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Nutrient budgets in forest soils at increased biomass removal

– do Swedish and Finnish studies provide the same conclusion?

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Summary

Nutrient budget calculations in forest soil are an important tool to assess the environmental effect of increased biomass harvesting and can be applied as a tool for policy makers to assess the environmental effect of different biomass scenarios. Environmental effects include losses of nutrients (phosphorous, nitrogen, base cations), which can reduce soil fertility and the soil buffering capacity against acidification.

Nutrient budget calculations are performed by means of a simple mass balance model where nutrient inputs to the forest ecosystem (weathering, deposition, nitrogen fixation) are compared with the outputs (leaching and harvesting). Nutrient budget calculations have been calculated both at site level and at regional level in Sweden and Finland. This study aims at comparing nutrient budget calculations focusing on conclusions and indata applied.

Despite the application of different inputs to the regional base cation budget calculations in Sweden and Finland, the result is similar, i.e. showing that the weathering rates is of the same magnitude or larger than the removal of nutrients at stem harvesting (particularly for Ca and Mg) except for some areas of the country. However, at whole tree harvesting, the output exceeds the input in many areas. When calculating the base cation balance also including leaching and deposition (only for Sweden), the output exceeds input in most of Sweden for Ca, Mg and K even at conventional stem harvesting.

In Finland, nutrient budgets for N and P have been calculated at site level, but not yet at the regional level. In Sweden, the regional mass balance calculation shows losses of P throughout the country, even at conventional stem harvesting. The N budget varies within the country, with nitrogen accumulation in southern Sweden and nitrogen losses in the north.

The similar conclusions from the Swedish and Finnish studies have strengthened the view of nutrient budget calculations as a useful tool to assess effects of increased biomass harvesting. Further work should concentrate on reducing uncertainties further, e.g. regarding nitrogen fixation and leaching of base cations. It is suggested that recommendations for nutrient compensation should be based on a combination of results from experiments (on intensive harvesting effects and fertilisation), nutrient budget calculations and dynamic modelling. Furthermore, it is important to maintain long-term experiments to assess long-term effects of intensive biomass harvesting on forest ecosystems.

Sammanfattning

Näringsbudgetberäkningar i skogsmark är ett viktigt verktyg för att utvärdera miljöeffekter av ett ökat biomassauttag från skogen och kan tillämpas av beslutsfattare för att utvärdera effekten av olika intensitet på biomassauttag. Miljöeffekter av ökat biomassauttag omfattar näringsförluster (baskatjoner, fosfor och kväve), vilket kan minska markens bördighet och markens buffringsförmåga mot försurning.

Näringsbudgetberäkningar görs med hjälp av en enkel massbalansmodell, där tillförseln av näringsämnen till skogen (via vittring, deposition och kvävefixering) jämförs med bortförseln av näringsämnen (via utlakning och skörd). Näringsbudgetberäkningar har beräknats både på beståndsnivå och på regional nivå både i Sverige och i Finland. Den här studien syftar till att jämföra näringsbudgetberäkningar med avseende på slutsatser och tillämpad indata.

Trots att olika indatakällor har tillämpats i de regionala baskatjonberäkningarna för Sverige och Finland, så pekar resultaten åt samma håll, det vill säga att vittring kan kompensera för uttaget av baskatjoner vid stamskörd (särskilt för Ca och Mg) med undantag av några delar av landet. Vid helträdsuttag däremot, överskrider bortförseln av näringsämnen (skördeförluster) det som tillförs via vittringen i många områden av landet. När baskatjonbalansen även omfattade utlakning och deposition (vilket endast har beräknats för Sverige), så överskred borttagandet tillförseln i större delen av Sverige för Ca, Mg och K, även vid konventionellt stamvedsuttag.

I Finland har näringsbudgetberäkningar för N och P beräknats på beståndsnivå, men ännu ej på regional nivå. I Sverige visar den regionala beräkningen på P-förluster i hela Sverige, till och med vid konventionellt stamvedsuttag. För N varierar det inom landet, med kväveupplagring i södra Sverige och kväveförluster i norr.

Den här studien har visat att näringsbalansberäkningar kan vara ett användbart verktyg för att utvärdera effekten av ett ökat biomassauttag. Det fortsatta arbetet bör fokusera på att minska osäkerheterna i beräkningen ytterligare till exempel genom att förbättra uppskattningen av utlakningen av baskatjoner samt kvävefixeringen. Rekommendationer för näringskompensation bör baseras på en kombination av resultat från experiment (effekter av gödsling och ett ökat biomassauttag), näringsbudgetberäkningar och dynamisk modellering. Det är viktigt att bibehålla långsiktiga experiment för att utvärdera långsiktiga effekter av ett intensivare biomasauttag från skogssystem.

1 Background

Intensive biomass removal from forests is becoming increasingly important as the demand for renewable energy is increasing. Intensive biomass removal includes several different forest management methods, including whole-tree harvesting, stump harvesting and fertilisation. The immediate benefits of an increased use of bioenergy are clear, but at the same time the long-term sustainability has to be assured. Environmental effects of increased biomass removal include losses of nutrients (nitrogen, phosphorous and base cations), which can reduce soil fertility and thus affect tree growth after harvest, and potentially also long term forest productivity (Proe et al., 1996; Egnell & Lejon, 1997; Jacobson et al., 2000; Bélanger et al., 2003, Rosenberg & Jacobson, 2004). Another potential negative effects is reduced soil buffering capacity against acidification (Nilsson et al., 1982). In areas with high nitrogen load, the removal of nitrogen-rich biomass can counteract the nitrogen accumulation (Akselsson et al., 2010) and thus the risk of elevated nitrogen leaching.

Nitrogen has often been the main focus in nutrient budgets as forest growth in Fennoscandia is limited by nitrogen. However, limitations of other nutrients such as phosphorous or potassium, can also be a problem, especially in areas with a significant nitrogen deposition (Stevens et al., 1993, Teng & Timmer, 1995, George & Seith, 1998). In Finland NP-fertilisation has increased Norway spruce growth more than N fertilisation on the most fertile site types in southern Finland (Kukkola & Saramäki, 1983).

During growth, tree biomass accumulates an excess of base cations compared with anions (Nilsson et al., 1982). The balance is restored when the trees decompose. However, when biomass is removed through harvesting, base cations are removed from the forest system, resulting in decreasing soil pH over time (Nykvist and Rosén, 1985). Consequently, more intense harvesting (harvest residues, branches and tops) results in a higher export of nutrients from the forest site. The buffering capacity of the soil is directly linked to the nutrient availability in forest soil and the removal of base cations (Ca^{2+}, Mg^{2+} and K^{+}) through harvesting therefore reduces the buffering capacity of the soil, which may result in increased acidification of soil- and surface water.

In Sweden and Finland, guidelines for careful biomass harvesting have been published (Skogsstyrelsen, 2008b & Koistinen & Äijälä, 2005). At present, the Finnish guidelines are being updated, and in the preparation process soil sustainability is discussed more than earlier.

Currently, two research programmes, focusing on the effects of increased biomass removal, are running in parallel in Sweden and Finland. In Sweden, the research program "Sustaninable supply and refinement of biofuels" (Bränsleprogrammet), financed by the Swedish Energy Agency is running during 2007-2010. In Finland, the research programme "Bio-energy from forests", financed by the Finnish Forest Research Institution (Metla), is running during 2007-2011. Both research programs aim at clarifying the acceptable, sustainable level of removal of biomass from forests. It has become evident that there are many areas in this field of research where Sweden and Finland can benefit from each other's research. Due to similar forestry conditions and policy aims, it is valuable to exchange knowledge within this field of research.

Nutrient budget calculations in forest soils can be useful in assessing the environmental effect of increased biomass harvesting and can be applied as a tool for policy makers to assess the environmental effect of different biomass scenarios. At present, regional nutrient budget calculations in relation to increased biomass harvesting have been carried out both in Sweden (Olsson et al., 1993; Hellsten et al., 2010) for N, P, Ca, Mg, K and Na, and Finland (Joki-Heiskala et al., 2003) for Ca, Mg and K. The two countries cover a steep nitrogen deposition gradient with a high deposition in the south west of Sweden with decreasing deposition towards north east (northern Finland), which provides the opportunity to investigate nutrient budgets at different deposition levels.

Today, Sweden and Finland apply different data input, approaches and methodologies to calculate nutrient budgets. There is a need to provide an overview, a synthesis, of results and research concerning calculations of nutrient budgets in forest ecosystems in Sweden and Finland to assess how the nutrient balance is affected by increased biomass removal and to improve current methodologies and input data applied. Assessing and compiling research results from both Sweden and Finland, provides the possibility to draw conclusions beyond the national research programs, hence, essential knowledge can be shared to further strengthen the nutrient budget calculations as a tool to assess the environmental effect of biomass harvesting.

2 Aim of the project

This study aims at comparing nutrient budget calculations in Sweden and Finland at the site level and at the regional level with respect to conclusions and input data applied. This will broaden the basis for conclusions regarding sustainability of whole-tree harvesting in the two countries, and has the potential to highlight uncertainties and possible improvements of input data.

3 Method

The study consists of a literature review of Swedish and Finnish research on nutrient budgets in forest soils to assess current knowledge. Nutrient budget calculations in each country are compared regarding conclusions, results, methodologies and input data. The methodologies and input data applied for weathering rates, deposition, nitrogen fixation, leaching and biomass harvesting are compared and possible improvements in input data and methodologies to calculate nutrient budgets are discussed.

4 Long-term experiments on biomass removal

Besides nutrient budget calculations it is important to look at empirical data on effects on the nutrient status following biomass harvesting. This section focuses on current and most recent research regarding empirical studies on effects of increased biomass removal on nutrient budgets and tree growth. This additional information will contribute to providing a more robust foundation for the effect analysis.

Both in Sweden and Finland, long-term experiments have been carried out to assess the effect of biomass removal on nutrient budgets and tree growth. Biomass harvesting is the forest management procedure that has the most important impact on nutrient availability in forest soil. Theoretically, increased biomass harvesting results in increased acidity in forest soil. At conventional stem harvesting, nutrients from branches and needles that are left on site are returned to the forest soil, hence neutralising the production of H^+ during tree growth.

Empirical studies on long-term effects of whole tree harvesting (WTH) in Sweden have shown an acidification effect at whole tree harvesting compared with stem harvesting only. Egnell et al. (1998)

compiled results on long term effects of whole tree harvesting from Sweden and other parts of the world. These results suggested that the pH increase at biomass harvesting was up to 0.4 pH units smaller in the humus layer at whole tree harvesting compared with stem harvesting and this effect lasted up to 20 years. In the mineral layer, no pH differences between whole tree harvesting and stem harvesting could be shown. These results suggest that the amount of buffering nutrients returned to the forest soil is smaller at whole tree harvesting, and therefore pH does not increase as much as during stem harvesting. A more recent compilation of long-term research results (Energimyndigheten, 2006) confirms these results, and also indicates some effects in the mineral soil. Conclusions from SLU:s long-term empirical studies on whole tree harvesting show that whole tree harvesting increases the acidity in the humus layer, and that the base saturation rate decreases both in the humus layer and in the mineral soil (Energimyndigheten, 2006). Measurements of ANC (acid neutralizing capacity) in soil water indicate decreasing ANC values at whole tree harvesting compared with conventional stem harvesting (Zetterberg, 2008). Furthermore, measurements of changes in the soil pool of base cations and uptake in biomass indicate that whole tree harvesting reduces the soil pool compared with stem harvesting (Olsson &Westling, 2006).

In Finland, nutrient budgets for nitrogen, phosphorus and base cations are quantified in long-term logging residue experiments for Norway spruce. The results from this task (*Empirical assessment of the effects of biomass removal on nutrient availability*) will also be used to parameterize and calibrate a dynamic forest ecosystem model for Norway spruce stands, using a new growth model and decomposition model, modified to Finnish conditions. This research is part of the Finnish Sustainable Energy Research Program (2008-2011) within the project "Economic-ecological optimisation of timber and bioenergy production and sequestration of carbon in Norway spruce stands" financed by the Academy of Finland. The main experiments used are 14 Finnish logging residue experiments established in 1977-1986. Data from other Nordic experiment series (additional 8 experiments in Norway and Sweden) established in 1983-1986, are also included in the study. Sample tree biomass (including logging residues) and soil and tree nutrients have been measured at harvesting, and the measurements have been repeated at regular intervals in these stands. Smolander et al. (2008) reported decreased soil C and N mineralisation in WTH plots in a Norway spruce stand, 12 years after thinning and logging residue removal. New results of Smolander et al. (personal communication) indicate similar results in the same spruce stands in Finland where there has been decreased stand volume increment after WTH (Helmisaari et al., 2011, in prep.).

Whole tree harvesting experiments in Sweden have shown growth decreases in the first 10 years after intensive harvesting (Jacobsson et al., 2000). In Finland, an overview of research regarding effects of energy tree harvesting was published in 2007 (Kuusinen & Ilvesniemi, 2008). A sub-chapter described the effects on nutrient balances (Helmisaari et al., 2008). The results of this study showed that the observed growth reduction after logging residue removal at thinning in Finnish conditions is related to site fertility and the removal of nitrogen in logging residues, leading to the conclusion that needles should be left at site if possible.

A manuscript (Helmisaari et al., 2011, in prep.) on long-term (0-25 years) tree growth changes after logging residue removal in thinnings in 22 stands in Finland, Sweden and Norway has recently been finalised. The results of this study showed that WTH caused a decrease in the volume increment in 14 of the studied 22 experiments already in the first 10-year period after thinning, and in 18 experiments during the second 10-year period. Even if half of the stands were thinned only once at establishment, the volume increment of the WTH treatment in them, as well as in twice thinned stands, further decreased during the second and/or third 10-year period.

Helmisaari et al. (2009) compared nitrogen outputs in logging residues to other fluxes in the tree stands in Finland, concluding that available nitrogen is in a closed nutrient cycle from which no large outputs in residues are desirable. Tree growth in Finland is limited by nitrogen deficiency, and the export of nitrogen in whole-tree harvesting at thinning has been shown to cause growth depression (Jacobson et al. 2000, Helmisaari et al., 2011, in prep.).

Logging residue needles can be considered "a slow-release natural fertiliser". Actually, part of the increased growth of the remaining trees after thinning with residues left at site, is caused by a fertilisation effect by residues, and not only by better light conditions and reduced competition (Helmisaari et al., 2009). Without a logging residue input, the only nitrogen flux affecting N availability after thinning is the decomposing litter. The 60-130 kg N ha^{-1} of Norway spruce residues and 25-60 kg N ha^{-1} of Scots pine residues at thinning (Luiro et al., 2010) quantitatively equal 3-8 years of needle litter N input to soil. The annual mean total nitrogen deposition in Finland is low, varying between 2 and 6 kg N ha^{-1} (Vuorenmaa, 2007). Even if rotation-long N balances may show nitrogen surplus (Raulund-Rasmussen et al., 2008), it is questionable how large part of deposition nitrogen is actually available to tree uptake as leaching at snow melt is a common phenomenon, but often not included in annual leaching estimates.

Currently (2010) an SNS-networking activity is running: *"Long-term effects of intensified harvesting for bioenergy – what can we learn from established experiments"*. The purpose of the newly established network is to search for already established experiments in the Nordic and Baltic countries for re-evaluation of the results and doing common syntheses, which may also include stand-specific nutrient budgets. Hence, many projects are currently running which are relevant for estimating the effects of increased biomass harvesting, and for improving nutrient budget calculations.

5 Nutrient budget calculations

Nutrient budget calculations are a means to assess the long-term sustainability of the forest system based on whether nutrients are accumulating or depleting from the forest soil and provide an indication of the rate of accumulation/depletion. Budget calculations can be applied to quantify the effect on the forest ecosystem nutrient status, soil acidification and eutrophication following different harvesting scenarios.

Nutrient budget calculations are performed by means of a simple mass balance model where nutrient inputs to the forest ecosystem are compared with the outputs. Inputs are weathering, deposition and N fixation and outputs are leaching, harvesting and denitrification.

The nitrogen nutrient budget can be calculated as:

$$\Delta = \text{Deposition} + \text{N Fixation} - \text{Harvesting} - \text{Leaching} - \text{Denitrification} \qquad \text{[eq 1]}$$

The nutrient budget for P, Ca, Mg, K and Na can be calculated as:

$$\Delta = \text{Deposition} + \text{Weathering} - \text{Harvesting} - \text{Leaching} \qquad \text{[eq 2]}$$

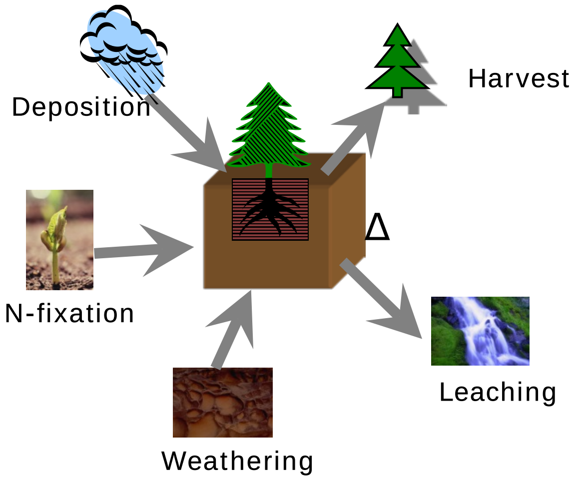

Figure 1. Mass balance calculation: Δ = Inflow – Outflow, parameters included in the nutrient budget calculation for forest soil.

In the nutrient budget calculation, all fluxes are calculated as an average annual flux although the flux may vary during the rotation period. The results of the calculation therefore provide the annual net change as an average of a forest rotation. Only the net fluxes in and out of the system are considered, i.e not the internal circulation of organic matter. Furthermore, denitrification is usually very small in well-drained forest soils, and is thus neglected in the calculations.

A negative balance indicates that the nutrient export exceeds import and that the system is unsustainable over time. Accumulation and net losses occur in natural ecosystems, however, normally at low rates. Net changes at high rates may indicate a risk of adverse environmental effects. A negative value may not be critical as long as there is still sufficient levels of nutrients available in the soil. However, a negative nutrient balance can be considered an indication that the system is not sustainable in the long term.

Nutrient budget calculations can be carried out, either at a few experimental sites with detailed input data, or at a regional level (many sites) with more generalised input data. Calculating nutrient budgets at the regional level provides the opportunity to use the calculations to identify areas at risk of acidification and eutrophication. However, a disadvantage is that nutrient budget calculations fail to incorporate dynamic feedback. Nutrient budget calculations are however relevant complements to experimental approaches and dynamic modelling.

At present, nutrient budget calculations in relation to increased biomass harvesting have been carried out at a few experimental sites in Sweden and Finland, related to sustainability estimates. Nutrient budget calculations at experimental sites are often based on detailed site-level data but are only representative for those particular sites and can not be considered as representative for the whole country. Nutrient budgets vary considerably due to deposition patterns and variations in weathering rates, tree growth, etc. Nutrient budget calculations at the regional level are usually based on more generalized data and the uncertainties are thus larger. However, they have the potential to capture the geographical pattern of nutrient balances within the country. Another advantage is that the same input data are applied across the country, hence making it possible to compare calculations in different regions.

In the following chapters (5.1 & 5.2), nutrient budget calculations at site level and regional level in Sweden and Finland are presented.

5.1 Nutrient budget calculations in Sweden

5.1.1 Site level

Nutrient budget calculations at a site level have been calculated at a range of sites in Sweden. Nykvist (1977), calculated probably the first nutrient budget calculation in Sweden. He calculated nutrient budgets for N and P for the whole rotation period at two spruce sites, one in northern Sweden (140 years old), and one in southern Sweden (100 years old), see Table 1. He did not, however, consider P weathering in the calculations, as sufficient quantitative information of weathering rates was lacking at the time.

Table 1. Nitrogen budget calculation (kg N ha^{-1}) from Nykvist (1977). N.E. = not estimated

		N-balance South Sweden (100 years)	N-balance North Sweden (140 years)	P-balance South Sweden (100 years)
Input	Deposition	700	280	27
	Weathering	N.E.	N.E	N.E
	Nitrogen fixation	280	390	N.E
Output	Denitrification	100	140	N.E
	Leaching	225	245	6
	Harvesting (stem)	220	260	20
Budget		**435**	**25**	**1**

Nykvist (1977) noted that the nitrogen input was sufficient at stem harvesting at both sites. He concluded that the nutrient budget would probably also be positive at whole tree harvesting in the southern site, due to the high nitrogen deposition.

For phosphorous, the deposition was higher than the export of P through stem harvesting and leaching. Nykvist suggested further research regarding e.g. quantitative estimates of chemical weathering, in order to make complete budget calculations of P, but also for base cations such as K, Ca and Mg.

The more recent nutrient budget calculations at site level in Sweden include weathering. For example Sverdrup et al. (2006) used the PROFILE model (Sverdrup & Warfinge, 1993; 1995) to estimate weathering rates at a site in Björnstorp in south west Sweden. They calculated mass balances of Ca, Mg, K, N and P for three different tree species with stem harvesting in Björnstorp. They concluded, based on the results, what type of nutrients that would be necessary to compensate at the different tree stands at Björnstorp to maintain sustainability at present production levels. For instance, several of the stands would need addition of Ca. Also addition of Mg, P and K was necessary for some of the stands to maintain sustainability.

Raulund-Rasmussen et al., (2008) assessed nutrient budget calculations (N, P, K, Mg & Ca) at Lammhult, a Norway spruce site in southern Sweden for two forestry scenarios: conventional stem harvesting and whole-tree harvesting (stems and branches and needles), see Table 2. The whole tree harvesting scenario included the removal of all above ground material in thinnings and clear cut. However, the calculations did not include leaching (not estimated), nor weathering for P. Weathering rates were assessed by consecutive dilute nitric acid extractions at pH~1 as suggested by Callesen & Raulund-Rasmussen (2004). Based on the nutrient budget calculation together with empirical data and knowledge from similar sites, Raulund-Rasmussen et al. (2008) made a qualitative assessment of site vulnerability at intensive biomass harvesting at Lammhult.

Table 2. Nutrient balance accounts (kg $ha^{-1}yr^{-1}$) for Lammhult (Sweden), derived from Raulund Rasmussen et al. (2008). N.E. = not estimated.

Lammhult	N	P	K	Mg	Ca
Weathering rate[1)]		N.E.	4.2	1.6	3.9
Deposition	11.7	0	1.9	1.0	2.0
Leaching			N.E.	N.E.	N.E.
Harvest (stem)[2)]	6.6	0.3	2.1	0.6	5.0
Harvest (whole-tree) [2)]	12.7	1.2	5.2	1.7	12.5
Balance (stem)	**5.1**	**N.E.**	**4.0**	**2.0**	**0.9**
Balance (whole tree)	**-1.0**	**N.E.**	**0.9**	**0.9**	**-6.6**

1. Callesen & Raulund-Rasmussen, unpublished, based on method applied in Callesen & Raulund-Rasmussen (2004).
2. Stupak, unpublished

At Lammhult, the nutrient budget was positive for all nutrients (N, K, Mg and Ca) at conventional stem harvesting. At whole tree harvesting, the budget was negative for Ca and N and the export of many of the other nutrients were close to the inputs. Raulund-Rasmussen et al. (2008) concluded that whole tree harvesting at Lammhult may result in growth reductions as the input of nitrogen is too small to compensate for the export. Therefore, both nitrogen compensation and ash recycling should be considered at Lammhult and at similar sites at whole tree harvesting.

5.1.2 Regional level

Regional mass balance calculations for base cations (Ca, Mg and K) for Swedish forests were calculated already in 1993 (Olsson et al., 1993). Since then nutrient budget calculations at national level have been developed further and now also include P and N (Sverdrup and Rosén, 1998; Akselsson et al., 2007a; 2007b; 2008; Hellsten et al., 2008; 2010). Both mass balance calculations including all parameters (Figure 1) and simplified mass balance calculations including only weathering and harvest losses were applied.

The most recent budget calculations applied (Hellsten et al., 2010) was developed within the Swedish national research program ASTA (*International and national abatement strategies for transboundary air pollution*), 1998-2006 and is continuously developed regarding data and methodology. The most recent improvement in the calculations is the nutrient concentrations and amounts in stumps to calculate nutrient budgets for stump removal. Nutrient concentrations in stumps were evaluated from stumps in Sweden, Finland and Denmark (Hellsten et al., 2009 & in prep.).

The most recent national mass balance calculation in Sweden (Hellsten et al., 2010), presents nutrient budget calculations for Ca, Mg, K, Na, P and N at 10 973 coniferous sites from the National Forest Inventory in Sweden (Hägglund, 1985), of which slightly more than half of them are pine, and the remaining are spruce. The calculations represent the root zone, including the organic layer, which was assumed to be 50 cm in the base cation calculations. For the P calculation, the root zone was set to 40 cm for spruce and 50 cm for pine. Four different forestry intensity scenarios were assessed, see Table 3. These scenarios are based on scenarios from the Forestry Agency, SKA-VB 08 (Skogsstyrelsen, 2008a) and were developed to reflect as realistic forestry scenarios as possible. Figure 2 shows the results for the N budget at spruce sites.

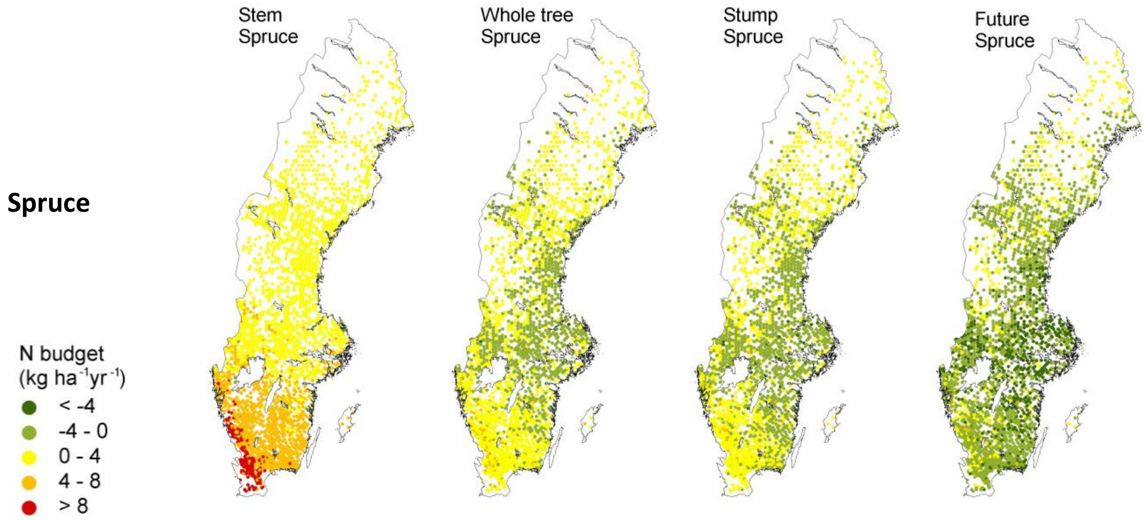

Figure 2. Nutrient budgets for nitrogen (N) in spruce sites at different forestry scenarios according to Table 3 (Hellsten et al., 2010).

Table 3. Four different forestry intensity scenarios were assessed in Hellsten et al. (2010).

Forestry intensity scenario	Description	Detailed description
1. Stem	Conventional stem harvesting	Harvesting 100 % of the stems.
2. Whole-tree	Harvesting of stem, branches and needles.	Harvesting 100 % of the stems and 60 % of the branches and tops. Branches are assumed to remain at the site for 6 months and 75 % of the needles from the branches are assumed to be included in the harvesting. The weight and nutrient concentration in these needles have been modified based on data from the decomposition of green needles (see Table 9).
3. Stump	Harvesting of stems, branches, needles and stumps.	In addition to the whole tree harvesting above, also 60 % of the stumps are assumed to be harvested.
4. Future	Harvesting of stems, and a more intense harvesting of branches, needles and stumps.	Harvesting of 100 % of the stems, 80 % of the branches, and 100 % of the needles from these branches, and 80 % of the stumps. Branches and needles are assumed to be harvested instantly.

A fertilizing module has been added to the model, allowing to calculate nitrogen budgets at different fertilising scenarios (Zetterberg et al., 2006). The effect of fertilisation on the N budget was considered by incorporating an additional input parameter (N-fertilising) to the budget calculation, and the uptake of nitrogen in biomass was modified and adapted to the increased growth due to the fertilisation effect. In a more recent version of the model (Hellsten et al., 2010), also the leaching effect has been incorporated in the model. However, only the direct effect (at fertilising) and not the indirect effect of increased leaching at harvesting was included. Hellsten et al. (2010) concluded that it is difficult to estimate this effect based on available data. However, currently relevant empirical studies are runnig (E. Ring, Skogforsk, personal communication), which would be useful, and hence the increased leaching effect at harvesting due to fertilisation may be included in the nutrient budget calculation in the future.

The results from the nutrient budget calculation at site level (10 973 sites) were also scaled up to catchment areas to improve the basis for compensation recommendations and to adjust to the Water Framework Directive, see example in Figure 3. The maps represent the median value for the nutrient budget for those spruce sites located within the catchment area. Some of the smaller catchment areas along the coast have insufficient data (< 3 sites). This upscaling regards natural water borders rather than administrative borders to facilitate work on water related environmental effects. Furthermore, the results were differentiated regarding site index and tree species, to provide an indication of how the site quality affects the nutrient budget. The methodology is further described in Hellsten et al. (2010). The idea is to develop this approach further to be able to identify areas where the demand for measures is greatest, based on geographical location, tree species and site characteristics.

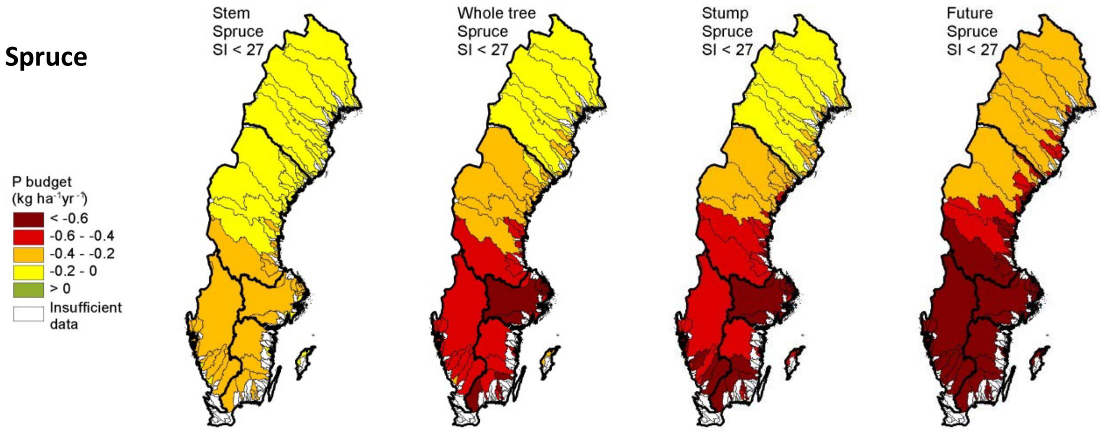

Figure 3. Phosphorous (P) budgets (median value for each catchment area) for spruce, site index < 27 (Hellsten et al., 2010).

In addition to the base cation nutrient budget calculation, a simplified mass balance calculation was carried out, only including weathering and harvesting, therefore concentrating on foresty's contribution to nutrient losses (Figure 4). This simplified mass balance is associated with smaller losses than the complete mass balance, as the leaching for base cations is significant.

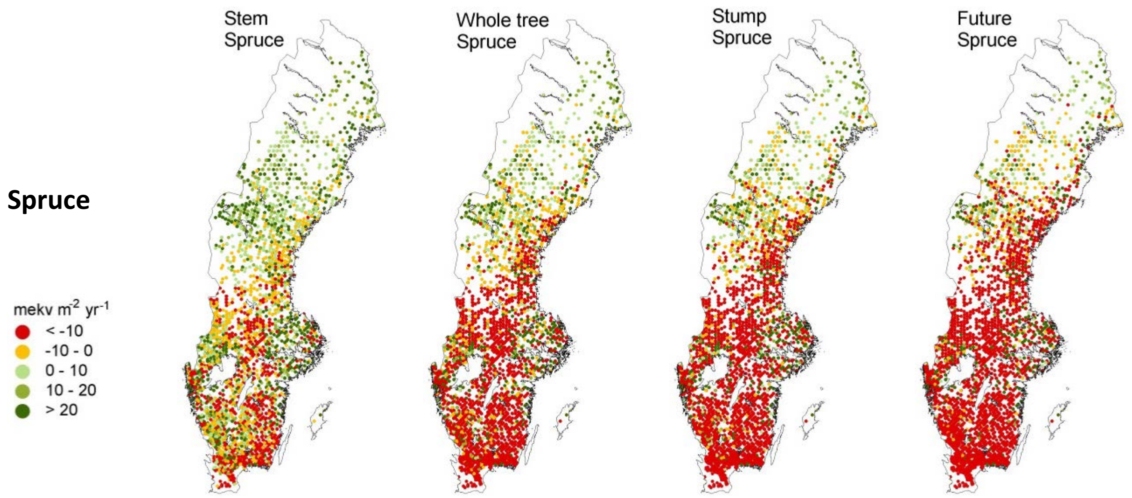

Figure 4. Weathering minus harvesting for base cations (Ca, Mg, Na, K). A negative value indicates that the removal of base cations at harvest exceeds the input from weathering (Hellsten et al., 2010).

Net losses of base cations are not necessarily a problem in the short run, providing that the pool of nutrients is large. Hellsten et al. (2010) therefore compared net losses of base cations (weathering minus harvesting) with the soil pool of exchangable base cations to get an indication of the rate of depletion. The comparison is highly hypothetical, since it assumes a linear depletion with the calculated rate, which is not expected. However, the calculation provides an indication of the size of the rate as compared with the pool. This comparison has been done at national level based on the simplifid mass balance (weathering minus harvesting) (Hellsten et al., 2010), see Figure 5.

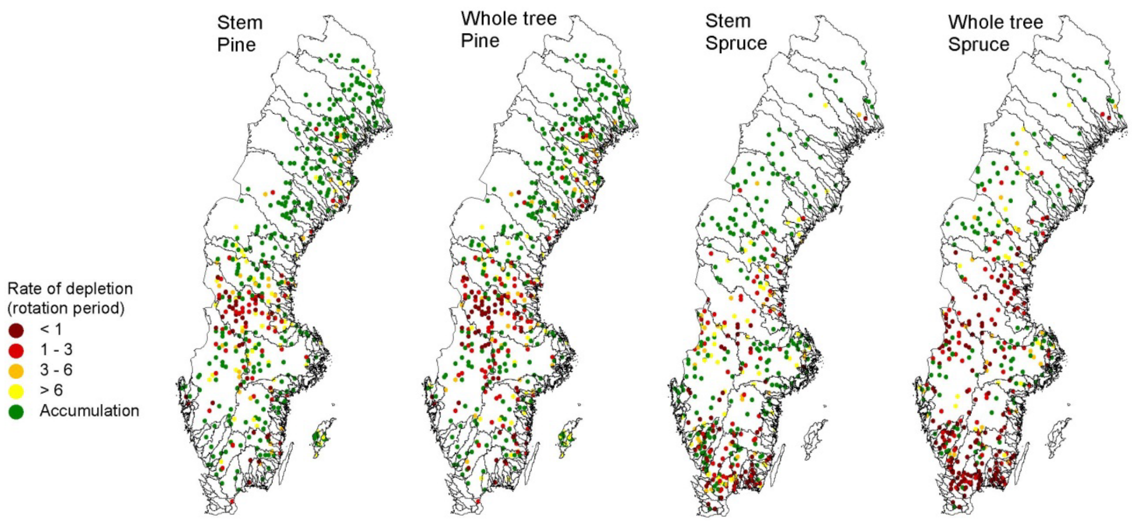

Figure 5. Hypothetical rate of depletion of the pool pf base cations (Ca, Mg, Na, K) in the soil, based on the rotation period (Hellsten et al., 2010).

Table 4 summarises the contribution from the input parameters to the overall balance (at stem harvesting as calculated by Hellsten et al. (2010). The results indicate that all parameters contribute substantially to the mass balance, which means that it is as important to work on minimizing uncertainties for all of them. For Mg and Ca leaching is the major parameter whereas for the P balance harvesting contributes the most (>50 % of the P mass balance). For N deposition is highly dominant (>50 % of the N mass balance), and therefore has the greatest impact on the overall uncertainty of the calculation.

Table 4. Contribution from the input parameters to the overall balance (at stem harvesting) for K, Ca, Mg, P and N based on Hellsten et al. (2010).

		Deposition	**Harvest (stem)**	**Weathering**	**Leaching**	**N fixation**
K	pine	19%	20%	32%	28%	
	spruce	15%	29%	37%	19%	
Ca	pine	11%	14%	36%	38%	
	spruce	13%	29%	21%	36%	
Mg	pine	20%	8%	13%	59%	
	spruce	20%	10%	17%	53%	
P	pine	17%	51%	21%	11%	
	spruce	10%	66%	17%	6%	
N	pine	55%	15%		15%	15%
	spruce	54%	22%		13%	11%

5.1.3 Main conclusions from nutrient budget calculations in Sweden

The main conclusions from Akselsson (2005); Akselsson & Westling (2005); Zetterberg et al. (2006); Akselsson et al. (2007a; 2007b; 2008); Hellsten et al. (2008; 2010) are summarized below.

General

- Whole-tree harvesting has a high impact on the nutrient budget, especially for N, Ca and K. This is because branches and needles removed at whole tree harvesting contain high concentrations of these nutrients.
- Nutrient losses at whole tree harvesting are bigger in spruce forests compared with pine forests.
- Stump harvesting does not affect the balance at the same level as whole tree harvesting, but the impact is still evident. Although the biomass removed at stump harvesting is large (> 30 % of the stem volume), nutrient concentrations in stumps are smaller compared with nutrient concentrations in branches and needles.
- Nutrient losses are greatest in spruce forests with a high site index. This indicates that it is valuable to include not only location, but also tree species and site index, when assessing nutrient losses and potential compensation at regional level.

Nitrogen

- Nutrient budgets for N are significantly affected by deposition (the most significant parameter in the balance).
- For nitrogen, nutrient balances vary within the country, mainly as a consequence of the nitrogen deposition pattern.

- In spruce forests, biomass harvesting affects the nutrient budget significantly. Nutrient budget calculations indicate that nitrogen accumulates in the whole country of Sweden at conventional stem harvesting, with the highest accumulation in the southwest. At increased biomass removal (whole tree harvesting and stump harvesting) there are net losses in large parts of the country. This indicates that increased biomass harvesting is a nitrogen relief in nitrogen saturated areas, but can lead to nitrogen depletion in areas with low nitrogen status.

Phosphorous

- Nutrient budgets for P are significantly affected by harvesting (the most significant parameter in the balance).
- Losses of phosphorous are greatest in the south of Sweden, due to high harvest losses. These areas coincide with the areas with the greatest nitrogen accumulation. This indicates a risk of phosphorous shortage in areas with high nitrogen status. This may potentially cause leaching of nitrogen (if phosphorous becomes limiting for growth rather than nitrogen).

Base cations

- Leaching is a significant parameter in base cation budget calculations, particularly for Ca and Mg. Also weathering is an important parameter, particularly for K.
- Losses of Ca and Mg occur in the whole country (indifferent of forestry scenario). The losses were greater in spruce forests compared with pine. Leaching is the dominating term.
- The nutrient balance for K is around zero in pine forests but generally negative in spruce forests, particularly in those scenarios where more forestry biomass was harvested.
- When comparing nutrient budgets with soil pools (of base cations), the results indicate that the net losses of base cations are large compared with the pools. Assuming a linear depletion, the soil pools would be depleted within a few rotation periods, particularly in spruce forests with a high site index.

5.2 Nutrient budget calculations in Finland

5.2.1 Site level

Raulund-Rasmussen et al. (2008) assessed nutrient budget calculations (N, P, K, Na & Ca) at two sites in Finland, Ilomantsi and Rääkkylä, both located in eastern Finland, Table 5. Two harvesting scenarios were assessed, conventional stem harvesting and whole-tree harvesting.

Table 5. Nutrient balance accounts (kg $ha^{-1}yr^{-1}$) for Ilomantsi & Rääkkylä (Finland), derived from Raulund Rasmussen et al. (2008). N.E. = not estimated.

Ilomantsi	N	P	K	Mg	Ca
Weathering rate [1]				0.4	2.0
Deposition [2]	3.1	0.002	1.4	0.2	1.1
Leaching [2]	0.2	Low	3.4	2.1	0.7
Harvest (stem) [3]	0.7	0.07	0.4	0.2	0.9
Harvest (whole-tree) [3]	2.3	0.2	1.1	0.4	1.4
Balance (stem)	**2.2**	**-0.07**	**-2.4**	**-1.7**	**1.5**
Balance (whole tree)	**0.6**	**-0.2**	**-3.1**	**-1.9**	**1.0**

Rääkkylä					
Weathering rate					
Deposition [4)]	4.0	0.1	1.0	0.1	0.9
Leaching [5)]	1.7	0.1	1.0	0.4	1.0
Harvest (stem) [6)]	0.6	0.04	0.3	0.1	0.7
Harvest (whole-tree) [6)]	2.0	0.2	0.7	0.3	1.3
Balance (stem)	**1.7**	**-0.04**	**-0.3**	**-0.4**	**-0.8**
Balance (whole tree)	**0.3**	**-0.2**	**-0.7**	**-0.6**	**-1.4**

1. Starr et al. (1998)
2. Helmisaari (1995)
3. Based on one thinning (1/3 of the biomass) at the age of 35 years and final clear-cutting at the age of 100 years.
4. Piirainen (2002)
5. Lehmusvuori (1980)
6. Estimated from Kaunisto and Paavilainen (1988) & Finér (1992)

Both Rääkkylä and Ilomantsi are nutrient poor sites which are reflected in a much lower removal of biomass (whole tree harvesting) compared with the Swedish site Lammhult (Table 2). The Finnish sites have a production class of 4 m^3 ha^{-1} yr^{-1} compared with 10 m^3 ha^{-1} yr^{-1} at Lammhult in Sweden.

Rääkkylä is a ditched, ombrotrophic, nutrient-poor peatland site, with a 2 m deep peat layer, and 85-year-old Scots pine growing on the site (Finér 1992). On such sites, the nutrient balance of most elements is negative even after conventional (only stems) harvesting. Compared with the soil stores, whole-tree harvesting during one rotation (one thinning + final harvesting) removes a large part of soil potassium. Because of the thick peat layer, there are no inputs through weathering.

Both Rääkkylä and Ilomantsi, a nutrient-poor upland Scots pine site on mineral soil, showed negative nutrient budgets for P, K and Mg, even at stem harvesting. In Rääkkylä also Ca showed a negative balance, while the Ca balance in Ilomantsi was positive. The input-output balance for the two Scots pine stands during a rotation in eastern Finland therefore resulted in a small deficit of P and larger deficits of K and Mg in both conventional harvesting and whole-tree harvesting. K and Mg were especially lost by leaching from the rooting layer. Weathering can only partly compensate the deficits (Raulund-Rasmussen et al., 2008).

The nitrogen balance was positive at both Ilomantsi and Rääkkylä, even at whole tree harvesting, i.e. the nitrogen deposition compensated for both leaching and biomass removal at harvesting (nitrogen fixation was not included in the balance). Although the nitrogen budget was positive, Raulund-Rasmussen et al. (2008) still recommended compensation with nitrogen, as the sites are located in an area where tree growth in general is limited by nitrogen deficiency. Furthermore, the nitrogen content in the soil was low at both sites. Raulund-Rasmussen et al. (2008) concluded that both sites are sensitive to whole-tree harvesting and that compensation with nitrogen and other elements (e.g. with ash fertilisation) is recommended.

Currently (2010) nutrient budget calculations are calculated at site level at 14 sites in Finland within the project *Economic-ecological optimization of timber and bioenergy production and sequestration of carbon in Norway spruce stands.*

5.2.2 Regional level

In Finland, nutrient balances at regional level have been calculated for base cations. Joki-Heiskala et al. (2003) calculated both a simplified mass balance (weathering minus harvest losses) and an acidity balance for Ca, Mg and K at national level in Finland. Two forestry scenarios were assessed, conventional stem harvesting and whole tree harvesting. Stem harvesting included stem and bark, while whole tree harvesting included stem (including bark), branches and needles. The calculation was carried out at 2 278 grids with a spatial resolution of 0.125° longitude x 0.25° latitude (approximately 14 x 14 km in southern Finland at 60°N).

Figure 6 shows the results of the simplified mass balance. For each grid, long-term average base cation weathering was compared with the average nutrient uptake by forest growth. Method and input data for the calculation of the balance between weathering rate and net uptake values are based on Finnish critical load calculations (Johansson, 1999). The methodology is further described in Section 6.3 (uptake in biomass) & 6.4 (weathering).

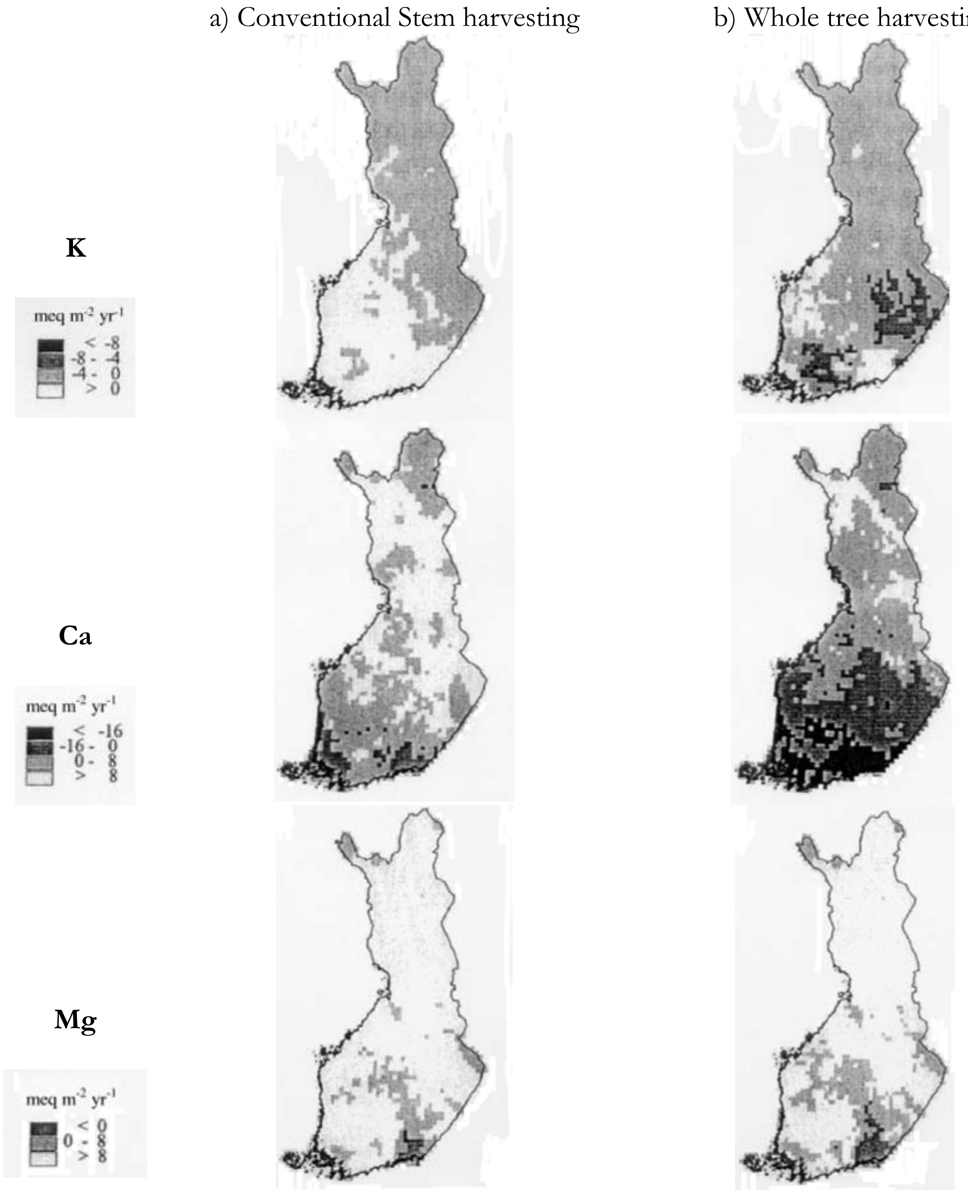

Figure 6. Base cation balances (chemical weathering minus growth uptake) in Finland for K, Ca and Mg at a) stem harvesting, and b) whole tree harvesting. From Joki-Heiskala et al. (2003).

Joki-Heiskala et al. (2003) also calculated a simplified acidity balance, i.e. weathering plus deposition minus deposition of S minus harvest (Bc_{dep} + Bc_{wr} - Bc_u – S_{dep}), for each grid in Finland, Figure 7. In this acidity balance, the influence of N on the acidification of soils was not included.

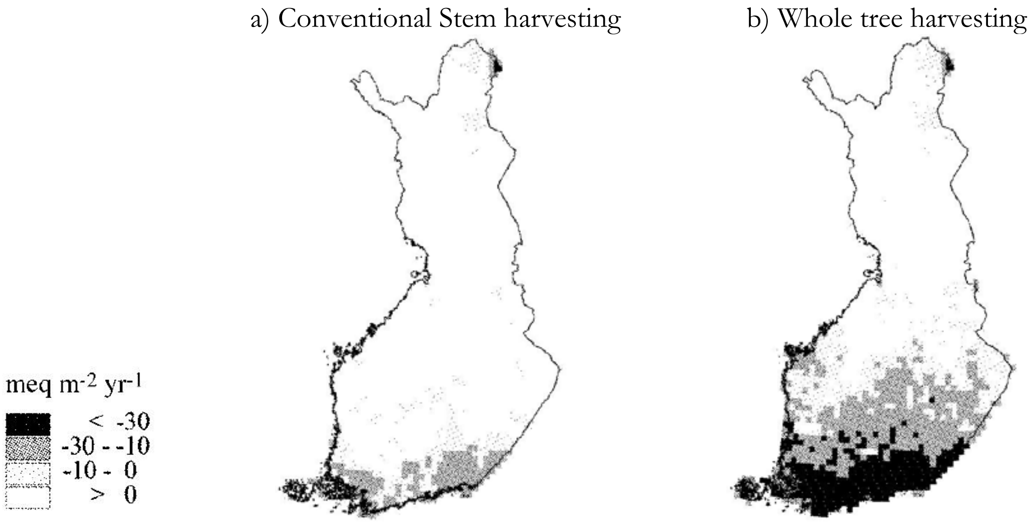

Figure 7. Base cations balances in Finland (weathering plus deposition minus deposition of S minus harvest) at two different forestry scenarios, a) stem harvesting, and b) whole tree harvesting.

Nutrient budget calculations can be applied to calculate the need for ash. For instance, Joki-Heiskala et al. (2003) applied the results from the base cation balance in Finland to calculate the need for ash. This estimation was based on the maximum depletion of base cations during the rotation period (70 years) and ash content from Anttila (1998). Joki-Heiskala et al. (2003) estimated that at least 400 kg ha^{-1} ash would be needed at 30 % of the grids, and more that 1000 kg ha^{-1} is needed in the most sensitive areas (7-10 %) if whole tree harvest would be practiced. The calculation indicated that the most sensitive grids would require 4000-5000 kg ha^{-1} to compensate for the losses of base cations at whole tree harvesting. However, ash application may result in increased leaching of base cations (Piirainen, 2000; Tulonen et al., 2000) and therefore the amount of ash needed for compensation may even be greater. However, since ash also contains heavy metals and especially cadmium, the application of ash is restricted by fertilisation legislation. In Finland, cadmium inputs into a forest cannot exceed 60 g ha^{-1} within a period of 40 years.

5.2.3 Main conclusions from nutrient budget calculations in Finland

- At stem harvesting, the simplified mass balance was negative in the north of Finland for K and in the south for Ca. For Mg the balance was mainly positive, however negative in some parts of southern Finland.
- At increased biomass harvesting, i.e. whole tree harvesting, the losses were even greater. When changing from stem harvesting to whole tree harvesting, the area extent with a negative nutrient balance would double.

- The simplified nutrient mass balance for K showed a negative balance in almost all of Finland at whole tree harvesting, which indicates that weathering does not compensate for the losses due to harvesting.
- Weathering can compensate for the harvesting losses of Ca and Mg at stem harvesting, except for the most sensitive areas in southeastern and southwestern parts of Finland. At whole tree harvesting, the harvest losses would exceed the input from weathering in south and central Finland.
- Ash recycling is a possible method to mitigate these problems, and would be most useful in mineral soils in southern and central parts of Finland.
- The acidity balance indicated a clear south-north gradient in depletion of base cations, which coincided with gradients in forest growth and sulphur deposition.

6 Nutrient budget parameters

Input data applied in the nutrient budget calculations are based on experimental studies and to some extent modelling results. In the following sub chapters, each of the individual parameters in the nutrient budget (deposition, leaching, harvesting, weathering and nitrogen fixation) is presented and discussed regarding input data and methodology in the nutrient balance calculation. Furthermore, uncertainties are discussed.

6.1 Deposition

Deposition data for nutrient budget calculations at site level mainly derive from deposition measurements at the site (or from a nearby site). Hence, these input data are representative for that particular site. However, measurements in forests cannot be used as is, to represent total deposition in forest, due to internal circulation in the canopy. For regional nutrient budget calculations it is not possible to derive deposition data at site level, hence deposition data at regional scale are associated with more uncertainties.

Sweden

Deposition input to the national mass balance calculation for N in Sweden (Hellsten et al., 2010) is based on modelled total deposition to coniferous forests from the Swedish MATCH model (20 x 20 km resolution), (Langner et al., 1996). Nitrogen deposition has been identified as the major parameter (50 % of the nitrogen mass balance), and therefore has the greatest impact on the overall uncertainty of the calculation, see Table 4. Modelled deposition values are associated with uncertainties, due to uncertainties in the the modelling approach and input data (meteorological data, emission data and atmospheric chemistry data). Dry deposition is especially difficult, since it is difficult to measure due to internal circulation in the tree. Furthermore, the organic nitrogen deposition has not been included in the mass balance calculation for nitrogen.

Base cation deposition in the national mass balance of Hellsten et al. (2010) is based on a combination of modelled and measured data, i.e. a previous modelled deposition pattern from 1998 was scaled to the deposition level of more recent measurements (Hellsten & Westling, 2006). Table 4 indicates that base cation deposition contributes to 11-20 % of the base cation mass balance (for K, Ca & Mg), and therefore has a smaller impact on the overall uncertainty of the calculation compared with weathering and leaching.

Hellsten et al. (2010) estimated a P deposition value of 0.055-0.065 kg P $ha^{-1}yr^{-1}$ based on 21 monitoring sites in Sweden. This P-deposition value is smaller compared with 0.27 kg $ha^{-1}yr^{-1}$ applied in the P balance by Nykvist (1977). The estimated P deposition was also significantly smaller than the P deposition (0.20 kg $ha^{-1}yr^{-1}$) applied in more recent previous studies (e.g. Akselsson, 2008). The new P deposition estimate is expected to be associated with smaller uncertainties compared with the previous estimates, as the new value is based on many measurements from Sweden (21 sites). Furthermore, an adequate data analysis method has been applied, which is important for P deposition as it easily gets contaminated by insects or birds. However, the available data only supports an average value for Sweden, and the regional and local variation can therefore not be covered.

Finland

In Finland the deposition data of base cations (Ca, Mg and K) was estimated from 38 monitoring sites with monthly bulk deposition during the years 1993-1995 (Järvinen and Vänni, 1990). The deposition value for each grid cell in the nutrient budget calculation was then estimated by applying data from the three nearest stations weighted with the inverse of the square of the distance. The dry deposition of base cations was not considered, and the input to the Finnish acidity balance is therefore underestimated.

The deposition values for base cations applied in Hellsten et al. (2010) suggest that the dry deposition of base cations constitute about 32 % (Ca), 48 % (Mg) and 26 % (K) of the total deposition. This indicates that the input fluxes from deposition in the Finnish nutrient budget calculations may have been underestimated by a factor of nearly 2.

6.2 Leaching

Leaching of nutrients depend on both water fluxes and nutrient concentrations in the seepage water. Forest biomass harvesting affects both the magnitude and the chemical composition of the seepage water. Growing, developing forest stands tend to retain added nutrients, especially N, P and K, hence reducing leaching losses. Leaching depends on nutrient status of the soil, e.g. leaching of inorganic nitrogen is not common in non-saturated nitrogen forests (Mustajärvi et al., 2008), and leaching of inorganic nitrogen is therefore generally small. Leaching of base cations is affected by soil acidity, weathering rates, deposition and uptake by trees.

Leaching estimates are associated with large uncertainties. The effect on the total uncertainties of the mass balance calculation for N and P is generally small, as the leaching term is in most cases small for N and P compared with other parameters in the calculation. Table 4 indicates that nitrogen leaching, together with nitrogen fixation, are the smallest parameters (11-15 % of the N mass balance), and therefore has the smallest impact on the overall uncertainty of the calculation. For P, leaching has an even smaller impact (6-11 % of the P mass balance). In the southwestern most part in Sweden there are, however, several examples of sites with elevated N leaching, and for these areas N leaching contributes substantially to the mass balance.

The effect of the uncertainties in leaching is greater for base cations. Table 4 indicates that leaching is the major parameter (36-59 % of the mass balance) for Ca and Mg. For K, it is the second most important input (19-28 %) of the balance. Leaching therefore has a significant impact on the overall uncertainty of the calculation for base cations. Leaching of base cations is associated with uncertainties, as leaching depends on the flow of anions and therefore is strongly affected by acidification. The concentration in the soil water therefore depends on the level of acidification. This is one of the reasons why a simplified mass balance is sometimes applied (only weathering and harvesting).

Sweden

In the national nutrient budget calculation in Sweden (Hellsten et al. 2010), nitrogen leaching (including organic N) from growing forests, is based on the average value for N concentration in runoff water (0.47 mg l^{-1}), based on N concentrations in surface waters from 23 catchments, representing south Sweden (Akselsson & Westling, 2005). Organic nitrogen normally represents the majority of the nitrogen leaching. Nitrogen leaching from clear-cuts in the south of Sweden was calculated based on an empirical correlation between nitrogen deposition and nitrogen concentration in soil water from clear-cuts:

$0.4 + (0.39 \times N_{dep} - 3.04)$ (minimum value: 0.95 mg l^{-1} (Akselsson et al., 2004; Akselsson & Westling, 2005).

For central and northern Sweden, nitrogen leaching was calculated as (Löfgren & Brandt, 2005):

$1.265 - 0.362 \log_{10}(\text{altitud[m]})$

For P, constant leaching fluxes were used (0.04 kg $ha^{-1}y^{-1}$), based on the average value from measurements in 25 streams in forest areas in Sweden (Uggla and Westling, 2003). This leaching flux is smaller compared with 0.06 kg $ha^{-1}yr^{-1}$ applied in Nykvist (1977).

In Sweden, leaching fluxes of base cations were based on soil water measurements from the Swedish Throughfall Monitoring Network (Pihl Karlsson et al., 2011, in prep.) at approximately 100 sites. Leaching fluxes applied in Hellsten et al. (2010) were interpolated from these 100 sites, see Table 6. Base cations in seepage water vary significantly at a local and regional level, and the soil water data are relatively few to scale up to represent the concentration at national level. Data on runoff derive from SMHI. These data may be overestimated for forest soil, as the data applied represent all landuse classes.

Table 6. Leaching fluxes (kg ha^{-1} yr^{-1}) applied in Hellsten et al. (2010).

	Leaching (average)	Leaching (median)
N*	1.5	1.4
P	0.04	0.04
K	1.3	1.2
Ca	4.2	4.0
Mg	2.3	2.0

*Inorganic and organic N

Finland

Leaching was not included in the simplified mass balance of Joki-Heiskala et al. (2003). Mustajärvi et al. (2008) reported annual total nitrogen leaching losses from the rooting layer in 8 Scots pine and 8 Norway spruce dominated stands to vary between 0.7 and 1.4 kg ha^{-1}, out of which a large part, between 0.6 and 1.1 kg ha^{-1}, was organic nitrogen. These values are smaller compared with the leaching fluxes applied in Hellsten et al. (2010), see Table 9. However, nitrogen leaching in Sweden is expected to be larger compared with Finnish conditions, as the nitrogen deposition in Sweden, particularly in the south west of Sweden, is larger. Leaching may temporarily increase after disturbances, such as clear-cutting. However, Piirainen et al. (2004) observed only slightly increased fluxes of P and base cations from below the B horizon after clear-cutting, despite increased fluxes from the 0 horizon.

6.3 Nutrient removal through biomass harvesting

At biomass harvesting, nutrients in the harvested biomass are removed from the forest system. Although these nutrients are removed in a short time span, it is relevant to consider the average annual nutrient removal in the whole rotation, to be able to compare with other fluxes that are more evenly distributed between years.

In the nutrient budget calculations in both Sweden and Finland, nutrient losses through harvesting were estimated by multiplying the average annual growth by the nutrient concentration in stems, branches, needles or stumps.

Table 4 indicates that the harvesting parameter is the most important parameter of the P mass balance. For N, harvesting is the second most important parameter. For Ca and K, harvesting contributes by 20-40% to the overall mass balance, whereas for Mg, harvesting only contributes about 10 % (Table 4).

Uncertainties in harvest losses are mainly associated with the growth rate estimates and the amount of branches, needles and stumps harvested, and uncertainties in nutrient concentrations in different tree parts. Nutrient concentrations in tree compartments can vary depending on site characteristics and edaphic factors, but in the calculation, a constant concentration value is applied for each tree species.

Hellsten et al. (2008) showed that uncertainties in nutrient concentrations in needles are a significant source of uncertainty for nitrogen balances. These uncertainties have the highest impact if the nutrient balance is around zero, as the result can be either negative or positive depending on the nutrient concentration applied. Therefore net balances around zero should be interpreted with caution. Furthermore, the sensitivity analysis showed that uncertainties in nutrient concentrations in needles for Ca and K are significant. However in most cases, the net result for the Swedish mass balance is negative no matter which concentrations are applied.

Sweden

In the nutrient budget calculation by Hellsten et al. (2010), average annual growth was estimated based on data from the National Forest Inventory in Sweden by reducing the site productivity by 20 %, then recalculating volume growth to mass growth using the densities 430 kg m^{-3} (spruce) and 490 kg m^{-3} (pine), derived from Lundmark (1988), see Table 7. Amount of branches and needles was calculated based on empirical correlations (Marklund, 1988). Annual stem growth applied in Hellsten et al (2010), was 3.5 m^3 ha^{-1} yr^{-1} (pine), 6.3 m^3 ha^{-1} yr^{-1} (spruce) and 4.0 m^3 ha^{-1} yr^{-1} (birch).

Table 7. Stem biomass density (kg m^{-3}) and fraction of stem over bark biomass for live branches and needles applied in Hellsten et al. (2010).

	Sweden density	f_{branch}	$f_{needles}$	f_{stumps}
Birch	610	-	-	-
Spruce	430	21.9	11.9	38
Pine	490	12.9	3.6	33

Nutrient concentrations in different tree parts applied in Hellsten et al. (2010) are based on data compiled by Jacobson and Mattson (1998), Egnell et al. (1998) and Hellsten et al. (2009 & in prep.), see Table 8. Different needle biomass and nutrient concentrations in needles were applied depending on the time the needles were left at site after harvesting, Table 9.

Table 8. Nutrient concentrations in biomass (mg/g) in Sweden, based on (Jacobson & Mattson, 1998; Egnell et al. 1998), nutrient concentrations in needles, following 6 months of decomposing (calculated by adapting nutrient concentrations in needles before decomposition with data on the rate of decomposition, from Berg, unpublished), and nutrient concentrations in stumps (based on Hellsten et al., 2009 & in prep.).

	Spruce					**Pine**				
	stem & bark	**branches**	**needles** 0 months	**needles** 6 months	**bark**	**stem & bark**	**branches**	**needles** 0 months	**needles** 6 months	**stumps**
N	1,1	5,3	11,3	15,8	1,1	0,89	3,4	12,4	16,0	0,93
P	0,14	0,61	1,3	1,03	0,13	0,1	0,35	1,3	1,0	0,11
K	0,73	2,4	4,7	1,1	0,88	0,49	1,5	5,1	0,93	0,78
Ca	1,3	3,7	6	7,9	1,5	0,86	2,3	3,3	3,6	0,6
Mg	0,18	0,62	1,0	0,55	0,19	0,16	0,39	0,8	0,6	0,19
Na	0,075	0,1	0,13	0,13*	0,002	0,075	0,1	0,13	0,13*	0,002

*Data missing, hence nutrient concentrations for green needles were applied.

Table 9. Remaining needle biomass, following 6 months of decomposition in Jädraås (pine needles) and Stråsan (spruce needles) (Berg, unpublished).

Type of needle	Proportion after 6 months
Pine needles	79%
Spruce needles	72%

Finland

In Finland, the average annual forest growth (m^3 ha^{-1} yr^{-1}) was calculated for spruce, pine and deciduous forest sites based on climatological effect on growth (effective temperature sum, ETS) applying the following equations (Joki-Heiskala et al., 2003):

$$g = 7.47/(1 + \exp(-0.0068 \times ETS + 7.48)) \quad \text{(birch)}$$
$$g = 10.3/(1 + \exp(-0.00584 \times ETS + 7.44)) \quad \text{(spruce)}$$
$$g = 4.41/(1 + \exp(-0.00670 \times ETS + 6.94)) \quad \text{(pine}$$

The annual average volume growth was converted to mass growth, applying stem biomass density values from Hakkila (1979). These density values are smaller compared with the density values applied in Sweden, Table 7 and Table 10. Estimated average biomass from branches and needles in Joki-Heiskala et al. (2003) were estimated as fractions of stem over bark growth based on Wihersaari (1996), see Table 7. These fractions were much higher in Finland compared with Sweden, particularly for spruce, where branches are assumed to constitute 53 % of the stem biomass, compared with only 22 % in Sweden.

Table 10. Stem biomass density (kg m^{-3}) and fraction of stem over bark biomass for live branches and needles applied in Joki-Heiskala et al. (2003).

	Finland density	f_{branch}	$f_{needles}$
Birch	483	16	-
Spruce	380	53	20
Pine	403	17	5

Comparison between Sweden and Finland

In Finland, annual stem growth was 1.8 (pine), 2.8 (spruce), and 2.3 m^3 ha^{-1} yr^{-1} (birch). This is smaller compared with annual stem growth in Sweden, 3.5 (pine), 6.3 (spruce) and 4.0 (birch), as calculated by Hellsten et al. (2010). Growth is hence about double the size in Hellsten et al. (2010) compared with Joki-Heiskala et al. (2003). It is expected that Swedish forest should have a higher growth rate due to more productive forests in the south of Sweden (warmer climate and higher nitrogen deposition). Both in Sweden and Finland, climatological effects were taken into account when calculating growth in different ways. In Finland, effective temperature sums were applied, and in Sweden, growth was calculated based on site productivity (which is dependent on climate), which was scaled down by 20 % to better reflect annual average growth. In Joki-Heiskala et al. (2003), nutrient concentrations in biomass in different tree parts derive from Olsson et al. (1993).

Uptake by stem (Ca, Mg & K) is generally larger in Sweden compared with Finland, Table 11. It is difficult to compare the values as the Finnish values contain mixed spruce and pine, and hence depend on the composition of spruce and pine. Table 11 indicates that uptake in spruce is about double the size of uptake in pine. Whole tree harvesting in Finland results in 2-3 times more nutrients being removed from the forestry system compared with stem harvesting. This is significantly more compared with Sweden, and is due to the fact that the amount of needles and branches removed at whole tree harvesting is greater in Finland compared with Sweden. In Finland, the estimated amount of branches and needles on each tree is greater than in Sweden, and the whole tree harvesting scenario in Finland constitute 100 % of the branches and needles, compared with 60 % of the branches and 75 % of the needles on these branches, to reflect current forestry practice in Sweden. According to current forestry practice in Finland, some of the branches and needles are left at site at whole tree harvesting, and consequently, the whole tree harvesting scenario in Finland likely overestimates the nutrients removed from the system.

Table 11. Estimated net uptake of base cations (harvesting), meq $m^{-2}yr^{-1}$, in a) Sweden based on Hellsten et al. (2010), and in b) Finland based on Joki-Heiskala et al. (2003).

	a) Sweden		**b) Finland**	
	Stem harvesting	**Whole tree harvesting[1)]**	**Stem harvesting**	**Whole tree harvesting[2)]**
Ca	7.3 (pine) 17.5 (spruce)	9.3 (pine) 28.2 (spruce)	6	13
Mg	2.3 (pine) 4.0 (spruce)	2.8 (pine) 6.3 (spruce)	1	3
K	2.1 (pine) 5.0 (spruce)	2.7 (pine) 7.5 (spruce)	1	3
N	10.9 (pine) 21.2 (spruce)	16.6 (pine) 46.4 (spruce)		
P	1.7 (pine) 3.7 (spruce)	2.3 (pine) 6.8 (spruce)		

1) 60 % of branches and 75 % of needles on these branches
2) 100 % of branches and needles

6.4 Weathering

Elements are released in the soil by weathering of soil minerals. The weathering rate is affected by soil temperature, the mineralogy of the parent materials, soil texture and soil pH. Biological activity affects weathering rates through removal of nutrients from the soil solution and generating acidity. Root depth is important for how much of the weathered nutrients the roots can reach.

Weathering is an important parameter in the mass balance of base cations. In the Swedish national mass balance calculation of Hellsten et al. (2010), weathering is the major parameter (about 35 %) of the mass balance for K and therefore has potentially great impact on the overall uncertainty of the calculation (Table 4). For Ca, weathering is the second most important factor, after leaching. Also for P, weathering is the second most important factor, with nutrient removal at harvesting being the most important factor.

The estimation of weathering rates may be associated with large uncertainties. Starr et al. (1998) compared the weathering results (Ca + Mg) of four different methods in the Integrated Monitoring catchment of Hietajärvi in Finland: i) the zirconium method (Johansson and Tarvainen, 1997), ii) catchment input and output budget (Starr et al., 1998), iii) weathering rates from the Swedish PROFILE model (Sverdrup and Warfvinge, 1993; 1995) and iv) temperature sum regression method (Olsson & Melkerud, 1991). The zirconium method provided the highest weathering rate (28 meq m^{-2} yr^{-1}), compared with the catchment budget (25 meq m^{-2} yr^{-1}), the regression method (23 meq m^{-2} yr^{-1}) and the PROFILE estimate (13 meq m^{-2} yr^{-1}). Joki-Heiskala et al. (2003) suggest that the zirconium method may overestimate the weathering rates, as they are based on element content in parent till, and that soil stone content is not considered. A thorough comparison requires a comparison between concepts and assumptions, e.g. regarding time scales and weathering depth. This type of comparison is currently in progress for weathering estimations from PROFILE and the zirconium method, based on estimations on 17 well investigated sites in Sweden (Stendahl et al., manuscript).

Sweden

In the regional nutrient budget of Hellsten et al. (2010), nutrient inputs from weathering, were modelled using the model PROFILE (Sverdrup and Warfvinge, 1993; 1995). PROFILE is a steady state model that includes process oriented descriptions of solution equilibrium reactions, chemical weathering of minerals, leaching and accumulation of dissolved chemical components. Weathering rates were calculated for the root zone. Mineralogy was calculated based on total elemental analyses from soil samples from 25 000 sites across Sweden (Akselsson et al., 2003). The 17333 National Forest Inventory sites were given mineralogy data from the closest mineralogy site.

Uncertainties associated with the weathering rate are typically more related to the quality of the input data (mineralogy) rather than to the PROFILE model itself. Moreover, in assessments of the amount of weathering products available for trees, the depth of the root zone leads to substantial uncertainties. Data on the specific area of the soil are usually burdened with high uncertainties, which have a big impact on the uncertainties of the modelled weathering rates. There are also uncertainties related to the fact that PROFILE is a steady-state model. For example, soil moisture is important input data, which varies over time, but an average value has to be used as input data to PROFILE.

Table 12. Estimated average values for weathering (kg $ha^{-1}yr^{-1}$) in a) Sweden applied in Hellsten et al. (2010), and in b) Finland, from Joki-Heiskala et al. (2003).

	Sweden(average) Weathering (root zone[1])	Sweden(median) Weathering (root zone[1])	Finland(average) Weathering
Ca	3.3	1.3	2.8
Mg	0.7	0.4	2.0
K	2.2	1.2	0.8
P	0.09	0.06	N.E.

[1] The root zone was defined as the upper 50 cm of the soil (including organic layer), except for P weathering in spruce forests, where a root depth of 40 cm was applied.

Finland

Weathering rates in Finland for Ca, Mg, K (meq m^{-2} yr^{-1}) applied in Joki-Heiskala et al. (2003) were estimated based on a zirconium method applying the following equations (Johansson and Tarvainen, 1997):

$$\max (0; Ca_{wr} = -5.63 + 0.13 \times Ca_{tot} \times ETS)$$
$$\max (0; Mg_{wr} = -8.93 + 0.036 \times Mg_{tot} \times ETS)$$
$$\max (0; K_{wr} = -13.40 + 0.0066 \times K_{tot} \times ETS)$$

The calculation demands the following input: effective temperature sum (ETS), i.e. number of degree days exceeding +5°C, and total element content in the unchanged C-horizon (Olsson et al., 1993). The weathering rate is based on the correlation of the loss of material in topsoil, compared with the resistant zirconium mineral content, temperature and initial elemental content. This correlation was derived from field studies (Olsson and Melkerud, 1991).

For the regional nutrient budget calculation in Finland, weathering rates were calculated at 1057 sites, where the necessary input data applied (geochemical data) was available from the Geological Survey of Finland. Joki-Heiskala et al. (2003) interpolated between the three nearest plots (weighting with the inverse of the square of the distance) to derive a representative weathering rate for each grid in the mass balance calculation. The estimated average values of weathering, 14 meq $m^{-2}yr^{-1}$ (Ca), 16 meq $m^{-2}yr^{-1}$ (Mg) and 2 meq $m^{-2}yr^{-1}$ (K) are shown in Table 12. Averages for Ca-weathering is almost at the same level as in Sweden, however Mg-weathering in Finland is almost three times higher compared with Sweden. For K, the weathering estimate was almost three times higher in Sweden compared with Finland. However, these weathering estimates are based on data from two different regions and are thus only meant to be used for comparing orders of magnitudes.

Joki-Heiskala et al. (2003) suggest that the weathering rates for base cations may be overestimated, as they are based on element content in parent till, and that soil stone content is not considered. Furthermore, the comparison with two other weathering methods (of which PROFILE was one) also indicated that the method applied arrived at the highest weathering rate.

6.5 Nitrogen fixation

Nitrogen can enter the forest system through biological fixation. Alder is a tree species that can fix atmospheric nitrogen via root nodules, in pure stands annually even up to 100-150 kg N ha^{-1} (Rytter et al. 1991). Alders are, however, rare as mixed species in coniferous stands. Lichens, and feather mosses, such as *Phleurozium schreberi*, are also able to fix atmospheric nitrogen, via their symbiosis with cyanobacteria (*Nostoc* sp.) in smaller, but however, significant amounts (DeLuca et al., 2002).

Although uncertainties in nitrogen fixation may be large, the impact on the overall uncertainty may be small. Table 4 indicates that nitrogen fixation was the minor parameter in nutrient budget calculations for spruce. However for pine stands, nitrogen fixation is equally important as weathering and leaching.

Sweden

In Sweden, in the nutrient budget calculations at regional level (Hellsten et al., 2010), nitrogen fixation was set to a constant value of 1.5 kg $ha^{-1}y^{-1}$, based on a study in northern Sweden (DeLuca et al., 2002). Nitrogen fixation is based on a single study and is probably overestimated in the south and central Sweden as studies have shown that nitrogen fixation is reduced at increased N access in the soil. Liengen & Olsen (1997) observed a positive correlation between nitrogen fixing by cyanobacteria and C/N ratios.

Raulund Rasmussen et al. (2008) did not include N-fixation in the nitrogen budget calculation. Nykvist (1977), applied 2.8 kg N $ha^{-1}y^{-1}$ in his nitrogen budgets at spruce sites. This value is based on the average value for Siljansfors from Granhall & Lindberg (1980). Granhall & Lindberg (1980) estimated annual N-fixation to be 0.27 kg N $ha^{-1}yr^{-1}$ (15-20 years old pine site), and 0.31 kg N $ha^{-1}yr^{-1}$ (120 years old pine stand) in Ivantjärnsheden. At Siljanfors (160 years old mixed pine and spruce site), the N-fixation was higher, 3.8 kg N $ha^{-1}yr^{-1}$. These values indicate that N-fixation can vary significantly, and therefore it can be concluded that it is not ideal to base nitrogen fixation on a single study.

Finland

In Finland, nitrogen fixation was not included in the nitrogen nutrient mass balance calculation by Raulund-Rasmussen et al. (2008).

7 Conclusions from nutrient budget calculations in Sweden and Finland

Nutrient budget calculation can be a useful tool to predict nutient sustainability, and to predict which nutrients (and to some extent the amount of nutrients) necessary to add to maintain sustainability (e.g. Sverdrup et al., 2006; Raulund-Rasmussen et al., 2008). Uncertainties in site-lvel calculations are likely to be smaller compared with uncertainties in regional calculations, as site specific data (e.g. measured deposition values at the site) can be applied as input data. However, many of the input data to the nutrient budget at site level still have to be estimated/ modelled, e.g. weathering, leaching, nutrient removal at harvesting and dry deposition. Different methods to estimate these inputs are applied, based on type of data available. For instance, Raulund-Rasmussen et al. (2008) showed nutrient budget calculations from six case studies in the Nordic-Baltic region, however applying different input data depending on data availability at the different sites. Therefore it is difficult to compare results of site specific nutrient budget calculations. Regional budget calculations, applying the same methodology, is however a means to provide the overall picture at regional level.

Despite the application of different inputs to the regional base cation budget calculations in Sweden and Finland, the main conclusions in Sweden (e.g. Olsson et al., 1993, Sverdrup & Rosén, 1998, Hellsten et al., 2010), to a large extent agree with the conclusions from the Finnish study by Joki-Heiskala et al. (2003). Joki-Heiskala et al. (2003) showed that weathering of Ca and Mg can support the nutrient removal at stem harvesting in most of Finland, except in the most sensitive areas in south east, and south west. Whole tree harvesting would expand these areas to south and central Finland for Ca, and southern Finland for Mg. These results agree with Olsson et al. (1993) who concluded that weathering of Mg and Ca can support the nutrient removal at stem harvesting in Sweden. The calculated base cation balances for Sweden, also including deposition and leaching (Hellsten et al., 2010), however, showed that the output exceeds input in most of Sweden for Ca, and Mg, even at conventional stem harvesting. Regarding K weathering, Joki-Heiskala et al. (2003) showed that weathering cannot support the nutrient removal at harvesting, even at stem harvesting, in large areas of Finland, particularly in the north east. Olsson et al. (1993) however, showed that weathering would support nutrient removal of K at stem harvesting, while whole tree harvesting would deplete the K pools, especially in southern Sweden. The calculated K balances for Sweden, also including deposition and leaching (Hellsten et al., 2010) showed that the output exceeds input in most of Sweden, even at conventional stem harvesting. However in the south of Sweden, the outputs did not exceed the inputs for K at pine sites.

Budget calculations for N and P have been calculated at site level, but not yet at regional level in Finland. Therefore it is not possible to compare the general geographical pattern of N or P accumulation or depletion within Sweden and Finland.

This study has shown that the inputs applied in nutrient budget calculations in Sweden and Finland differ, both at site level and at regional level. For instance, deposition values in Sweden (at regional level) are mainly based on modelling results, while deposition values in Finland mainly derive from bulk measurements (hence not including the contribution from dry deposition). Furthermore, the estimation of weathering is different, as weathering values in Finland have been estimated based on a zirconium method, while weathering values in Sweden mainly derive from modelling (PROFILE). Estimating weathering is associated with large uncertainties, but comparing these two methods indicate that PROFILE generally tends to provide smaller weathering rates compared with the zirconium method. Joki-Heiskala et al. (2003) suggest that the zirconium method may overestimate the weathering rates. Leaching of base cations is difficult to estimate and this parameter was not included in the regional mass balance calculation in Finland, as only the simplified mass balance was calculated. Leaching is often not considered in nutrient budget calculations, and since leaching is one of the major parameters for base cations, this has to be taken into account in the interpretation. Hellsten et al. (2010) included leaching in the base cation balance, which resulted in relatively high losses of base cations from the forest ecosystems.

Although nutrient budget calculations is a useful tool for systainability assessments, it may be inadequate to show the qualitative changes in the availability of an element, affecting its uptake and further, stand production. For instance, removal of logging residue needles also means that soil nutrient input changes not only quantitatively, but also qualitatively. In addition, removal of organic matter may affect the decomposers, and through their changed activity also nutrient availability and stand production. These processes can be incorporated in dynamic modelling by including not only inputs and outputs but also the biological cycle. Therefore, it is suggested that recommendations for nutrient compensation should be based on a combination of results from experiments (on intensive harvesting effects and fertilisation), nutrient budget calculations and dynamic modelling. Furthermore, it is important to maintain long-term experiments to assess long-term effects of intensive biomass harvesting on forest ecosystems.

8 Areas for improvement

Research on nutrient budget calculations is ongoing both in Sweden and Finland. In Finland, currently this research is focused on budget calculations at site level, within the project *"Economic-ecological optimization of timber and bioenergy production and sequestration of carbon in Norway spruce stands"*. In Sweden, recently a study was carried out to improve the regional nutrient budget calculations (Hellsten et al, 2010). The regional estimates in Sweden could benefit from incorporating data from the Finnish budget calculations at site level, and in return, Sweden could contribute with knowledge regarding the upscaling to national level.

For instance the results of the nutrient budget calculations at regional level in Finland could be improved, applying a higher resolution (smaller grid cells) or, as was done in Sweden, calculating the budgets at site level. In Finland, forestry site data at regional level is available through VMI (Valtakunnah metsien inventointi). VMI data are available at nearly 50 000 forestry sites in Finland (Antti Ihalainen, Metla, personal communication). An advantage of calculating regional nutrient budgets at many sites is that it is possible to up-scale the data to required output, e.g. grid level or catchment areas. Furthermore applying VMI data would make it possible to separate different tree species (pine, spruce and deciduous forest), and even separate the calculation based on other factors derived from the VMI data, e.g. site productivity. Hellsten et al. (2010) showed that both tree species and site productivity (site index) is important to concider, as nutrient losses tend to be higher at spruce sites with a high site index.

Regional nutrient balances for N & P have not yet been calculated in Finland. However, nutrient balance estimation work has started at 14 sites in Finland in the research project *"Economic-ecological optimization of timber and bioenergy production and sequestration of carbon in Norway spruce stands"*. This project also includes quantification of the biological cycle (nutrient uptake / use/ retranslocation/ litterfall/ decomposition). At present, the research group works with model development of a dynamic model to combine the growth model with the soil decomposition model, the two models running in parallel, enabling the comparison of the soil nitrogen budget with the nitrogen requirement of the stand.

Nutrient budgets for boron have not been calculated, neither in Sweden nor in Finland, but in Finland this work is in progress (Tamminen et al., in prep.) Critically low boron concentrations in needles have been observed in parts of Sweden (Möller, 1983). In Finland, boron deficiency has been observed, especially in stands located in central and eastern Finland (Tamminen & Saarsalmi, 2004, Saarsalmi & Tamminen, 2005). Boron deficiency depends on the proximity to the sea, as seawater is the most important natural boron source in Scandinavia (Möller, 1983, Wikner, 1983). Other important factors are dry sites and high basal area and density of Norway spruce stands (Tamminen & Saarsalmi, 2004, Saarsalmi & Tamminen, 2005). Stem biomass contain most boron, followed by needle biomass. Although no nutrient budgets have so far been calculated for boron, it may be concluded that harvesting, and especially whole tree harvesting, at sites with boron deficiency, should be compensated.

Nitrogen deposition has been identified as the most significant parameter in the nitrogen nutrient budget. The deposition values representing nitrogen are associated with uncertainties, as it is difficult to estimate the total nitrogen deposition to forests due to internal circulation. The nitrogen deposition is hence difficult to estimate both regarding modelling and measurements. Throughfall measurements do not include the total deposition of nitrogen as nitrogen is taken up by the trees. Currently research is ongoing to improve the estimation of the total nitrogen deposition (e.g. Karlsson et al., 2011, in prep.).

The deposition of base cations is also difficult to estimate, particularly dry deposition. In Sweden, total base cation deposition was included in the nutrient budget calculation, but in Finland, only wet deposition was considered. Hence the base cation input to the balance is likely underestimated. In Sweden, dry deposition has been estimated to constitute about 32 % (Ca), 48 % (Mg) and 26 % (K) which indicates that the dry deposition constitutes a substantial amount of the total deposition. Further research to improve the estimation of base cations is recommended to reduce uncertainties in the base cation balance.

The P deposition has recently been estimated, based on bulk measurements in Sweden. However, also for P, the contribution from dry deposition is associated with uncertainties. In the P deposition values applied in Hellsten et al. (2010), the dry deposition was assumed to represent the dry deposition proportion for Ca, K and Mg. Further work to improve the estimation of the total P deposition is recommended to reduce uncertainties in the P balance.

In Joki-Heiskala et al. (2003), nutrient concentrations in different tree parts were applied from Swedish studies (Olsson et al., 1993). Studies have shown that nutrient concentrations in trees vary depending on site characteristics and nutrient deposition (Hellsten et al., 2009 & in prep.). Therefore, it is recommended to apply nutrient concentration values based on Finnish data in the Finnish nutrient budget calculations. Many studies of nutrient concentrations in Finland are available, (e.g. Helmisaari & Siltala, 1989; Mustajärvi et al., 2008; Helmisaari et al., 2009; Hellsten et al., 2009 & in prep.).

In Joki-Heiskala et al. (2003), the whole tree harvesting scenario comprised all branches and needles, which is not realistic in current Finnish forestry practice, resulting in a likely overestimation of the nutrients removed. Hence, further work on estimating realistic Finnish forestry harvesting scenarios would reduce uncertainties in the nutrient budget calculation further. Nutrient budget calculations in Finland have not been calculated for stump harvesting so far. However, input to nutrient budget calculations for stump harvesting could derive from a study comparing nitrogen outputs in logging residues to other fluxes in the tree stands (Helmisaari et al., 2009), and a study on stump nutrient concentrations (Hellsten et al., 2009 & in prep.).

The estimation of nitrogen fixation is associated with uncertainties. In many nitrogen budgets, the nitrogen input to the system through nitrogen fixation is not included. Although the contribution is likely to be small, it can still be relevant, particularly in areas with a low nitrogen deposition. Further work is recommended to assess the variability of N-fixation at regional level. A sensitivity analysis, i.e. applying minimum and maximum values for N-fixation in the nutrient budget calculation at national level, is recommended, to provide an indication of the sensitivity of the parameter.

Base cation leaching is a difficult parameter to estimate in the budget calculations, since it varies widely over time, e.g. due to the reduced impact of acidic deposition. More accurately quantifications of base cation leaching, and how it varies geographically and temporally, would be useful in the calculations. However, calculations where leaching is excluded, which have been done both in Finland and Sweden, could also be useful, although the effect on base cation budgets of acidification caused by acidic deposition is not included in these calculations, and the losses from the forest ecosystems are thus often underestimated in high deposition areas in these calculations.

Weathering rates are difficult to measure but there are several indirect ways to quantify it. It is important to compare these different approaches in order to be able to get more robust quantifications of weathering rates as well as measures of the uncertainties. The Swedish and Finnish studies presented in this study gives a basis of some comparisons, but there are more data available from other studies.

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