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Sensitivity analyses of MAGIC modelled predictions of future impacts of whole-tree harvest on soil calcium supply and stream acid neutralizing capacity

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HIGHLIGHTS

- Long-term impact of whole-tree harvest was modelled with MAGIC.
- Whole-tree harvest had a large effect on modelled soil calcium pools.
- The effect on modelled stream water acid neutralizing capacity was generally small.
- The robustness of modelled predictions was tested with sensitivity analyses.
- Largest impact was exerted by varying the tree biomass calcium concentration.

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ABSTRACT

Forest biofuel is a main provider of energy in Sweden and the market is expected to grow even further in the future. Removal of logging residues via harvest can lead to short-term acidification but the long-term effects are largely unknown. The objectives of this study were to 1) model the long-term effect of whole-tree harvest (WTH) on soil and stream water acidity and 2) perform sensitivity analyses by varying the amounts of logging residues, calcium (Ca^{2+}) concentrations in tree biomass and site productivity in nine alternate scenarios. Data from three Swedish forested catchments and the Model of Acidification of Groundwater in Catchments (MAGIC) were used to simulate changes in forest soil exchangeable Ca^{2+} pools and stream water acid neutralizing capacity (ANC) at Gammtratten, Kindla and Aneboda. Large depletions in soil Ca^{2+} supply and a reversal of the positive trend in stream ANC were predicted for all three sites after WTH. However, the magnitude of impact on stream ANC varied depending on site and the concentration of mobile strong acid anions. Contrary to common beliefs, the largest decrease in modelled ANC was observed at the well-buffered site Gammtratten. The effects at Kindla and Aneboda were much more limited and not large enough to offset the general recovery from acidification. Varying the tree biomass Ca^{2+} concentrations exerted the largest impact on modelled outcome. Site productivity was the second most important variable whereas changing biomass amounts left on site only marginally affected the results. The outcome from the sensitivity analyses pointed in the same direction of change as in the base scenario, except for Kindla where soil Ca^{2+} pools were predicted to be replenished under a given set of input data. The reliability of modelled outcome would increase by using site-specific Ca^{2+} concentrations in tree biomass and field determined identification of site productivity.

1. Introduction

As part of the EU's 2020 energy goals, each member state is committed to increase their share of renewable energy in final consumption to meet the overall target of 20% (European Commission, 2007). Every member state has its own national goal and in 2012 Sweden already reached its goal of 50% renewable energy sources, much thanks to increased use of biofuels (The Ministry of Enterprise EaC, 2013). Harvest of forest logging residues, part of biofuels, has steadily increased (Swedish Forest Agency, 2013b) and is expected to increase even further in the future. This has raised concern about the long-term impact on soil and surface water acid–base status since the utilization of branches, tops and needles along with the stem (WTH) removes a greater amount of base-cations relative to conventional harvesting (CH) of stems-only.

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It is well-known from field experiments that WTH leads to lower soil exchangeable base cation (BC) concentrations and/or pools compared with CH, at least in the short- and medium-term (25 years) (Brandtberg and Olsson, 2012; Hendrickson et al., 1989; Johnson and Todd, 1998; Saarsalmi et al., 2010; Thiffault et al., 2006; Zetterberg et al., 2013). The differences are usually explained by a relocation of BC from decomposing logging residues to the soil exchange complex in CH-plots, thereby creating a measurable difference compared with WTH-plots (Brandtberg and Olsson, 2012). As a result, the solute leaching from soils subjected to WTH is expected to have lower concentrations of BC leading to surface water acidification. WTH is also believed to delay, or in worst case prevent, the recovery from acidification in areas suffered from acid deposition, despite declines in sulphur deposition. There is, however, limited evidence on the negative effects of WTH on soil water acidity (Zetterberg et al., 2013) and long-term effects covering an entire rotation period (60–120 years) are unknown since most experiments were established after the oil crisis in the 1970s. Little is also known about feed-back mechanisms such as increased weathering (McLaughlin and Phillips, 2006) which could compensate for the loss of BC in the soil.

When long-term data are limited, future changes in stream water chemistry can be predicted by mechanistic models. Mass-balance models have been widely used in Sweden for assessing the acidifying effect of forestry on soils and for revising environmental goals (Swedish Environmental Protection Agency, 2007a). The result from these models suggests that input of Ca^{2+} and magnesium (Mg^{2+}) via atmospheric deposition and weathering is not sufficient to counterbalance the output via leaching and harvest for large parts of Sweden, independent of CH or WTH (Akselsson et al., 2007). By extrapolating the results, Akselsson et al. (2007) suggested that depletion of BC in forest soil could also lead to negative effects on "runoff water quality".

In order to include temporally variable parameters, more complex dynamic models can be used. MAGIC was developed in the 1980s (Cosby et al., 1985a,1985b,1985c) and later refined (Cosby et al., 2001; Oulehle et al., 2012) to model the long-term impact of acid deposition on surface water chemistry. The model structure also makes it suitable to explore the impact of other forcing variables. In the last three decades, MAGIC has been used to predict the potential effect of land use change and different forest management scenarios for a number of countries including Scotland (Cosby et al., 1990; Jenkins et al., 1990; Neal et al., 1986; Wright et al., 1994), Wales (Waters and Jenkins, 1992; Whitehead et al., 1988a,1988b), Spain (Neal et al., 1995), France (Durand et al., 1992), Czech Republic (Oulehle et al., 2007), Germany (Ferrier et al., 1995), Finland (Aherne et al., 2008, 2012) and USA (McDonnell et al., 2013). A number of these studies provide examples how land use changes such as afforestation can deplete the soil of BC and increase surface water acidity, despite declines in sulphate (SO_4^{2-}) deposition (Ferrier et al., 1995; Jenkins et al., 1990). However, the effect of CH or WTH on surface water acidity in already forested areas has only been considered in a few studies (Aherne et al., 2008, 2012; McDonnell et al., 2013).

In the current study, MAGIC was calibrated to three small Swedish forested catchments to examine future acidification trends in soils and streams following WTH. Long-term variations in dry deposition, nutrient uptake, and decomposition during a forest rotation period were considered whereas short-term changes during the clear-cut phase were assumed to be of minor importance. Future deposition of (SO_4^{2-}) and nitrate (NO_3^-) and ammonia (NH_4^+) was expected to decrease to 2020 relative to present day following the Gothenburg protocol (Posch et al., 2012) and then remain constant.

The impact of WTH was determined by measuring changes in soil Ca^{2+} pools and stream water ANC. Calcium is the BC typically affected by WTH (Thiffault et al., 2011) and is the most important cation for base saturation (BS) at the three sites because it occupies more than 60% of the cation exchange sites. ANC measures the buffering capacity of surface waters and is in Sweden used to calculate pH as a criterion for surface water acidification (Swedish Environmental Protection Agency, 2007b). In this study, stream water concentrations of Ca^{2+} and sodium (Na^+) accounted for >75% of the BC sum. However, Na^+ was largely balanced by chloride (Cl^-), and this is why changes in ANC primarily depended on the WTH impact on the concentration of other mobile anions and Ca^{2+}.

The objective of this study was to use MAGIC to explore if WTH can cause long-term (55 to 80 years) soil depletion and stream water acidification compared to present day soil exchangeable Ca^{2+} pools and ANC, assuming no major future changes in forest management (= base scenario). A second objective was to test uncertainties in modelled outcome by varying Ca^{2+} concentrations in above-ground tree biomass, site productivity, and biofuel removal amounts. The results provide increased guidance on how to implement sustainable forestry and on the potential limitations of using simple mass-balance approaches.

2. Material and methods

2.1. Study sites

Data from the Swedish Integrated Monitoring sites Gammtratten (N 63° 51′ E 18° 06′), Kindla (N 59° 05′ E 12° 01′), and Aneboda (N 57° 05′ E 12° 32′) were used to calibrate MAGIC (Fig. 1). The catchments are situated along a north–south gradient of climate, marine influence, past and present deposition of SO_4^{2-}, NO_3^-, and NH_4^+. In short, the northern site Gammtratten has received much lower amounts of sea salts, SO_4^{2-}, NO_x and NH_x compared with the central (Kindla) and southern (Aneboda) sites. The temperature gradient shows a similar pattern with the shortest vegetation period at Gammtratten, while Kindla annually receives approximately 150 mm more rain compared with the other two sites. The forest covered catchments are dominated by Norway spruce (*Picea abies* (L.) Karst.) mixed with smaller amounts of Scots pine (*Pinus sylvestris* L.) and deciduous trees, notably white birch (*Betula pubescens* Ehrh.). The dominant soil type is podzols except for recharge areas where histosols, gleysols, and regosols occur. More detailed information about the catchment characteristics is in Starr (2011).

Historical forest management was minimal and the areas are currently considered as semi-natural forests. At Gammtratten, the existing spruce stands are <150 years old while the pine stands (13%) are much older. There are traces of fires during the 18th century indicating that no spruce trees were present prior to 1860. Hence, Norway spruce regenerations likely took place after 1860 in occasionally created open patches during the first rotation period. Selective cutting of pine trees was carried out in the central part of the catchment at the beginning of the 20th century. In 1990, six hectares of spruce forest along the water

Fig. 1. Location of the study sites.