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Does the harvest of logging residues and wood ash application affect the mobilization and bioavailability of trace metals? ☆

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ABSTRACT

Residue biomass from conventional forestry, such as slash (i.e., tree tops and branches) and stumps, are used at an increasing rate for energy purposes in Sweden. This review examined current knowledge on how extraction of forest biomass for large-scale energy production, including the practice of ash application for nutrient recycling, influences the mobility and stocks of trace metals in the forest environment at different time scales. The study focussed on Swedish energy production systems and contemporary forest management practices, as well as the heavy metals lead (Pb), cadmium (Cd) and mercury (Hg). The historic accumulation of these elements in forest soils has mainly originated from diffuse, long-term atmospheric deposition.

There is little conclusive evidence that slash harvest generally increases the risk for mobilization of trace metals from soils during the regeneration phase, compared with stem-only harvesting. However, microbial transformation of mercury into the highly toxic methyl mercury (MeHg) species is facilitated in suboxic soil conditions that may increase during the regeneration phase. Therefore it has been hypothesized that stump harvest could result in increased mercury methylation and transport to surface waters, owing to stump harvest effects on soil physical conditions and hydrological pathways. The few studies available on the stump harvest effects of Hg showed no consistent difference in runoff from clear-felled and stump harvested catchments compared to clear-felled and soil-scarified catchments in terms of concentrations or fluxes of MeHg.

Assuming that the highest trace metal concentrations in wood ash recommended by the Swedish Forest Authority are not exceeded, wood ash application does not currently increase metal loads at the national scale, because trace metal export in harvested biomass is much larger than that returned in wood ash. The net load of Pb, Cd, and Cu will not increase at the local scale if ash doses do not greatly exceed the compensation for nutrients exported in harvested biomass. Biomass harvest and ash application have negligible effects on the load of mercury to forest soils.

A large number of studies have examined the effects of wood ash on trace metal content in soil, water and biota. Most studies showed no effect of wood ash application. When increased concentrations were found (Cd, Cr, Cu, Zn), this was in soils where concentrations remained well below harmful levels. Relatively fewer reports of increased concentrations are reported for soil water and plants, and no effects were reported for edible berries or fungi.

1. Introduction

Forest biomass has become a substantial source of bioenergy in Sweden over recent decades, (Swedish Energy Agency, 2013). This development has been supported by government and society in order to help fulfil the national goal to replace fossil fuels by increasing the share of renewable energy (Swedish Energy Agency, 2013), as well as to comply with EU's (2009) directive on renewable energy to mitigate climate change. The tops and branches from final fellings and thinnings (slash), together with sawdust and bark residues from the wood industry, are used for energy production in large plants for district heat and power production (Helmisaari et al., 2014). Stump biomass is another,

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potentially important but largely unexploited source of bioenergy in Sweden that has received growing attention during the recent decade (Swedish Forest Agency, 2009).

However, using forest biomass for energy may be in conflict with a number of criteria for sustainable use of forest resources, e.g., protecting biodiversity and the quality of soils and water, as specified by the Swedish Environmental Quality Objectives (e.g., de Jong et al., 2017). The increased export of nutrient elements in harvested biomass causes soil acidification (e.g., Löfgren et al., 2017) and reduces nutrient availability. Therefore nutrient compensation with wood-ash is recommended in Sweden (Swedish Forest Agency, 2008). One aspect of sustainability associated with increased biomass harvesting involves the risks posed by harmful trace metals and their bioavailability in the forest environment. Non-essential heavy metals like lead (Pb), cadmium (Cd) and mercury (Hg) have no biological function, hamper important biological processes in the environment e.g., microbial activity and are severely toxic to human health and wildlife. This has contributed to these three having been listed as Priority Substances by the EU (EC, 2008). Traces of heavy metals like zinc (Zn) and copper (Cu) are essential for enzymatic function in most organisms and are therefore required in small amounts but are detrimental or lethal at higher concentrations (Fraústo da Silva and Williams, 2001). Any additional anthropogenic input in addition to atmospheric deposition may well add extra stress to ecosystems that are already under pressure.

Using slash and stump biomass for large scale energy production can influence the loads, transformations, fluxes and bioavailability of harmful trace metals (Aronsson and Ekelund, 2004) resulting from the whole system of biomass harvesting and the associated forest management, including wood ash application (Narodoslawsky and Obernberger, 1996). The return of nutrients with wood ash applications to forest soils can become more important for sustainable forest production when harvesting slash or stumps in addition to stems (Stupak et al., 2007).

The total loads of trace metals to the forest environment are influenced by both the export of trace metals in harvested biomass and the return in wood ash. These fluxes should also be viewed in the context of the diffuse air-borne deposition of heavy metals that has resulted in a long-term accumulation of heavy metals in forest soils (e.g., Johansson et al., 2001).

The risk posed by toxic heavy metals is more than just a matter of load though. The bioavailability and toxicity of trace metals depends on transformations for some elements (Hg, Cr), and on binding properties to organic matter for most trace metals (Kabata-Pendias, 2004). Harvesting of slash and stumps and wood ash application can influence soil pH and other soil chemical characteristics that may influence the bioavailability of e.g., Cd, Pb and Hg present in the soil (Zetterberg et al., 2013). The transformation of inorganic Hg (Hg^{2+}) to the highly toxic methyl-mercury (MeHg) is a microbial process in anoxic/suboxic conditions that is potentially facilitated in environments caused by changes in soil moisture related to forest harvest as well as to the soil disturbance from heavy machinery, site preparation and stump lifting (Eklöf et al., 2016). The release of trace metals bound in the wood ash itself is also an important aspect of bioavailability. Fluxes of many trace metals with runoff water are also often influenced by the fluxes of dissolved and particulate organic carbon (DOC and POC) since many metals have a strong affinity to organic matter (Lydersen et al., 2002; Tyler and Olsson, 2002). Compared to stem-only harvesting, slash and stump harvesting at final felling may change both the water quality and runoff patterns that influence trace metal fluxes.

The aim of the present study is to review the current knowledge on how extraction of forest biomass for large-scale energy production, including the practice of nutrient recycling with wood ash, influences the fluxes and stocks of trace metals in the forest environment in both a short-term and a long-term perspective. The study has a focus on Swedish conditions in terms of energy production systems and contemporary forest management practices, but the study does review international studies in hemi-boreal systems in northern Europe and North America. In the next section (2), the practice of different harvesting systems and ash application in Sweden is described to set the scene. The following sections review historic emissions and deposition of heavy metals (Section 3), effects on trace metal fluxes as well as the stocks in slash and stumps during the regeneration phase (Section 4), the effects of wood ash application (Section 5) and trace metal mass balance considerations for the Swedish bioenergy system (Section 6).

2. Management scenarios

The differences in management between three levels of harvesting intensity is outlined in Fig. 1. Clearcutting is the principal forest operation that creates disturbance by increasing runoff and raising ground water tables, as well as increasing solar radiation to the ground (Andréassian, 2004; Sørensen et al., 2009). Logging and hauling with heavy machinery cause soil disturbance and compaction on base and strip roads, but slash can be used to armour roads where the bearing capacity is low (Cambi et al., 2015). Site preparation exposes mineral soil by harrowing or mounding and is typically made within a few years following felling to facilitate seedling survival and growth (Nilsson et al., 2010).

When slash is to be harvested after final felling in Sweden, the slash is gathered in piles. The method used is hereafter referred to as fuel-adapted harvesting (Jacobson and Filipsson, 2013). The slash piles are then collected in a separate operation using a forwarder. Roughly 70% of the slash is harvested at each site. There is often a time-delay of several months between clear-felling and the transport of the slash to the landing site by the road. This can be followed by additional months of storage at the roadside until further transport to the energy plant. When slash is taken for biofuel, site preparation is made in the same manner as following stem-only harvest.

The Swedish Forest Agency (2008) recommends that stabilized (hardened) wood ash (WA) be applied to forest sites following whole-tree harvesting WTH). WA doses are recommended to correspond to nutrient contents removed in harvested biomass. Since whole-tree harvest can occur at both final fellings and thinnings, nutrient compensation with WA can be made on several occasions during a rotation, although this is not frequently practiced today. Therefore, the maximum dose is recommended to be 6 tonnes per hectare and rotation, separated on two or more applications with 3 tonnes per hectare as the maximum rate. WA for application to forest should meet quality targets including minimum contents of macronutrients and maximum contents of trace metals and organic pollutants. The recommended dose and maximum levels of trace metals in ash was calculated based on the mass balance concept that trace metal load in recycled ash should not exceed the amounts exported in the harvested biomass. These calculations were made at a general scale based on published data from a number of Swedish forest ecosystems and the element content in wood ash (H. Eriksson, Swedish Forest Agency, pers. comm. April 2016). Nutrient compensation with WA should be made in growing forests, but earliest in the late regeneration phase to reduce the risk that ash stimulates nitrification in N-rich soils, which increases nitrate leaching (Swedish Forest Agency, 2008). WA is applied to both mineral and peat soils. On peat soil sites, WA application generally increases tree growth significantly due to its content of P and K (Huotari et al., 2015), but on mineral soil sites the effects on tree growth are small and variable (Jacobson et al., 2014).