fuels, if the branches, tops and needles are used as a biofuel replacing fossil fuels. However, it will cause net losses of nitrogen and base cations in large parts of Sweden, which means that forestry will not be sustainable unless nutrients are added through compensatory fertilization. To prevent net losses following whole-tree harvesting, compensatory fertilization of base cations would be required in almost the whole country, whereas nitrogen fertilization would be needed only in areas with low present and historical nitrogen deposition, mainly in northern Sweden.
- Nitrogen fertilization is controversial since it increases forest production and thus also carbon sequestration in the forest in an nitrogen-limited system, at least on short term, but at the same time it leads to risks of increased eutrophication and acidification of terrestrial and aquatic ecosystems. The regional nitrogen budget calculations can be used for decision support together with other information about, for example, effects of nitrogen on ground vegetation.
- The methodology and the database in the present study constitute a good basis for further development regarding methodologies as well as data updating. The static mass balance methods should be combined with site-level dynamic modelling in order to study changes with time in more detail.

10 Future work

10.1 Development of mass balance calculations

The mass balance calculations of N and base cations can continually be updated as new data become available. The uncertainties identified should be further investigated in order to reduce them. The most significant uncertainties that should be addressed are, according to the present knowledge, those in base cation leaching, deposition and the concentrations of nutrients in different tree parts. New scenarios can be investigated, adapted to the continuously changing conditions. The scenarios are presently restricted to various types of forestry and deposition conditions. Climate change may change conditions in forests substantially through, for example, increased temperature, changes in precipitation patterns and an increased frequency of storms, and it would thus be interesting to include the climate perspective in scenarios in future work.

10.2 Updating methods for calculating critical loads

The database used for the budget calculations in the present study provides a good basis for further development of methods for evaluating environmental objectives regarding acidification, eutrophication and climate change, for example through different critical load approaches. The results of the N budget calculations (Paper VI) are given as an average for all existing tree species, while in the base cation budget study (Paper V) results are given for spruce and pine separately. An interesting development would be to distinguish between more tree species, including deciduous species, and also between different site indexes.

10.3 Combination with dynamic tools for temporal resolution

The budget calculations of N, base cations and C show the change (accumulation or net loss) for each element separately. They can, as shown in this thesis, be used for discussions on future risks in different areas of N leaching and lack of nutrients, and for estimates of the C sequestration potential. Static models in a dynamic world have, however, the drawback that extrapolation to the future is difficult on anything more than a theoretical level. Thus, dynamic models are required as a complement to budget calculations, as stated by Forsius et al. (1998).

A dynamic model, ForSAFE, with the potential of integrated modelling of acidification, eutrophication and C sequestration in forests, has recently been developed (Wallman et al., 2005). It can be used for future predictions, but it is difficult to obtain the regional picture that can be derived with the mass balance calculations, since the amount of input data required is much larger for ForSAFE. Combining high-resolution budget calculations with a dynamic tool such as ForSAFE for use at a site level makes it possible to achieve both a high degree of spatial resolution and to take into account the dynamics involved. In practice, this means that various well-documented sites representing conditions of various types (such as net loss, accumulation and neither net loss nor accumulation) can be chosen for dynamic modelling, based on the results and scenarios presented in Paper VI, as illustrated in Figure 20. The results of the modelling can provide more detailed information concerning the future N budgets at such sites. This in turn can improve the understanding of high-resolution N balance calculations, making them more useful for long-term predictions.

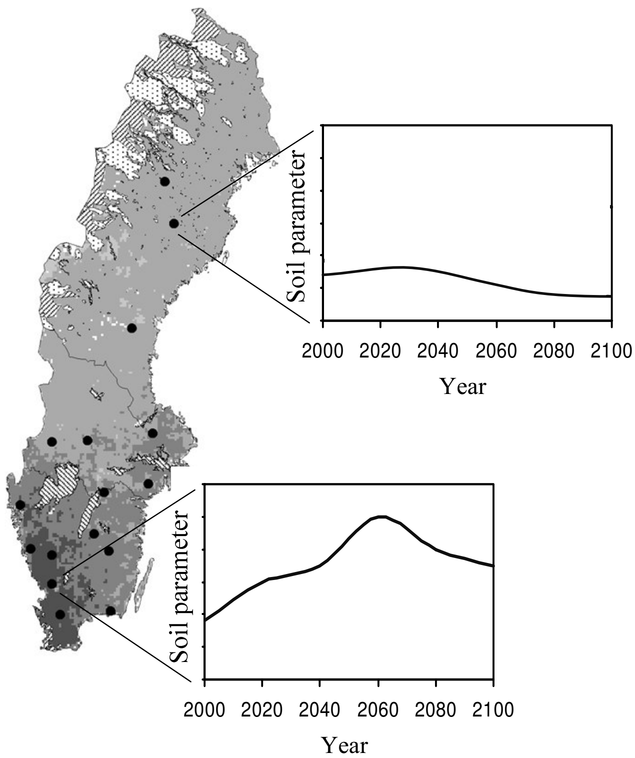


Figure 20. *Schematic picture illustrating how high-resolution mass balance calculations, exemplified by the N budget calculations, and single-site dynamic modelling of, for example, soil conditions can constitute a powerful combination for decision support.*

10.4 Other nutrients

This thesis focuses on the nutrients Ca, Mg, K and N, while phosphorous (P) and trace elements are not considered. In traditional research considering northern forest ecosystems, much more emphasis has been placed on N and base cations than on other nutrients, since N is generally considered to be the limiting factor for growth (Tamm, 1991), while base cations are central in acidification issues. Recent research has, however, illuminated the importance of P, which is essential for growth but appears naturally in low amounts in the soil (Fransson, 2000; Wardle et al., 2004). Stevens et al. (1993) showed experimentally that nitrate leaching in Sitka spruce stands in North Wales decreased after fertilization with P and K, suggesting that P and/or K was limiting for growth. Studies in southern Sweden indicate that P is the nutrient most likely to replace N in limiting the growth of spruce (Rosengren-Brinck and Nihlgård, 1995; Thelin et al., 2002, Thelin, 2005). Calculations, corresponding to those for base cations and N, are thus desirable also for P.

Populärvetenskaplig sammanfattning

Skogen är en av Sveriges mest betydelsefulla naturresurser. Utöver det ekonomiska värdet är skogen även viktig ur ett ekologiskt, socialt och kulturellt perspektiv. För att uppnå ett långsiktigt uthålligt skogsbruk måste alla dessa aspekter beaktas. Uthålliga näringsbalanser i den brukade skogsmarken är nödvändiga för att bevara produktionsförmågan samt minska risken för försurning och övergödning av terrestra och akvatiska ekosystem. De är därmed centrala i de svenska miljökvalitetsmålen "Levande skogar", "Bara naturlig försurning" och "Ingen övergödning". Möjligheterna att uppnå målet "Begränsad klimatpåverkan" påverkas av dessa mål på grund av den nära kopplingen mellan kol och kväve i organiskt material.

Skogsmarkens näringsbalanser påverkas starkt av antropogena faktorer såsom nedfall av svavel och kväve samt skogsbruk. Regional kartläggning av näringsbalanser för olika depositions- och skogsbruksscenarier behövs som beslutsunderlag vid utformning av rekommendationer inom skogsbruket samt som underlag vid förhandlingar kring behov av ytterligare utsläppsminskningar. Denna avhandling beskriver regionala näringsbalanser för kväve och baskatjoner samt kolinbindning i skogsmark i relation till luftföroreningar och skogsbruk.

Massbalanser för baskatjonerna kalcium, magnesium och kalium beräknades i regional skala. Vittringshastigheten modellerades i hög upplösning baserat på över 25 000 lokaler över hela Sverige där markgeokemin undersökts. Resultaten av balansberäkningarna visade på nettoförluster av baskatjoner i både gran- och tallskog, även om skörden begränsades till stamuttag, förutom för kalium i tallskog där näringsbalanserna var i huvudsak positiva. Resultaten tyder på att förrådet av utbytbara baskatjoner i marken minskar med en hastighet som kan innebära negativa effekter i form av försämrad trädvitalitet eller sämre trädtillväxt samt försurad avrinning redan inom en skogsgeneration. Utlakningen, som i viss mån är påverkad av nedfall av försurande luftföroreningar, var den dominerade termen i balansberäkningarna för kalcium och magnesium och var även av stor betydelse för kalium. Helträdsuttnyttjande innebar påtagligt ökade förluster och situationen var betydligt värre i granskog än i tallskog, vilket bör tas hänsyn till vid utformning av rekommendationer i skogsbruket.

Balansberäkningar för kväve visade att kvävefrågan måste hanteras olika i skilda delar av landet, på grund av stora geografiska skillnader i kvävetillgång. I södra Sverige finns det en klar risk för ökad utlakning i växande skogar i en helt annan omfattning än nu, även om depositionen minskar enligt överenskommelserna i Göteborgsprotokollet, det internationella avtalet från 1999. I centrala och norra Sverige finns det däremot risk för ökad kvävebrist i den brukade skogen. Beräkningar visade att kolinlagring i skogsmark inte är ett effektivt sätt att balansera emissionerna av koldioxid. Den långsiktiga kapaciteten är låg och kolinlagring i marken innebär även att kväve lagras in i marken, vilket ökar risken för kväveutlakning och övergödning samt försurning.

Resultaten belyser flera målkonflikter beträffande näringstillgång i brukad skogsmark. Kvävegödsling kan öka produktionen på kort sikt, vilket även ökar kolinbindningen i systemet, men ökar risken för kväveutlakning, övergödning och försurning. Den framtida utvecklingen av kvävefrågan beror på utvecklingen vad gäller emissioner och skogsbruksåtgärder. Kvävebalansberäkningarna i denna studie kan bidra till beslutsunderlaget för utformning av rekommendationer och allmänna råd.

Uttag av grenar och toppar (GROT) utöver stamuttaget minskar risken för negativa effekter orsakade av kväveöverskott. Om GROT används som biobränsle, som ersättning för fossila bränslen, kan de nuvarande svenska koldioxidutsläppen från fossila bränslen minskas avsevärt. I områden med låg nuvarande och historisk kvävedeposition kan dock helträdsutnyttjande leda till ökat kväveunderskott och behov av kvävegödsling för att upprätthålla produktionsförmågan. Beräkningarna av baskatjonbalanser visade att kompensationsgödsling av baskatjoner kan vara nödvändig över hela Sverige för att undvika stora nettoförluster, speciellt vid helträdsuttag i granskog.

Metoderna för beräkning av näringsbalanser och kolupplagring kan användas som en del av beslutsunderlaget för att ta fram rekommendationer i skogsbruket. Samverkan med avnämare är viktig vid utformning av scenarier och tolkning av beräkningsresultat. Databasen och scenarioverktyget som tagits fram gör det enkelt att uppdatera data om ny information blir tillgänglig, samt utföra beräkningar med nya scenarier. Massbalansberäkningar för näringsämnen kan med fördel kompletteras med dynamiska beräkningar för att belysa tidsaspekten på förändringar i miljötillståndet.

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