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Long-term soil calcium depletion after conventional and whole-tree harvest

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ABSTRACT

Whole-tree harvest (WTH) may compromise tree productivity and health and lead to soil and surface water acidification. The aim of this study was to assess the long-term change (up to circa 40 years) in soil exchangeable calcium (Ca^{2+}) pools following conventional (CH) and WTH at three Swedish coniferous sites. A second aim was to evaluate how well the results could be reproduced by the dynamic model MAGIC (Model of Acidification of Groundwater in Catchments). Soil Ca^{2+} pools (down to 20 cm) decreased at all three sites from stand age 15–16 to 37–38 years. The depletion ranged from 2.6 to 8.6 kEq ha^{-1} (26.5–52.7%) and 0.2 to 5.0 kEq ha^{-1} (2.3–49.1%) in the CH and WTH treatment, respectively. The presence of an interaction effect indicated that the main effect of time was not statistically significant at all three sites. Over the course of time, soil Ca^{2+} pools have also become more similar between the CH and WTH treatments, but the Ca^{2+} pools were still significantly lower ($p < 0.05$) after WTH at stand age 37–38 years. The measured declines in Ca^{2+} pools were generally greater than what has been found in other studies and were largely explained by high soil Ca^{2+} availability and high tree Ca^{2+} uptake, especially in the CH-plots, as indicated by the MAGIC mass balance budgets. Model simulations by MAGIC partly agreed with the measured data. However, the model exaggerated the soil Ca^{2+} losses between 1990 and 2013 (CH = 3.6–9.9 kEq ha^{-1}; WTH = 3.0–8.3 kEq ha^{-1}), especially at the spruce sites. Furthermore, MAGIC could not reproduce the rapid diminishing differences between CH and WTH. Uncertainties in model parameters, underestimated soil Ca^{2+} pools or biological feed-back mechanisms could explain this discrepancy. Until these have been resolved, interpretations of Ca^{2+} changes related to CH or WTH using dynamic modelling or mass balance budget calculations should be done with caution.

1. Introduction

Forest logging residues are a renewable energy source which can lower the need for fossil fuels and reduce net carbon dioxide emissions. However, the nutrient concentrations are higher in logging residues than in stemwood, why the export of nitrogen, phosphorous and base cations becomes greater during whole-tree harvesting (WTH) compared to stem-only, conventional harvesting (CH). The additional loss of nutrients during WTH may lead to lower soil productivity and more acid soils (Thiffault et al., 2011). There is also a growing concern in Sweden that WTH may lead to surface water acidification associated with lower concentrations of base cations in runoff water (Swedish Environmental Protection Agency, 2007a). In areas with slow recovery from acidification, WTH may also delay or prevent further improvement in surface water acid-base status (Futter et al., 2014).

The impacts of CH and WTH on soil and water quality over relatively short periods are well described in the literature (Kreutzweiser et al., 2008; Thiffault et al., 2011). Of all macronutrients, calcium (Ca^{2+}) appears to be most frequently affected by increased harvest intensity (Federer et al., 1989; Thiffault et al., 2011). As a result, there is a growing interest how to conserve Ca^{2+} through proper forest management (McLaughlin, 2014). Forest trees in Fennoscandia normally have Ca^{2+} levels in foliage that far exceeds their physiological needs (Knecht and Göransson, 2004), even after WTH (Olsson et al., 2000). The role of Ca^{2+} for tree production is therefore considered inferior compared with other nutrients (nitrogen, phosphorous, magnesium and potassium), especially in boreal forests where tree growth is usually limited

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by nitrogen (Tamm, 1991; Egnell, 2011). More important, however, Ca^{2+} plays a dominant role for the base saturation of soils and acid neutralizing capacity (ANC) of surface waters.

The long-term effect of WTH on soils and waters is only known from a few empirical studies, most of which were established in the seventies or early eighties (Walmsley et al., 2009; Saarsalmi et al., 2010; Vanguelova et al., 2010; van der Heijden et al., 2013; Zetterberg et al., 2013). One of the oldest field experiments for studying the impact of CH and WTH was established in Sweden between 1974 and 1976 by Björkroth and Rosén (1977). Soil and tree growth studies in this experiment have shown that WTH can reduce tree growth (Egnell and Leijon, 1999; Egnell and Valinger, 2003; Egnell, 2011), lower the nutrient concentrations in needles (Olsson et al., 2000) and increase the soil acidity (Olsson et al., 1996). Out of the four base cations, Ca^{2+} was the element most affected by WTH although nitrogen controlled tree growth. Furthermore, soil solution sampled at stand age 27–30 years showed that the concentrations of Ca^{2+} and ANC were lower in WTH-plots compared with CH-plots (Zetterberg et al., 2013). However, the effect of WTH did not appear to be permanent since Brandtberg and Olsson (2012) showed that the differences in exchangeable Ca^{2+} pools between WTH and CH observed at stand age 15–16 years had decreased but not completely diminished at stand age 26–27 years. Also, resampling of the soil solution at stand age 32–35 years indicated still present effects only at the most well-buffered site (Zetterberg et al., 2013).

Overall, the results from these Swedish studies have clearly demonstrated that the impact of WTH was distributed through the various compartments of the ecosystem. The amounts of Ca^{2+} in the soil, the soil solution and foliage were lowered although not to levels where tree growth was affected. The studies have provided valuable empirical evidence on the effects of WTH in Swedish boreal forests. However, they provide little information on the effects over a full rotation period, which is necessary for assessing the long-term sustainability of WTH practices. The long-term perspective also includes historical changes in deposition and forest growth prior to the treatments. From an acidification perspective, estimates on weathering rates, deposition, leaching and accumulation of Ca^{2+} in tree biomass also need to be included in analyses of the sustainability of increased forest biomass harvesting.

In addition to field experiments, a number of steady state mass balances have been conducted to evaluate the long-term impact of WTH on soil Ca^{2+} pools, defined as the difference between inputs (deposition and weathering) and outputs (leaching and tree uptake). Generally, these budgets indicate negative balances for a variety of tree species and soil types across Europe (Rademacher et al., 2001; Akselsson et al., 2007; van der Heijden et al., 2011; Johnson et al., 2015), Canada (Watmough and Dillon, 2003) and the United States (Huntington et al., 2000; Vadeboncoeur et al., 2014). Dynamic models that account for time-dependant changes (MAGIC, ForSAFE, etc.) has likewise been used to simulate the biogeochemical response to WTH and CH (Aherne et al., 2012; McDonnell et al., 2013; Zanchi et al., 2014; Zetterberg et al., 2014). These simulations also imply large soil Ca^{2+} losses due to tree growth and harvest (McDonnell et al., 2013) especially following WTH (Aherne et al., 2012). Concern about the long-term nutrient availability and the risk of acidification has therefore been expressed by Swedish authorities (Swedish Environmental Protection Agency, 2007a) although it has been difficult to verify the model estimates with long-term experimental data (Zetterberg et al., 2013).

In this study, soil and soil solution data from the experiment established by Björkroth and Rosén (1977) was used to quantify changes in soil exchangeable Ca^{2+} pools and to calibrate the dynamic model MAGIC (Cosby et al., 2001). Weathering and leaching outputs from the MAGIC simulations were used together with estimates of deposition, tree accumulation and decomposition of logging residues to establish long-term Ca^{2+} mass balances.

The overall goal is to analyse the effect of WTH and CH on the Ca^{2+} dynamics and to identify shortcomings and knowledge gaps potentially affecting the simulated Ca^{2+} mass-balances. Specific aims were to (1) assess long-term (1990–2013; stand age 15–16 to 37–38 years) changes in soil Ca^{2+} pools after different treatments (CH and WTH), (2) simulate changes in soil Ca^{2+} pools during one and a half forest generation using MAGIC and (3) evaluate if the MAGIC simulations provide reasonable estimates of changes in Ca^{2+} pools compared with the measured data.

Based on measured and modelled data our hypotheses are that: (1) Ca^{2+} accumulation in tree biomass is the principal sink of Ca^{2+}, (2), treatment differences in soil exchangeable Ca^{2+} pools diminish over time because an excess of Ca^{2+} originating from logging residues will eventually be taken up in new biomass or lost by leaching, (3) the magnitude of WTH effects on the soil Ca^{2+} pools depends on soil Ca^{2+} availability and tree productivity. Unless otherwise stated, Ca^{2+} pools or concentrations mentioned in this paper always refer to the exchangeable (1 M NH_4Cl) and not the total pools. Furthermore, by tree uptake we mean net accumulation of Ca^{2+} in tree biomass.

2. Material and methods

2.1. Study areas

The experiment was established in 1974–76 at four Swedish coniferous sites using a randomized block design with three treatments repeated in four blocks at each site (Björkroth and Rosén, 1977). Each plot was 20 × 20 m surrounded by at 10 m buffer zone. The treatments included (a) CH, (b) WTH and (c) harvest of all above-ground biomass except for the needles (BSH). The logging residues were either removed during the harvest (WTH) or left on site for one year for the needles to fall off (BSH). In this study we used data from three (Tönnersjöheden, Kosta and Lövliden) of the four sites and two (CH and WTH) of the three treatments (Table 1). The fourth site (Lund) and the BSH treatment were omitted due to lack of soil solution data.

Tönnersjöheden (T103) is a second-generation Norway spruce (*Picea abies* (L.) Karst.) forest situated on the Swedish west coast (56°42′N 13°50′E) (Fig. 1). The current stand was planted in 1976 following clearcutting of a 70 year old stand in 1975. Prior to afforestation in 1904, the area consisted of open moorland dominated by *Calluna vulgaris* (L.) Hull with scatters of Scots pine (*Pinus sylvestris* L.), European white birch (*Betula pendula* Roth) and juniper (*Juniperus communis* L.) (Malmström, 1937). The first thinning occurred in 2004 leaving the logging residues (tops and branches) left on site, independent of the original treatment in 1974–76. A storm in 2005 felled 2–5 trees per plot but this disturbance was considered to result in only marginal changes on the nutrient fluxes.

Kosta is a Scots pine forest located at about the same latitude as Tönnersjöheden but farther inland (56°52′N 15°23′E). The site was established in 1976 after cutting of a mixed 100-year old conifer forest in 1975 where Norway spruce and Scots pine were represented in equal proportions. Forest grazing by sheep and cattle were probably common before the 20th century. First and second thinning of the current stand was carried out in the autumn of 2000 and autumn of 2010. The original treatments (CH and WTH) were repeated during the first but not the second thinning. That is, only stems were removed from the CH-plots while all of the thinning biomass (stems and logging residues) was transported away from the WTH-plots during the first thinning. At the second thinning, tops and branches were left on the ground while the