Critical biomass harvesting – Applying a new concept for Swedish forest soils

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Critical biomass harvesting – applying a new concept for Swedish forest soils

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Abstract

The contribution of forest harvesting to base cation losses and soil acidification has increased in recent years in Sweden, as the demand for bioenergy has increased and the sulphur deposition has decreased. Thus, new policy tools are required to evaluate the progress of the recovery from acidification, and as a basis for forest management recommendations. In this study we introduce and test a concept, “Critical biomass harvesting”. The concept builds on the concept “Critical loads”, which has been used world-wide for several decades as a bridge between science and policies related to transboundary air pollution and acidification. The basis for the concept is an acidity mass balance, with sources and sinks of acidity. A critical limit defines the highest acceptable acidification status of the water leaving the root zone. Based on the critical limit, the highest allowed biomass harvesting can be calculated, keeping the other parameters constant. In this study the critical limit was set to ANC (Acid Neutralizing Capacity) = 0. Nitrogen was assumed to be affecting acidity only if it leaches from the root zone. The critical biomass harvesting was calculated for almost 12 000 National Forest Inventory sites with spruce and pine forest, using the best available data on deposition, weathering and nitrogen leaching. The exceedance of critical biomass harvesting was calculated as the difference between the estimated harvest losses and the critical biomass harvesting. The results were presented as median values in merged catchments in a catchment database, with totally 2079 merged catchments in Sweden. According to the calculations, critical biomass harvesting was exceeded in the southern half of Sweden already at stem harvesting in spruce forests. Whole-tree harvesting expanded the exceedance area, and increased the exceedance levels in southern Sweden. The exceedance in pine forest was lower and affected smaller areas. It was concluded that the concept of critical biomass harvesting can be successfully applied on the same database that has been used for critical load calculations in Sweden, using basically the same approach as has been extensively applied, evaluated and discussed in a critical load context. The results from the calculations in Sweden indicate that whole-tree harvesting, without wood ash recycling, can be expected to further slow down recovery, especially in the most acidified parts of the country, in the southwest.

Key words

whole-tree harvesting;acidification;base cations;Norway spruce;Scots pine;Sweden

Introduction

Emission reductions of sulphur have been successful in Europe (Nyiri et al., 2009) and recovery of soils and surface waters has started (Evans et al., 2001; Skjelkvåle et al., 2001; Fölster et al., 2002). However, the recovery is slow (Graf Pannatier et al., 2011; Pihl Karlsson et al., 2011; Akselsson et al., 2013; Futter et al., 2014) and problems with acidified soils and waters are predicted to remain for many decades (Sverdrup et al., 2005; Belyazid et al., 2006).

Whereas the importance of acidifying emissions for acidification has decreased, the acidification effect of forestry has increased, due to the increased demand of renewable energy (Iwald et al., 2013). The extent of harvesting of tops and branches has increased from 17% to 34% of final fellings between the years 2011 and 2015, whereas stump harvesting is still not common (Swedish Forest Agency, 2016). High concentrations of base cations in branches, tops and needles means substantially increased losses of base cations associated with whole-tree harvesting compared to stem harvesting (Akselsson et al., 2007; Palvainen et al., 2012; Riek et al., 2012; Lucas et al., 2014). Iwald et al. (2013) estimated the acidifying effect of whole-tree harvesting of spruce (branches, tops and stumps) to be 114–263% of that of acid deposition. The corresponding interval for pine was estimated to be 57–108%.

Effects of increased biomass harvesting on soil base cation status have also been found in experiments. Measurements in four long term experiments in Sweden showed that whole-tree harvesting led to smaller soil pools of exchangeable base cations compared to whole-tree harvesting (Brandtberg et al., 2012; Zetterberg et al., 2016). The effects were largest for calcium, where the difference could be observed more than 25 years after the final felling. Achat et al. (2015) performed a meta-analysis on 168 experiments in Europe and North America, and found a significant decrease of base saturation in the upper 20 cm of the mineral soil after whole-tree harvesting as compared to stem harvesting. However, the effects varied between different experiments. Helmisaari et al. (2014) referred in a literature review to several whole-tree harvesting experiments in the Nordic countries, some of which showed negative effects on soil acidification indicators after whole-tree harvesting whereas others showed no significant effect.

The critical load of acidity was an important tool in adjusting policies to reduce emissions of sulphur and nitrogen oxides (Sundqvist et al., 2002). Critical loads of acidity are defined as “a quantitative estimate of an exposure to one or more pollutants below which significant harmful effects on specified elements of the environment do not occur according to present knowledge” (Nilsson et al., 1988). Calculations of critical loads of acidity are based on acidity mass balances, and can be modelled using the SMB model (Sverdrup et al., 1994) or PROFILE (Sverdrup et al., 1993).

As the deposition of acidifying substances has been reduced and the impact of forestry has increased, the need of a new policy tool, focusing on biomass harvesting, has emerged. The aims of this paper were to put forward a policy tool for sustainable biomass harvesting based on the critical load of acidity concept, “Critical biomass harvesting”, and to test it on the Swedish national critical load database.

Materials and Methods

Concept and equations

The calculations of Critical biomass harvesting were based on the same concept as the calculations of Critical load of acidity (Sverdrup et al., 1994). The SMB formula (Eq. 1, Posch et al., 1995) was used as a basis for the calculations, and was applied for the root zone, which was assumed to be 50 cm in depth.

$$S_{dep}+N_{dep}+Cl_{dep}+BC_{harv}+Alk_{leach} = BC_{dep}+BC_{weath}+N_{imm}+N_{harv}+N_{de} \quad \text{(Eq. 1)}$$

where dep = deposition (eq/m^2,yr)

BC = base cations (Ca, Mg, Na and K)

harv = net losses at harvesting

Alk_{leach} = Alkalinity leaching

weath = weathering

imm = immobilization

de = denitrification

The critical load of acidity is generally calculated according to Eq. 2, which is based on Eq. 1. The critical load is the highest deposition that still leads to acceptable runoff water quality, based on a chemical criterion and a critical limit, used to calculate the critical alkalinity leaching ($Alk_{leach(crit)}$ in Eq. 2). In Sweden, the criterion most often used has been the $Bc:Al_i$, (where Bc refers to the sum of Ca, Mg and K), a criterion associated with tree health, and the critical limit has often been set to 1 (Sverdrup et al., 1994). Exceedance is calculated according to Eq. 3.

$$CL\ (S_{dep}+N_{dep}) = BC_{dep}+BC_{weath}+N_{imm}+N_{harv}+N_{de}-Cl_{dep}-BC_{harv}-Alk_{leach(crit)} \quad \text{(Eq. 2)}$$

$$\text{Exceedance} = S_{dep}+N_{dep}-CL\ (S_{dep}+N_{dep}) \quad \text{(Eq. 3)}$$

For critical biomass harvesting, ANC in the runoff water was used as a chemical criterion, with a critical limit of 0. This means no acidification exported from the soils to the leaching water, but neither any acid neutralizing capacity. Setting the ANC limit to 0 was motivated by the assumption that the water gains some neutralizing capacity on the way from the 50 cm root zone through the mineral soil and to the surface water.

The nitrogen (N) calculations were greatly simplified. Almost all of the inorganic N deposition is taken up by vegetation and soil organisms in most Swedish forest soils, and the inorganic N concentrations in soil water below the root zone are thus very low, although in the southwesternmost part of Sweden highly elevated concentrations of inorganic N is common (Akselsson et al., 2010). In the clearcut phase, when the N uptake is interrupted, leaching of inorganic N from the root zone occurs, which has been shown on seven stem harvested sites in Sweden, on latitudes between 57° and 62° (Futter et al., 2010). The leaching is generally higher in the southwest (Akselsson et al., 2004), where the N accumulation has been the highest (Akselsson et al., 2005). The acidifying effect of N was calculated based on following assumptions:

(1) The N that is leached from the soil as nitrate (NO_3-N) is acidifying, one equivalent (based on reasoning in Galloway, 1995).

(2) The N that is leached from the soil as NH_4-N counteracts acidification, one equivalent (based on reasoning in Galloway, 1995).

(3) Whole-tree harvesting does not affect N leaching.

(4) N stored in soil organic matter will not acidify in the future.

Assumption 3 and 4 are rough assumptions required to simplify calculations, and have to be kept in mind when interpreting the results.

The equations for calculating critical biomass harvesting based on the reasoning above are given in Eq. 4-5.

$$\text{Crit } BC_{harv} = BC_{weath} + BC_{dep} + NH_4\text{-}N_{leach} - S_{dep} - Cl_{dep} - NO_3\text{-}N_{leach} \qquad \text{(Eq. 4)}$$

$$\text{Exceedance} = BC_{harv} - \text{Crit } BC_{harv} \qquad \text{(Eq. 5)}$$

National database for Sweden

Weathering rates, deposition, leaching and harvest losses were estimated on 5412 spruce sites (where Norway spruce makes up more than 70% of the forest stand) and 6361 pine sites (where Scots pine makes up more than 70% of the stand) within the Swedish National Forest Inventory (Hägglund, 1985). The critical harvest and the exceedance were then calculated according to Equations 4 and 5 respectively for all sites. The results were transferred to a national catchment database with 2079 merged catchments from the Swedish Environmental Emissions Data (SMED) Consortium; Brandt et al., 2008). This platform gives a better overview than the National Forest Inventory platform, but has high enough geographical resolution to account for the regional variation in e.g weathering rates and deposition. The platform is widely used in Swedish policy applications, which also makes it suitable. Spruce sites were present in 877 and pine sites in 959 of the merged catchments. Medians were calculated for spruce and pine for those merged catchments.

Deposition

Sulphur deposition (excluding sea salt) for the year 2020, as simulated by the 2011 EMEP model (www.emep.int) under the current legislation scenario of the latest revision of the Gothenburg protocol, was used. The deposition has been modelled in grid cells of 50 by 50 km, and each National Forest Inventory site was assigned the deposition from the corresponding grid cell. Sulphur deposition from sea salt was estimated based on sodium deposition (see below), based on the assumption that all Na comes from sea salt.

The 2020 data were used instead of today's deposition, since the critical harvest calculations are meant to be interpreted on a long-term (at least one forest rotation).

Base cation deposition (Ca, Mg, Na and K) was derived from the MATCH model (Langner et al., 1996), in the resolution 20*20 km. There are no clear trends in base cation deposition during the last decade, and the future deposition is very difficult to predict. In this study, the median deposition for 2007-2009 was used. Cl deposition was estimated based on Na deposition and the composition of sea salt, assuming that all Na and Cl deposition derives from sea salt.

Base cation losses at stem- and whole-tree harvesting

Harvest losses at stem only harvesting and whole-tree harvesting were based on data on site productivity on the sites. The site productivity gives the optimal growth of a stand (m^3 stem wood per hectare and year), and would therefore overestimate the actual growth. Thus the site productivity was reduced by 20% in an effort to imitate real conditions. Volume growth was recalculated to mass growth using the stem density of 430 kg m^{-3} for spruce and 490 kg m^{-3} for pine. Harvest losses for the stem harvesting scenario were then estimated by multiplying the volume growth by the base cation concentration in stems according to Table 1, assuming that 100% of the stems were harvested. In the whole-tree harvesting scenario, 100% of the stems were assumed to be removed together with 60% of the branches, in accordance with a scenario from Swedish Forest Agency (2008). Furthermore, 75% of the needles were assumed to accompany the branches. The amount of branches and needles available for harvesting was estimated from stem data and fractions between biomass of stems, branches and needles from standard methods (Marklund, 1988). The available mass of branches and needles were reduced according to the removal percentages given above, to derive the loss of branches and needles from the forest sites. By multiplying the mass of branches and needles removed from the sites, by base cation concentrations in branches and needles respectively (Table 1), the loss off base cations from the sites was derived. The base cation concentrations were national average values (see table below), due to lack of site specific data. Zetterberg et al. (2014) performed a sensitivity analysis for Ca, and concluded that the lack of site specific nutrient concentration data was the main source of uncertainties in calculations of harvest losses of Ca, whereas uncertainties in site productivity and in the amount of branches left on the ground, contributed less to the overall uncertainties. However, in national calculations, using national averages of nutrient concentrations is the only option, since there are no available studies indicating that the concentration varies geographically, or that they can be linked to site conditions.

Element	Spruce			Pine		
	Stem+ bark	Branches+ tops	Needles	Stem+ bark	Branches+ tops	Needles
Ca (mg g^{-1})[a]	1.3	3.7	6.0	0.9	2.3	3.3
Mg (mg g^{-1}) [a]	0.2	0.6	1.0	0.2	0.4	0.8
K (mg g^{-1}) [a]	0.7	2.4	4.7	0.5	1.5	5.1
Na (mg g^{-1}) [b]	0.08	0.1	0.1	0.08	0.1	0.1

[a] Average concentrations compiled in Egnell et al. (1998), based on 22 spruce sites in Sweden, spanning over latitudes from 56 to 64, and 17 pine sites, spanning over latitudes from 56 to 66 (S. Jacobson, pers. comm).

[b] Data compiled in Anon. (2003).

Table 1. Concentrations in stems, branches and needles used in the calculations.

Weathering

Weathering rates were modelled with the PROFILE model, a soil chemistry model originally developed to calculate the effect of acid rain on soil chemistry (Sverdrup et al., 1993). It includes process oriented descriptions of chemical weathering of minerals, leaching and accumulation of dissolved chemical components and solution equilibrium reactions. PROFILE is a steady state model, which means that yearly data or long-term averages are required as input to the model, not time-series as in dynamic models. PROFILE then calculates the soil solution chemistry at steady state, i.e. the chemistry that finally settles using the constant input data. In PROFILE, the soil is divided into soil layers with different properties, preferably based on the naturally occurring soil stratification. Weathering is calculated using transition state theory. The geochemical properties of the soil system, such as soil wetness, mineral surface area, hydrogen, cation and organic acid concentrations, temperature and mineral composition, are important inputs.

Weathering rates were modelled on the National Forest Inventory sites, to a depth of 50 cm (including the organic layer) based on the same methodology and database as in

Akselsson et al. (2008), but with updated deposition data according to the description above.

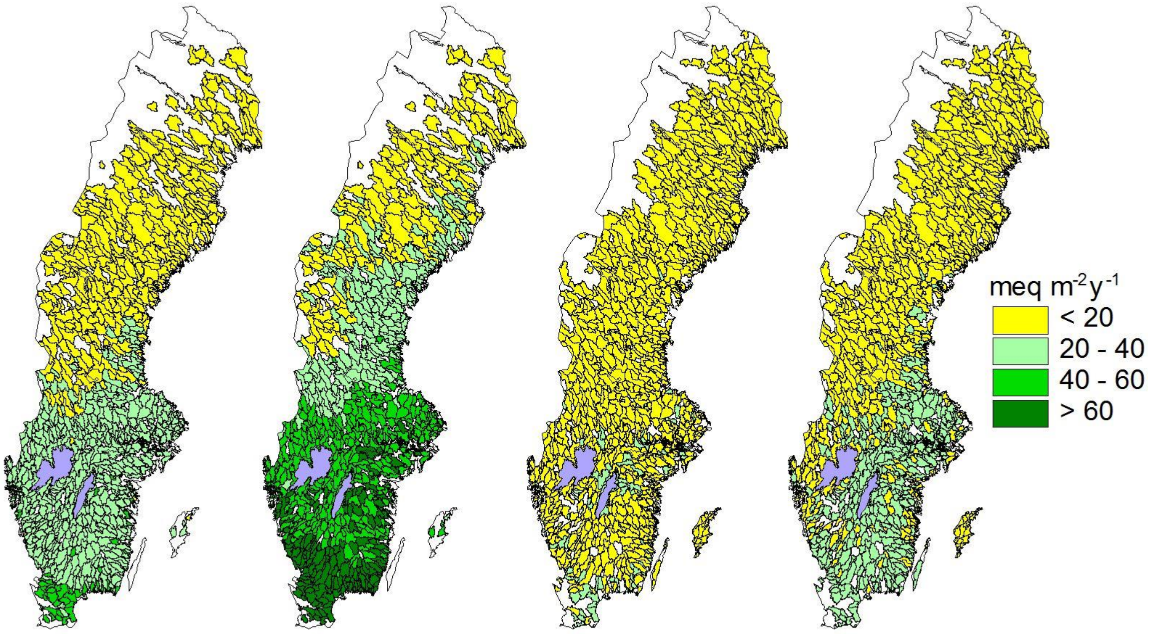
Leaching of inorganic nitrogen from growing forests and clearcuts

The leaching of NO_3-N and NH_4-N from the root zone in growing forests was estimated using concentrations in soil water from the Swedish Throughfall Monitoring Network, SWETHRO (Pihl Karlsson et al., 2011) in combination with runoff data from the Swedish Meteorological and Hydrological Institute, SMHI (average 1961-1990; Raab et al., 1995). Median concentrations 2010-2012 (three measurements per year) on 60 sites were estimated, and a median of that was used for the whole country since the dataset did not support different concentrations in different parts of the country. Most farthest to the southwest there are several sites with elevated NO_3-concentrations (Akselsson et al., 2010), but there are also sites with low concentrations. By using a median for the whole country, the N leaching was probably underestimated in soutwesternmost Sweden, but since there are no measurements of N leaching at the National Forest Inventory sites, the median from the SWETHRO network was still used.

The NO_3-N leaching from clearcuts was calculated based on an empirical relationship in Futter et al. (2010), where NO_3-N leaching is a function of site quality on seven sites in Sweden, covering site quality classes (defined as mean annual stemwood increment) of 3 to 11 m^3 per hectare and year. Since site quality is available on all National Forest Inventory sites, the NO_3-N leaching could be estimated. To convert leaching to yearly values, a rotation period of 85 years was assumed for southern Sweden, and 105 years for northern Sweden.

Results

The net losses of base cations were substantially higher in spruce forests than in pine forests (Figure 1; Table 2), due to more biomass in spruce forests. Harvesting of residues (branches and tops) led to 70% more losses in spruce forests whereas the corresponding increase in pine forests was 30%. There is a gradient in Sweden with higher base cation losses in the south than in the north, corresponding to the climate gradient. In the northern part there is a gradient with higher losses in the east than in the west.



a. b. c. d.

Figure 1. Losses of base cations (Ca, Mg, Na, K) at stem harvesting in spruce forests (a), whole-tree harvesting in spruce forests (b), stem harvesting in pine forests (c) and whole-tree harvesting in pine forests (d).

	Spruce			Pine		
	Median	5-perc.	95-perc	Median	5-perc.	95-perc
Harvest losses stem	26	8	42	13	6	21
Harvest losses wht	43	13	69	17	8	26
Critical harvesting	19	5	104	13	-1	48
Exceedance stem	3	-77	29	0	-35	16
Exceedance wht	19	-58	53	3	-30	20

Table 2. Harvest losses, critical harvesting and exceedance at stem-only and whole-tree harvesting in spruce and pine forest (meq m^{-2} y^{-1}). Medians, 5- and 95-percentiles of the merged catchments.

The critical harvesting was the highest in southwestern Sweden, parts of northern Sweden and the western part of central Sweden (Figure 2). The critical harvesting was generally slightly lower for pine than for spruce, since pine forests are more frequently occurring on poorer soils.

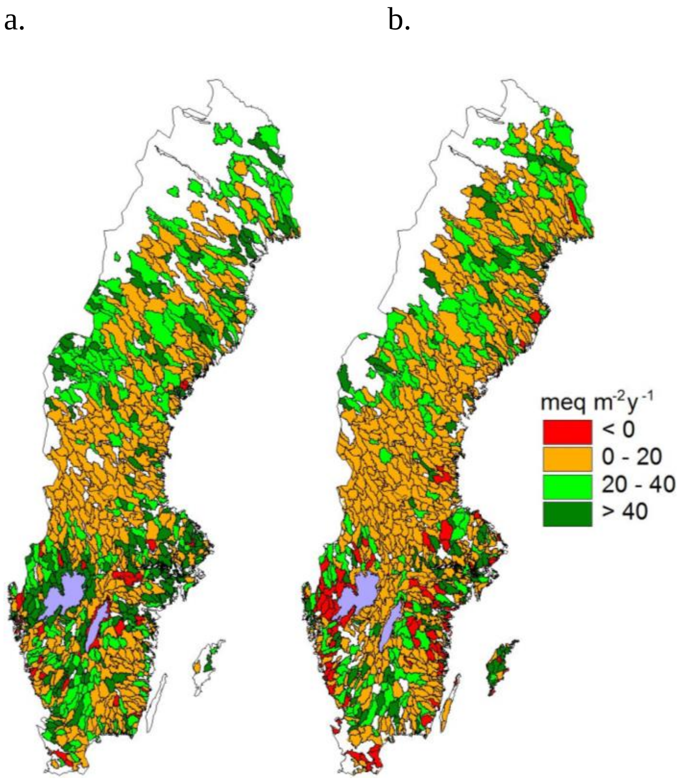


Figure 2. Critical harvesting at the deposition of 2020 according to the EMEP model in spruce forests (a) and in pine forests (b).

In spruce forest the critical harvesting was exceeded in most parts of the southern half of Sweden and along the coast in the north, already at stem-harvesting (Figure 3). Whole-tree harvesting increased the area with exceeded critical harvesting slightly, but above all it led to higher exceedances in southern Sweden (Figure 3, Table 2). In pine forests the critical harvesting was exceeded in 50% of the merged catchments at stem harvesting, but the exceedance was generally low (Figure 4; Table 2). Whole-tree harvesting led to a somewhat larger fraction of catchments where the critical harvesting was exceeded.

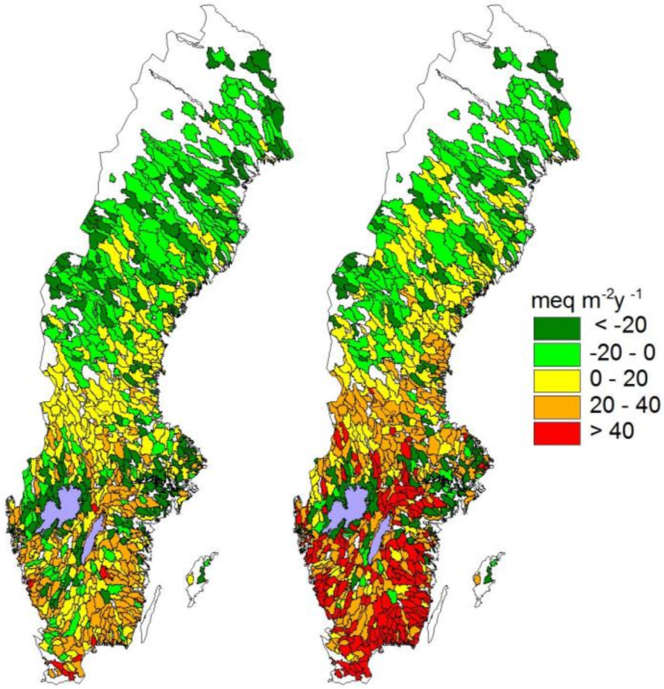


Figure 3. Exceedance of critical harvesting in spruce forest at stem harvesting (a) and whole-tree harvesting (b)

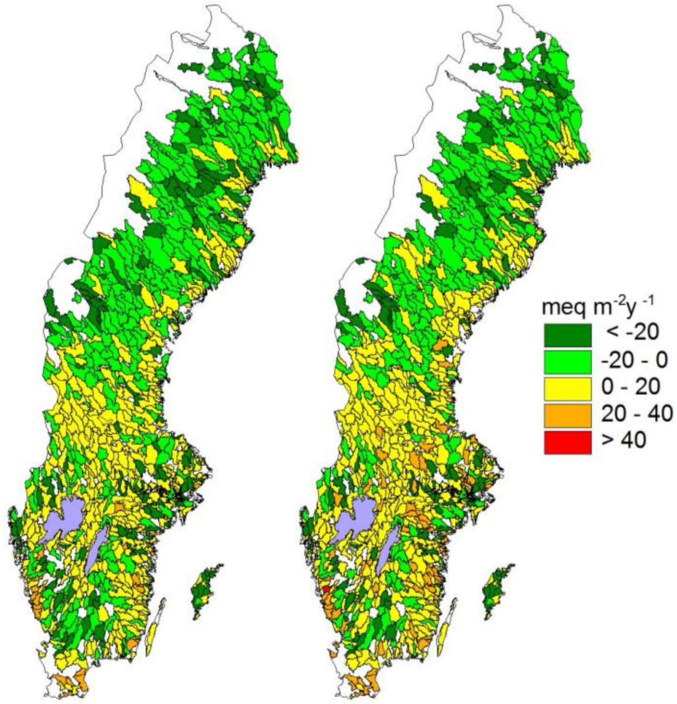


Figure 4. Exceedance of critical harvesting in pine forest at stem harvesting (a) and whole-tree harvesting (b)

Discussion

Going from critical load of acidifying deposition to critical biomass harvesting is a natural step in a country like Sweden, where the acidifying impact of biomass harvesting is often equal or greater than that of atmospheric deposition (Iwald et al., 2013). Along with the decreasing deposition, and the increasing demand of renewable energy, biomass harvesting will play an even larger role for acidification in the future. An advantage of using the steady state mass balance approach is that it is robust in that it has been applied, evaluated and discussed extensively in the critical load context (Sverdrup et al., 1995; Kurz et al., 2001; Freer-Smith et al., 2003; Kennedy et al., 2001; Jönsson et al. (1995).

Whereas the robustness and transparency are advantages of the steady state concept, the lack in dynamics is a drawback. Inputs are constant values of deposition and other parameters, thus neither historical nor future deposition and land use are taken into account. This means, for example, that the critical harvesting is overestimated in the areas with the highest deposition such as southwestern Sweden, where the historical deposition has been much higher (Pihl Karlsson et al., 2011), and where the soils accordingly have been depleted of base cations.

Dynamic models are required to account for changes over time. In Zanchi et al. (2014) the dynamic model ForSAFE has been used to study different management methods, such as stem and whole-tree harvesting have been compared, using historical deposition and climate data as well as future predictions for deposition and climate. A conclusion was that the effect of whole-tree harvesting on soil chemistry varied over the forest rotation. As opposed to the steady state concept, the advantage of dynamic modelling is the dynamic representation of processes over time, whereas the drawbacks are the less opportunities to generalize over large regions. By combining the different approaches, by applying steady state calculations and dynamic modelling in the same areas, the advantages of both approaches can be utilized (Akselsson et al., 2010).

Another effect of lacking dynamics is that climate change effects are not accounted for. A substantial effect of a changed climate on weathering was simulated in Sweden using the steady state model PROFILE in Akselsson et al. (2016). The increased weathering rates were compared with the increased losses of base cations at whole-tree harvesting, and the conclusions drawn were that the increased weathering could not compensate for the increased base cation losses at whole-tree harvesting in most areas. Aherne et al. (2012) used the more dynamic MAGIC model in Finland, and came to similar conclusions. A fully dynamic approach was used in Gaudio et al. (2015), where the ForSAFE model was used on two forest sites in France to assess the effect of climate and deposition changes on soil chemistry. In accordance with the PROFILE and MAGIC studies, climate change gave a substantial effect on base cations, in this case shown as increased base saturation.

Both in critical load and critical harvesting calculations the handling of N requires some assumptions, since the acidifying effect of N is more complex than the effect from sulphur (Galloway, 1995). In many critical load calculations all N terms, i.e. deposition, uptake, denitrification and immobilization have been accounted for, as in Sverdrup et al. (1995). Immobilization and denitrification are terms that are difficult to quantify and thus require assumptions. In the present study it was assumed that the acidifying effect of N was limited to the present NO_3 leaching based on measurements in soil water. A median value for the whole country was used, since the concentrations are similar (very low) on most sites in Sweden. However, there are sites in southwestern Sweden with highly elevated NO_3 leaching, and in this region the acidifying effect of N can be assumed to be underestimated for many forests.

The assumption that only the NO_3 that is leaching is acidifying means that potential changes in NO_3 leaching in the future, and effects of whole-tree harvesting on NO_3 leaching, are not accounted for. In N-rich areas whole-tree harvesting could lead to reduced risk of NO_3 leaching, counteracting the acidifying effect of the base cation removal (Zanchi et al., 2014). However, results from experiments are contradictory. Gundersen et al. (2006) concluded in a review paper that whole-tree harvesting has resulted in decreased NO_3 leaching in some studies, and increased NO_3 leaching in others. Ring et al. (2016) demonstrated in an experiment lower NO_3 concentrations in soil solution after whole-tree harvesting than after conventional harvesting. In Ring et al. (2015) one of the two investigated sites showed decreasing NO_3 concentrations with decreasing amount of logging residues left on the clearcuts, whereas the other showed no such tendency. de Jong et al. (2017) concluded in a synthesis article that whole-tree harvesting leads to no or a slightly decreased risk of N leaching.

The choice of critical limit is naturally important for the results. In critical load studies, the critical limits used were often focusing on tree health. One of the most commonly used criteria is Bc:Al ratio (Sverdrup et al., 1995). The critical limit chosen in this study, ANC=0 at 50 cm depth, is focusing on water quality. It gives no margins for recovery at that soil depth, and thus it can be seen as too low a limit, especially in areas with thin soil layers. In areas with thick soil layers, however, the weathering in deeper layers can increase the ANC before it reaches surface waters, and thus the limit is more appropriate.

The clear gradient, with increasing exceedance from north to south, corresponds to the higher base cation losses at harvesting and to the higher sulphur deposition in the south. In the southern part the exceedance is higher towards the east, although the sulphur deposition is higher in the western part. This is due to the higher weathering rate and base cation deposition in the western part, which increases the critical biomass harvesting.

The results show that whole-tree harvesting in spruce forest in the southern half of Sweden and along the coast in the north is generally not sustainable, unless nutrients are added. Also stem harvesting leads to exceedance in the southern part of the country, but the exceedance is much smaller. The areas with high exceedance coincide with the areas with most acidified soils due to historical acid deposition (Pihl Karlsson et al., 2011). The recovery in those areas are generally slow (Akselsson et al., 2013) and increased base cation losses can be expected to hamper recovery further. In pine forests there is small or no exceedance at stem harvesting, and whole-tree harvesting only changes the picture slightly. The results are important as a basis for forest management policies related to whole tree harvesting and wood ash recycling.

Conclusions

Critical biomass harvesting can be estimated based on the same steady state mass balance concept and the same national input database as for critical load of deposition. The approach is robust in that it has been extensively applied, evaluated and discussed in a critical load context. As for the critical load calculations, two important decisions have to be made, about assumptions related to the N processes and about which chemical criteria and critical limit to use.

The calculations for Sweden showed that critical biomass harvesting was exceeded in the southern half of Sweden already at stem harvesting in spruce forests, when ANC=0 was used as a critical limit. Whole-tree harvesting expanded the exceedance area, and increased the exceedance levels in southern Sweden. In pine forests the exceedance was lower, and affected smaller areas.

The areas with exceedance coincide with the most acidified soils from acid deposition, where recovery is slow. Whole-tree harvesting, without wood ash recycling, especially in spruce forests in those areas can be expected to further slow down recovery.

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References

Achat, D.L., Deleuze, C., Landmann, G., Pousse, N., Ranger, J., Augusto, L., 2015. Quantifying consequences of removing harvesting residues on forest soils and tree growth – a meta-analysis. Forest Ecology and Management. 348, 124–141. doi:10.1016/j.foreco.2015.03.042

Aherne, J., Posch, M., Forsius, M., Lehtonen, A., Härkönen, K., 2012. Impacts of forest biomass removal on soil nutrient status under climate change: a catchment-based modelling study for Finland. Biogeochemistry 107, 471-488. doi:10.1007/s10533-010-9569-4

Akselsson, C., Belyazid, S., Hellsten, S., Klarqvist, M., Pihl-Karlsson, G., Karlsson, P.E., Lundin, L., 2010. Assessing the risk of N leaching from Swedish forest soils across a steep N deposition gradient in Sweden. Environmental Pollution 158, 3588-3595. doi:10.1016/j.envpol.2010.08.012

Akselsson, C., Hultberg, H., Karlsson, P.E., Pihl Karlsson, G., Hellsten, S., 2013. Acidification trends in south Swedish forest soils 1986-2008 – slow recovery and high sensitivity to sea-salt episodes. Science of the Total Environment 444, 271-287. doi:10.1016/j.scitotenv.2012.11.106

Akselsson, C., Olsson, J., Belyazid, S., Capell, R., 2016. Can increased weathering rates due to future warming compensate for base cation losses following whole-tree harvesting in spruce forests? Biogeochemistry 128: 89-105. doi: 10.1007/s10533-016-0196-6

Akselsson, C., Westling, O., 2005. Regionalized nitrogen budgets in forest soils for different deposition and forestry scenarios in Sweden. Global Ecology and Biogeography 14, 85-95. doi:10.1111/j.1466-822X.2004.00137.x

Akselsson, C., Westling, O., Sverdrup, H., Holmqvist, J., Thelin, G., Uggla, E., Malm, G., 2007. Impact of harvest intensity on long-term base cation budgets in Swedish forest soils. Water, Air, and Soil Pollution: Focus 7, 201-210. doi:10.1007/s11267-006-9106-6

Akselsson, C., Westling, O., Örlander, G., 2004. Regional mapping of nitrogen leaching from clearcuts in southern Sweden. Forest Ecology and Management 202, 235-243. doi:10.1016/j.foreco.2004.07.025

Akselsson, C., Westling, O., Alveteg, M., Thelin, G., Fransson, A-M., Hellsten, S., 2008. The influence of N load and harvest intensity on the risk of P limitation in Swedish forest soils. Science of the Total Environment 404, 284-289. doi:10.1016/j.scitotenv.2007.11.017

Anonymous, 2003. Ecocyclic pulp mill – ‘KAM’. Final report 1996–2002. KAM report A100, pp. 109–134. Swedish Pulp and Paper Institute, Stockholm, Sweden.

Belyazid, S., Westling, O., Sverdrup, H., 2006. Modelling changes in forest soil chemistry at 16 Swedish coniferous forest sites following deposition reduction. Environmental Pollution 144, 596-609. doi:10.1016/j.envpol.2006.01.018

Brandt, M., Ejhed, H., Rapp, L., 2008. Näringsbelastning på Östersjön och Västerhavet 2006: Underlag till Sveriges PLC5-redovisning till HELCOM. Swedish Environmental Protection Agency Report 5815, Stockholm (In Swedish with English summary).

Brandtberg, P.O., Olsson, B., 2012. Changes in the effects of whole-tree harvesting on soil chemistry during 10 years of stand development. Forest Ecology and Management 277, 150–162. doi:10.1016/j.foreco.2012.04.019

de Jong, J., Akselsson, C., Egnell, G., Löfgren, S., Olsson, B., 2017. Realizing the energy potential of forest biomass in Sweden - how much is environmentally sustainable? Forest Ecology and Management 383, 3-13. doi: 10.1016/j.foreco.2016.06.028

Egnell, G., Nohrstedt, H.Ö., Weslien, J., Westling, O., Örlander, G., 1998. Miljökonsekvensbeskrivning av skogsbränsleuttag, asktillförsel och övrig näringskompensation. National Board of Forestry, Report 1:1998. Jönköping, Sweden. (In Swedish).

Evans, C.D., Cullen, J.M., Alewell C., Kopácek, J., Marchetto, A., Moldan, F., Prechtel, A., Rogora, M., Veselý, J., Wright, R., 2001. Recovery from acidification in European surface waters. Hydrology and Earth System Sciences 5 (3), 283–297. doi:10.5194/hess-5-283-2001

Freer-Smith, P., Kennedy, F., 2003. Base Cation Removal in Harvesting and Biological Limit Terms for Use in the Simple Mass Balance Equation to Calculate Critical Loads for Forest Soils. Water, Air and Soil Pollution 145, 409-427. doi:10.1023/A:1023615004433

Futter, M., Ring, E., Högbom, L., Entenmann, S., Bishop, K., 2010. Consequences of nitrate leaching following stem-only harvesting of Swedish forests are dependent on spatial scale. Environmental Pollution 158, 3552-3559. doi:10.1016/j.envpol.2010.08.016

Futter, M., Valinia, S., Löfgren, S., Köhler, S., Fölster, J., 2014. Long-term trends in water chemistry of acid-sensitive Swedish lakes show slow recovery from historic acidification. Ambio 43, 77-90. doi:10.1007/s13280-014-0563-2

Fölster, J., Wilander, A., 2002. Recovery from acidification in Swedish forest streams. Environmental Pollution 117, 379-389. doi:10.1016/S0269-7491(01)00201-9

Galloway, J., 1995. Acid deposition: Perspectives in time and space. Water, Air, and Soil Pollution 85, 15-24.doi:10.1007/BF00483685

Gaudio, N., Belyazid, S., Gendre, X., Mansat, A., Nicolas, M., Rizzetto, S., Sverdrup, H., Probst, A., 2015. Combined effect of atmospheric nitrogen deposition and climate change on temperate forest soil biogeochemistry: A modeling approach. Ecological Modelling 306, 24-34. doi:10.1016/j.ecolmodel.2014.10.002

Graf Pannatier, E., Thimonier, A., Schmitt, M., Walthert, L., Waldner, P., 2011. A decade of monitoring at Swiss long-term forest ecosystem research (LWF) sites: Can we observe trends in atmospheric acid deposition and in soil solution acidity? Environmental monitoring and assessment 174, 3-30. doi:10.1007/s10661-010-1754-3

Gundersen, P., Schmidt, I., Rauland-Rasmussen, K., 2006. Leaching of nitrate from temperate forests e effects of air pollution and forest management. Environmental Reviews 14, 1-57. doi: 10.1139/A05-015

Helmisaari, H-S., Kaarakka, L., Olsson, B., 2014. Increased utilization of different tree parts for energy purposes in the Nordic countries. Scandinavian Journal of Forest Research 29(4), 312-322. doi:10.1080/02827581.2014.926097

Hägglund, B., 1985. En ny svensk riksskogstaxering (A new Swedish National Forest Survey). Swedish University of Agricultural Sciences, Report 37. Uppsala, Sweden. (In Swedish with English summary).

Iwald, J., Löfgren, S., Stendahl, J., Karltun, E., 2013. Acidifying effect of removal of tree stumps and logging residues as compared to atmospheric deposition. Forest Ecology and Management 290, 49-58. doi:10.1016/j.foreco.2012.06.022

Jönsson, C., Warfvinge, P., Sverdrup, H., 1995. Uncertainty in predicting weathering rates and environmental stress factors with the profile model. Water, Air and Soil Pollution 81, 1–23. doi:10.1007/BF00477253.

Kennedy, F., Rowell, D., Moffat, A. J. M., Singh, B., 2001. An Analysis of the Structure of the Simple Mass Balance Equation – Implications for Testing National Critical Loads Maps. Water, Air and Soil Pollution:Focus 1, 281–298. doi:10.1023/A:1011531922278

Kurz, D., Rihm, B., Alveteg, M., Sverdrup, H., 2001. Steady-state and dynamic assessment of forest soil acidification in Switzerland. Water, Air and Soil Pollution 130, 1217-1222. doi:10.1023/A:1013964731876

Langner, J., Persson, C., Robertson, L., Ullerstig, A., 1996. Air pollution assessment study using the MATCH Modelling System. Application to sulphur and nitrogen compounds over Sweden 1994. Swedish Meteorological and Hydrological Institute, Report no. 69. Norrköping, Sweden.

Lucas, R.W., Holmström, H., Lämås, T., 2014. Intensive forest harvesting and pools of base cations in forest ecosystems: A modeling study using the Heureka decision support system. Forest Ecology and Management 325, 26-36. doi:10.1016/j.foreco.2014.03.053

Marklund L.G., 1988. Biomass functions for pine, spruce, and birch in Sweden. Department of Forest Taxation, Swedish University of Agricultural Sciences, SLU, Report 45. (In Swedish with English summary).

Nilsson, J., Grennfelt, P., 1988. Critical loads for sulphur and nitrogen. NORD 1988: 15 Nordic Council of Ministers, Copenhagen. Miljörapport 15, 418 pp.

Nyiri, A., Gauss, M., Klein, H., 2009. Transboundary Air Pollution by Main Pollutants (S, N, O_3) and PM. MSC-W Data Note 1;2009.

Palvainen, M., Finér, L. 2012. Estimation of nutrient removals in stem-only and whole-tree harvesting of Scots pine, Norway spruce, and birch stands with generalized nutrient equations. European Journal of Forest Research 131, 945–964. doi:10.1007/s10342-011-0567-4

Pihl Karlsson, G., Akselsson, C., Hellsten, S., Karlsson, P.E., 2011. Reduced European emissions of S and N – Effects on air concentrations, deposition and soil water chemistry in Swedish forests. Environmental Pollution 159, 3571-3582. doi:10.1016/j.envpol.2011.08.007

Posch, M., de Smet, P., Hettelingh, J-P., Downing, R., 1995. Calculation and mapping of critical thresholds in Europe. Status report 1995, Coordination center of effects. RIVM Report No. 259101009.

Raab, B., Vedin, H., 1995. Klimat, sjöar och vattendrag. Sveriges Nationalatlas, band nr 14. Bra Böcker, Höganäs, Sweden. (In Swedish).

Riek, W., Russ, A., Martin, J. 2012. Soil acidification and nutrient sustainability of forest ecosystems in the northeastern German lowlands – Results of the national forest soil inventory. Folia Forestalia Polonica (series A) 54 (3), 187–195. doi:10.5281/zenodo.30835

Ring, E., Högbom, L., Nohrstedt, H-Ö., Jacobson, S., 2015. Soil and soil-water chemistry below different amounts of logging residues at two harvested forest sites in Sweden. Silva Fennica 49 (4), 1-19. doi: 10.14214/sf.1265

Ring, E., Jacobson, S., Jansson, G., Högbom, L., 2016. Effects of whole-tree harvest on soil-water chemistry at fiveconifer sites in Sweden. Canadian Journal of Forest Research 47, 349–356. doi: 10.1139/cjfr-2016-0338

Skjelkvåle B, Mannio J, Wilander A, Andersen T., 2001. Recovery from acidification of lakes in Finland, Norway and Sweden 1990–1999. Hydrology and Earth System Sciences 5(3), 327–337. doi:10.5194/hess-5-327-2001

Sundqvist, G., Letell, M., Lidskog, R., 2002. Science and policy in air pollution abatement strategies. Environmental Science & Policy 5, 147–156. doi:10.1016/S1462-9011(02)00032-1

Sverdrup, H., de Vries, W., 1994. Calculating critical loads for acidity with the simple mass balance method. Water, Air, and Soil Pollution 72, 143-162. doi: 10.1007/BF01257121

Sverdrup, H., Martinson, L., Alveteg, M., Moldan, F., Kronnäs, V., Munthe, J., 2005. Modeling recovery of Swedish Ecosystems from Acidification. Ambio 34 (1), 25-31. doi:10.1579/0044-7447-34.1.25

Sverdrup H, Warfvinge P., 1993. Calculating field weathering rates using a mechanistic geochemical model (PROFILE). Journal of Applied Geochemistry 8, 273–83. doi:10.1016/0883-2927(93)90042-F

Sverdrup, H., Warfvinge, P., 1995. Critical loads of acidity for Swedish forest ecosystems. Ecological Bulletins 44, 75-89.

Swedish Forest Agency (2008) Skogliga konsekvensanalyser 2008: SKA-VB 08. Swedish Forest Agency Report 25, Jönköping. (In Swedish).

Swedish Forest Agency, 2016. Sweden´s official forest statistics, available at www.skogsstyrelsen.se/en/.

Zanchi, G., Belyazid, S., Akselsson, C., Yu, L., 2014. Modelling the effects of management intensification on multiple forest services: A Swedish case study. Ecological Modelling 284, 48-59. doi:10.1016/j.ecolmodel.2014.04.006

Zetterberg, T., Köhler, S., Löfgren, S., 2014. Sensitivity analyses of MAGIC modelled predictions of future impacts of whole-tree harvest on soil calcium supplu and stream acid neutralizing capacity. Science of the Total Environment 494-495, 187-201. doi: 10.1016/j.scitotenv.2014.06.114

Zetterberg, T., Olsson, B., Löfgren, S., Hyvönen, R., Brandtberg, P.O., 2016. Long-term soil calcium depletion after conventional and whole-tree harvest. Forest Ecology and Management 369, 102-115. doi:10.1016/j.foreco.2016.03.027