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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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Abstract

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

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

1. Introduction

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

Climate change affects ecosystem processes such as tree growth, decomposition and mineral weathering. The net effect on acidification may be reinforcement or counteraction, depending on the effects of climate change and the conditions prevailing at each site. Climate change may lead to increased tree growth and thus increased base cation uptake, through increased air concentrations of CO_2 in combination with increased temperatures and prolonged growing seasons (Bergh et al. 2010). However, in areas where climate change leads to drier conditions and possibly drought, the effect may be the opposite (Kellomäki et al. 2007). Changes in temperature and moisture affect the rates of both weathering (Brady and Weil 1999) and decomposition (Berg and McClaugherty 2003). An increase in the release of base cations through weathering and decomposition has the potential to accelerate recovery from acidification. However, in nitrogen-rich areas, increased decomposition can lead to nitrate leaching (van Breemen et al. 1998; Wright and Jenkins 2001), which is an acidifying process. Other effects related to climate change that may affect recovery are changes in the frequency of sea-salt episodes (Akselsson et al. 2013; Skjelvåle et al. 2007; Laudon 2008; Hindar et al. 1995), the frequency of drought (Laudon 2008), and changes in conditions affecting pests (Netherer and Schopf 2010). To conclude, temperature, soil moisture and other effects related to climate change are key factors in controlling soil and vegetation processes that may affect recovery from acidification.

Both the temperature and precipitation are expected to increase substantially throughout Sweden in the coming decades (see e.g. Lind and Kjellström 2008; Kjellström et al. 2011). Increased temperature and precipitation may affect soil moisture in different ways, and the net effect is highly uncertain due to the limited accuracy with which precipitation and evapotranspiration can be simulated by climate models (e.g. Ehret et al. 2012). The natural long-term process resulting from climate change that can be expected to counteract acidification most is a potential increase in the weathering rate due to higher temperatures. The effect can be strengthened or weakened by changed soil moisture, depending on the net effect from increased temperature and precipitation on the soil moisture. The rate of soil organic matter decomposition and the subsequent release of nutrients through mineralization may also increase due to increasing temperatures, but this process is short-lived in the time frame of the current study, and its effect on acidification remains uncertain. In this study we focused on the impact on weathering of the future change in temperature, which is generally believed to be more robust than the change in precipitation. The main aim of this study was to determine whether the temperature-induced increase in weathering rate could counteract the increase in base cation loss due to whole-tree harvesting, including branches and tops, in different parts of Sweden. The study also comprises a sensitivity analysis for the effect of moisture on weathering rates. The study was limited to spruce forests, which cover 42% of the forested areas in Sweden, where most of the whole-tree harvesting is performed, and where the nutrient losses resulting from harvesting are greatest (Akselsson et al. 1997). Effects of climate change on other processes than weathering, such as tree growth, are not accounted for in this study.

2. Methods

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

2.1 Temperature projections

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

Table 1. Temperature and harvesting scenarios.

2.2 Harvesting scenarios

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

2.3 Base cation weathering rates at different temperatures

Weathering rates were modelled with the PROFILE model, a soil chemistry model originally developed to calculate the effect of acid rain on soil chemistry (Sverdrup and Warfvinge 1993). It includes process-oriented descriptions of chemical weathering of minerals, leaching and accumulation of dissolved chemical components and solution equilibrium reactions. PROFILE is a steady-state model, which means that yearly data or long-term averages are used as input, and not time series as in dynamic models. PROFILE then calculates the soil solution chemistry at steady state. The soil is divided into soil layers with different properties, preferably based on the naturally occurring soil stratification. Weathering is calculated using transition state theory and the geochemical properties of the soil system, such as soil wetness, mineral surface area, the concentrations of hydrogen, cations and organic acids, temperature and mineral composition. Four weathering reactions are included in PROFILE, the reaction with H^+, H_2O, CO_2 and organic ligands (R^-) (Sverdrup and Warfvinge 1993; Warfvinge and Sverdrup 1995). The dependence of temperature in PROFILE is calculated with rate coefficients for different minerals and different reactions, taken from laboratory studies and standardized to 8°C using an Arrhenius relation (Sverdrup and Warfvinge, 1993; Brantley 2008). The expression to adjust the coefficient to ambient temperatures is given in Equation 1.

$$\ln (k_T/k_{8°C}) = (E_A/R) \cdot ((1/281) - (1/T)) \qquad \text{(Equation 1)}$$

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

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

Table 2. Temperature dependence factors (E_A/R) used in PROFILE for all included minerals, and for the reactions with H^+, H_2O, CO_2 and organic ligands (R^-).

Weathering rates for the root zone, here defined as the upper 50 cm of the soil, were modelled based on data from 17333 Swedish National Forest Inventory (NFI) sites (Hägglund 1985), using the same methodology and database as described by Akselsson et al. (2008). The root zone was chosen since the soils on the sites can be regarded as well-drained, and the contribution of weathering products from lower layers via ground water transport can be assumed to be of minor importance. The profiles were divided in four layers, where the upper layer was organic.

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

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

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

2.4 Sensitivity analysis of effects of moisture changes on weathering rates

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

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

Harvest losses due to stem-only harvesting and whole-tree harvesting were based on data on site fertility for 5412 spruce forest sites (sites with at least 70% spruce) in the Swedish National Forest Inventory (Hägglund 1985). The site fertility is a measure of the optimal growth in a stand (m^3 stem wood per hectare per year), and the actual growth is generally lower than the optimal growth. The site fertility was therefore reduced by 20% in an effort to imitate real growth conditions, in accordance with earlier studies (Akselsson et al. 2008). The growth data were then interpolated using kriging in a 1 x 1 km grid using Gaussian Markov random fields (Lindgren et al. 2011, Rue et al. 2009), and the mean values were calculated for each merged catchment, based on the kriging results. Volume growth was recalculated to give mass growth using a spruce stem density of 430 kg m^{-3}.

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

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

3. Results

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

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

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

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

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

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

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

The sensitivity analysis of effects of moisture changes showed that the median weathering rate in Sweden varied between 24 and 28 mEq m^{-2} y^{-1} if the lowest respective highest value in the moisture change interval was used in the ECHAM scenario, which means a percentage change of -11% to +4% compared to if no moisture change is assumed, as in the original runs (Table 7). The corresponding interval for HADLEY was 24 and 33 mEq m^{-2} y^{-1} (-20% to +10 %). These results emphasize the importance of future moisture development for weathering rates and highlight the uncertainty in the projected changes. However, not even a maximum moisture reduction would fully counteract the increase of weathering rates due to increased temperature, which underlines the significance of the projected changes caused by increased temperatures.

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

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

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

Base cation weathering rates at present temperatures were higher than base cation losses resulting from stem-only harvesting in the northern half of Sweden, and in some parts of the southern half (Figure 6a). The areas with a positive base cation balance were substantially smaller following whole-tree harvesting, and were mainly restricted to an area in the north of the country (Figure 6b). Increased weathering due to an increase in temperature in combination with whole-tree harvesting increased the areas with positive base cation balances, and led to a less negative balance in the other areas, compared with the scenario at the present temperature and whole-tree harvesting (Figure 6c and d). The effect was most evident when the temperature projected by HADLEY was used (Figure 6d). Comparing the change in weathering rate from present conditions to 2050 with the change in base cation losses when whole-tree harvesting is applied instead of stem harvesting, showed that the effect of whole-tree harvesting exceeded the effect of increased weathering due to the temperature increase in Sweden, except in the northernmost part of the country, where the effect was the opposite (Figure 7). The area in the north was more extensive when using the HADLEY projection (greater temperature increase) than when using ECHAM.

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

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

4. Discussion

The results of this study suggest that, although the projected increase in temperature will have a substantial effect on weathering rates, it will not be sufficient to counteract the increased loss of base cations resulting from whole-tree harvesting, compared with conventional stem-only harvesting, except in a small area in the northernmost part of the country. A steep gradient was seen from north to south, showing increasing dominance of the effect of whole-tree harvesting in the south, compared to the effect of the temperature increase on weathering rates. The main explanation is the substantially higher loss of base cations due to whole-tree harvesting towards the south, in accordance with the increasing site productivity in the more favourable climate and nitrogen conditions in the south. The change in weathering rates due to increased temperatures also affects the geographical pattern. The change in weathering rates depends on the projected temperature change, the variation in present weathering rates (Figure 3a), which is closely linked to the mineralogy (Figure 1), and the temperature dependence for different minerals. The difference between temperature dependence for different minerals is relatively small (Table 2; Hodson et al. 1996). Thus the present weathering rates and the projected temperature change are the most important factors. The temperature change is predicted to be the highest in the northernmost parts (Figure 4a), and in this area the present weathering rates are relatively high according to the model results (Figure 3). Thus, a relatively large weathering increase in the north can be a contributing factor to the results showing that increased weathering can counteract for base cation losses at whole-tree harvesting in the north. Also the southwestern part of Sweden and the eastern part of central Sweden show relatively high weathering rates (Figure 3), which can be seen at the differences between base cation weathering and harvest losses, that are positive or only slightly negative in these areas, whereas the differences in the surrounding areas are more negative (Figure 6). The overall gradient is, however, determined by the geographical variation of the harvest loss parameter rather than the variation in the weathering parameter. The sensitivity analysis for moisture indicated that the climate change on soil moisture could either hamper or slightly reinforce the effect of temperature on weathering rates, but it would not substantially change the conclusions about temperature effects on weathering rates in relation to base cation losses from whole-tree harvesting.

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

The results are in line with results presented by Aherne et al. (2012), who used the MAGIC model (Cosby et al. 1985; Cosby et al. 2001) in combination with Arrhenius factors (Sverdrup and Warfvinge 1993) and relationships between temperature and respiration to model the effects of biomass removal on soil nutrient status as a result of climate change in catchments in Finland. They concluded that climate change would have a positive net effect on base cation supply, taking increased weathering rates due to increasing temperatures and increased uptake due to increased tree growth into account, but that the negative effect of whole-tree harvesting (including foliage) would be greater than the beneficial effects of climate change. Reinds et al. (2009) used a dynamic model, VSD (Posch and Reinds 2009), to predict the recovery from soil acidification in forests in Europe as a result of climate change. Their results also showed positive, although small, effects on recovery, due to increased weathering rates. Campbell et al. (2009) used the PnET-BGC model (Gbondo-Tugbawa et al. 2001) to study the effects of climate change on the biogeochemistry of forest ecosystems in north-eastern North America, and found somewhat contradictory results. According to their study, tree growth and nitrate leaching would be increased, but weathering rates slightly decreased, due to a decrease in soil moisture. These results underline the importance of soil moisture in determining weathering rates. Depending on the size of the temperature change in relation to the size of the moisture change, the weathering rate could increase, as in the present study for Sweden, in Aherne et al. (2012) and in Reinds et al. (2009), or decrease, as suggested in Campbell et al. (2009) for North America.

In this study, two of the most important direct and indirect factors related to climate change that can affect recovery from acidification were compared, namely temperature effects on weathering rates and increased biomass harvesting to meet the demand of renewable fuel, but there are several other ways in which climate change could affect base cation balances and acidification. Thus, the results should only be used as an indication of the potential of a temperature-induced increase in weathering rates in counteracting base cation losses due to whole-tree harvesting. According to Bergh et al. (2010), increased tree growth would increase the loss of base cations resulting from harvesting, leading to more negative balances. In areas with reduced growth due to drought, the effect would be the opposite. Weathering rates are not only affected by temperature, but also by moisture (Brady and Weil 1999) and tree growth. Tree growth influences weathering rates through its effect on the concentration of base cations in soil solution, which controls the product inhibition, i.e the reduction of weathering rates with increased concentration of weathering products (Sverdrup 1990). Increased moisture and increased tree growth will increase weathering rates and vice versa. A sensitivity analysis of the PROFILE model in an earlier study identified temperature and moisture as two of the most important parameters determining weathering rates, whereas base cation load was of less importance (Hodson et al. 1996). Thus, changed uptake of base cations due to changed tree growth is of less importance according to the PROFILE model description. The sensitivity analysis in the present study indicated that the effect of temperature is greater than the effect of moisture, with the predicted changes of temperature and precipitation in Sweden. Decomposition is also highly temperature-dependent (Berg and McClaugherty 2003), and can be expected to increase in the future. Decomposition could, however, decrease in areas of drought. Enhanced decomposition may increase the short-term supply of base cations, hampering weathering rates. At the same time, nitrification leading to increased hydrogen ion concentrations, and the release of DOC, accelerates weathering rates. To give a more holistic picture of the effect of climate change on weathering rates, dynamic modelling approaches are required, e.g. with the ForSAFE model (Wallman et al. 2005; Belyazid et al.2006), where weathering, tree growth and decomposition is modelled dynamically, with feed-backs in between.

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

The modelled temperatures and weathering rates, and the harvesting estimates are associated with uncertainties. The use of average air temperatures instead of soil temperatures may affect the absolute weathering rates. According to Zheng et al. (1993) there is a very strong correlation between yearly average soil temperature at 10 cm depth and air temperature, but the soil temperature is on average 2 degrees higher than the air temperature. Thus, using air temperature would lead to an underestimation of weathering rates, but the effect on the difference between the two periods studied here can be expected to be minor. Concerning the two temperature projections used, they represent the upper and lower range of the spectrum of future temperature changes in a large ensemble of projections (e.g. Kjellström et al. 2011). Thus the most probable change is somewhere between these two projections, although changes outside the range cannot be excluded. The uncertainties in temperature affect the numerical results, as can be seen by comparing the results from the HADLEY and the ECHAM projection, but they do not change the overall conclusions.

PROFILE is one of the most commonly used methods for estimating weathering rates, and thus uncertainties in the model have been investigated in numerous studies. Weathering rates estimated with PROFILE have been compared with those given by different approaches at the same sites. Sverdrup and Warfvinge (1993) compared results from different approaches at 15 sites in Europe and North America, and concluded that the estimates of weathering rates provided by PROFILE are within about ±20% of the rates determined by the other, independent, methods. Sverdrup et al. (1998) compared weathering rates from six different approaches, including PROFILE, in Gårdsjön in south-western Sweden, and found the results to be consistent with each other, with only relatively small variations. Koseva et al. (2010) compared the results from catchment mass balance calculations at 19 sites in Canada with PROFILE results. The results from the mass balance calculations were, in most cases, somewhat higher than the PROFILE results, as expected, since the catchment approach includes a thicker soil horizon. They concluded that PROFILE provides reasonable estimates of weathering rates. Klaminder et al. (2011) compiled weathering rates for Ca and K obtained using different approaches at Svartberget in northern Sweden, and found somewhat contradictory results, with very wide weathering rate intervals. However, they compared weathering estimates valid for different soil compartments (from 0.2 m depth to the whole soil compartment within a catchment), and site-level assessments were used together with regional estimates. Harmonization of the assumptions and delimitations in the different approaches, e.g. the use of the same soil depth, would narrow the span, which is discussed further in Futter et al. (2012). Jönsson et al. (1995) performed a sensitivity analysis in which they estimated the range in the uncertainty of input parameters to be 10-100%, and concluded that these uncertainties would lead to a variation in the results of ±40%. Furthermore, they identified the physical parameters of soil, such as moisture content, bulk density and exposed mineral surface, to be the input parameters with the greatest influence on the output, which is in line with the results from uncertainty analyses performed by Hodson et al. (1996) and Zak et al. (1997). In the regional calculations in the present study, a certain degree of generalization of the input data for the sites was required (Akselsson et al. 2004), and the uncertainties can thus be expected to be towards the higher values, or even higher than the intervals intended for single well-investigated sites. However, the use of median values for merged catchments reduces the uncertainties compared to the uncertainties for specific sites, since the variability at specific sites within a single catchment, regarding e.g. soil depth and texture, may cancel out.

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

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

5. Conclusions

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

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

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

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Tables

Table 1

Scenario	Description
Temperature scenarios	
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
Harvesting scenarios	
Stem-only harvesting	100% stems+bark
Whole-tree harvesting	100% stems+bark, 60% branches+tops

Table 2

	E_A/R			
Mineral	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

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

[a] Net uptake of nitrogen (N) and base cations (BC) is defined as the N and BC lost at harvesting. The ranges in the table apply to the stem harvesting scenario.

[b] The ranges given apply to the lowest of the soil layers in the profile.

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

[a]Based on data compiled by Egnell et al. (1998).

[b]Based on data from STFI (2003).

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

Table 6

	Weathering rate (mEq m^{-2} y^{-1})		
	Present temperature	Temperature 2050 ECHAM	Temperature 2050 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%)

Table 7.

	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

Figures

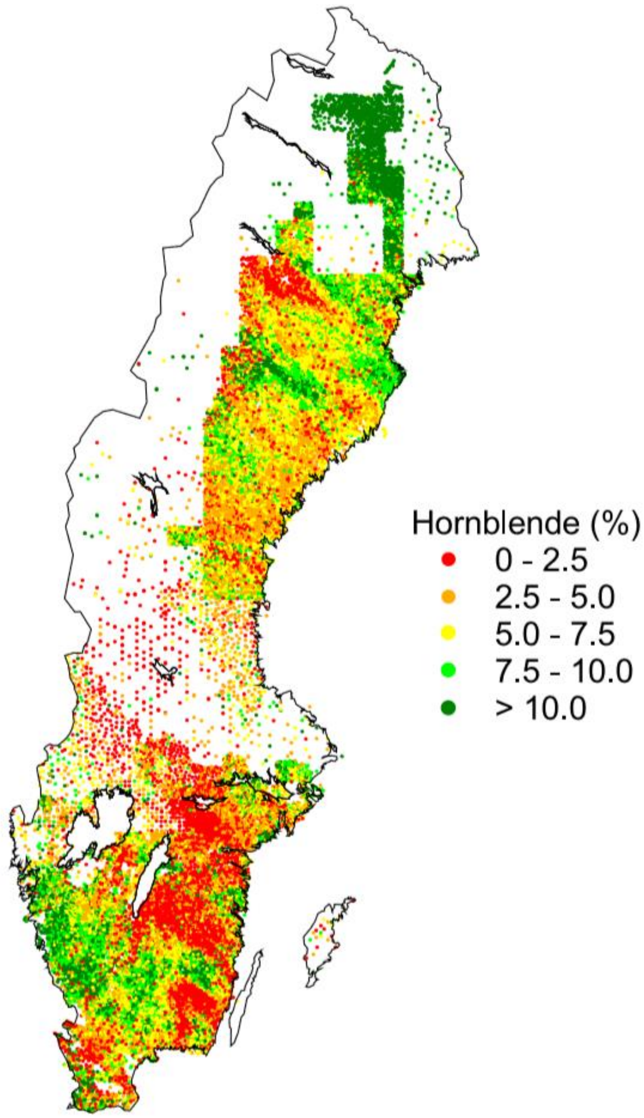


Fig. 1

Fig. 2

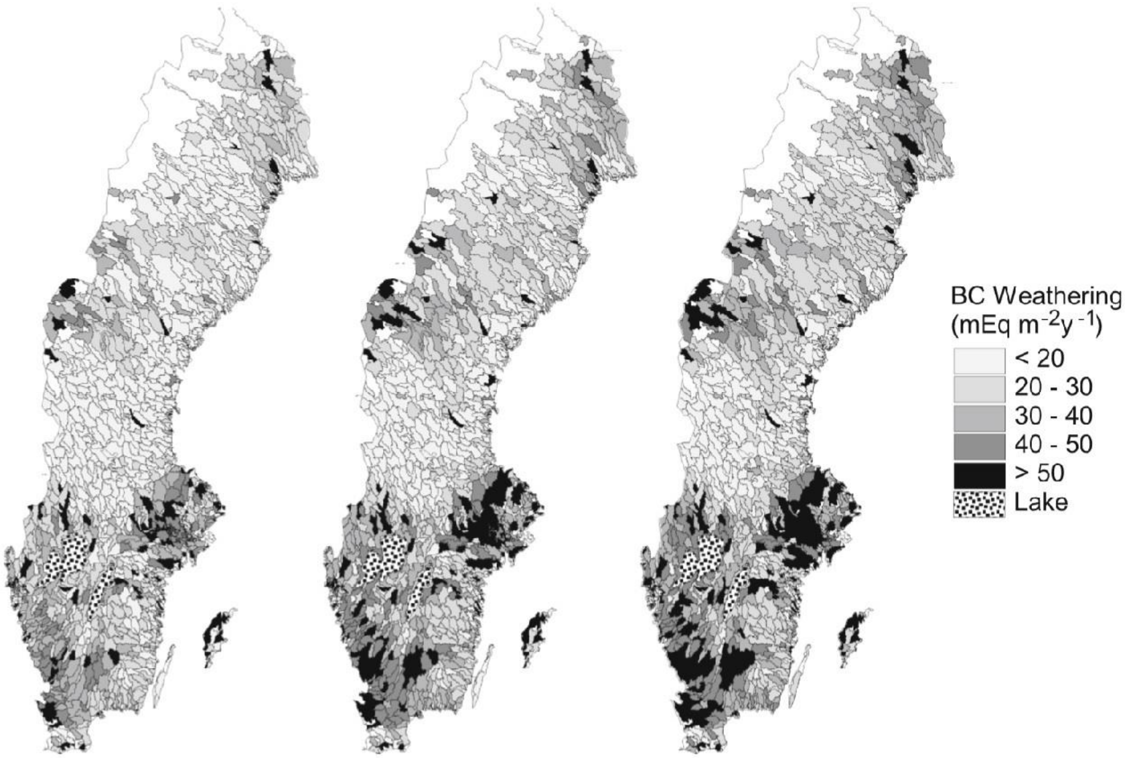


Fig. 3

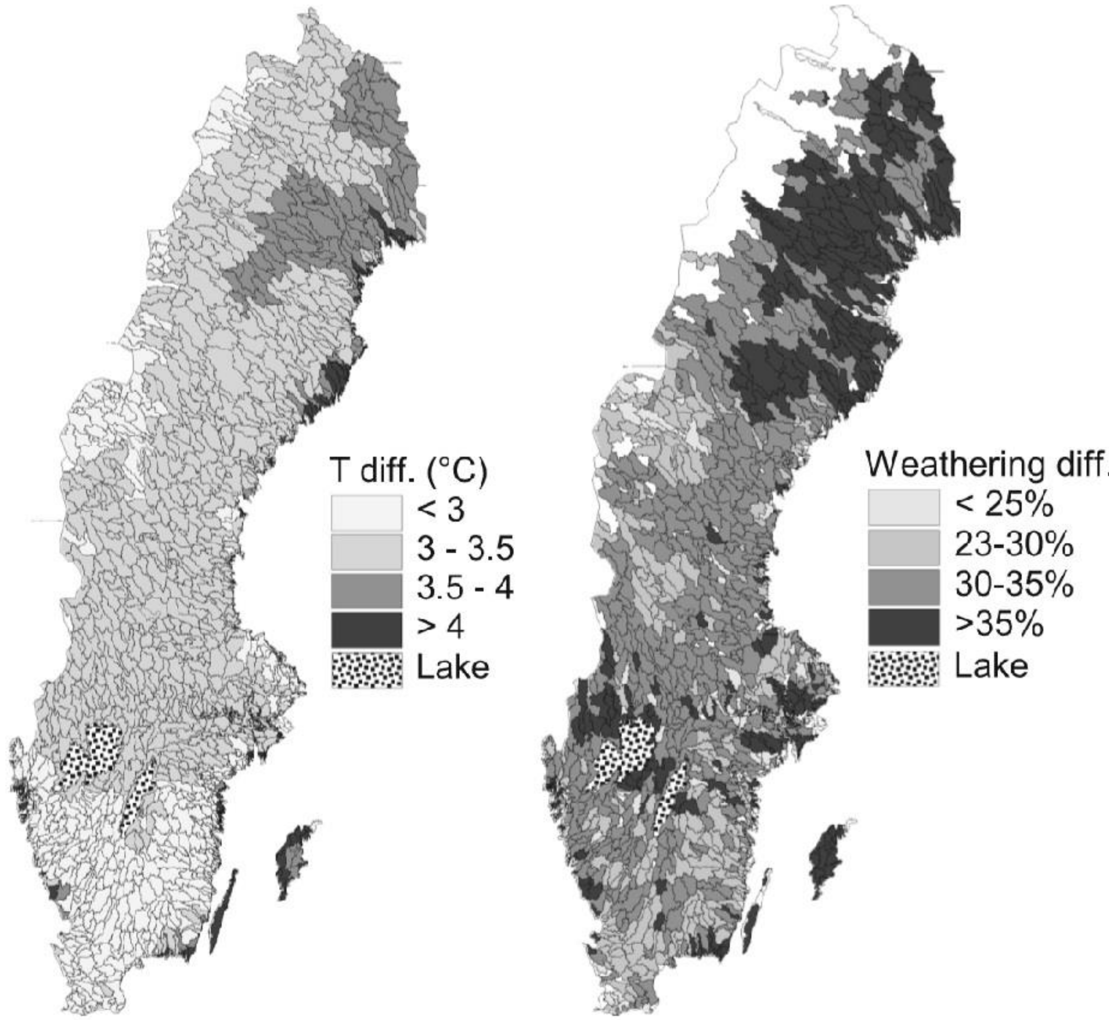
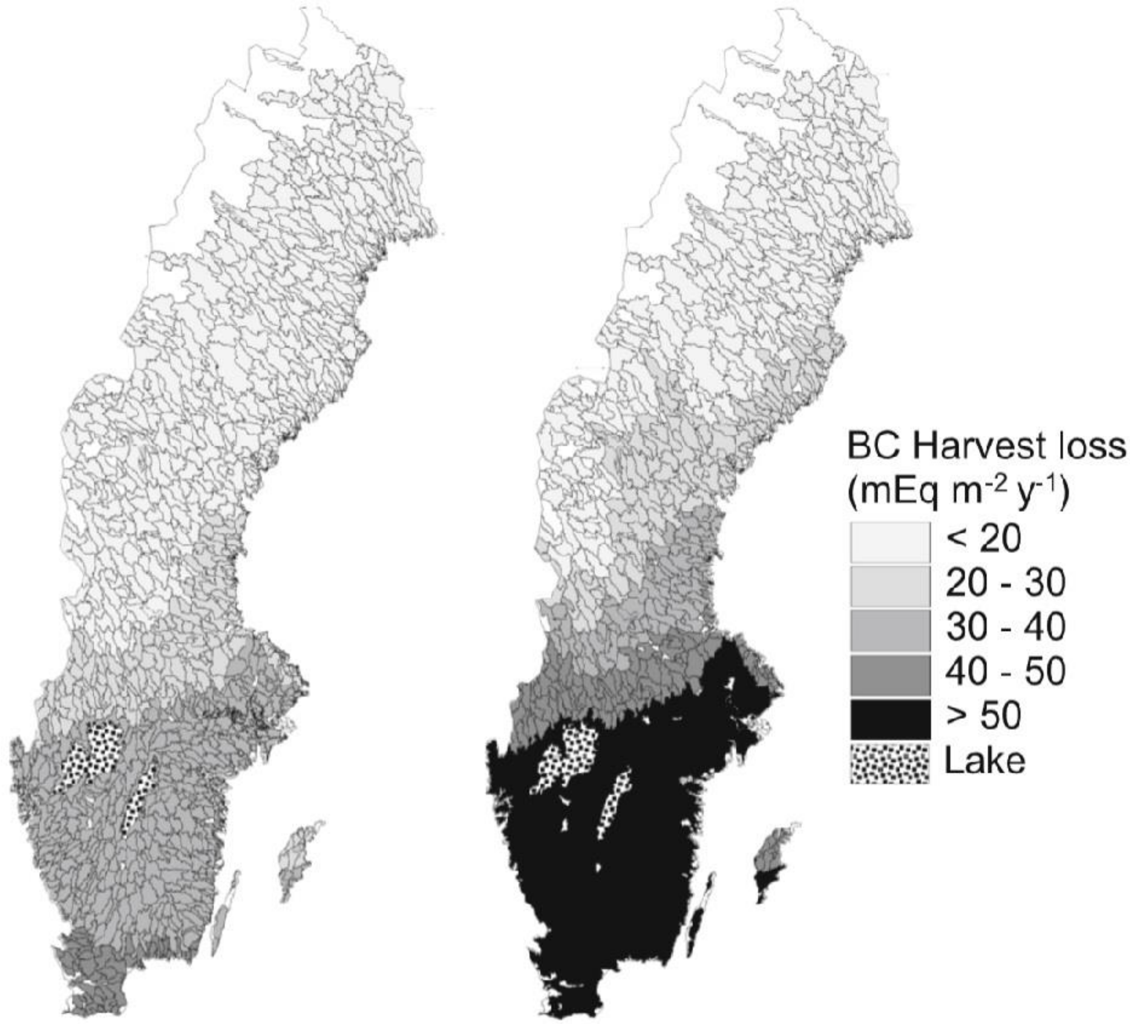


Fig. 4



741
742 Fig. 5

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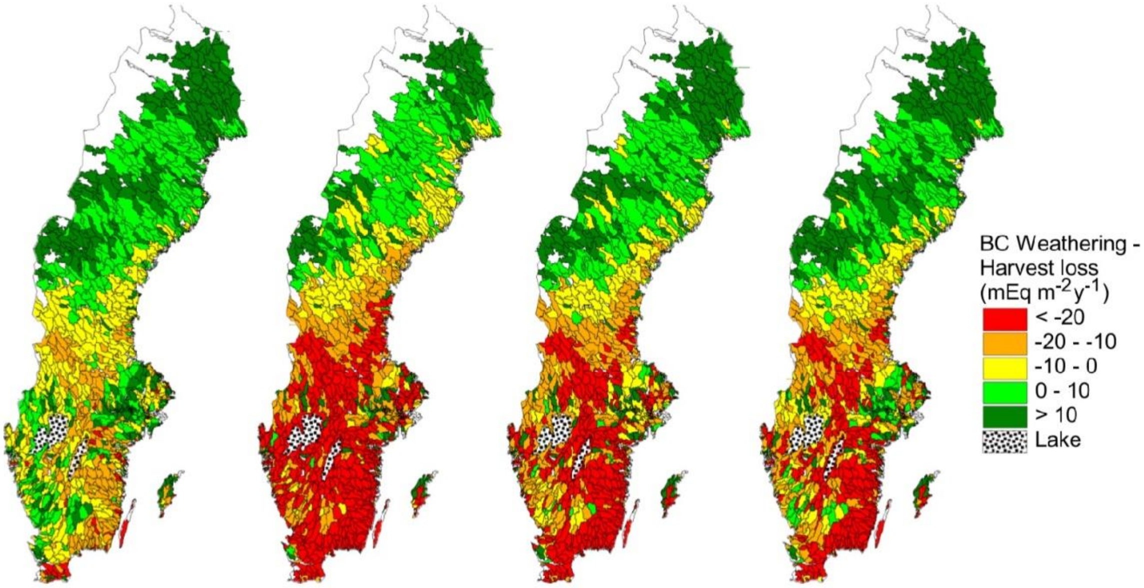

Fig. 6

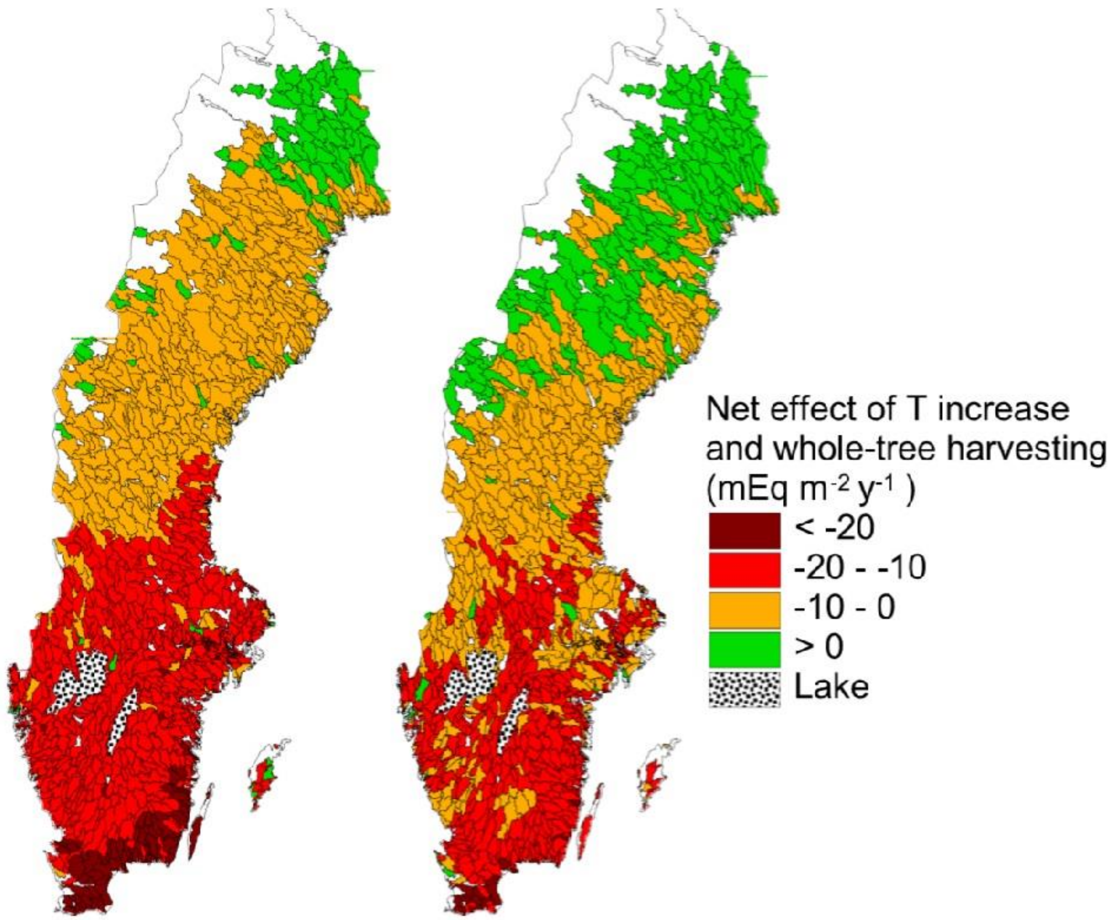
Net effect of T increase
and whole-tree harvesting
(mEq m-2 y-1)
< -20
-20 - -10
-10 - 0
> 0
Lake

Fig. 7