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

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17

18   **Abstract**

19   The contribution of forest harvesting to base cation losses and soil acidification has

20   increased in recent years in Sweden, as the demand for bioenergy has increased and the

21   sulphur deposition has decreased. Thus, new policy tools are required to evaluate the

22   progress of the recovery from acidification, and as a basis for forest management

23   recommendations. In this study we introduce and test a concept, "Critical biomass

24   harvesting". The concept builds on the concept "Critical loads", which has been used

25   world-wide for several decades as a bridge between science and policies related to

26   transboundary air pollution and acidification. The basis for the concept is an acidity mass

27   balance, with sources and sinks of acidity. A critical limit defines the highest acceptable

28   acidification status of the water leaving the root zone. Based on the critical limit, the

29   highest allowed biomass harvesting can be calculated, keeping the other parameters

30   constant. In this study the critical limit was set to ANC (Acid Neutralizing Capacity) = 0.

31   Nitrogen was assumed to be affecting acidity only if it leaches from the root zone. The

32   critical biomass harvesting was calculated for almost 12 000 National Forest Inventory

33   sites with spruce and pine forest, using the best available data on deposition, weathering

34   and nitrogen leaching. The exceedance of critical biomass harvesting was calculated as

35   the difference between the estimated harvest losses and the critical biomass harvesting.

36   The results were presented as median values in merged catchments in a catchment

37   database, with totally 2079 merged catchments in Sweden. According to the calculations,

38   critical biomass harvesting was exceeded in the southern half of Sweden already at stem

39   harvesting in spruce forests. Whole-tree harvesting expanded the exceedance area, and

40   increased the exceedance levels in southern Sweden. The exceedance in pine forest was

2

41   lower and affected smaller areas. It was concluded that the concept of critical biomass

42   harvesting can be successfully applied on the same database that has been used for

43   critical load calculations in Sweden, using basically the same approach as has been

44   extensively applied, evaluated and discussed in a critical load context. The results from

45   the calculations in Sweden indicate that whole-tree harvesting, without wood ash

46   recycling, can be expected to further slow down recovery, especially in the most acidified

47   parts of the country, in the southwest.

48

49   **Key words**

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

51

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

76 for calcium, where the difference could be observed more than 25 years after the final

77 felling. Achat et al. (2015) performed a meta-analysis on 168 experiments in Europe and

78 North America, and found a significant decrease of base saturation in the upper 20 cm of

79 the mineral soil after whole-tree harvesting as compared to stem harvesting. However, the

80 effects varied between different experiments. Helmisaari et al. (2014) referred in a

81 literature review to several whole-tree harvesting experiments in the Nordic countries,

82 some of which showed negative effects on soil acidification indicators after whole-tree

83 harvesting whereas others showed no significant effect.

84

85 The critical load of acidity was an important tool in adjusting policies to reduce emissions

86 of sulphur and nitrogen oxides (Sundqvist et al., 2002). Critical loads of acidity are

87 defined as "a quantitative estimate of an exposure to one or more pollutants below which

88 significant harmful effects on specified elements of the environment do not occur

89 according to present knowledge" (Nilsson et al., 1988). Calculations of critical loads of

90 acidity are based on acidity mass balances, and can be modelled using the SMB model

91 (Sverdrup et al., 1994) or PROFILE (Sverdrup et al., 1993).

92

93 As the deposition of acidifying substances has been reduced and the impact of forestry

94 has increased, the need of a new policy tool, focusing on biomass harvesting, has

95 emerged. The aims of this paper were to put forward a policy tool for sustainable biomass

96 harvesting based on the critical load of acidity concept, "Critical biomass harvesting",

97 and to test it on the Swedish national critical load database.

98

99

100 **Materials and Methods**

101 *Concept and equations*

102 The calculations of Critical biomass harvesting were based on the same concept as the

103 calculations of Critical load of acidity (Sverdrup et al., 1994). The SMB formula (Eq. 1,

104 Posch et al., 1995) was used as a basis for the calculations, and was applied for the root

105 zone, which was assumed to be 50 cm in depth.

106

107 $S_{dep}+N_{dep}+Cl_{dep}+BC_{harv}+Alk_{leach} = BC_{dep}+BC_{weath}+N_{imm}+N_{harv}+N_{de}$ (Eq. 1)

108

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

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

111 harv = net losses at harvesting

112 Alk_{leach} = Alkalinity leaching

113 weath = weathering

114 imm = immobilization

115 de = denitrification

116

117 The critical load of acidity is generally calculated according to Eq. 2, which is based on

118 Eq. 1. The critical load is the highest deposition that still leads to acceptable runoff water

119 quality, based on a chemical criterion and a critical limit, used to calculate the critical

120 alkalinity leaching ($Alk_{leach(crit)}$ in Eq. 2). In Sweden, the criterion most often used has

121 been the $Bc:Al_i$, (where Bc refers to the sum of Ca, Mg and K), a criterion associated

122   with tree health, and the critical limit has often been set to 1 (Sverdrup et al., 1994).

123   Exceedance is calculated according to Eq. 3.

124

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

126

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

128

129

130

131   For critical biomass harvesting, ANC in the runoff water was used as a chemical

132   criterion, with a critical limit of 0. This means no acidification exported from the soils to

133   the leaching water, but neither any acid neutralizing capacity. Setting the ANC limit to 0

134   was motivated by the assumption that the water gains some neutralizing capacity on the

135   way from the 50 cm root zone through the mineral soil and to the surface water.

136

137   The nitrogen (N) calculations were greatly simplified. Almost all of the inorganic N

138   deposition is taken up by vegetation and soil organisms in most Swedish forest soils, and

139   the inorganic N concentrations in soil water below the root zone are thus very low,

140   although in the southwesternmost part of Sweden highly elevated concentrations of

141   inorganic N is common (Akselsson et al., 2010). In the clearcut phase, when the N uptake

142   is interrupted, leaching of inorganic N from the root zone occurs, which has been shown

143   on seven stem harvested sites in Sweden, on latitudes between 57° and 62° (Futter et al.,

144   2010). The leaching is generally higher in the southwest (Akselsson et al., 2004), where

7

145   the N accumulation has been the highest (Akselsson et al., 2005). The acidifying effect of

146   N was calculated based on following assumptions:

147

148   (1) The N that is leached from the soil as nitrate (NO_3-N) is acidifying, one equivalent

149   (based on reasoning in Galloway, 1995).

150

151   (2) The N that is leached from the soil as NH_4-N counteracts acidification, one equivalent

152   (based on reasoning in Galloway, 1995).

153

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

155

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

157

158   Assumption 3 and 4 are rough assumptions required to simplify calculations, and have to

159   be kept in mind when interpreting the results.

160

161   The equations for calculating critical biomass harvesting based on the reasoning above

162   are given in Eq. 4-5.

163

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

165

166   $\text{Exceedance} = \text{BC}_{harv} - \text{Crit BC}_{harv}$ (Eq. 5)

167

8

168   *National database for Sweden*

169   Weathering rates, deposition, leaching and harvest losses were estimated on 5412 spruce

170   sites (where Norway spruce makes up more than 70% of the forest stand) and 6361 pine

171   sites (where Scots pine makes up more than 70% of the stand) within the Swedish

172   National Forest Inventory (Hägglund, 1985). The critical harvest and the exceedance

173   were then calculated according to Equations 4 and 5 respectively for all sites. The results

174   were transferred to a national catchment database with 2079 merged catchments from the

175   Swedish Environmental Emissions Data (SMED) Consortium; Brandt et al., 2008). This

176   platform gives a better overview than the National Forest Inventory platform, but has

177   high enough geographical resolution to account for the regional variation in e.g

178   weathering rates and deposition. The platform is widely used in Swedish policy

179   applications, which also makes it suitable. Spruce sites were present in 877 and pine sites

180   in 959 of the merged catchments. Medians were calculated for spruce and pine for those

181   merged catchments.

182

183   *Deposition*

184   Sulphur deposition (excluding sea salt) for the year 2020, as simulated by the 2011

185   EMEP model (www.emep.int) under the current legislation scenario of the latest revision

186   of the Gothenburg protocol, was used. The deposition has been modelled in grid cells of

187   50 by 50 km, and each National Forest Inventory site was assigned the deposition from

188   the corresponding grid cell. Sulphur deposition from sea salt was estimated based on

189   sodium deposition (see below), based on the assumption that all Na comes from sea salt.

190 The 2020 data were used instead of today's deposition, since the critical harvest

191 calculations are meant to be interpreted on a long-term (at least one forest rotation).

192

193 Base cation deposition (Ca, Mg, Na and K) was derived from the MATCH model

194 (Langner et al., 1996), in the resolution 20*20 km. There are no clear trends in base

195 cation deposition during the last decade, and the future deposition is very difficult to

196 predict. In this study, the median deposition for 2007-2009 was used. Cl deposition was

197 estimated based on Na deposition and the composition of sea salt, assuming that all Na

198 and Cl deposition derives from sea salt.

199

200 *Base cation losses at stem- and whole-tree harvesting*

201 Harvest losses at stem only harvesting and whole-tree harvesting were based on data on

202 site productivity on the sites. The site productivity gives the optimal growth of a stand

203 (m^3 stem wood per hectare and year), and would therefore overestimate the actual

204 growth. Thus the site productivity was reduced by 20% in an effort to imitate real

205 conditions. Volume growth was recalculated to mass growth using the stem density of

206 430 kg m^{-3} for spruce and 490 kg m^{-3} for pine. Harvest losses for the stem harvesting

207 scenario were then estimated by multiplying the volume growth by the base cation

208 concentration in stems according to Table 1, assuming that 100% of the stems were

209 harvested. In the whole-tree harvesting scenario, 100% of the stems were assumed to be

210 removed together with 60% of the branches, in accordance with a scenario from Swedish

211 Forest Agency (2008). Furthermore, 75% of the needles were assumed to accompany the

212 branches. The amount of branches and needles available for harvesting was estimated

10

213   from stem data and fractions between biomass of stems, branches and needles from

214   standard methods (Marklund, 1988). The available mass of branches and needles were

215   reduced according to the removal percentages given above, to derive the loss of branches

216   and needles from the forest sites. By multiplying the mass of branches and needles

217   removed from the sites, by base cation concentrations in branches and needles

218   respectively (Table 1), the loss off base cations from the sites was derived. The base

219   cation concentrations were national average values (see table below), due to lack of site

220   specific data. Zetterberg et al. (2014) performed a sensitivity analysis for Ca, and

221   concluded that the lack of site specific nutrient concentration data was the main source of

222   uncertainties in calculations of harvest losses of Ca, whereas uncertainties in site

223   productivity and in the amount of branches left on the ground, contributed less to the

224   overall uncertainties. However, in national calculations, using national averages of

225   nutrient concentrations is the only option, since there are no available studies indicating

226   that the concentration varies geographically, or that they can be linked to site conditions.

227

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

229   over latitudes from 56 to 64, and 17 pine sites, spanning over latitudes from 56 to 66 (S. Jacobson, pers.

230   comm).

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

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

233

234   *Weathering*

235   Weathering rates were modelled with the PROFILE model, a soil chemistry model

236   originally developed to calculate the effect of acid rain on soil chemistry (Sverdrup et al.,

237   1993). It includes process oriented descriptions of chemical weathering of minerals,

238   leaching and accumulation of dissolved chemical components and solution equilibrium

239   reactions. PROFILE is a steady state model, which means that yearly data or long-term

240   averages are required as input to the model, not time-series as in dynamic models.

241   PROFILE then calculates the soil solution chemistry at steady state, i.e. the chemistry

242   that finally settles using the constant input data. In PROFILE, the soil is divided into soil

243   layers with different properties, preferably based on the naturally occurring soil

244   stratification. Weathering is calculated using transition state theory. The geochemical

245   properties of the soil system, such as soil wetness, mineral surface area, hydrogen, cation

246   and organic acid concentrations, temperature and mineral composition, are important

247   inputs.

248

249   Weathering rates were modelled on the National Forest Inventory sites, to a depth of 50

250   cm (including the organic layer) based on the same methodology and database as in

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

252 above.

253

254 *Leaching of inorganic nitrogen from growing forests and clearcuts*

255 The leaching of NO_3-N and NH_4-N from the root zone in growing forests was estimated

256 using concentrations in soil water from the Swedish Throughfall Monitoring Network,

257 SWETHRO (Pihl Karlsson et al., 2011) in combination with runoff data from the

258 Swedish Meteorological and Hydrological Institute, SMHI (average 1961-1990; Raab et

259 al., 1995). Median concentrations 2010-2012 (three measurements per year) on 60 sites

260 were estimated, and a median of that was used for the whole country since the dataset did

261 not support different concentrations in different parts of the country. Most farthest to the

262 southwest there are several sites with elevated NO_3-concentrations (Akselsson et al.,

263 2010), but there are also sites with low concentrations. By using a median for the whole

264 country, the N leaching was probably underestimated in soutwesternmost Sweden, but

265 since there are no measurements of N leaching at the National Forest Inventory sites, the

266 median from the SWETHRO network was still used.

267

268 The NO_3-N leaching from clearcuts was calculated based on an empirical relationship in

269 Futter et al. (2010), where NO_3-N leaching is a function of site quality on seven sites in

270 Sweden, covering site quality classes (defined as mean annual stemwood increment) of 3

271 to 11 m^3 per hectare and year. Since site quality is available on all National Forest

272 Inventory sites, the NO_3-N leaching could be estimated. To convert leaching to yearly

273   values, a rotation period of 85 years was assumed for southern Sweden, and 105 years for

274   northern Sweden.

275

276   **Results**

277   The net losses of base cations were substantially higher in spruce forests than in pine

278   forests (Figure 1; Table 2), due to more biomass in spruce forests. Harvesting of residues

279   (branches and tops) led to 70% more losses in spruce forests whereas the corresponding

280   increase in pine forests was 30%. There is a gradient in Sweden with higher base cation

281   losses in the south than in the north, corresponding to the climate gradient. In the northern

282   part there is a gradient with higher losses in the east than in the west.

283

284   a.   b.   c.   d.
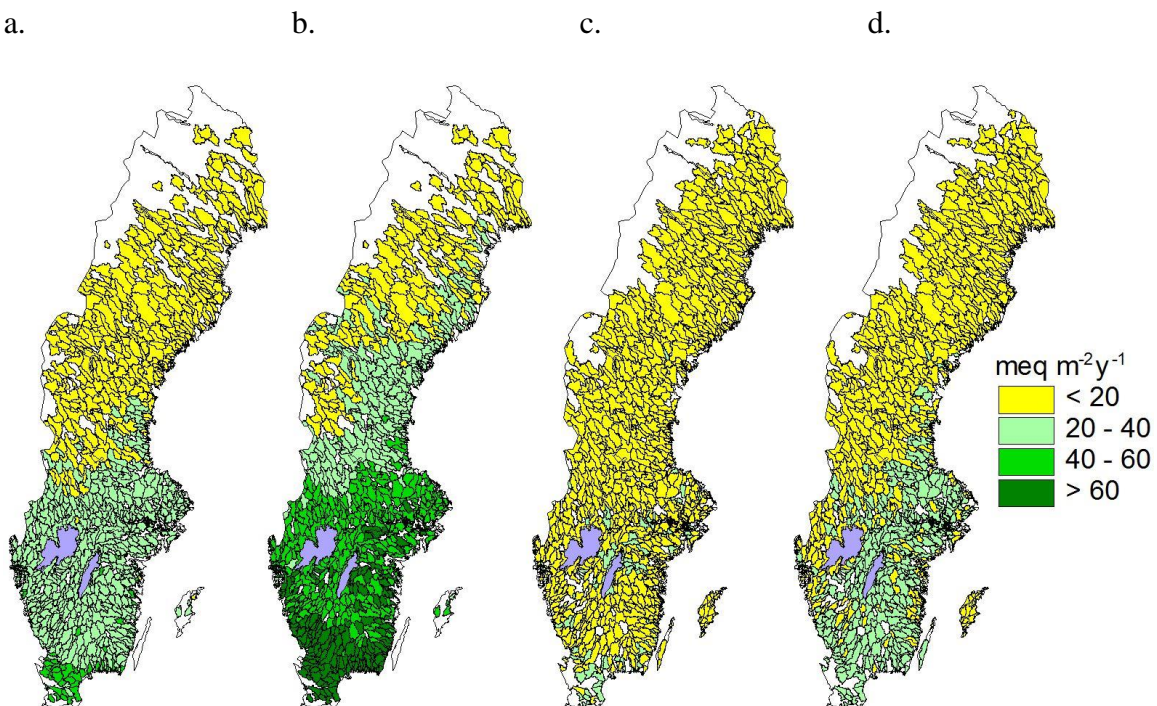

285

14

286   Figure 1. Losses of base cations (Ca, Mg, Na, K) at stem harvesting in spruce forests (a),

287   whole-tree harvesting in spruce forests (b), stem harvesting in pine forests (c) and whole-

288   tree harvesting in pine forests (d).

289

290

	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

291   Table 2. Harvest losses, critical harvesting and exceedance at stem-only and whole-tree

292   harvesting in spruce and pine forest (meq m^{-2} y^{-1}). Medians, 5- and 95-percentiles of the

293   merged catchments.

294

295   The critical harvesting was the highest in southwestern Sweden, parts of northern Sweden

296   and the western part of central Sweden (Figure 2). The critical harvesting was generally

297   slightly lower for pine than for spruce, since pine forests are more frequently occurring
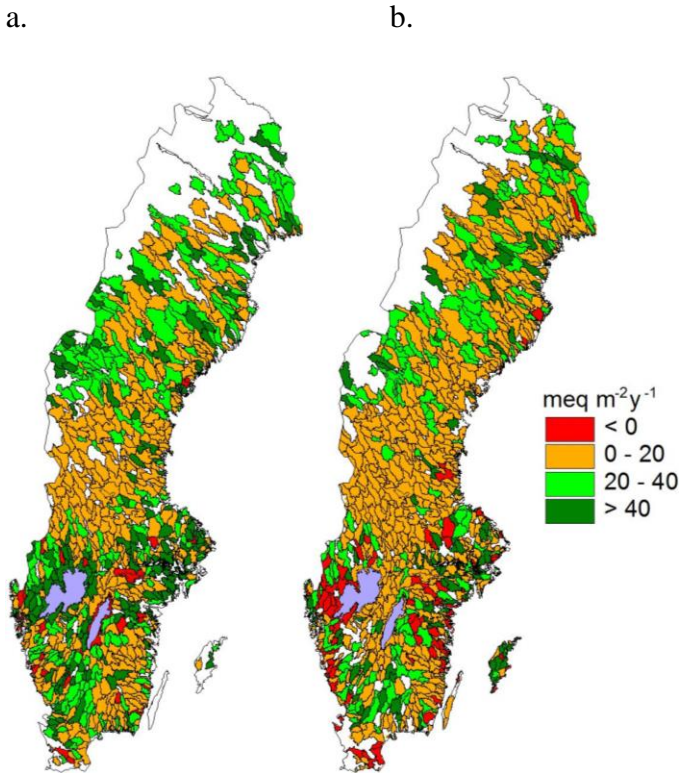
298   on poorer soils.

299

300

301

15

302 a.   b.

303

304 Figure 2. Critical harvesting at the deposition of 2020 according to the EMEP model in

305 spruce forests (a) and in pine forests (b).

306

307 In spruce forest the critical harvesting was exceeded in most parts of the southern half of

308 Sweden and along the coast in the north, already at stem-harvesting (Figure 3). Whole-

309 tree harvesting increased the area with exceeded critical harvesting slightly, but above all

310 it led to higher exceedances in southern Sweden (Figure 3, Table 2). In pine forests the

311 critical harvesting was exceeded in 50% of the merged catchments at stem harvesting, but

312 the exceedance was generally low (Figure 4; Table 2). Whole-tree harvesting led to a

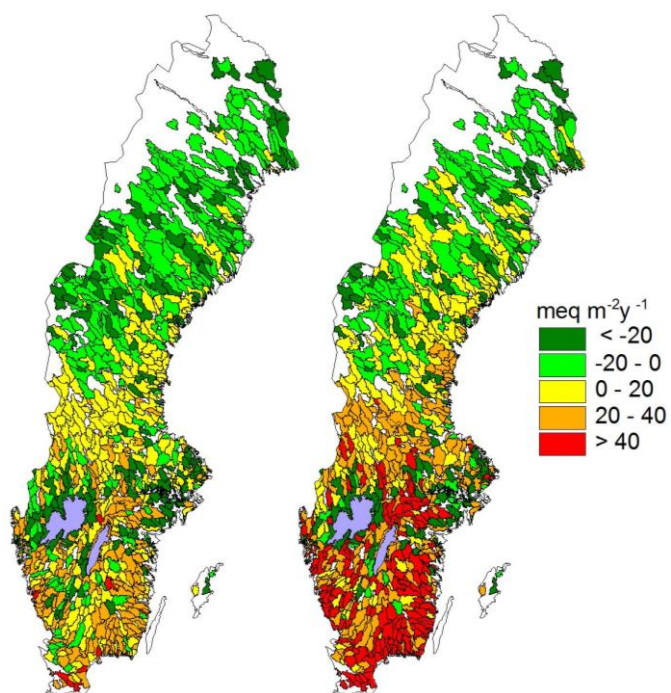313 somewhat larger fraction of catchments where the critical harvesting was exceeded.

314

315

16

316

317   Figure 3. Exceedance of critical harvesting in spruce forest at stem harvesting (a) and

318   whole-tree harvesting (b)

319

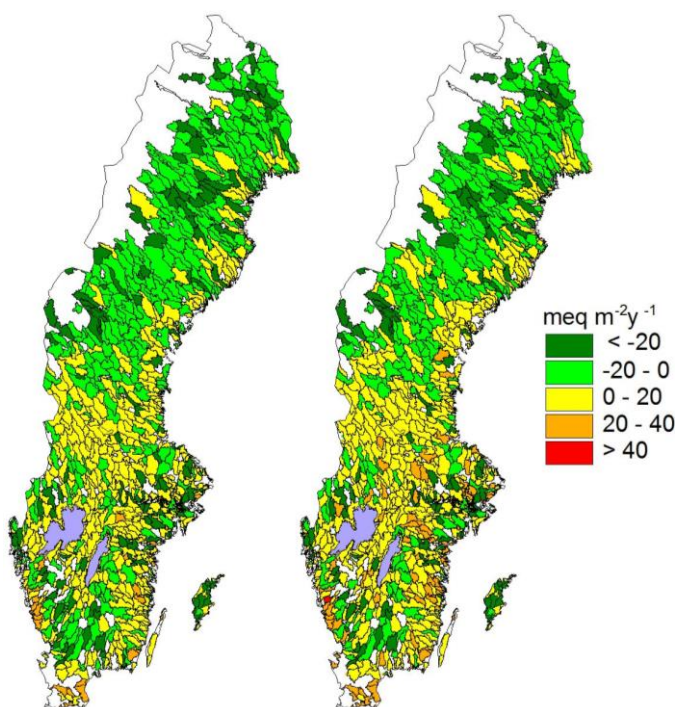320

321

322

323   Figure 4. Exceedance of critical harvesting in pine forest at stem harvesting (a) and

324   whole-tree harvesting (b)

325

Discussion

327   Going from critical load of acidifying deposition to critical biomass harvesting is a

328   natural step in a country like Sweden, where the acidifying impact of biomass harvesting

329   is often equal or greater than that of atmospheric deposition (Iwald et al., 2013). Along

330   with the decreasing deposition, and the increasing demand of renewable energy, biomass

331   harvesting will play an even larger role for acidification in the future. An advantage of

332   using the steady state mass balance approach is that it is robust in that it has been applied,

333   evaluated and discussed extensively in the critical load context (Sverdrup et al., 1995;

334   Kurz et al., 2001; Freer-Smith et al., 2003; Kennedy et al., 2001; Jönsson et al. (1995).

335

18

336　Whereas the robustness and transparency are advantages of the steady state concept, the

337　lack in dynamics is a drawback. Inputs are constant values of deposition and other

338　parameters, thus neither historical nor future deposition and land use are taken into

339　account. This means, for example, that the critical harvesting is overestimated in the areas

340　with the highest deposition such as southwestern Sweden, where the historical deposition

341　has been much higher (Pihl Karlsson et al., 2011), and where the soils accordingly have

342　been depleted of base cations.

343

344　Dynamic models are required to account for changes over time. In Zanchi et al. (2014)

345　the dynamic model ForSAFE has been used to study different management methods, such

346　as stem and whole-tree harvesting have been compared, using historical deposition and

347　climate data as well as future predictions for deposition and climate. A conclusion was

348　that the effect of whole-tree harvesting on soil chemistry varied over the forest rotation.

349　As opposed to the steady state concept, the advantage of dynamic modelling is the

350　dynamic representation of processes over time, whereas the drawbacks are the less

351　opportunities to generalize over large regions. By combining the different approaches, by

352　applying steady state calculations and dynamic modelling in the same areas, the

353　advantages of both approaches can be utilized (Akselsson et al., 2010).

354

355　Another effect of lacking dynamics is that climate change effects are not accounted for. A

356　substantial effect of a changed climate on weathering was simulated in Sweden using the

357　steady state model PROFILE in Akselsson et al. (2016). The increased weathering rates

358　were compared with the increased losses of base cations at whole-tree harvesting, and the

359 conclusions drawn were that the increased weathering could not compensate for the

360 increased base cation losses at whole-tree harvesting in most areas. Aherne et al. (2012)

361 used the more dynamic MAGIC model in Finland, and came to similar conclusions. A

362 fully dynamic approach was used in Gaudio et al. (2015), where the ForSAFE model was

363 used on two forest sites in France to assess the effect of climate and deposition changes

364 on soil chemistry. In accordance with the PROFILE and MAGIC studies, climate change

365 gave a substantial effect on base cations, in this case shown as increased base saturation.

366

367 Both in critical load and critical harvesting calculations the handling of N requires some

368 assumptions, since the acidifying effect of N is more complex than the effect from

369 sulphur (Galloway, 1995). In many critical load calculations all N terms, i.e. deposition,

370 uptake, denitrification and immobilization have been accounted for, as in Sverdrup et al.

371 (1995). Immobilization and denitrification are terms that are difficult to quantify and thus

372 require assumptions. In the present study it was assumed that the acidifying effect of N

373 was limited to the present NO_3 leaching based on measurements in soil water. A median

374 value for the whole country was used, since the concentrations are similar (very low) on

375 most sites in Sweden. However, there are sites in southwestern Sweden with highly

376 elevated NO_3 leaching, and in this region the acidifying effect of N can be assumed to be

377 underestimated for many forests.

378 The assumption that only the NO_3 that is leaching is acidifying means that potential

379 changes in NO_3 leaching in the future, and effects of whole-tree harvesting on NO_3

380 leaching, are not accounted for. In N-rich areas whole-tree harvesting could lead to

381 reduced risk of NO_3 leaching, counteracting the acidifying effect of the base cation

382 removal (Zanchi et al., 2014). However, results from experiments are contradictory.

383 Gundersen et al. (2006) concluded in a review paper that whole-tree harvesting has

384 resulted in decreased NO_3 leaching in some studies, and increased NO_3 leaching in

385 others. Ring et al. (2016) demonstrated in an experiment lower NO_3 concentrations in soil

386 solution after whole-tree harvesting than after conventional harvesting. In Ring et al.

387 (2015) one of the two investigated sites showed decreasing NO_3 concentrations with

388 decreasing amount of logging residues left on the clearcuts, whereas the other showed no

389 such tendency. de Jong et al. (2017) concluded in a synthesis article that whole-tree

390 harvesting leads to no or a slightly decreased risk of N leaching.

391 The choice of critical limit is naturally important for the results. In critical load studies,

392 the critical limits used were often focusing on tree health. One of the most commonly

393 used criteria is Bc:Al ratio (Sverdrup et al., 1995). The critical limit chosen in this study,

394 ANC=0 at 50 cm depth, is focusing on water quality. It gives no margins for recovery at

395 that soil depth, and thus it can be seen as too low a limit, especially in areas with thin soil

396 layers. In areas with thick soil layers, however, the weathering in deeper layers can

397 increase the ANC before it reaches surface waters, and thus the limit is more appropriate.

398

399 The clear gradient, with increasing exceedance from north to south, corresponds to the

400 higher base cation losses at harvesting and to the higher sulphur deposition in the south.

401 In the southern part the exceedance is higher towards the east, although the sulphur

402 deposition is higher in the western part. This is due to the higher weathering rate and base

403 cation deposition in the western part, which increases the critical biomass harvesting.

404

405   The results show that whole-tree harvesting in spruce forest in the southern half of

406   Sweden and along the coast in the north is generally not sustainable, unless nutrients are

407   added. Also stem harvesting leads to exceedance in the southern part of the country, but

408   the exceedance is much smaller. The areas with high exceedance coincide with the areas

409   with most acidified soils due to historical acid deposition (Pihl Karlsson et al., 2011). The

410   recovery in those areas are generally slow (Akselsson et al., 2013) and increased base

411   cation losses can be expected to hamper recovery further. In pine forests there is small or

412   no exceedance at stem harvesting, and whole-tree harvesting only changes the picture

413   slightly. The results are important as a basis for forest management policies related to

414   whole tree harvesting and wood ash recycling.

415

416   **Conclusions**

417   Critical biomass harvesting can be estimated based on the same steady state mass balance

418   concept and the same national input database as for critical load of deposition. The

419   approach is robust in that it has been extensively applied, evaluated and discussed in a

420   critical load context. As for the critical load calculations, two important decisions have to

421   be made, about assumptions related to the N processes and about which chemical criteria

422   and critical limit to use.

423

424   The calculations for Sweden showed that critical biomass harvesting was exceeded in the

425   southern half of Sweden already at stem harvesting in spruce forests, when ANC=0 was

426   used as a critical limit. Whole-tree harvesting expanded the exceedance area, and

427 increased the exceedance levels in southern Sweden. In pine forests the exceedance was

428 lower, and affected smaller areas.

429

430 The areas with exceedance coincide with the most acidified soils from acid deposition,

431 where recovery is slow. Whole-tree harvesting, without wood ash recycling, especially in

432 spruce forests in those areas can be expected to further slow down recovery.

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