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Can increased weathering rates due to future warming compensate for base cation losses following whole-tree harvesting in spruce forests?

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1 Title:

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4

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29

30 Abstract

31 Whole-tree harvesting, i.e. harvesting of stems, branches and tops, has become increasingly common
32 during recent decades due to the increased demand for renewable energy. Whole-tree harvesting leads to an
33 increase in base cation losses from the ecosystem, which can counteract recovery from acidification. An
34 increase in weathering rates due to higher temperatures is sometimes suggested as a process that may
35 counteract the acidifying effect of whole-tree harvesting. In this study the potential effect of increasing
36 temperature on weathering rates was compared with the increase in base cation losses following whole-tree
37 harvesting in spruce forests, along a temperature gradient in Sweden. The mechanistic model PROFILE
38 was used to estimate weathering rates at National Forest Inventory sites at today's temperature and the
39 temperature in 2050, as estimated by two different climate projections. The same dataset was used to
40 calculate base cation losses following stem-only and whole-tree harvesting. The calculations showed that
41 the increase in temperature until 2050 would result in an increase in the base cation weathering rate of 20–
42 33%, and that whole-tree harvesting would lead to an increase in base cation losses of 66% on average,
43 compared to stem-only harvesting. A sensitivity analysis showed that moisture changes are important for
44 future weathering rates, but the effect of the temperature change was dominating even when the most
45 extreme moisture changes were applied. It was concluded that an increase in weathering rates resulting
46 from higher temperatures would not compensate for the increase in base cation losses following whole-tree
47 harvesting, except in the northernmost part of Sweden.

48

49 Keywords: weathering, climate change, whole-tree harvesting, forest fuels, acidification

50

51 1. Introduction

52 Emissions of acidifying substances have decreased substantially in Europe in recent decades (Nyiri et al.
53 2009), which has led to the initiation of the recovery of surface waters in many areas (Evans et al. 2001;
54 Skjelkvåle et al. 2001; Fölster and Wilander 2002). However, both measurements (Graf Pannatier et al.
55 2011; Pihl Karlsson et al. 2011; Akselsson et al. 2013) and modelling (Sverdrup et al. 2005) indicate that
56 the recovery of soils is slow, which can be explained by the slow replacement, through weathering and
57 deposition, of the base cations that were lost during acidification. Lakes can not be expected to fully
58 recover until soils are recovered. Moreover, the acidifying impact of forestry in Sweden has increased in
59 recent decades, which may further delay recovery (Hultberg and Ferm 2004; Akselsson et al. 2007). In
60 relation to the EU directive 2009/28/EG, Sweden has committed to achieving a share of energy from
61 renewable sources in total energy consumption of 49% by 2020. The increasing demand for renewable
62 energy has made whole-tree harvesting, i.e. harvesting of not only stems but also branches and tops, more
63 common. In 2013, harvesting of branches and tops was reported for almost half of the planned final
64 fellings. Stump harvesting was still not common (Swedish Forest Agency 2014). The high concentrations
65 of base cations in branches and tops lead to a substantial increase in the loss of base cations following
66 whole-tree harvesting compared to conventional stem harvesting (Akselsson et al. 2007). Iwald et al.
67 (2013) estimated that the acidifying effect of harvesting of spruce (including branches, tops and stumps)
68 was 114–263% of that of acidic deposition, while the corresponding range for pine was 57–108%. Using
69 dynamic modelling, Aherne et al. (2012) showed that whole-tree harvesting may have a serious effect on
70 soil nutrient status. Brandtberg and Olsson (2012) studied the long-term effects of whole-tree harvesting,
71 and found significantly lower concentrations of exchangeable base cations in mineral soil after 15 years.
72 After 25 years, the exchangeable base cation concentration still tended to be lower after whole-tree
73 harvesting than after stem-only harvesting, but the effect was not significant. Zetterberg et al. (2013)
74 studied Ca concentrations in soil and soil water 27-30 years after treatment in the same experiments. They
75 found that the Ca concentrations in soil water as well as exchangeable Ca in soil were lower after whole-
76 tree harvesting than after stem-only harvesting. A few years later, 32-35 years after treatment, the effect of
77 whole-tree harvesting on Ca concentrations in soil water only remained on one of the sites.

78

79 Climate change affects ecosystem processes such as tree growth, decomposition and mineral weathering.
80 The net effect on acidification may be reinforcement or counteraction, depending on the effects of climate
81 change and the conditions prevailing at each site. Climate change may lead to increased tree growth and
82 thus increased base cation uptake, through increased air concentrations of CO₂ in combination with
83 increased temperatures and prolonged growing seasons (Bergh et al. 2010). However, in areas where
84 climate change leads to drier conditions and possibly drought, the effect may be the opposite (Kellomäki et
85 al. 2007). Changes in temperature and moisture affect the rates of both weathering (Brady and Weil 1999)
86 and decomposition (Berg and McClaugherty 2003). An increase in the release of base cations through
87 weathering and decomposition has the potential to accelerate recovery from acidification. However, in
88 nitrogen-rich areas, increased decomposition can lead to nitrate leaching (van Breemen et al. 1998; Wright
89 and Jenkins 2001), which is an acidifying process. Other effects related to climate change that may affect
90 recovery are changes in the frequency of sea-salt episodes (Akselsson et al. 2013; Skjelvåle et al. 2007;
91 Laudon 2008; Hindar et al. 1995), the frequency of drought (Laudon 2008), and changes in conditions
92 affecting pests (Netherer and Schopf 2010). To conclude, temperature, soil moisture and other effects
93 related to climate change are key factors in controlling soil and vegetation processes that may affect
94 recovery from acidification.

95

96 Both the temperature and precipitation are expected to increase substantially throughout Sweden in the
97 coming decades (see e.g. Lind and Kjellström 2008; Kjellström et al. 2011). Increased temperature and
98 precipitation may affect soil moisture in different ways, and the net effect is highly uncertain due to the
99 limited accuracy with which precipitation and evapotranspiration can be simulated by climate models (e.g.
100 Ehret et al. 2012). The natural long-term process resulting from climate change that can be expected to
101 counteract acidification most is a potential increase in the weathering rate due to higher temperatures. The
102 effect can be strengthened or weakened by changed soil moisture, depending on the net effect from
103 increased temperature and precipitation on the soil moisture. The rate of soil organic matter decomposition
104 and the subsequent release of nutrients through mineralization may also increase due to increasing
105 temperatures, but this process is short-lived in the time frame of the current study, and its effect on

106 acidification remains uncertain. In this study we focused on the impact on weathering of the future change
107 in temperature, which is generally believed to be more robust than the change in precipitation. The main
108 aim of this study was to determine whether the temperature-induced increase in weathering rate could
109 counteract the increase in base cation loss due to whole-tree harvesting, including branches and tops, in
110 different parts of Sweden. The study also comprises a sensitivity analysis for the effect of moisture on
111 weathering rates. The study was limited to spruce forests, which cover 42% of the forested areas in
112 Sweden, where most of the whole-tree harvesting is performed, and where the nutrient losses resulting from
113 harvesting are greatest (Akselsson et al. 1997). Effects of climate change on other processes than
114 weathering, such as tree growth, are not accounted for in this study.

115

116 2. Methods

117 A database from the Swedish Environmental Emissions Data (SMED) consortium, with 2079 areas
118 covering Sweden and where each area consists of a number of subcatchments merged together, was chosen
119 as a common platform for the calculations (Brandt et al. 2008). All the data required for the calculations
120 were transferred to these merged catchments. The weathering rates of the base cations Ca, Mg, K and Na in
121 the root zone were modelled with the PROFILE model (Sverdrup and Warfvinge 1993) for two time
122 periods representing present conditions and the conditions in 2050. The changes in temperature projected
123 by two different climate models were used to obtain an indication of the sensitivity of weathering to the
124 uncertainties in climate modelling. The effect of moisture on weathering rates was studied in a sensitivity
125 analysis by performing two extra weathering model runs for each climate scenario, with maximum and
126 minimum moisture changes based on model-predicted changes in soil moisture over Sweden. Base cation
127 losses as a result of harvesting were calculated for two forest management scenarios: stem-only and whole-
128 tree harvesting, as these are common practices in Sweden. Finally, base cation loss through harvesting was
129 subtracted from the amount provided by weathering, for different combinations of weathering rates
130 (resulting from temperature projections by the two climate models over the two periods studied) and
131 management scenarios (stem-only and whole-tree harvesting). The different steps are described in detail
132 below.

133

134 2.1 Temperature projections

135 In PROFILE yearly averages of soil temperatures in the root zone (the upper 50 cm of the soil) are
136 required, but these are often not available. However, the average annual soil temperature may be assumed
137 to be similar to the air temperature (e.g. Zheng et al. 1993), and thus mean yearly air temperatures were
138 used in this study. The average temperature for the period 1981–2010, meant to represent present
139 conditions, and the average temperature for the period 2036–2065, meant to represent the temperature
140 2050, were estimated for the merged catchments, based on the results from two climate model projections,
141 in the following denoted ECHAM and HADLEY (Table 1). In these projections, global climate simulations
142 for the period 1961–2100 by models ECHAM5 (Roeckner et al. 2003) and HadCM3 (Johns et al. 2003), in
143 both cases forced by IPCC emission scenario A1B (Nakićenović et al. 2000), have been regionally
144 downscaled over Europe by the RCA3 model (Samuelsson et al. 2011; Kjellström et al. 2011). The two
145 projections were chosen to represent different levels of expected future temperature change. Of the 16
146 climate model projections reviewed by Kjellström et al. (2011), HADLEY is one of those projecting the
147 greatest temperature increase in Scandinavia, whereas ECHAM projects a temperature increase in the lower
148 range. Daily surface temperatures (°C) were bias-corrected using distribution-based scaling (Yang et al.
149 2010).

150

151 Table 1. Temperature and harvesting scenarios.

152

153 2.2 Harvesting scenarios

154 In the whole-tree harvesting scenario, it was assumed that 100% of the stems was removed together with
155 60% of the branches and tops, in accordance with a scenario meant to imitate common practise, used by the
156 Swedish Forest Agency (2008) (Table 1). Furthermore, it was assumed that 75% of the needles
157 accompanied the branches and tops.

158

159 2.3 Base cation weathering rates at different temperatures

160 Weathering rates were modelled with the PROFILE model, a soil chemistry model originally developed to
161 calculate the effect of acid rain on soil chemistry (Sverdrup and Warfvinge 1993). It includes process-

162 oriented descriptions of chemical weathering of minerals, leaching and accumulation of dissolved chemical
163 components and solution equilibrium reactions. PROFILE is a steady-state model, which means that yearly
164 data or long-term averages are used as input, and not time series as in dynamic models. PROFILE then
165 calculates the soil solution chemistry at steady state. The soil is divided into soil layers with different
166 properties, preferably based on the naturally occurring soil stratification. Weathering is calculated using
167 transition state theory and the geochemical properties of the soil system, such as soil wetness, mineral
168 surface area, the concentrations of hydrogen, cations and organic acids, temperature and mineral
169 composition. Four weathering reactions are included in PROFILE, the reaction with H⁺, H₂O, CO₂ and
170 organic ligands (R⁻) (Sverdrup and Warfvinge 1993; Warfvinge and Sverdrup 1995). The dependence of
171 temperature in PROFILE is calculated with rate coefficients for different minerals and different reactions,
172 taken from laboratory studies and standardized to 8°C using an Arrhenius relation (Sverdrup and
173 Warfvinge, 1993; Brantley 2008). The expression to adjust the coefficient to ambient temperatures is given
174 in Equation 1.

175

$$176 \ln(k_T/k_{8^\circ\text{C}}) = (E_A/R) \cdot ((1/281) - (1/T)) \quad (\text{Equation 1})$$

177

178 where E_A = activation energy (kJ/kmol), R = universal gas constant (kJ/kmol/K) and T = absolute
179 temperature (K).

180

181 The temperature dependence factors (E_A/R), used in PROFILE for the minerals in this study, are listed in
182 Table 2.

183

184 Table 2. Temperature dependence factors (E_A/R) used in PROFILE for all included minerals, and for the
185 reactions with H⁺, H₂O, CO₂ and organic ligands (R⁻).

186

187 Weathering rates for the root zone, here defined as the upper 50 cm of the soil, were modelled based on
188 data from 17333 Swedish National Forest Inventory (NFI) sites (Hägglund 1985), using the same
189 methodology and database as described by Akselsson et al. (2008). The root zone was chosen since the

190 soils on the sites can be regarded as well-drained, and the contribution of weathering products from lower
191 layers via ground water transport can be assumed to be of minor importance. The profiles were divided in
192 four layers, where the upper layer was organic.

193 PROFILE requires soil input data, e.g. mineralogy, specific surface area, density and soil moisture, as well
194 as temperature data and data on deposition and net uptake of base cations and nitrogen in trees. Mineralogy
195 from earlier national studies (e.g. Akselsson et al. 2007), where total chemistry from a national soil
196 geochemistry database has been recalculated to mineralogy using a normative model (Akselsson et al.
197 2004), was used. Each NFI site was assigned with the mineralogy composition from the nearest site in the
198 national soil geochemistry database. Soil texture and moisture has been classified on all NFI sites, and the
199 classes were translated to specific surface area and volumetric water content using translation tables from
200 Warfvinge and Sverdrup (1995). Constant, layer-specific values for densities were used for all sites, in
201 accordance with the national PROFILE modelling in Warfvinge and Sverdrup (1995). Deposition data were
202 derived from the MATCH model (Langner et al. 1996), and the average deposition from 2006–2008 was
203 used. Net uptake of base cations and nitrogen, here defined as the base cations and nitrogen lost at
204 harvesting, was calculated for the stem harvesting scenario and the whole-tree harvesting scenario for all
205 NFI sites, based on tree growth data on the NFI sites. The methodology is described more thoroughly in
206 section 2.5. Important input data parameters, their ranges throughout Sweden and their data sources are
207 summarized in Table 3. The mineralogy distribution for one of the minerals, hornblende, that contributes
208 substantially to the weathering rates, is shown in Figure 1, as an example of the variation in mineralogy
209 over Sweden. PROFILE was applied with temperatures for the two time periods and the two climate model
210 projections, according to the description above. Median weathering rates were finally calculated for each
211 merged catchment.

212

213 Table 3. The most important input parameters in PROFILE, their ranges throughout Sweden and their data
214 sources. The data sources are described in more detail in the text.

215

216 **Fig. 1** The fraction of hornblende in soils across Sweden, modelled with a normative model, based on a
217 national soil geochemistry database (Akselsson et al. 2004).

218

219 2.4 Sensitivity analysis of effects of moisture changes on weathering rates

220 The potential effect of a change in moisture due to climate change was studied through a sensitivity
221 analysis using model-predicted changes in soil moisture ranges over Sweden for the mid-century projection
222 period. Projected changes from the S-HYPE model were used. S-HYPE is a Sweden-wide model set-up of
223 the HYPE model (Hydrological Predictions for the Environment), a conceptual rainfall-runoff and nutrient-
224 transfer model (Strömqvist et al. 2012). In S-HYPE, Sweden is divided into 37000 sub-basins, and rainfall-
225 runoff dynamics are computed for each of those. Soil storages are modelled as linear reservoirs. Projected
226 maximum and minimum moisture changes in Sweden were calculated using both ECHAM and HADLEY
227 forcing data sets. Root zone moisture changes were then computed as differences between long-term
228 averages of baseline (1981-2010) and mid-century (2036-2065) periods for each of the sub-basins. These
229 sub-basin change projections were then used to derive bracketing minimum and maximum moisture
230 changes for the sensitivity analysis on weathering rates. Four new PROFILE runs were performed, with the
231 maximum and minimum moisture change for ECHAM and HADLEY separately. The resulting ranges of
232 weathering rates provide a sensitivity measure using the widest range of computed soil moisture changes in
233 Sweden, implicitly accounting for the accumulated uncertainty of the impact model chain.

234

235 2.5 Base cation losses due to stem-only and whole-tree harvesting

236 Harvest losses due to stem-only harvesting and whole-tree harvesting were based on data on site fertility
237 for 5412 spruce forest sites (sites with at least 70% spruce) in the Swedish National Forest Inventory
238 (Hägglund 1985). The site fertility is a measure of the optimal growth in a stand (m^3 stem wood per hectare
239 per year), and the actual growth is generally lower than the optimal growth. The site fertility was therefore
240 reduced by 20% in an effort to imitate real growth conditions, in accordance with earlier studies (Akselsson
241 et al. 2008). The growth data were then interpolated using kriging in a 1 x 1 km grid using Gaussian
242 Markov random fields (Lindgren et al. 2011, Rue et al. 2009), and the mean values were calculated for each

243 merged catchment, based on the kriging results. Volume growth was recalculated to give mass growth
244 using a spruce stem density of 430 kg m⁻³.

245

246 Losses of base cations arising from stem-only harvesting were estimated by multiplying the volume growth
247 by the base cation concentration in stems (Table 4), assuming that 100% of the stems was harvested. Losses
248 of base cations arising from whole tree harvesting were estimated as the sum of base cation losses through
249 the removal of stems and the losses through removal of branches and tops, and the needles accompanying
250 the branches and tops. The amount of biomass removed through harvesting of branches and tops was
251 estimated by combining data on stem biomass for the sites and generalised empirical data on fractions
252 between the biomass of stems, branches, tops and needles, by the use of standard methods (Marklund
253 1988). The estimated amount of branches, tops and needles removed was then multiplied by the base cation
254 concentrations in branches, tops and needles (Table 4). The estimated total mass of branches, tops and
255 needles was reduced according to the harvest percentages given above, to give the base cation losses
256 resulting from the removal of branches, tops and needles.

257

258 Table 4. Concentrations of base cations in stems, branches, tops and needles used in the calculations.

259

260 3. Results

261 The two climate models, HADLEY and ECHAM, gave very similar results for temperature for the present
262 climate, after bias correction, as expected, i.e. an average annual temperature over the whole of Sweden of
263 4.3°C, with a span from about -5°C in the north to 9°C in the south. However, the temperatures projected
264 by the two models for 2050 differed substantially, as can be seen in Figure 2 and Table 5. ECHAM
265 projected an average annual soil temperature of 6.5°C, i.e. an increase of 2.2°C compared with today, while
266 HADLEY projected an average temperature of 7.6°C, which is an increase of 3.3°C.

267

268 **Fig. 2** Temperatures predicted for the present time, (a) and (b), and for 2050 (c) and (d), by the ECHAM
269 and the HADLEY model respectively

270

271 Table 5. Modelled annual average, maximum and minimum temperatures for the merged catchments for
272 the present (1981-2010) and for 2050 (2036-2065), using ECHAM and HADLEY.

273

274 When using the temperature projected for 2050 by ECHAM, the base cation weathering rate increased by
275 an average of 20%, and the increase when using the temperature projected by HADLEY was 33%. These
276 results are presented in Figure 3 and Table 6. The change in weathering rate varied between the north and
277 south of the country, and was similar to the regional variation in temperature change, i.e. the highest
278 relative difference was seen in the northernmost part of the country (Figure 4).

279

280 **Fig. 3** Modelled total weathering rates of base cations based on present temperatures (a) and the predicted
281 temperatures in 2050, according to ECHAM (b) and the HADLEY model (c). (The map for the present
282 temperatures is based on the ECHAM results, but the HADLEY results were almost identical)

283

284 Table 6. Average weathering rates of Ca, Mg, K, Na and total base cations (Tot. BC) over all merged
285 catchments for the present temperature and the temperatures predicted for 2050 by ECHAM and the
286 HADLEY model. (ECHAM and HADLEY give the same average present temperatures when rounded to
287 one decimal.)

288

289 **Fig. 4** Difference between the present temperature and the temperature in 2050 predicted by the HADLEY
290 model (a), and the relative difference in base cation weathering rates between the two periods using the
291 temperatures predicted by the HADLEY model (b)

292

293 The sensitivity analysis of effects of moisture changes showed that the median weathering rate in Sweden
294 varied between 24 and 28 mEq m⁻² y⁻¹ if the lowest respective highest value in the moisture change interval
295 was used in the ECHAM scenario, which means a percentage change of -11% to +4% compared to if no
296 moisture change is assumed, as in the original runs (Table 7). The corresponding interval for HADLEY

297 was 24 and 33 mEq m⁻² y⁻¹ (-20% to +10 %). These results emphasize the importance of future moisture
298 development for weathering rates and highlight the uncertainty in the projected changes. However, not
299 even a maximum moisture reduction would fully counteract the increase of weathering rates due to
300 increased temperature, which underlines the significance of the projected changes caused by increased
301 temperatures.

302

303 Table 7. Median base cation weathering rates for Sweden with the temperature for today and for the
304 temperature of 2050 with unchanged moisture, and with a maximum and minimum change of moisture
305 according to the sensitivity analysis interval (ECHAM and HADLEY).

306

307 A clear north-south gradient was also seen in base cation losses due to harvesting, with substantially higher
308 losses in the south than in the north (Figure 5), due to the higher site productivity and thus more biomass
309 removal at harvesting in the south, where the climate is more favorable and the nitrogen availability is
310 higher (Akselsson et al. 2005). Whole-tree harvesting was predicted to lead to on average 66% higher base
311 cation losses than stem-only harvesting.

312

313 **Fig. 5** Base cation losses resulting from stem-only harvesting (a) and whole-tree harvesting (b) of spruce
314 forest

315

316 Base cation weathering rates at present temperatures were higher than base cation losses resulting from
317 stem-only harvesting in the northern half of Sweden, and in some parts of the southern half (Figure 6a).
318 The areas with a positive base cation balance were substantially smaller following whole-tree harvesting,
319 and were mainly restricted to an area in the north of the country (Figure 6b). Increased weathering due to
320 an increase in temperature in combination with whole-tree harvesting increased the areas with positive base
321 cation balances, and led to a less negative balance in the other areas, compared with the scenario at the
322 present temperature and whole-tree harvesting (Figure 6c and d). The effect was most evident when the
323 temperature projected by HADLEY was used (Figure 6d). Comparing the change in weathering rate from
324 present conditions to 2050 with the change in base cation losses when whole-tree harvesting is applied

325 instead of stem harvesting, showed that the effect of whole-tree harvesting exceeded the effect of increased
326 weathering due to the temperature increase in Sweden, except in the northernmost part of the country,
327 where the effect was the opposite (Figure 7). The area in the north was more extensive when using the
328 HADLEY projection (greater temperature increase) than when using ECHAM.

329

330 **Fig. 6** Difference between base cation weathering rate and loss of base cations in spruce forests
331 resulting from stem-only harvesting using weathering rates based on present temperatures (a), whole-tree
332 harvesting and weathering rates based on the present temperatures (b), whole-tree harvesting and
333 weathering rates based on the average temperature in 2050 predicted by ECHAM (c), and whole-tree
334 harvesting and weathering rates based on the average temperature in 2050 predicted by the HADLEY
335 model (d). (Maps (a) and (b) are based on ECHAM results, but the HADLEY results were almost identical)

336

337 **Fig. 7** The increase of base cation weathering at a temperature increase minus the increase in base cation
338 losses at whole-tree harvesting in spruce forests, using temperatures from ECHAM (a) and HADLEY (b).
339 In the red and orange areas the effect of whole-tree harvesting exceeds the effect of increased weathering
340 due to the temperature increase. In the green areas the effect of temperature on weathering exceeds the
341 effect of whole-tree harvesting

342

343 4. Discussion

344 The results of this study suggest that, although the projected increase in temperature will have a substantial
345 effect on weathering rates, it will not be sufficient to counteract the increased loss of base cations resulting
346 from whole-tree harvesting, compared with conventional stem-only harvesting, except in a small area in the
347 northernmost part of the country. A steep gradient was seen from north to south, showing increasing
348 dominance of the effect of whole-tree harvesting in the south, compared to the effect of the temperature
349 increase on weathering rates. The main explanation is the substantially higher loss of base cations due to
350 whole-tree harvesting towards the south, in accordance with the increasing site productivity in the more
351 favourable climate and nitrogen conditions in the south. The change in weathering rates due to increased
352 temperatures also affects the geographical pattern. The change in weathering rates depends on the projected

353 temperature change, the variation in present weathering rates (Figure 3a), which is closely linked to the
354 mineralogy (Figure 1), and the temperature dependence for different minerals. The difference between
355 temperature dependence for different minerals is relatively small (Table 2; Hodson et al. 1996). Thus the
356 present weathering rates and the projected temperature change are the most important factors. The
357 temperature change is predicted to be the highest in the northernmost parts (Figure 4a), and in this area the
358 present weathering rates are relatively high according to the model results (Figure 3). Thus, a relatively
359 large weathering increase in the north can be a contributing factor to the results showing that increased
360 weathering can counteract for base cation losses at whole-tree harvesting in the north. Also the
361 southwestern part of Sweden and the eastern part of central Sweden show relatively high weathering rates
362 (Figure 3), which can be seen at the differences between base cation weathering and harvest losses, that are
363 positive or only slightly negative in these areas, whereas the differences in the surrounding areas are more
364 negative (Figure 6). The overall gradient is, however, determined by the geographical variation of the
365 harvest loss parameter rather than the variation in the weathering parameter. The sensitivity analysis for
366 moisture indicated that the climate change on soil moisture could either hamper or slightly reinforce the
367 effect of temperature on weathering rates, but it would not substantially change the conclusions about
368 temperature effects on weathering rates in relation to base cation losses from whole-tree harvesting.

369

370 The southern half of Sweden, where whole-tree harvesting dominates, is also the most acidified area of
371 Sweden. This area has had the highest historical and present acidic deposition and a low ANC (acid
372 neutralizing capacity), negative or close to 0, in soil water below the root zone (Pihl Karlsson et al. 2011).
373 The loss of base cations in this region has previously been highly elevated due to ion exchange caused by
374 acidic deposition (Akselsson et al. 2013). The results of the present study reinforce earlier conclusions that
375 whole-tree harvesting in this part of the country may counteract recovery from acidification if the nutrient
376 losses are not compensated for (Akselsson et al. 2007; Iwald et al. 2013). In the northern part, the increase
377 in weathering rate due to the temperature increase counteracted base cation losses due to whole-tree
378 harvesting. This region is not as greatly affected by acidic deposition, and the ANC in soil water is above 0
379 in most soils. The risk of negative effects of whole-tree harvesting on acidification is thus much lower than
380 in the south. However, taking the potential increase in growth rate due to climate change into account may

381 lead to other conclusions. Increased growth rates will increase base cation uptake and possibly lead to
382 shorter rotations periods and thus more frequent harvesting events, removing more base cations from the
383 system.

384

385 The results are in line with results presented by Aherne et al. (2012), who used the MAGIC model (Cosby
386 et al. 1985; Cosby et al. 2001) in combination with Arrhenius factors (Sverdrup and Warfvinge 1993) and
387 relationships between temperature and respiration to model the effects of biomass removal on soil nutrient
388 status as a result of climate change in catchments in Finland. They concluded that climate change would
389 have a positive net effect on base cation supply, taking increased weathering rates due to increasing
390 temperatures and increased uptake due to increased tree growth into account, but that the negative effect of
391 whole-tree harvesting (including foliage) would be greater than the beneficial effects of climate change.

392 Reinds et al. (2009) used a dynamic model, VSD (Posch and Reinds 2009), to predict the recovery from
393 soil acidification in forests in Europe as a result of climate change. Their results also showed positive,
394 although small, effects on recovery, due to increased weathering rates. Campbell et al. (2009) used the
395 PnET-BGC model (Gbondo-Tugbawa et al. 2001) to study the effects of climate change on the
396 biogeochemistry of forest ecosystems in north-eastern North America, and found somewhat contradictory
397 results. According to their study, tree growth and nitrate leaching would be increased, but weathering rates
398 slightly decreased, due to a decrease in soil moisture. These results underline the importance of soil
399 moisture in determining weathering rates. Depending on the size of the temperature change in relation to
400 the size of the moisture change, the weathering rate could increase, as in the present study for Sweden, in
401 Aherne et al. (2012) and in Reinds et al. (2009), or decrease, as suggested in Campbell et al. (2009) for
402 North America.

403

404 In this study, two of the most important direct and indirect factors related to climate change that can affect
405 recovery from acidification were compared, namely temperature effects on weathering rates and increased
406 biomass harvesting to meet the demand of renewable fuel, but there are several other ways in which climate
407 change could affect base cation balances and acidification. Thus, the results should only be used as an
408 indication of the potential of a temperature-induced increase in weathering rates in counteracting base

409 cation losses due to whole-tree harvesting. According to Bergh et al. (2010), increased tree growth would
410 increase the loss of base cations resulting from harvesting, leading to more negative balances. In areas with
411 reduced growth due to drought, the effect would be the opposite. Weathering rates are not only affected by
412 temperature, but also by moisture (Brady and Weil 1999) and tree growth. Tree growth influences
413 weathering rates through its effect on the concentration of base cations in soil solution, which controls the
414 product inhibition, i.e the reduction of weathering rates with increased concentration of weathering
415 products (Sverdrup 1990). Increased moisture and increased tree growth will increase weathering rates and
416 vice versa. A sensitivity analysis of the PROFILE model in an earlier study identified temperature and
417 moisture as two of the most important parameters determining weathering rates, whereas base cation load
418 was of less importance (Hodson et al. 1996). Thus, changed uptake of base cations due to changed tree
419 growth is of less importance according to the PROFILE model description. The sensitivity analysis in the
420 present study indicated that the effect of temperature is greater than the effect of moisture, with the
421 predicted changes of temperature and precipitation in Sweden. Decomposition is also highly temperature-
422 dependent (Berg and McLaugherty 2003), and can be expected to increase in the future. Decomposition
423 could, however, decrease in areas of drought. Enhanced decomposition may increase the short-term supply
424 of base cations, hampering weathering rates. At the same time, nitrification leading to increased hydrogen
425 ion concentrations, and the release of DOC, accelerates weathering rates. To give a more holistic picture of
426 the effect of climate change on weathering rates, dynamic modelling approaches are required, e.g. with the
427 ForSAFE model (Wallman et al. 2005; Belyazid et al.2006), where weathering, tree growth and
428 decomposition is modelled dynamically, with feed-backs in between.

429

430 Base cation deposition is of the same order of magnitude as base cation weathering (Akselsson et al. 2007),
431 and changes in deposition are thus as important as changes in weathering rates with regard to the recovery
432 progress. Measurements have shown a decrease in base cation deposition together with the decrease in
433 sulphur deposition (Hedin et al. 1994). Base cation deposition in the future may be affected by various
434 factors related to climate change, such as increased biomass burning for energy production and changes in
435 deposition patterns. The net effect is, however, difficult to predict.

436

437 The modelled temperatures and weathering rates, and the harvesting estimates are associated with
438 uncertainties. The use of average air temperatures instead of soil temperatures may affect the absolute
439 weathering rates. According to Zheng et al. (1993) there is a very strong correlation between yearly average
440 soil temperature at 10 cm depth and air temperature, but the soil temperature is on average 2 degrees higher
441 than the air temperature. Thus, using air temperature would lead to an underestimation of weathering rates,
442 but the effect on the difference between the two periods studied here can be expected to be minor.

443 Concerning the two temperature projections used, they represent the upper and lower range of the spectrum
444 of future temperature changes in a large ensemble of projections (e.g. Kjellström et al. 2011). Thus the
445 most probable change is somewhere between these two projections, although changes outside the range
446 cannot be excluded. The uncertainties in temperature affect the numerical results, as can be seen by
447 comparing the results from the HADLEY and the ECHAM projection, but they do not change the overall
448 conclusions.

449

450 PROFILE is one of the most commonly used methods for estimating weathering rates, and thus
451 uncertainties in the model have been investigated in numerous studies. Weathering rates estimated with
452 PROFILE have been compared with those given by different approaches at the same sites. Sverdrup and
453 Warfvinge (1993) compared results from different approaches at 15 sites in Europe and North America,
454 and concluded that the estimates of weathering rates provided by PROFILE are within about $\pm 20\%$ of the
455 rates determined by the other, independent, methods. Sverdrup et al. (1998) compared weathering rates
456 from six different approaches, including PROFILE, in Gårdsjön in south-western Sweden, and found the
457 results to be consistent with each other, with only relatively small variations. Koseva et al. (2010)
458 compared the results from catchment mass balance calculations at 19 sites in Canada with PROFILE
459 results. The results from the mass balance calculations were, in most cases, somewhat higher than the
460 PROFILE results, as expected, since the catchment approach includes a thicker soil horizon. They
461 concluded that PROFILE provides reasonable estimates of weathering rates. Klaminder et al. (2011)
462 compiled weathering rates for Ca and K obtained using different approaches at Svartberget in northern
463 Sweden, and found somewhat contradictory results, with very wide weathering rate intervals. However,

464 they compared weathering estimates valid for different soil compartments (from 0.2 m depth to the whole
465 soil compartment within a catchment), and site-level assessments were used together with regional
466 estimates. Harmonization of the assumptions and delimitations in the different approaches, e.g. the use of
467 the same soil depth, would narrow the span, which is discussed further in Futter et al. (2012). Jönsson et al.
468 (1995) performed a sensitivity analysis in which they estimated the range in the uncertainty of input
469 parameters to be 10-100%, and concluded that these uncertainties would lead to a variation in the results of
470 $\pm 40\%$. Furthermore, they identified the physical parameters of soil, such as moisture content, bulk density
471 and exposed mineral surface, to be the input parameters with the greatest influence on the output, which is
472 in line with the results from uncertainty analyses performed by Hodson et al. (1996) and Zak et al. (1997).
473 In the regional calculations in the present study, a certain degree of generalization of the input data for the
474 sites was required (Akselsson et al. 2004), and the uncertainties can thus be expected to be towards the
475 higher values, or even higher than the intervals intended for single well-investigated sites. However, the use
476 of median values for merged catchments reduces the uncertainties compared to the uncertainties for
477 specific sites, since the variability at specific sites within a single catchment, regarding e.g. soil depth and
478 texture, may cancel out.

479

480 The uncertainties in the estimates of base cation losses as a result of harvesting are mainly associated with
481 the estimated net stem growth, the amount of branches and needles collected, and the concentrations of
482 base cations in different parts of the tree. Hellsten et al. (2008) performed a sensitivity analysis based on
483 the measured variation in base cation concentrations in different parts of the tree, and demonstrated that
484 particularly the variation Ca concentrations contributed to the uncertainties in the results of mass balance
485 calculations. The different concentrations changed the size of the net losses, but did not lead to completely
486 different conclusions being drawn. The amount of branches and needles harvested is of considerable
487 importance for the final results, and although the assumptions were intended to reflect real conditions, the
488 amount of branches harvested, as well as the amount of needles accompanying the branches, varies
489 considerably, depending on natural and practical factors.

490

491 Although all the terms in the calculations are associated with uncertainties, the general pattern, with higher
492 biomass harvesting and a greater effect of whole-tree harvesting in the south of the country, and higher
493 weathering rates in response to temperature in the north, is well-founded. Although the boundary between
494 areas where the effect of temperature on weathering exceeds the base cation loss is uncertain, the overall
495 conclusion that harvest losses are highly dominant in the south, and of less importance towards the north, is
496 reliable.

497

498 5. Conclusions

499 The effects of whole-tree harvesting and increased weathering rates on base cation cycling varied widely
500 from the north to the south of Sweden. These results highlight the importance of studying climate change
501 effects at different geographical locations.

502

503 The increase in weathering rates at higher temperatures could not compensate for the increase in base
504 cation losses resulting from whole-tree harvesting, except in the northernmost part of the country. Thus,
505 the results indicate that whole-tree harvesting is not sustainable, unless nutrient compensation is applied,
506 even with the predicted higher weathering rates. The results strengthen existing recommendations of
507 nutrient compensation after whole-tree harvesting if the removal of branches and tops exceeds a specified
508 amount.

509

510 Whereas the results in this study give an indication of the potential of the temperature-induced increase in
511 weathering rates of base cations in counteracting losses due to whole-tree harvesting, as well as of the
512 effect of changes in soil moisture, it does not give a holistic picture of the effect of climate change on
513 weathering rates, since many other important processes are involved. Dynamic modelling approaches are
514 therefore required to give a more holistic picture.

515

516

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700

701 Tables

702

703 Table 1

Scenario	Description
<i>Temperature scenarios</i>	
Present temperature	HADLEY, Average 1981-2010
Present temperature	ECHAM, Average 1981-2010
Temperature in 2050	HADLEY, Average 2036-2065
Temperature in 2050	ECHAM, Average 2036-2065
<i>Harvesting scenarios</i>	
Stem-only harvesting	100% stems+bark
Whole-tree harvesting	100% stems+bark, 60% branches+tops

704

705

706 Table 2

Mineral	E _A /R			
	k _H	k _{H₂O}	k _{CO₂}	k _R
K-feldspar	3500	2000	1700	1200
Plagioclase	4200	2500	1700	1200
Hornblende	4300	3800	1700	2000
Pyroxene	2700	3800	1700	2000
Epidote	4350	3800	1700	2000
Apatite	3500	4000	1700	2200
Calcite	444	4000	2180	2200
Biotite	4500	3800	1700	2000
Muscovite	4500	3800	1700	2000
Illite	4500	3800	1700	2000
Chlorite	4500	3800	1700	2000
Vermiculite	4300	3800	1700	2000

707

708 Table 3

Parameter	Unit	Range	Source
Temperature	°C	-2.9 – 8.7	Modelled average 1981-2010, HADLEY and ECHAM
SO ₄ -S deposition	mEq m ⁻² y ⁻¹	6.3-55.4	MATCH model, average 2006-2008
NO ₃ -N deposition	mEq m ⁻² y ⁻¹	8.9-61.3	MATCH model, average 2006-2008
NH ₄ -N deposition	mEq m ⁻² y ⁻¹	3.8-38.6	MATCH model, average 2006-2008
Ca deposition	mEq m ⁻² y ⁻¹	1.4-15.5	MATCH model, average 2006-2008
Mg deposition	mEq m ⁻² y ⁻¹	1.3-32.4	MATCH model, average 2006-2008
K deposition	mEq m ⁻² y ⁻¹	0.6-4.8	MATCH model, average 2006-2008
Na deposition	mEq m ⁻² y ⁻¹	5.0-200.0	MATCH model, average 2006-2008
BC net uptake	mEq m ⁻² y ⁻¹	2.2-73.4 ^a	Estimations based on data from NFI sites
N net uptake	mEq m ⁻² y ⁻¹	2.0-62.6 ^a	Estimations based on data from NFI sites
Mineral surface area	m ² m ⁻³	150 000-6 500 000 ^b	Classification on NFI sites
Soil moisture	m ³ m ⁻³	0.15-0.35	Classification on NFI sites
Density	kg m ⁻³	1400 ^b	One value for all sites

Minerals:

K-feldspar	weight %	0-29 ^b	Estimated from national total chemistry databases
Plagioclase	weight %	1-45 ^b	Estimated from national total chemistry databases
Hornblende	weight %	0-32 ^b	Estimated from national total chemistry databases
Pyroxene	weight %	0-6 ^b	Estimated from national total chemistry databases
Epidote	weight %	0-9 ^b	Estimated from national total chemistry databases
Apatite	weight %	0-2 ^b	Estimated from national total chemistry databases
Calcite	weight %	0-46 ^b	Estimated from national total chemistry databases
Biotite	weight %	0-8 ^b	Estimated from national total chemistry databases
Muscovite	weight %	0-13 ^b	Estimated from national total chemistry databases
Illite	weight %	0-43 ^b	Estimated from national total chemistry databases
Chlorite	weight %	0-17 ^b	Estimated from national total chemistry databases
Vermiculite	weight %	0-20 ^b	Estimated from national total chemistry databases

709 ^a Net uptake of nitrogen (N) and base cations (BC) is defined as the N and BC lost at harvesting. The

710 ranges in the table apply to the stem harvesting scenario.

711 ^b The ranges given apply to the lowest of the soil layers in the profile.

712

713

Table 4

Element	Stem+bark	Branches+tops	Needles
Ca (mg g ⁻¹) ^a	1.3	3.7	6.0
Mg (mg g ⁻¹) ^a	0.18	0.62	1.0
K (mg g ⁻¹) ^a	0.73	2.4	4.7
Na (mg g ⁻¹) ^b	0.075	0.1	0.13

714

^aBased on data compiled by Egnell et al. (1998).

715

^bBased on data from STFI (2003).

716

717

718 Table 5

	Average (°C)	Minimum (°C)	Maximum (°C)
Present ECHAM	4.3	-4.7	8.7
Present HADLEY	4.3	-4.7	8.8
2050 ECHAM	6.5	-2.7	11.0
2050 HADLEY	7.6	-1.6	13.5

719

720

721 Table 6

Weathering rate (mEq m ⁻² y ⁻¹)			
	Present	Temperature 2050	Temperature 2050
	temperature	ECHAM	HADLEY
Ca	12.4	15.0 (+21%)	16.7 (+35%)
Mg	5.2	6.3 (+21%)	7.1 (+37%)
K	4.6	5.4 (+17%)	5.9 (+28%)
Na	11.1	13.1 (+18%)	14.4 (+30%)
Tot. BC	33.2	39.9 (+20%)	44.1 (+33%)

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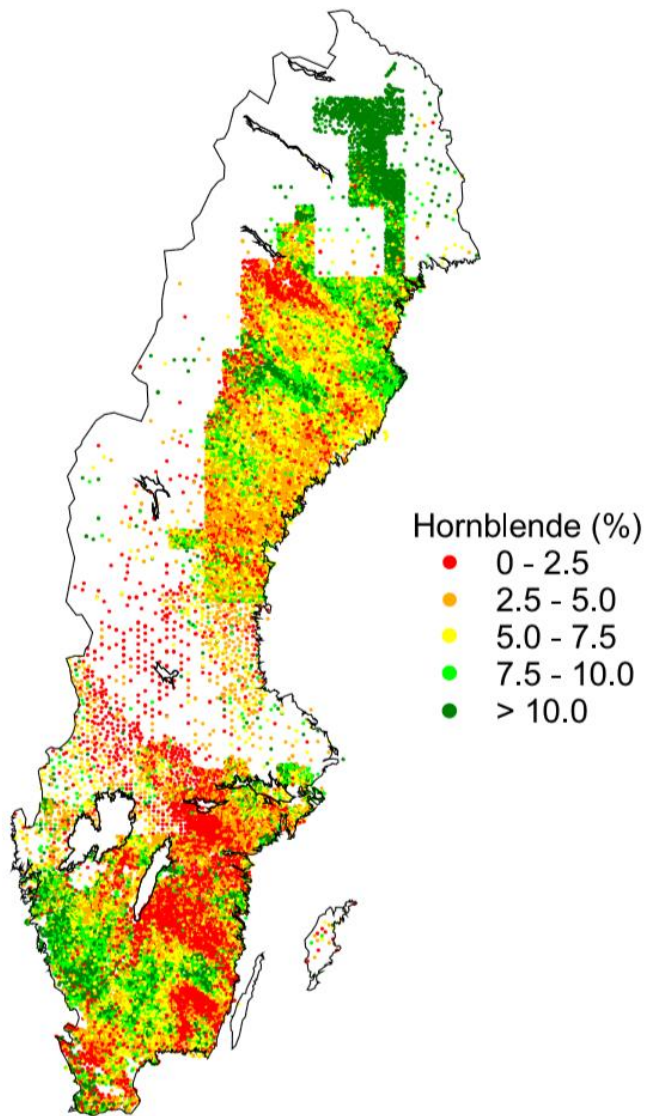
724 Table 7.

725

	Weathering rate (mEq m ⁻² y ⁻¹)		Moisture change (%)		Weathering rate (mEq m ⁻² y ⁻¹)	
	T present.	T 2050	Min	Max	T 2050, moist min	T 2050, moist max
ECHAM	22.4	27.1	-10.6	+3.9	24.0	28.2
HADLEY	22.4	29.8	-19.3	+9.2	23.7	32.8

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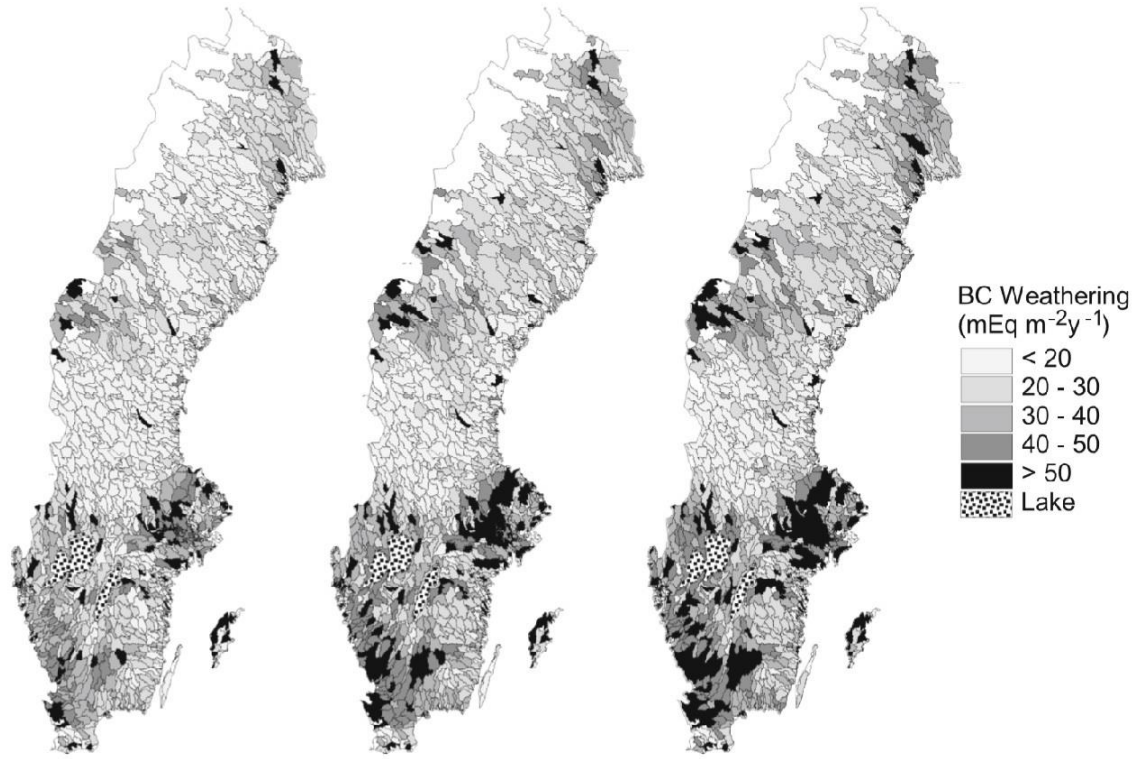
729

730 Fig. 1

731

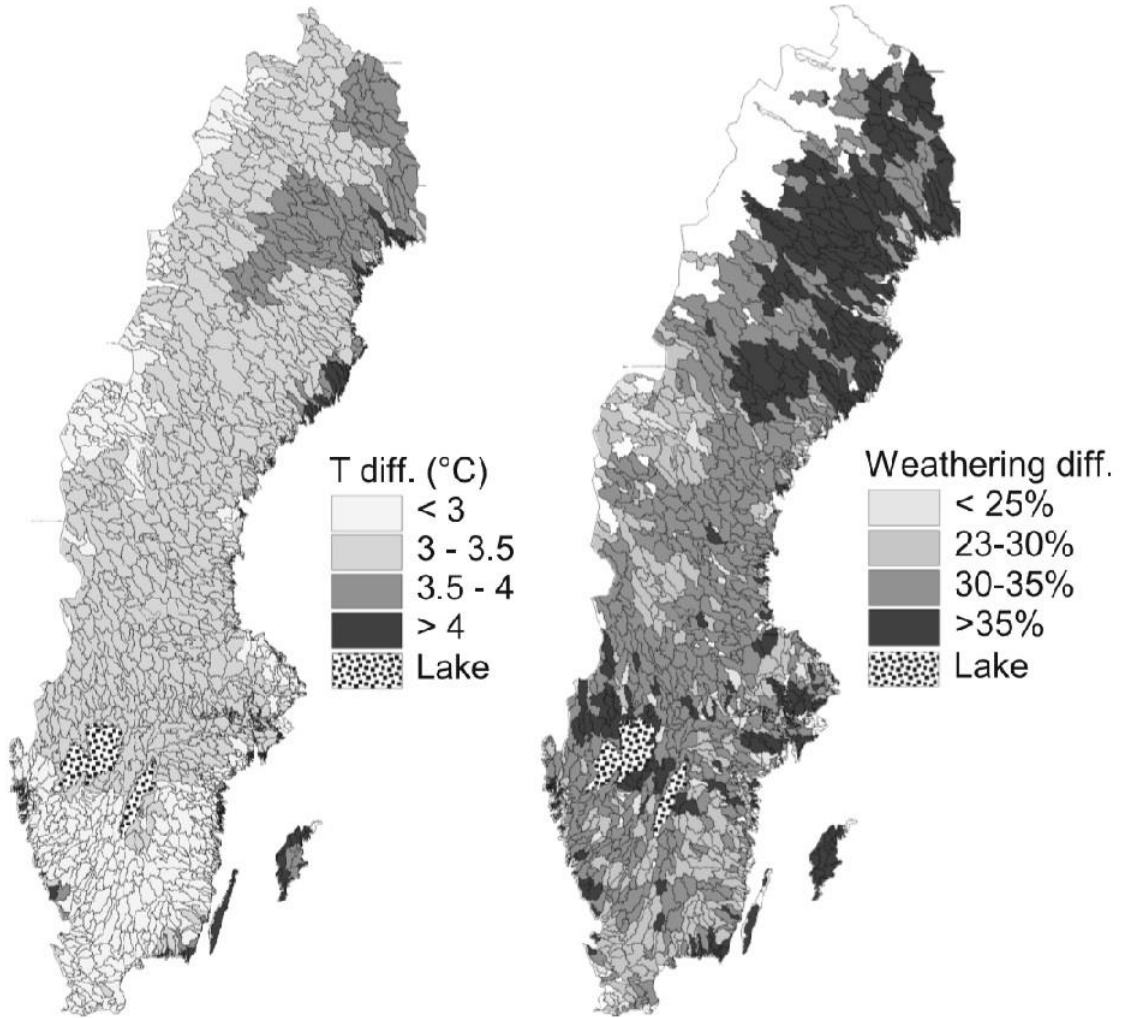


732
733 Fig. 2
734

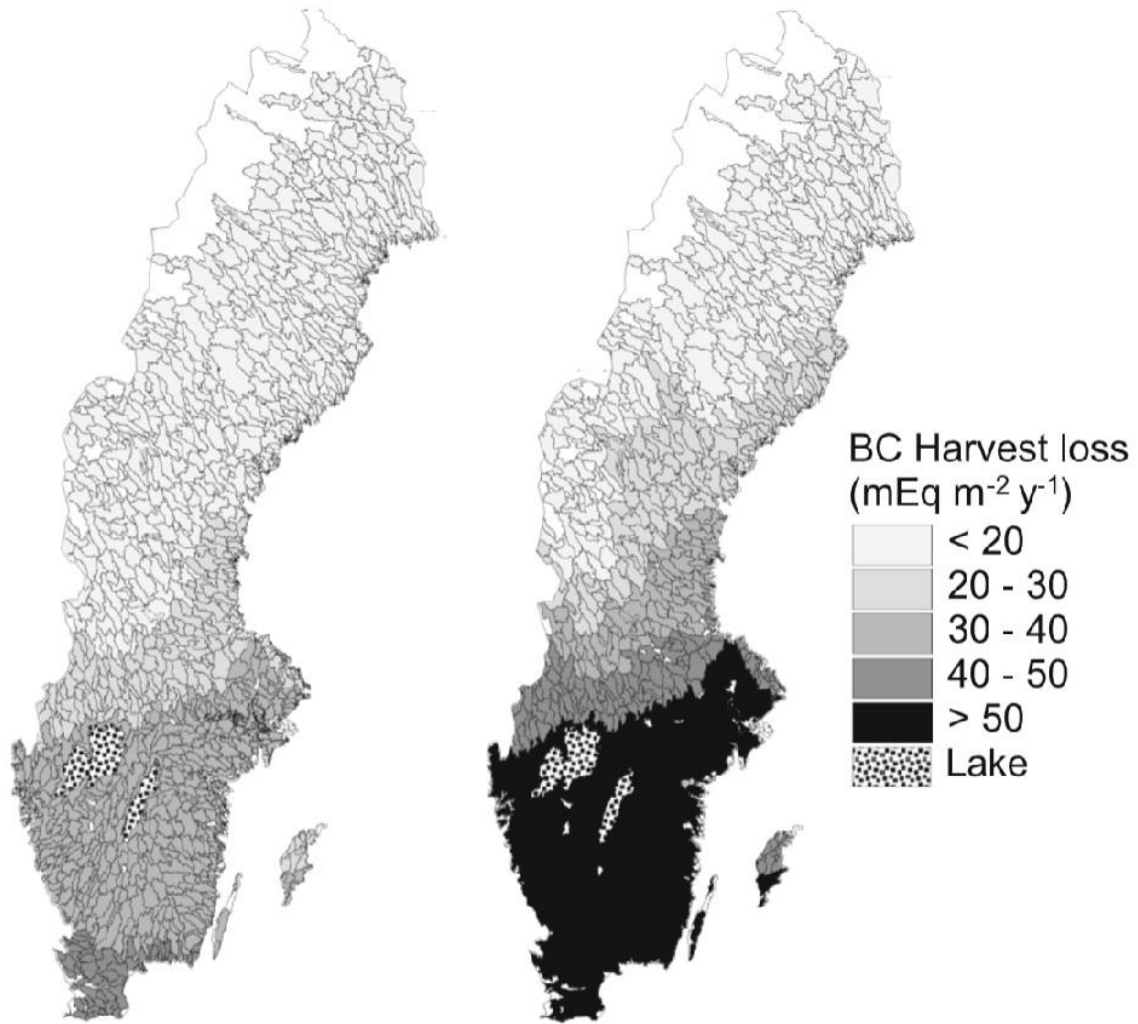


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736 Fig. 3

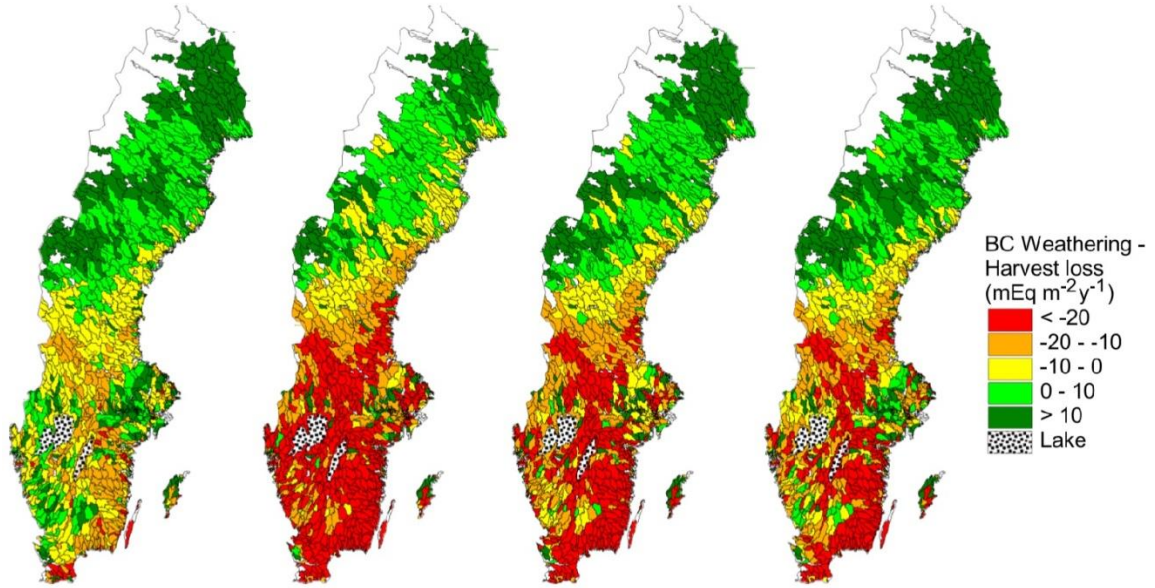
737



738
 739 Fig. 4
 740

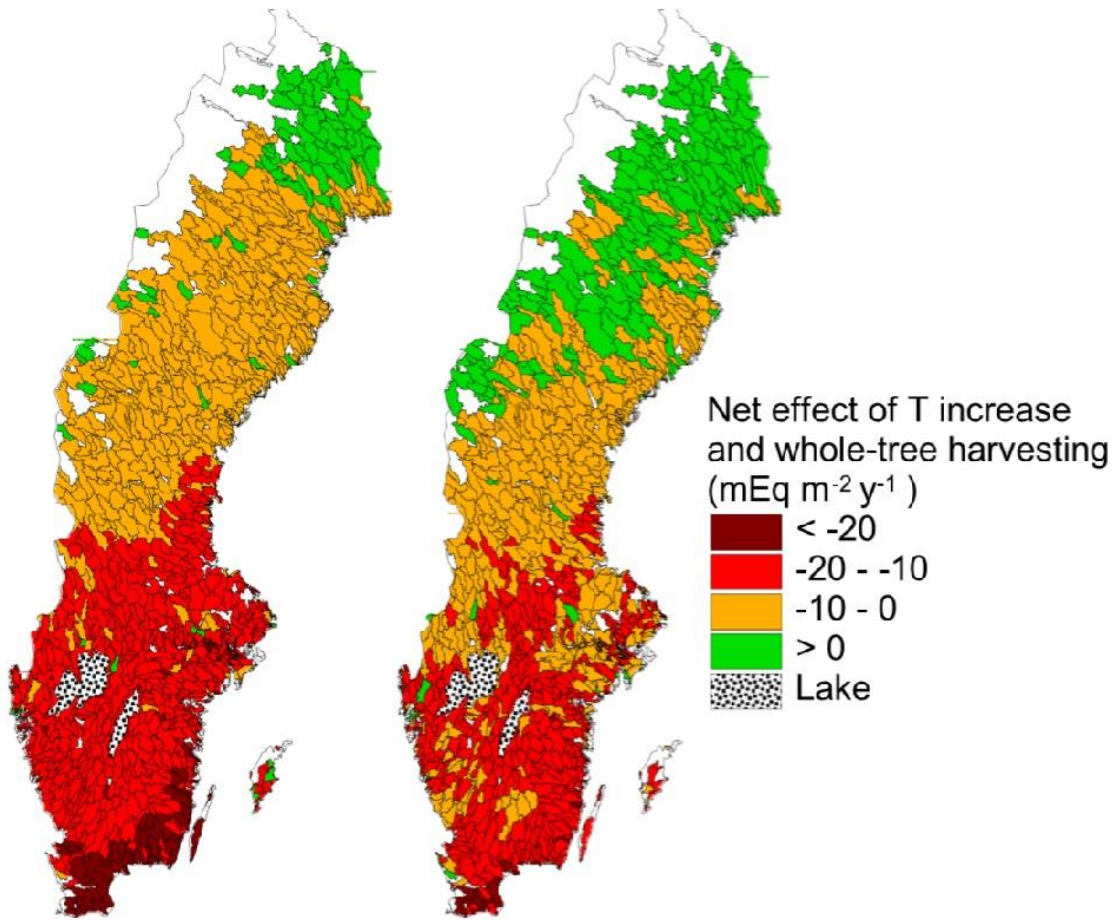


741
742 Fig. 5
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744
745 Fig. 6

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747
748 Fig. 7