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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 12000 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.

## 1. 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 feelings 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

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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.

## 2. Materials and methods

### 2.1. 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.

$$S_{dep} + N_{dep} + Cl_{dep} + BC_{harv} + Alk_{leach} = BC_{dep} + BC_{weath} + N_{imm} + N_{harv} + N_{de} \tag{1}$$

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).

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

$$Exceedance = S_{dep} + N_{dep} - CL(S_{dep} + N_{dep}) \tag{3}$$

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 south-westernmost 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 Eqs. (4) and (5).

$$Crit\ BC_{harv} = BC_{weath} + BC_{dep} + NH_4{-}N_{leach} - S_{dep} - Cl_{dep} - NO_3{-}N_{leach} \tag{4}$$

$$Exceedance = BC_{harv} - Crit\ BC_{harv} \tag{5}$$

### 2.2. 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 Eqs. (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.

### 2.3. 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