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Review

Bioaccumulation of cadmium in soil organisms – With focus on wood ash application

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ABSTRACT

Harvesting whole-tree biomass for biofuel combustion intensifies removal of nutrients from the ecosystem. This can be partly amended by applying ash from the combustion back to the system and thus recycle the nutrients. However, besides being rich in inorganic nutrients, ash also contains trace amounts of heavy metals. Due to the risk of toxic effects and trophic transfer of heavy metals, especially cadmium, legislation usually restricts the use of ash as a soil amendment.

In order to provide researchers and governmental agencies with a tool to assess the risk of cadmium bioaccumulation in specific soil systems after ash application, we review: 1) the properties of ash; 2) the chemical and toxic properties of cadmium; 3) the key factors affecting cadmium bioavailability, cadmium uptake-, storage- and elimination-abilities in soil organisms and the risk of cadmium accumulation and biomagnification in the soil food web; 4) how ash impact on soil can change the risk of cadmium bioaccumulation.

We conclude that for assessing the risk of cadmium bioaccumulation for specific sites, it is necessary to consider both the type and composition of ash, the soil conditions and organism composition on the site. On a general basis, we conclude that granulated ashes low in cadmium content, applied to low pH soils with high organic matter content, in systems with low abundances of earthworms, isopods and gastropods, will have a low risk of cadmium accumulation.

1. Introduction

Burning of fossil fuels and greenhouse gas emissions are the major causes for current global climate change. Therefore, the European Council in 2006 established a mandatory target of 20% renewable energy of the total energy consumption by 2020. Part of the use of fossil fuels is replaced by burning of biomass, e.g. wood chips, for heating and electricity (COM, 2006). Harvesting whole-tree biomass from the forest intensifies nutrient removal from the ecosystem, compared to traditional harvest of timber (Raulund-Rasmussen et al., 2008). Burning of wood generates up to 1% ash by weight and ash is thus a significant by-product from biofuel power plants (Pitman, 2006). Disposal of ash at waste disposal sites is costly (Ingerslev et al., 2011), but as forest fertilizer, ash can help compensate for the removal of biomass for biofuel production (Swedish National Board of Forestry, 2002). Wood ash contains high amounts of plant nutrients, but also trace amounts of heavy metals (Pitman, 2006), which generally sets the limits for the use of ash as a fertilizer. The legislative restriction in Denmark sets the maximum threshold for cadmium (Cd) in ash application to 60 g Cd ha^{-1} 75 $year^{-1}$ for forest systems and 0.8 g Cd ha^{-1} $year^{-1}$ for farmland (Danish Ministry of the Environment, 2008). Several reviews have covered research of wood ash effects on forest soil ecosystems (Augusto et al., 2008; Huotari et al., 2015; Pitman, 2006; Vance, 1996) and toxicity and accumulation of heavy metals in organisms (Anderson et al., 2013; Bengtsson and Tranvik, 1989; Heikens et al., 2001), but very little has been published on the combination of wood ash application and Cd bioaccumulation (Perkiömäki and Fritze, 2005). Because many of the legislative restrictions for wood ash application are grounded in the accumulation risk of heavy metals (Danish Ministry of the Environment, 2008), and because biomass burning and hence ash production is increasing, it is highly relevant to elucidate the risk of terrestrial Cd bioaccumulation after wood ash application.

The aim of this review is to make a detailed analysis of the risk of Cd accumulation in soil organisms after ash application to soils. To achieve this, we review: 1) the properties of ash; 2) the chemical and toxic properties of Cd; 3) the physical and biological factors affecting the risk

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of Cd accumulation in soil organisms; 4) how the ash impact on soil can change the risk of cadmium bioaccumulation. Lastly, we will combine this to elucidate which specific factors should be assessed before amending a soil system with ash, in order to minimize the ecological risk of Cd in the system. Our hope is that the conclusions and synthesis will provide researchers, governmental agencies and forest managers a tool to assess Cd bioaccumulation risk in their specific targeted soil system.

2. Application of wood ash

Acidification is a common problem in production forestry. Wood ash is generally highly alkaline and the neutralizing effect is probably the most important characteristic of ash amendment to soil, but the effect depends on ash quantity and quality, as well as the site. Soils with intrinsically low pH and low organic matter content have shown the highest pH increases (Demeyer et al., 2001). For humus and peat surfaces pH increases between 0.5 and 3 pH units have been reported depending on the ash dose (Huotari et al., 2015).

Because ash contains valuable plant nutrients, it is also an efficient fertilizer (Demeyer et al., 2001). The major components of wood ash are calcium (Ca), potassium (K), magnesium (Mg) and phosphorus (P). Other macro-elements are aluminium (Al), iron (Fe), sodium (Na), manganese (Mn) and sulphur (S). Due to evaporation during combustion, all ashes are very low in nitrogen (N) (Demeyer et al., 2001; Etiégni and Campbell, 1991; Ingerslev et al., 2011; Karltun et al., 2008). Thus, the efficiency of ash as a fertilizer depends on the existing N in the system and/or the rate of N deposition. Fertilization with wood ash has shown positive effects on tree production at sites, which receive N deposition or are rich in organic matter, like peat soils. However, no positive effects are seen on e.g. mineral soils where N is the limiting nutrient (Huotari et al., 2015; Karltun et al., 2008). In spite of the negligible N content in wood ash, the increased pH can indirectly increase microbial activity and thus N mineralization and availability (Genenger et al., 2003; Jäggi et al., 2004; Martikainen, 1985; Weber et al., 1985; Vestergård et al., 2017).

Wood ash also consists of a range of trace elements that originate from the incinerated wood. These include arsenic (As), silver (Ag), molybdenum (Mo), mercury (Hg), nickel (Ni), vanadium (V), zinc (Zn) and cadmium (Cd) (Demeyer et al., 2001; Etiégni and Campbell, 1991; Karltun et al., 2008). Some of these are micro-nutrients; some are non-essential heavy metals (Huotari et al., 2015). Because ash usually originates from trees grown on a larger area than the area where the ash is used as a fertilizer, the heavy metals from the wood ash will concentrate in the amended area. This can increase the total heavy metal content in the soil (Huotari et al., 2015). The biggest concern regarding ash amendment is the heavy metal content, particularly Cd (Beyer, 2000; Saarsalmi et al., 2001).

3. Toxicity of Cd

Cd taken up by plants or other organisms is incorporated into biological systems, and can be transferred to higher trophic levels via consumption. Due to loss of biomass during respiration and in excretion products, there is a risk of bioaccumulation at higher trophic levels (Janssen et al., 1993). Increasing Cd concentrations in consumers can have detrimental effects, as seen during the first half of the 20th century in Japan, where Cd poisoning caused osteomalacia (severe pain and fracture of bones and joints) in humans after consumption of Cd contaminated rice (Nordberg, 2009).

Because Cd mobility is high compared to other heavy metals ($Cd > Ni > Zn > Mn > Cu > Pb = Cr > Hg$ (Brümmer, 1986; Kim et al., 2015)) it has a high potential for bioaccumulation in food webs. Cd resembles the essential metals Zn and Cu and may be taken up along the same pathways as Zn and Cu (Tyler et al., 1989). As a non-essential metal, regulation is probably either less pronounced or absent for Cd (Janssen and Hogervorst, 1993; Van Gestel et al., 1993). With no or little regulation, Cd can 'hitchhike' into the cells and accumulate in the organism. Cd can also replace Zn in metabolic processes, which is one of its toxic actions in the cell (Qiu et al., 2011; Rani et al., 2014). Additionally, Cd causes indirect oxidative stress, which can lead to DNA damage, inhibit DNA repair mechanisms and inhibit apoptosis (Rani et al., 2014).

In soil organisms this has been expressed as decreased growth (Bengtsson and Tranvik, 1989; Posthuma et al., 1992; Russell et al., 1981; Swaileh and Ezzughayyar, 2000; Van Straalen et al., 2005), prolongation of the juvenile period (Russell et al., 1981), decreased reproduction (Anderson et al., 2013; Bengtsson and Tranvik, 1989; Russell et al., 1981; Scheirs et al., 2006) and increased mortality (Qiu et al., 2011). On an ecosystem scale, Cd toxicity has disrupted ecological processes by affecting decomposition (Vig et al., 2003), changing community structure (Khalil et al., 2009) and reducing biomass (Tyler et al., 1989), diversity (Lodenius et al., 2009; Tyler et al., 1989) and relative abundance of species (Lodenius et al., 2009). The concentration of Cd can also increase in higher trophic levels, e.g. in birds (Roodbergen et al., 2008) or mice (Hunter et al., 1987b), which can export Cd from the contaminated system and disrupt the ecological functioning of other ecosystems. Furthermore, it is at risk of entering the human food chain.

4. Bioaccumulation of Cd in soil organisms

Janssen et al. (1993) defines bioaccumulation as the concentration increase of a substance in an organism compared to its environmental concentration through any kind of uptake process. Predicting how ash will influence Cd bioaccumulation in a soil system is difficult, but bioaccumulation is often used as a parameter when assessing the risk of toxicants in the environment (McGeer et al., 2003). The Cd concentration in soil/litter/ash cannot accurately predict the concentration in soil organisms (Bengtsson and Tranvik, 1989). However, by considering relevant factors, an estimate of potential bioaccumulation after ash application can be made. Firstly, we need to identify the most important physicochemical factors in the soil that influence Cd binding properties and bioavailability. Secondly, we need to address the factors that determine Cd accumulation in the soil organisms. The following will summarize and pinpoint the key factors that generally influence bioaccumulation of Cd in soil organisms – irrespective of ash addition.

4.1. Physical factors affecting Cd bioavailability and Cd uptake in organisms

Although often used, total content of heavy metal in a soil is not the best measure for contaminant exposure to soil dwelling organisms (Lanno et al., 2004; Plette et al., 1999; Sauvé et al., 2000b). Only part of the heavy metal present in soil is available for uptake and incorporation into the organisms. The metal must be bioavailable and not irreversibly bound to the soil matrix (Blume and Brümmer, 1991; Brümmer, 1986; Kim et al., 2007; Lanno et al., 2004). We define the bioavailable fraction as that part of the total amount of Cd that can be sorbed by an organism in a terrestrial system.

Many studies investigating bioavailability in soil focus on plant availability (Blume and Brümmer, 1991; Brown et al., 2004; Gall et al., 2015; Kirkham, 2006; McLaughlin et al., 1998; Scheifler et al., 2003; Wang et al., 2010). Cd is most readily available to plants as Cd^{++}, whereas plants take up $CdCl^{+}$ more slowly and do not take up Cd-humate (Crea et al., 2013).

Several different methods have been used to evaluate bioavailability (Brümmer, 1986; Lanno et al., 2004; Yin et al., 2014), for example soil concentration of dissolved metals (Blume and Brümmer, 1991; Brown et al., 2004; Christensen, 1989; Kim et al., 2015; Paradelo et al., 2011), metal partitioning coefficient – the ratio between soluble and total metal concentration in the soil (Anderson and Christensen, 1988;