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Wood ash as a soil amendment in Canadian forests: what are the barriers to utilization?

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1 **Wood ash as a soil amendment in Canadian forests: what are the barriers to**
2 **utilization?**

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Abstract

The contribution of forest biomass to Canada's energy production is small but growing. As the forest bioenergy industry in Canada expands, there is growing interest in more sustainably managing the wood ash that is generated as a by-product. Despite being rich in nutrients, wood ash is usually landfilled in Canada. Soil applications of ash in Canadian forests could be used to mimic some of the effects of wildfire; to replace nutrients removed during harvesting; to counteract the negative effects of acid deposition; and to improve tree growth. At present, the provincial/territorial processes for obtaining regulatory approval to use wood ash as a forest soil amendment can be challenging to navigate. Furthermore, the costs for obtaining approval, transporting and soil-applying wood ash can render landfilling a more cost-effective method of ash management. To ensure that wood ash applications in Canadian forests are conducted safely, effectively and efficiently, experience from European countries could provide a useful starting point for developing best practices. The results of Canadian research trials will assist policy makers and forest managers in refining management guidelines that encourage soil applications of wood ash as a forest management tool while protecting the ecology, water quality, biodiversity and productivity of Canadian forests.

Keywords (up to 6):

bioenergy; wood ash; forest soil; biomass harvesting; waste management.

55 **Introduction**

56 Canada meets its energy needs using a combination of fossil fuels, nuclear power,
57 and renewables. Efforts to mitigate greenhouse gas emissions depend on replacing fossil
58 fuel-based energy with that from renewable sources. The contribution of renewables to
59 Canada's total energy production is increasing rapidly (11% in 2013; 16% in 2014; 20%
60 in 2015; Nyboer et al. 2014; Nyboer and Melton 2015; Griffin and Nyboer 2016). At
61 present, hydroelectricity accounts for the bulk of Canada's renewable energy capacity
62 (72%), followed by biomass (15%) (Griffin and Nyboer 2016). Approximately 65% of
63 the biomass combusted is used to provide thermal energy, with increasing amounts used
64 to generate electricity and liquid fuels (Griffin and Nyboer 2016). Most of Canada's
65 renewable energy capacity is used to generate electricity, and the contribution of biomass
66 to electricity generation is also trending upward (from 7875 GWh in 2005 to 13107 GWh
67 in 2015; National Energy Board of Canada 2016).

68 The primary users of bioenergy in Canada are the timber and pulp and paper
69 industries, which generate heat and power for on-site use by combusting the by-products
70 of the manufacturing process (e.g., off-cuts, hog fuel, black liquor; Bradburn 2014).
71 Increasingly, however, the use of forest biomass for energy is diversifying. Many
72 Canadian provinces and territories have implemented policies that promote investment in
73 forest biomass-based energy production. For example, as required under the
74 Environmental Protection Act, Ontario Power Generation (OPG) has phased out coal-
75 fired electricity production and converted the generating stations at Thunder Bay and
76 Atikokan to wood or torrefied pellet combustion (Bradburn 2014; Ontario Power
77 Generation 2015). In the Northwest Territories (NWT), the 2010 Biomass Energy

Strategy has facilitated the installation of wood pellet boilers for the provision of residential, commercial and institutional heating; with the goal of ‘leading by example’, twenty-eight pellet boiler systems have been installed in government facilities across the NWT and currently provide 24% of the government’s total heat requirements (Government of the Northwest Territories 2017).

The forest industry is already the largest producer of bioenergy in Canada (Bradburn 2014; Roach and Berch 2014; Griffin and Nyboer 2016). Declining demand for traditional forest products (e.g., newsprint, lumber) has encouraged investment in emerging products (e.g., wood pellets) that can be used to generate bioenergy both domestically and abroad (Roach and Berch 2014; Lamers et al. 2016). Wood pellets can be produced from a variety of woody materials that have, until recently, had little economic value. Wood processing residues, tree branches, tops and un-merchantable stems that were traditionally piled at the roadside and burned or left within the stand to decay; trees salvaged after insect outbreaks or wildfire; and dead woody material generated during stand break-up and self-thinning are viewed as possible source material for pellet production (Ontario Ministry of Natural Resources 2008; Dymond et al. 2010; Roach and Berch 2014). There is enormous potential to further expand energy production in Canada using forest biomass (Dymond et al. 2010; Yemshanov et al. 2014; Paré et al. 2016).

The expansion of forest bioenergy capacity across the country will also increase the rate of wood ash production. Wood ash is often treated as a waste material in Canada, and landfilled, although this situation is changing. In 1995, 84% of the ash produced in power and recovery boilers at Canadian pulp and paper mills was landfilled; by 2013,

landfilling rates had fallen to 63% (Elliott and Mahmood 2006; Elliott and Mahmood 2015). Nevertheless, wood ash management practices vary considerably among provinces. Approximately half of the ash produced each year in Alberta (~30 000 Mg; G. Dinwoodie, Land Reclamation Specialist - Alberta Environment and Parks, Land Policy Branch, personal communication, September 2016) and Québec (~150 000 Mg; Hébert and Breton 2009) is soil-applied; the remainder is usually landfilled. By contrast, almost all of the ash produced each year in British Columbia pulp and paper mills, sawmills and bioenergy plants is landfilled (~226 000 Mg; Nishio 2016).

Depending on its chemical and physical properties, wood ash can have a wide range of beneficial uses, e.g., liming agent and fertilizer on agricultural soils; capping material at landfills; road aggregate; fill material in building construction; cement manufacturing; odour absorbent (Elliott and Mahmood 2006; Knapp and Insam 2011; Swedish Energy Ashes 2014). Numerous studies have also demonstrated that applications of wood ash on forest soils can be used to replace some of the nutrients (e.g., phosphorus (P), calcium (Ca), magnesium (Mg), potassium (K)) removed during forest harvesting; to counteract the acidifying effects of atmospheric deposition on forest soils and surface water bodies; and to improve tree growth (Augusto et al. 2008; Reid and Watmough 2014; Huotari et al. 2015). In several European countries, forest soil applications of wood ash are encouraged, particularly on sites from which harvesting residues have been removed for bioenergy production (Skogsstyrelsen 2008; Stupak et al. 2008; Forestry Commission 2009). Thus, disposal of wood ash in Canadian landfills may represent a wasted opportunity to obtain greater economic value from forest biomass and to more

sustainably manage the forest resource by closing a loop in the cycling of nutrients during forestry operations. The objectives of this paper are to:

- provide a brief description of the possible benefits of wood ash use as a soil amendment in Canadian forests;
- provide an evaluation of the current regulatory and knowledge barriers to the use of wood ash as a forest soil amendment in Canada; and
- outline some of the factors to consider when developing guidelines for the use of wood ash as a forest soil amendment in Canada.

Possible benefits of using wood ash as a forest soil amendment in Canada

There is a large and growing body of literature, especially from Scandinavia, demonstrating the utility of wood ash as a soil amendment on forest sites. We provide some selected references to illustrate that soil applications of wood ash can be used to meet a number of complementary forest management objectives.

To mimic some of the effects of wildfire on soil properties

Increasingly, management practices that ‘emulate natural disturbance’ (END) are being promoted as a means of accommodating conflicting demands for ecological and economic goods and services from Canadian forests (Perera et al. 2004; Ontario Ministry of Natural Resources 2010; Stockdale et al. 2016). Wildfire is the dominant high-mortality disturbance agent in forest ecosystems across much of Canada (Government of Canada 2015). Although wood ash applications do not impose the same high surface soil temperatures associated with wildfire or cause a rapid oxidation of the forest floor layer

(Nave et al. 2011), they can elevate soil pH and enhance concentrations of Ca, Mg and K (Augusto et al. 2008; Huotari et al. 2015; Reid and Watmough 2014) in a similar manner to wildfire (Certini 2005; Bodí et al. 2014; Maynard et al. 2014). Thus, applications of wood ash may have potential as a management tool for END (Noyce et al. 2016).

To replace nutrients removed during biomass harvesting

In 2013, woody biomass provided 26% and 31% of total primary energy needs in Finland and Sweden, respectively (Thiffault et al. 2016). Most of this energy was derived from the combustion of small diameter woody residues generated during stand thinning, timber harvesting and wood processing (Thiffault et al. 2016). Given that a significant quantity of the nutrients (e.g., Ca, Mg, K and P) contained in forest biomass can be recovered in the ash fraction remaining after combustion (Ingerslev et al. 2011), the practice of returning wood ash to the forest can be used to replenish ecosystem nutrient pools and preserve forest productivity after intensive biomass removal (Skogsstyrelsen no date; Karlton et al. 2008; Skogsstyrelsen 2008). Indeed, wood ash can improve foliar P, K and Ca concentrations for decades after application (Augusto et al. 2008; Reid and Watmough 2014). To ensure that the nutrients removed during biomass harvesting are replaced during ash application, Finland, Lithuania and Sweden have established minimum Ca, K and P content limits for any wood ash that is used as a forest soil amendment (Stupak et al. 2008).

To counteract the acidifying effects of atmospheric deposition and forest harvesting

Atmospheric sulphur and N deposition has led to severe acidification of surface waters and soils, and depletion of soil base cation pools on acid-sensitive sites in central Europe and north-eastern North America (Driscoll et al. 2003; Canadian Council of Ministers of the Environment 2008; European Environmental Agency 2012). This phenomenon has been shown to alter lake ecology and has raised concerns that soils and forests on base-poor sites have been rendered more sensitive to biological acidification caused by nutrient removals associated with timber and biomass removal (Watmough et al. 2003; Jeziorski et al. 2008, McLaughlin, 2014; Löfgren et al. 2017). According to a recent meta-analysis (of predominantly European and North American studies), biomass harvesting can lower the pH and base saturation of surface soils and reduce concentrations of foliar calcium in the regenerating stand, but only when foliage is removed along with tree stems and branches (Achat et al. 2015). Research has shown that applications of wood ash can be used to increase soil pH and base saturation, thereby increasing surface water pH which, in turn, may facilitate the ecological recovery of surface waters (Westling and Zetterberg 2007; Johansson 2014; Huotari et al. 2015).

To improve tree growth

Applications of wood ash do not consistently improve tree growth. Current evidence suggests that a positive growth response to applications of wood ash is most likely on N-rich sites, including forests that receive high rates of atmospheric N deposition, and stands established on naturally fertile peatland or mineral soils (Jacobson et al. 2014; Huotari et al. 2015). On these sites, ash is believed to stimulate the decay of soil organic matter, releasing N which can then be taken up by tree roots (Augusto et al.

2008; Karlton et al. 2008; Huotari et al. 2015). Tree growth typically remains unchanged or even decreases when wood ash is applied to mineral soils where forest productivity is limited by the availability of N (Augusto et al. 2008; Karlton et al. 2008; Huotari et al. 2015).

Current barriers in Canada to the use of wood ash as a forest soil amendment

The process of obtaining regulatory approval is challenging

The use of wood ash as a soil amendment is largely under provincial or territorial jurisdiction and, consequently, it varies significantly across Canada. In addition, oversight of soil applications of wood ash are administered by various government departments, and ash can be classified differently (e.g., solid waste, fertilizer, soil amendment) depending on the mandate of the department under which ash management falls in each jurisdiction. In many provinces and territories, ash is defined as a waste material that should be landfilled. As such, some form of environmental impact assessment is often required to obtain approval to apply it to forest or agricultural soils (Hannam et al. 2016). In other provinces, an approval process has been put in place for soil applications of wood ash, specifically, (Alberta Environment 2002) or for soil applications of industrial by-products, in general, (Government of Ontario 2002; Government of British Columbia 2007; Hébert 2008; New Brunswick Department of Environment and Local Government 2014; Hébert 2015) but the focus is on agricultural systems. Furthermore, the application process is often confusing, onerous and time-consuming (Hannam et al. 2016).

214 *Landfilling is often the most cost-effective method of ash disposal*

215 The economic costs of soil-applying wood ash are another important potential
216 barrier to the increased diversion of wood ash from the landfill (van Eijk et al. 2012;
217 Risse 2013). Regulatory costs include both the fees associated with obtaining approval to
218 apply wood ash on forest sites and with creating landfill space and depositing the ash in a
219 landfill. The construction of new landfills for wood ash disposal is typically more costly
220 than application on forest soils (Hope et al. 2017). Given that some jurisdictions are
221 becoming reluctant to grant long-term approval to landfill wood ash, insisting instead on
222 the development of more sustainable ash management strategies, the use of wood ash as a
223 soil amendment may become increasingly cost-effective from a regulatory standpoint.

224 Pre-treatment costs are those associated with processing wood ash to ease its
225 handling and application to the soil. In Canada, water is typically added to suppress dust,
226 facilitate ash removal from the boiler, and extinguish any remaining embers (Sylvia
227 Environmental, 2008; Hébert and Breton 2009) but, in general, wood ash is not processed
228 any further. In some European countries, however, ash pre-treatment (or ‘stabilization’) is
229 recommended. Ash pre-treatment involves wetting the ash and allowing highly reactive
230 and caustic oxides in the ash to react with carbon dioxide and water, and ‘harden’ into
231 more chemically stable carbonates (Emilsson 2006; Karlun et al. 2008). This pre-
232 treatment step is believed to prevent scorching of vegetation, prolong the fertilization
233 effect of wood ash and reduce the mobility of heavy metals (Emilsson 2006; Pitman
234 2006; Skogsstyrelsen 2008).

235 Finally, transportation costs include the fees associated with transporting the ash
236 and ash spreading equipment to and from the application site or landfill. In general, the

use of wood ash as a soil amendment is not economically viable when sites are located more than 100 km from the ash production facility (Hope et al. 2017).

Ash quality can be highly variable

The chemical and physical properties of wood ash are highly variable (Table 1). Ash properties are strongly affected by the moisture content, physical form and tree species composition of the feedstock, the type of combustion system utilized, and the combustion conditions applied (Elliott and Mahmood 2006; Pitman 2006; James et al. 2014). Furthermore, ash properties vary depending on their physical point of origin within biomass boilers. Typically, fly ash is more enriched in trace elements than bottom ash (Narodoslawsky and Obernberger 1996; Swedish University of Agricultural Sciences 2008; Nurmesniemi et al. 2011). Ash chemistry data from paired sets of Canadian fly and bottom ash samples demonstrate this trend (Figure 1).

There is some concern that soil applications of ash-borne trace elements could lead to contamination of forest soil, water and biota (Aronsson and Ekelund 2004; Pitman 2006; Augusto et al. 2008; Huotari et al. 2015). This concern can be addressed, in part, by collecting and managing fly and bottom ash fractions separately and by basing ash dosage rates on the results of their chemical analyses (Government of Ontario 2002; Sylvis Environmental 2008; New Brunswick Department of Environment and Local Government 2014; Hébert 2015). In most provinces and territories, the trace element limits set for compost by the Canadian Council of Ministers of the Environment (CCME) are applied to wood ash that will be used as a soil amendment (Canadian Council of Ministers of the Environment 2005; Hannam et al. 2016). According to these criteria, soil

applications of wood ash can be ‘unrestricted’, ‘restricted’ or ‘not permitted’, depending on ash trace metal concentrations (Figure 2; Table 2). Of the 13 provinces and territories in Canada, four (Alberta, British Columbia, Ontario and Quebec) have developed their own trace element limits, which would apply to wood ash used as a soil amendment; these are often modified versions of the CCME trace element limits (Hannam et al. 2016).

According to the CCME guidelines, trace element limits for unrestricted wood ash applications in Canada (Table 2, CCME Compost A) are generally lower than limiting values for wood ash in Europe (Table 3). Trace elements limits for wood ash that can be used in restricted applications (CCME Compost B) are generally higher than limiting values for wood ash in Europe (Table 3). This suggests that, under current guidelines, wood ash with higher concentrations of trace elements could legally be applied to Canadian forest soils than to European forest soils, as long as provincial or territorial control measures are followed. That being said, the mean concentrations of chromium, cobalt, copper, lead and nickel in fly and bottom ash sampled from Canadian boilers, and cadmium, molybdenum and zinc in bottom ash sampled from Canadian boilers were less than the CCME Category A limits (Figure 2). Wood ash with these concentrations could also be applied under European regulations. Although mean concentrations of arsenic in fly and bottom ash sampled from Canadian boilers, and cadmium and zinc in fly ash sampled from Canadian boilers were greater than the Category A limits (Figure 2), they were still generally below European limits (Table 3).

Studies have shown that wood ash composition can be improved via careful control of feedstock quality and combustion conditions (Narodoslawsky and Obernberger

1996; Elliott and Mahmood 2006; Nurmesniemi et al. 2011). Indeed, some measures have been put in place in a few Canadian provinces to improve the quality of ash used as a soil amendment, but these are typically focussed on preventing organic compound contamination, rather than reducing trace element concentrations. To prevent contamination of soils with dioxins and furans (persistent organic pollutants formed during the combustion of chloride-containing organic materials), for example, British Columbia prohibits soil applications of fly ash produced from wood that has been immersed in marine waters (Government of British Columbia 2007). If wood ash becomes more widely recognized as a valuable commodity, bioenergy producers could be motivated to more carefully manipulate feedstock quality and combustion conditions to improve wood ash chemical characteristics.

Lack of knowledge of the effects of wood ash applications specifically on forest sites

At present, none of the provincial/territorial policies and regulations that apply to forestry operations in Canada encourage soil applications of wood ash. In order to maintain support from the Canadian public for expanding bioenergy production (and the ash that it generates), guidance is required that directly addresses the use of wood ash as a forest soil amendment. Research trials have been established in British Columbia, Saskatchewan, Manitoba, Ontario, Québec and Prince Edward Island (Table 4). The trials are linked through AshNet (<http://cfs.nrcan.gc.ca/projects/140>), a nascent national network investigating wood ash applications in Canadian forests, and are designed to examine the implications for tree growth, water quality and biodiversity of applying wood ash to forest soils. Given that most of the trials have been established in the last 10

years, monitoring is ongoing and only initial results (< 5 years after ash application) have been published for a limited number of sites (Table 4). To date, however, the overall effects of ash application on forest soils in Canada appear to be similar to those observed in European trials. To illustrate this point, the effects of ash application on soil pH and tree growth for a few sites are briefly summarised below.

The short-term effects of wood ash application on soil pH in Canadian wood ash trials have mostly been positive but treatment effects vary with ash dosage rate and soil depth. In a young jack pine plantation in northeastern Ontario (Island Lake site; Table 4), for example, forest floor pH was increased two years after the application of 5.6 Mg ha^{-1} of wood ash but not after the application of 0.7 Mg ha^{-1} , 1.4 Mg ha^{-1} or 2.8 Mg ha^{-1} of wood ash (Noyce et al. 2016). In an uneven-aged hardwood forest in central Ontario (Haliburton site; Table 4), forest floor pH was increased one year after the application of 4 Mg ha^{-1} or 8 Mg ha^{-1} of fly ash or bottom ashes but not after the application of 1 Mg ha^{-1} of fly or bottom ashes (Noyce et al. 2016). In a ~ 53 year-old boreal stand in northwestern Québec (Senneterre-1 site; Table 4), forest floor pH increased in the first year following application of 2 Mg ha^{-1} or 8 Mg ha^{-1} of wood ash, and treatment effects remained constant at years 2 and 5 (Brais et al. 2015). In a white spruce plantation in north-central BC, forest floor pH had increased five months after the application of 5 Mg ha^{-1} low-carbon gasifier ash or high-carbon boiler ash; treatment effects were strongest following the application of gasifier ash, particularly when applied in combination with 100 kg ha^{-1} urea (Domes et al. in press). In all of the above studies, wood ash application had no significant effect on the pH of the surface (0-10 cm) mineral soil. In a white spruce plantation in northwestern Saskatchewan (Meadow Lake site; Table 4), however,

increased soil pH was observed at 0-10 cm, 10-20 cm and 20-30 cm soil depths two years after the application of 5 Mg ha⁻¹ of wood ash (though not after the application of 1 Mg ha⁻¹ of wood ash; Staples and Van Rees 2001).

The short-term effects of wood ash applications on tree growth in Canadian wood ash trials have mostly been negative. In a nine year-old western red cedar plantation on Vancouver Island, British Columbia (Port McNeill site; Table 4), reduced height growth was observed every year for five years after application of 5 Mg ha⁻¹ of wood ash (McDonald et al. 1994; Prescott and Brown 1998). At the Senneterre-1 site, no change in the growth of jack pine or small diameter (dbh < 10 cm) black spruce was observed five years after application of 8 Mg ha⁻¹ of wood ash, but the growth of large diameter (dbh > 10 cm) black spruce was reduced (Brais et al. 2015). At the Meadow Lake site, reduced height and diameter growth was observed two years after application of 5 Mg ha⁻¹ of wood ash (Staples and Van Rees 2001).

Continued assessments of these experimental trials will help answer questions concerning the longer-term effects of wood ash applications on soil properties and site productivity in Canadian forest ecosystems. For example, reviews of European trials suggest that increased soil pH in deeper mineral soils, and enhanced tree growth are more often observed > 10 years after ash additions (Pitman 2006; Reid and Watmough 2014). Linking the Canadian research sites through AshNet will also enable researchers to identify research gaps and ensure that critical environmental indicators are being monitored across a broad range of forest and soil types.

Developing guidelines for the use of wood ash as a forest soil amendment in Canada

While ongoing monitoring of Canadian wood ash trials will provide much needed information on the ecological effects of wood ash applications, it is not practical to wait until all the implications are known before relevant policies can be revised or developed (Puddister et al. 2011). European standards for wood ash applications on forest soils can provide an initial framework for the development of Canadian guidelines.

Sites to which ash should not be applied

Some provinces/territories discourage the removal of harvesting residues on sites with nutrient-poor soils (Roach and Berch 2014). At the same time, most provinces/territories discourage the use of soil amendments on sites with coarse-textured or shallow soils because of concerns over nutrient leaching and water contamination (Hannam et al. 2016). Such policies contrast with those developed for Finland, Lithuania, Sweden and the United Kingdom (UK), where applications of wood ash are encouraged to prevent nutrient deficiencies following biomass harvesting, particularly on nutrient-poor sites (Karlton et al. 2008; Raulund-Rasmussen et al. 2008; Forestry Commission 2009).

European guidelines have identified several types of sites to which wood ash should not be applied. In order to prevent N leaching and contamination of surface water, applications of wood ash are not recommended in the UK on upland forest soils that receive high rates of atmospheric N deposition (Pitman 2006; Forestry Commission 2009) or in Sweden on N-rich clearcuts that are adjacent to watercourses (Skogsstyrelsen 2008). In Sweden, ash applications are not recommended on sites with sensitive flora, such as sphagnum moss, because burning of foliage has been observed (Karlton et al.

2008; Skogsstyrelsen 2008). In Denmark, analysis of forest soils is mandatory prior to wood ash applications, and dosage rates are calculated to ensure that the concentrations of trace elements in the soil remain below specified limits (Stupak et al. 2008). Soil testing is also required in Austria if trace element concentrations in the ash are above specified limits (van Eijk et al. 2012). Such restrictions could be particularly important on sites that are naturally enriched in certain trace elements or that have been contaminated by industrial activity (Pitman 2006). In fact, soil analysis of trace elements would already be required in order to obtain approval to apply wood ash in many Canadian jurisdictions (Hannam et al. 2016).

Optimal dosage rates

In Canada, wood ash dosage rates for agricultural applications are typically calculated from the characteristics of the ash and receiving soil (Alberta Environment 2002; Government of Ontario 2002; Sylvis Environmental 2008; Hébert 2015). Similar considerations are used when determining ash dosage rates for forest applications in many European countries (Stupak et al. 2008). For example, several countries, including Austria, Denmark, Finland, Germany, Lithuania and Sweden, have set strict limits on the maximum concentrations of trace elements allowed in any ash to be used as a forest soil amendment (Table 3; Stupak et al. 2008; van Eijk et al. 2012). Measured concentrations of trace elements in the ash and (in some countries) receiving soil, together with maximum recommended ash dosage rates, are used to ensure that ash applications do not substantially increase trace element loads within forest ecosystems (Stupak et al. 2008; van Eijk et al. 2012). However, other site factors can also be considered, e.g., the tree

species composition and fertility of the soil (Emilsson 2006; Stupak et al. 2008; Varnagirytė-Kabašinskienė 2012); the acidity of atmospheric deposition (Stupak et al. 2008); and/or the quantity of nutrients removed during harvesting (Emilsson 2006; Skogsstyrelsen 2008; Stupak et al. 2008).

No maximum dosage rates have been developed specifically for wood ash applications on forest soils in Canada. Instead, maximum dosage rates for wood ash (or soil amendments, in general) in Canada were developed with a focus on agricultural soils and are typically much higher than those recommended for forest soils in Europe (Table 5).

Optimal application timing and frequency

Applications of wood ash in clearcut management systems could probably be conducted during site preparation, prior to replanting, in order to reduce the number of stand entries and minimize damage to regenerating trees (Lomander et al. 2005; Emilsson 2006). During thinning or partial harvesting operations, machinery trails could be used to access the stand for ash spreading without damaging retained trees. Due to concerns about K and nitrate leaching, several European guidelines suggest that ash only be applied on sites with established vegetation (Emilsson 2006; Skogsstyrelsen 2008; Stupak et al. 2008) and that only very stable ash products be applied on clearcuts (Emilsson 2006; Wildbacher 2007; Skogsstyrelsen 2008). Recommendations in some European guidelines for ash applications later in stand development appear to be motivated by the desire to improve forest productivity and/or pre-emptively replace nutrients that will be

removed during future harvests (Pitman 2006; Stupak et al. 2008; Varnagirytė-Kabašinskienė 2012).

Co-applications of wood ash with N-rich amendments

Co-applications of ash and N are recommended in Sweden for vigorously growing stands (Emilsson 2006), and for sites with low levels of N deposition and high levels of biomass extraction (Skogsstyrelsen 2008). Applications of granules produced from a mixture of wood ash and N-rich pulp and paper mill sludge have also been proposed (Emilsson 2006). To date, the effects on tree growth and foliar nutrition of co-applications of wood ash with urea (Brais et al. 2015) and N-rich fish silage (Prescott and Brown 1998) have been reported for two forest sites in Canada but, in both studies, increased tree growth appeared to be a response to the added N and not the wood ash.

Conclusions

Forest biomass is a relatively small but growing source of renewable energy in Canada. As the forest bioenergy industry expands, disposal of the ash generated during the combustion process will become a more important issue. At present, much of the wood ash produced in Canada is landfilled. Its use as a soil amendment on forest sites could mimic some of the effects of wildfire on soil processes in logged forests, help replace the nutrients removed during biomass harvesting, counteract the effects of acid deposition on soil and surface water, and prolong the lifespan of landfills. The long-term effects of ash applications on forest productivity require more study. At present, the process for obtaining regulatory approval to apply wood ash on forest soils is seen as a significant

barrier in Canada. As well, the costs of obtaining approval, transporting and applying ash often render landfilling the most cost-effective option for disposal. Recognition of the potential economic value of wood ash could encourage bioenergy producers to more carefully control feedstock composition and combustion conditions in order optimize ash quality. To ensure that wood ash applications on Canadian forest sites are conducted safely, effectively and efficiently, guidelines developed for countries in Europe may be instructive.

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References

Achat, D.L., Deleuze, C., Landman, G., Pousse, N., Ranger, J., and Augusto, L. 2015. Quantifying consequences of removing harvesting residues on forest soils and tree growth – A meta-analysis. *For. Ecol. Manage* 348: 124-141.

Alberta Environment. 2002. Standards and guidelines for the use of wood ash as a liming material for agricultural soils. Available from:
<http://environment.gov.ab.ca/info/library/6680.pdf> [accessed 22 July 2016]

Aronsson, K.A. and Ekelund, N.G.A. 2004. Biological effects of wood ash application to forest and aquatic ecosystems. *J. Environ. Qual.* 33: 1595-1605.

Augusto, L., Bakker, M.R. and Meredieu, C. 2008. Wood ash applications to temperate forest ecosystems – potential benefits and drawbacks. *Plant Soil* 306: 181-198. doi: 10.1007/s11104-008-9570-z.

Bodí, M.B., Martin, D.A., Balfour, V.N., Santín, C. Doerr, S.H., Pereira, P., Cerdà, A., and Mataix-Solera, J. 2014. Wildland fire ash: Production, composition and eco-hydro-geomorphic effects. *Earth-Science Reviews* 130: 103-127. doi: 10.1016/j.earscirev.2014.07.005.

Bradburn, K. 2014. CANBIO report on the status of bioenergy in Canada. Available from: http://www.fpac.ca/wp-content/uploads/2014_CanBio_Report.pdf [accessed 22 July 2016].

Brais, S., Bélanger, N. and Guillemette, T. 2015. Wood ash and N fertilization in the Canadian forest forest: soil properties and response of jack pine and black spruce. *For. Ecol. Manage.* 348: 1-14. doi: 10.1016/j.foreco.2015.03.021.

Canadian Council of Ministers of the Environment. 2005. Guidelines for Compost Quality. Available from:

http://www.ccme.ca/files/Resources/waste/compost_quality/compostgdlns_1340_e.pdf

[accessed 22 July 2016]

Canadian Council of Ministers of the Environment. 2008. A national picture of acid deposition critical loads for forest soils in Canada. PN 1412. Available from:

http://www.ccme.ca/files/Resources/air/acid_rain/national_picture_acid_deposition_pn1412.pdf [accessed 22 July 2016]

Certini, G. 2005. Effects of fire on properties of forest soils: a review. *Oecologia* 143: 1-10. doi: 10.1007/s00442-004-1788-8.

Domes, K.A., de Zeeuw, T., Massicotte, H.B., Elkin, C., McGill, W.B., Jull, M.J., Chisholm, C.E. and Rutherford, P.M. In press. Short-term changes in spruce foliar nutrients and soil properties in response to wood ash application in the sub-boreal climate zone of British Columbia. *Can. J. Soil Sci.*

Driscoll, C.T., Driscoll, K.M., Mitchell, M.J., and Raynal, D.J. 2003. Effects of acidic deposition on forest and aquatic ecosystems in New York State. *Environ. Poll.* 123: 327-336. doi: 10.1016/S0269-7491(03)00019-8.

Dymond, C.C., Titus, B.D., Stinson, G. and Kurz, W.A. 2010. Future quantities and spatial distribution of harvesting residue and dead wood from natural disturbances in Canada. *For. Ecol. Manage.* 260: 181-192. doi: 10.1016/j.foreco.2010.04.015.

Elliott, A. and Mahmood, T. 2006. Beneficial uses of pulp and paper power boiler ash residues. *TAPPI Journal* 5: 9-16.

Elliott, A. and Mahmood, T. 2015. Generation and management of solid residues by Canadian pulp and paper mills in 2013. Confidential report prepared for FPInnovations.

Emilsson, E. 2006. From extraction of forest fuels to ash recycling: international handbook. Available from: http://ec.europa.eu/environment/life/project/Projects/index.cfm?fuseaction=home.showFile&rep=file&fil=Recash_International_Handbook_Final2006_EN.pdf. [accessed 22 July 2016]

European Environmental Agency. 2012. Exceedance of critical loads of acidity [online] Available from <http://www.eea.europa.eu/data-and-maps/figures/exceedance-of-critical-loads-of-acidity> [accessed 22 July 2016].

Forestry Commission. 2009. Guidance on site selection for brash removal. Available from:

[http://www.forestry.gov.uk/pdf/Brash_residue_protocol.pdf/\\$file/Brash_residue_protocol.pdf](http://www.forestry.gov.uk/pdf/Brash_residue_protocol.pdf/$file/Brash_residue_protocol.pdf) [accessed 22 July 2016]

Gorgolewski, A., Caspersen, J., Hazlett, P., Jones, T., Tran, H., and Basiliko, N. 2016. Responses of Eastern Red-backed Salamander (*Plethodon cinereus*) abundance 1 year after application of wood ash in a northern hardwood forest. *Can. J. For. Res.* 46: 402-409. doi: 10.1139/cjfr-2015-0230.

Government of British Columbia. 2007. Code of practice for soil amendments under the Environmental Act and the Public Health Act. Available from: http://www.BritishColumbialaws.ca/Recon/document/ID/freeside/210_2007. [accessed 22 July 2016]

Government of Canada. 2015. National Forest and Forest Management Statistics. Available from: http://nfdp.ccfm.org/index_e.php [accessed 22 July 2016]

Government of Ontario 2002. Nutrient Management Act. O. Reg. 267/03: GENERAL. Available from: <https://www.ontario.ca/laws/regulation/030267>. [accessed 22 July 2016]

Government of the Northwest Territories. 2017. 2030 Energy Strategy – A Path to More Affordable, Secure and Sustainable Energy in the Northwest Territories. August 2017

Draft for Public Comment. Available from:

https://www.inf.gov.nt.ca/sites/inf/files/resources/gnwt_inf_7047_energy_strategy_p7_0.pdf. [accessed December 2017].

Griffin, B., and Nyboer, J. 2016. Renewable Energy in Canada 2015. Canadian Industrial Energy End-use Data and Analysis Centre. Simon Fraser University, Burnaby, B.C.

Available from:

http://www2.cieedac.sfu.ca/media/publications/Renewable_Energy_Report_2016_-_Final.pdf (accessed 29 August 2016).

Hannam, K.D., Deschamps, C., Kwiaton, M., Venier, L. and Hazlett, P.W. 2016. Regulations and guidelines for the use of wood ash as a soil amendment in Canadian forests. Information Report GLC-X-18.

Hébert, M. 2008. Guidelines for the Beneficial Use of Fertilising Residuals – Edition 2008. Available from: http://www.mddelcc.gouv.qc.ca/matieres/mat_res-en/fertilisantes/critere/guide-mrf.pdf [accessed 22 July 2016]

Hébert, M. 2015. Guide sur le recyclage des matières résiduelles fertilisantes: Critères de référence et norms réglementaires – Edition 2015. Available from: http://www.mddelcc.gouv.qc.ca/matieres/mat_res/fertilisantes/critere/guide-mrf.pdf [accessed 22 July 2016]

Hébert, M and Breton, B. 2009. Agricultural wood ash recycling in Québec and in northern climate: current situation, impact and agri-environmental practices. Available from: <http://www.weao.org/assets/docs/residualsBiosolids/2009-5th-canadian-residuals-and-biosolids-presentation.pdf> [accessed 22 July 2016]

Hope, E.S., McKenney, D.W., Allen, D.J. and Pedlar, J.H. 2017. A cost analysis of bioenergy-generated ash disposal options in Canada. *Canadian Journal of Forest Research* 47: 1222-1231.

Huotari, N., Tillman-Sutela, E., Moilanen, M. and Laiho, R. 2015. Recycling of ash – For the good of the environment? *For. Ecol. Manage.* 348: 226-240. doi: 10.1016/j.foreco.2015.03.008.

Ingerslev, M., Skov, S., Sevel, L., and Pedersen, L.B. 2011. Element budgets of forest biomass combustion and ash fertilisation – A Danish case-study. *Biomass Bioenergy* 35: 2697-2704.

Jacobson, S., Lundstrom, H., Nordlund, S., Sikstrom, U. and Pettersson, F. 2014. Is tree growth in boreal coniferous stands on mineral soils affected by the addition of wood ash? *Scand. J. For. Res.* 29: 675-685.

James, A.K., Helle, S.S., Thring, R.W., Sarohia, G.S., and Rutherford, P.M. 2014. Characterization of inorganic elements in woody biomass bottom ash from a fixed-bed

combustion system, a downdraft gasifier and a wood pellet burner by fractionation.

Energy Environ. Res. 4: 85-94. doi: 10.5539/eer.v4nlp85.

Jeziorski, A., Yan, N.D., Paterson, A.M., DeSellas, A.M., Turner, M.A., Jeffries, D.S., Keller, B. Weeber, R.C., McNicol, D.K., Palmer, M.E., McIver, K., Arseneau, K., Ginn, B.K., Cumming, B. F., Smol, J.P. 2008. The widespread threat of calcium decline in fresh waters. *Science* 322: 1374-1377. doi: 10.1126/science.1164949.

Johansson, M. 2014. Wood-ash application on forest soil - a meta-analysis of the effects on surface water acid-base chemistry. M.Sc. thesis. Faculty of Forest Sciences. Swedish Agricultural University, Umeå, Sweden.

Karlton, E., Saarsalmi, A., Ingerslev, M., Mandre, M., Andersson, S., Gaitnieks, T., Ozolinčius, R., Varnagiryte-Kabasinskiene, I. 2008. Wood ash recycling – possibilities and risks. *In* D. Röser, A. Asikainen, K. Raulund-Rasmussen and I. Stupak (eds.) *Sustainable use of forest biomass for energy: a synthesis with focus on the Baltic and Nordic Region*. pp. 79-108. Springer, Dordrecht, The Netherlands.

Knapp, B.A. and Insam, H. 2011. Recycling of biomass ashes: current technologies and future research needs. *In* Insam, H. and B.A. Knapp (eds) *Recycling of Biomass Ashes*. pp. 1-16. Springer, Dordrecht, The Netherlands.

Lamers, P., Mai-Moulin, T., and Junginger, M. 2016. Challenges and opportunities for international trade in forest biomass. *In* E. Thiffault, G. Berndes, M. Junginger, J.N. Saddler and C.T. Smith (eds.). Mobilisation of forest bioenergy in the boreal and temperate biomes: challenges, opportunities and case studies. pp. 127-164. Academic Press, London, UK.

Lomander, A., Wallstedt, A. and Kalén, C. 2005. Recirculating wood ash – theory, practise and recommendations. Available from:
[http://www.skogsstyrelsen.se/Global/myndigheten/Projekt/RecAsh/Utbildningsmaterial%20Education%20Material/3.%20Utbildningsmaterial%20på%20engelska%20International%20Education%20Package/Askåterföring,%20teori,%20praktik%20och%20rekommendationer%20\(engelska\).pdf](http://www.skogsstyrelsen.se/Global/myndigheten/Projekt/RecAsh/Utbildningsmaterial%20Education%20Material/3.%20Utbildningsmaterial%20på%20engelska%20International%20Education%20Package/Askåterföring,%20teori,%20praktik%20och%20rekommendationer%20(engelska).pdf) [accessed 22 July 2016]

Löfgren, S., Ågran, A., Gustafsson, J.P., Olsson, B.A., and Zetterberg, T. 2017. Impact of whole-tree harvest on soil and stream water acidity in southern Sweden based on HD-MINTEQ simulations and pH-sensitivity. *For. Ecol. Manage.* 383: 49-60.
<http://dx.doi.org/10.1016/j.foreco.2016.07.018>.

Mahendrappa, M.K., Pitt, C.M., Kingston, D.G.O., and Morehouse, T. 2006. Environmental impacts of harvesting white spruce on Prince Edward Island. *Biomass Bioenergy* 30: 363-369. doi: 10.1016/j.biombioe.2005.07.016.

Maynard, D.G., Paré, D., Thiffault, E., Lafleur, B., Hogg, K.E., and Kishchuk, B. 2014. How do natural disturbances and human activities affect soils and tree nutrition and growth in the Canadian boreal forest? *Environ. Rev* 22: 161-178. doi: 10.1139/er-2013-0057.

McDonald, M.A., Hawkins, B.J., Prescott, C.E., and Kimmins, J.P. 1994. Growth and foliar nutrition of western red cedar fertilized with sewage sludge, pulp sludge, fish silage and wood ash on northern Vancouver Island. *Can. J. For Res.* 24: 297-301.

McLaughlin, J.W. 2014. Forest soil calcium dynamics and water quality: implications for forest management planning. *Soil Sci. Soc. Am. J.* 78: 1003-1020. doi: 10.2136/sssaj2013.11.0474.

Narodoslawsky, M. and Obernberger, I. 1996. From waste to raw material – the route from biomass to wood ash for cadmium and other heavy metals. *J. Hazard. Mater.* 50: 157-168.

National Energy Board of Canada. 2016. Canada's renewable power landscape: Energy market analysis 2016. Available from: <https://www.neb-one.gc.ca/nrg/sttstc/lctrct/rprt/2016cndrnwblpwr/2016cndrnwblpwr-eng.pdf> (accessed 28 October 2016).

Nave, L.E., Vance, E.D., Swanston, C.W., and Curtis, P.S. 2011. Fire effects on temperate forest soil C and N storage. *Ecol. Appl.* 21: 1189-1201. doi: 10.1890/10-0660.1.

New Brunswick Department of Environment and Local Government. 2014. Guidelines for the Beneficial Use of Industrial By-Products as Soil Amendments. Available from: <http://www2.gnb.ca/content/dam/gnb/Departments/env/pdf/LandWaste-TerreDechets/GuidelinesForSoilAmendments.pdf> [accessed 22 July 2016]

Nishio, G. 2016. Forest biomass ash production in British Columbia. Confidential report prepared for FPInnovations.

Noyce, G.L., Fulthorpe, R., Gorgolewski, A., Hazlett, P., Tran, H., and Basiliko, N. 2016. Soil microbial responses to wood ash addition and forest fire in managed Ontario forests. *Appl. Soil Ecol.* 107: 368-380. doi: 10.1016/j.apsoil.2016.07.006.

Nurmesniemi, H., Makela, M., Poykio, R., and Dahl, O. 2011. Comparison of the fertilizer properties of ash fractions from medium-sized (32MW) and small-sized (6 MW) municipal district heating plant. *Int. J. Eng. Appl. Sci.* 7: 87-91.

Nyboer, J., and Melton, N. 2015. Renewable Energy in Canada 2014. Canadian Industrial Energy End-use Data and Analysis Centre. Simon Fraser University, Burnaby, B.C. Available from:

http://www2.cieedac.sfu.ca/media/publications/Renewable_Energy_Report_Final-1.pdf

[Accessed 4 October 2016].

Nyboer, J., Melton, N., and Goldberg, S. 2014. Renewable Energy in Canada 2013.

Canadian Industrial Energy End-use Data and Analysis Centre. Simon Fraser University, Burnaby, B.C. Available from:

http://www2.cieedac.sfu.ca/media/publications/Renewables_Report_Final.pdf [Accessed 4 October 2016].

Obernberger, I., and Supancic, K. 2009. Possibilities of ash utilisation from biomass combustion plants. In ETA-Renewable Energies. Proceedings of the 17th European Biomass Conference & Exhibition, Hamburg, Germany, June/July 2009. pp. 1-12. ETA Renewable Energies, Italy.

Ontario Ministry of Natural Resources. 2008. Forest biofibre – allocation and use. For. Manag. Br., Toronto, ON. For. Manag. Direct. FOR 03 02 01. Available from: <https://dr6j45jk9xcmk.cloudfront.net/documents/3099/stdprod-099834.pdf> (accessed 16 October 2016).

Ontario Ministry of Natural Resources. 2010. Forest management guide for conserving biodiversity at the stand and site scales. Queen's Printer for Ontario, Toronto, ON. Available from: <https://dr6j45jk9xcmk.cloudfront.net/documents/4816/stand-amp-site-guide.pdf> (accessed 13 October 2016).

Ontario Power Generation. 2015. From coal to biomass: Generating a sustainable future.

Available from:

<http://www.opg.com/about/environment/documents/opgbiomassconversion.pdf>.

(accessed 22 March 2016).

Paré, D., Thiffault, E., Cyr, G., and Guindon, L. 2016. Quantifying forest biomass mobilisation potential in the boreal and temperate biomes. *In* E. Thiffault, G. Berndes, M. Junginger, J.N. Saddler and C.T. Smith (eds.). Mobilisation of forest bioenergy in the boreal and temperate biomes: challenges, opportunities and case studies. pp. 36-50. Academic Press, London, UK.

Perera, A.H. Buse, L.J., and Weber M.G. (Eds.), 2004. Emulating Natural Forest Landscape Disturbances: Concepts and Applications. Columbia University Press, NY, pp. 315.

Pitman, R.A. 2006. Wood ash use in forestry – a review of the environmental impacts. *Forestry* 79: 563-588. doi: 10.1093/forestry/cp1041.

Prescott, C.E. and Brown, S.M. 1998. Five-year growth response of western redcedar, western hemlock and amabilis fir to chemical and organic fertilizers. *Can. J. For Res.* 28: 1328-1334.

Puddister, D., Dominy, S.W.J., Baker, J.A., Morris, D.A. Maure, J., Rice, J.A., Jones, T.A., Majumdar, I., Hazlett, P.W., Titus, B.D., Fleming, R.L., and Wetzal, S. 2011. Opportunities and challenges for Ontario's bioeconomy. *For. Chron.* 87: 468-477.

Raulund-Rasmussen, K., Stupak, I., Clarke, N., Callesen, I., Helmisaari, H-S., Karlton, I., and Varnagiryte-Kabasinskiene, I. 2008. Effects of very intensive forest biomass harvesting on short and long term site productivity. *In* D. Röser, A. Asikainen, K. Raulund-Rasmussen and I. Stupak (eds.) Sustainable use of forest biomass for energy: a synthesis with focus on the Baltic and Nordic Region. pp. 155-196. Springer, Dordrecht, The Netherlands.

Reid, C. and Watmough, S.A. 2014. Evaluating the effects of liming and wood-ash treatment on forest ecosystems through systematic meta-analysis. *Can. J. For. Res.* 44: 867-885. doi: 10.1139/cjfr-2013-0488.

Risse, M. 2013. Best management practices for wood ash as agricultural soil amendment. The University of Georgia Cooperative Extension. Bulletin 1142. Available from: <http://extension.uga.edu/publications/detail.cfm?number=B1142> [accessed 12 October 2016]

Roach, J., and Berch, S.M. 2014. A compilation of forest biomass harvesting and related policy in Canada. Prov. B.C., Victoria, B.C. Tech. Rep. 081. Available from: <https://www.for.gov.bc.ca/hfd/pubs/docs/tr/TR081.pdf> (accessed 16 August 2016).

Skogsstyrelsen . no date. Regular recycling of wood ash to prevent waste production:

RecAsh – A Life-environment demonstration project. Available from:

http://ec.europa.eu/environment/life/project/Projects/index.cfm?fuseaction=home.showFile&rep=file&fil=LIFE03_ENV_S_000598_LAYMAN.pdf [accessed 22 July 2016]

Skogsstyrelsen. 2008. Recommendations for extraction of harvesting residues and ash recycling. Available from:

<http://www.skogsstyrelsen.se/Global/PUBLIKATIONER/InEnglish/guidelines.pdf>
[accessed 22 July 2016]

Staples, T.E. and Van Rees, K.C.J. 2001. Wood/sludge ash effects on white spruce seedling growth. *Can. J. For. Res.* 31: 85-92.

Stockdale, C., Flannigan, M., and Macdonald, E. 2016. Is the END (emulation of natural disturbance) a new beginning? A critical analysis of the use of fire regimes as the basis of forest ecosystem management with examples from the Canadian western Cordillera.

Environ. Rev. doi: 10.1139/er-2016-0002

Stupak, I., Asikainen, A., Röser, D., and Pasanen, K. 2008. Review of recommendations for forest energy harvesting and wood ash recycling. *In* D. Röser, A. Asikainen, K.

Raulund-Rasmussen and I. Stupak (eds.) *Sustainable use of forest biomass for energy: a*

synthesis with focus on the Baltic and Nordic Region. pp. 155-196. Springer, Dordrecht, The Netherlands.

Swedish Energy Ashes. 2014. Environmentally correct handling of energy ash. Available from: <http://www.energiaskor.se/pdf-dokument/Eng-broschyr%20NY.pdf> [accessed 22 July 2016]

Swedish University of Agricultural Sciences. 2008. Wood ash database – wood for energy. Available from: <http://woodash.slu.se/eng/stats.cfm> (accessed 29 August 2016).

Sylvis Environmental. 2008. Land Application Guidelines for the Organic Matter Recycling Regulation and the Soil Amendment Code of Practice: Best Management Practices. Available from: [www2.gov.British Columbia.ca/assets/gov/environment/waste-management/recycling/landappguidelines.pdf](http://www2.gov.bc.ca/assets/gov/environment/waste-management/recycling/landappguidelines.pdf) [accessed 22 July 2016]

Thiffault, E., Asikainen, A., and Devlin, G. 2016. Comparisons of forest biomass supply chains from the boreal and temperate biomes. *In* E. Thiffault, G. Berndes, M. Junginger, J.N. Saddler and C.T. Smith (eds.). *Mobilisation of forest bioenergy in the boreal and temperate biomes: challenges, opportunities and case studies*. pp. 11-35. Academic Press, London, UK.

van Eijk, R.J., Obernberger, I., and Supancic, K. 2012. Options for increased utilization of ash from biomass combustion and co-firing. KEMA Nederland B.V. Available from: http://www.ieabcc.nl/publications/Ash_Utilization_KEMA.pdf (accessed 15 August 2016)

Varnagirytė-Kabašinskienė, I. 2012. Toward the rational use of forest biomass: Lithuanian case study. *J. For. Sci* 58: 465-471.

Watmough, S.A., Aherne, J. and Dillon, P.J. 2003. Potential impact of forest harvesting on lake chemistry in south-central Ontario at current levels of acid deposition. *Can. J. Fish. Aquat. Sci.* 60: 1095-1103. doi: 10.1139/f03-093.

Westling, O., and Zetterberg, T. 2007. Recovery of acidified streams in forests treated by total catchment liming. *Water Air Soil Pollut: Focus*. 7: 347-356. doi: 10.1007/s11267-006-9107-5.

Wildbacher, N. 2007. BYE/03/G31 Project 'Biomass energy for heating and hot water supply in Belarus – fact sheet ash utilisation'. Available from: http://energoeffekt.gov.by/bioenergy/htdocs/books_media_campaign/Ash_utilisation.pdf (accessed 24 August 2016).

Yemshanov, D., McKenney, D.W., Fraleigh, S., McConkey, B., Huffman, T., and Smith, S. 2014. Cost estimates of post harvest forest biomass for Canada. *Biomass Bioenergy* 69: 80-94. doi: 10.1016/j.biombioe.2014.07.002.

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Tables:

Table 1. Chemical properties of fly and bottom ashes generated in bioenergy plants across Canada. Data represent the mean, range and number of samples of fly ash and bottom ash produced from a range of feedstocks, boilers and provinces across Canada. (Source: AshNet - Ash Chemistry Database <http://cfs.nrcan.gc.ca/projects/140>).

	Fly ash	Bottom ash
pH in H ₂ O	11.3 (8.6 – 13.8) 8	10.9 (7.5 – 12.9) 14
Total C (%)	18.1 (2.7 – 43) 8	20.4 (0.5 – 51.8) 14
Total Inorganic C (%)	2.6 (0.2 – 7.2) 3	1.7 (0.02 – 3.3) 6
Total N (%)	0.2 (0.04 – 0.4) 9	0.09 (<0.01 – 0.3) 14
Total P (g kg ⁻¹)	6.3 (3.2 – 10.6) 9	4.9 (0.1 – 11.9) 16
Total Ca (g kg ⁻¹)	153.5 (92.1 – 247.9) 9	103.7 (3.9 – 211.0) 16
Total Mg (g kg ⁻¹)	14.6 (6.4 – 29.4) 9	11.8 (0.6 – 33.1) 16
Total K (g kg ⁻¹)	33.1 (13.5 – 90.8) 9	24.1 (0.8 – 50.8) 16
Total S (g kg ⁻¹)	11.0 (<0.1 – 47.4) 9	3.8 (<0.1 – 25.9) 13

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Table 2. Maximum trace element limits (mg kg⁻¹) applied to wood ash in many Canadian provinces/territories; these limits were originally developed for compost (Source: Canadian Council of Ministers of the Environment 2005).

	Category A Compost	Category B Compost
Arsenic	13	75
Cadmium	3	20
Chromium	210	1060
Cobalt	34	150
Copper	400	757
Lead	150	500
Mercury	0.8	5
Molybdenum	5	20
Nickel	62	180
Selenium	2	14
Zinc	700	1850

Note: **Category A Compost:** wood ash with ‘trace element’ concentrations that fall below the limits set for category A compost is considered ‘unrestricted’ and can be used as a soil amendment in any application; **Category B Compost:** wood ash with ‘trace element’ concentrations that fall above the limits for category A compost but below the limits for category B compost has ‘restricted’ use and ‘may require additional control when deemed necessary by a province or territory’. Wood ash with ‘trace element’ concentrations above the limits for Category B Compost ‘must be used or disposed of appropriately’.

Table 3. Limiting values (mg kg^{-1}) for trace elements in biomass ash for application on forest lands in European countries (modified from Stupak et al. 2008 and van Eijk et al. 2012).

	Austria	Denmark	Finland	Germany	Lithuania	Sweden
Arsenic	20/20		40	40	30	30
Cadmium	5/8	20	25	1.5	30	30
Chromium	150/250	100	300		100	100
Copper	200/250		700		400	400
Lead	100/200	250	150	150	300	300
Mercury		0.8	1	1	3	3
Nickel	150/200	60	150	80	70	70
Zinc	1200/1500		4500		700	7000

Note: Austria: Class A/Class B: ashes which meet the limiting values of Class A may be applied without a chemical analysis of the soil, ashes with heavy metal contents between the limiting values of Class A and Class B may only be applied after a chemical analysis of the soil shows that the application of ashes is harmless in terms of heavy metal input.

Table 4. Canadian wood ash field trials.

Site	Prov.	Year established	Soil type	Stand age when trial established	Tree species	Ash applied (dry wt) [‡]	References
Aleza Lake	BC	2015	Luvisol,	18 years (North)	<i>Picea engelmannii</i> x	5 Mg ha ⁻¹ untreated bottom	Domes et al. in
North & South			Luvic Gleysols	24 years (South)	<i>Picea glauca</i>	ash	press
Charlottetown *	PEI	1990	unknown	Newly planted	<i>Picea glauca</i> & <i>Pinus strobus</i>	0.5 Mg ha ⁻¹ (ash type unknown)	Mahendrappa et al. 2006
Haliburton	ON	2013	Dystic Brunisols	Uneven aged	<i>Acer saccharum</i> , <i>Fagus grandifolia</i> & <i>Betula alleghaniensis</i> and others	1, 4 or 8 Mg ha ⁻¹ untreated fly & bottom ashes	Noyce et al. 2016; Gorgolewski et al. 2016
Island Lake	ON	2011	Dystic Brunisols	Newly planted	<i>Pinus banksiana</i>	0.7, 1.4, 2.8 or 5.6 Mg ha ⁻¹ untreated bottom ash	Noyce et al. 2016
Meadow Lake	SK	1995	Grey Luvisol	Newly planted	<i>Picea glauca</i>	1 or 5 Mg ha ⁻¹ hardened bottom ash	Staples & Van Rees 2001
Pineland	MB	2015	Luvisol	Newly planted	<i>Pinus banksiana</i>	1.5 Mg ha ⁻¹ mixed fly & bottom ash	
Port McNeill*	BC	1990	Ferro-Humic Podzols	9 years	<i>Thuja plicata</i>	5 Mg ha ⁻¹ (ash type unknown)	McDonald et al. 1994; Prescott & Brown 1998
Senneterre - 1 [†]	QC	2005	Eluvated Brunisols	53 years	<i>Picea mariana</i> & <i>Pinus banksiana</i>	1, 2, 4 or 8 Mg ha ⁻¹ untreated fly ash	Brais et al. 2015
Senneterre – 2	QC	2006	Eluvated Brunisols	Newly planted	<i>Picea glauca</i> , <i>Pinus banksiana</i> & <i>Larix marschlinii</i>	2.5 or 5 Mg ha ⁻¹ untreated fly ash	
Senneterre – 3	QC	2007	Eluvated Brunisols	Newly planted	<i>Picea mariana</i> & <i>Pinus banksiana</i>	7.5 or 15 Mg ha ⁻¹ untreated fly ash	
25 th Sideroad	ON	2012	Eutric Brunisols	Newly planted	<i>Picea glauca</i> & <i>Picea mariana</i>	1 or 10 Mg ha ⁻¹ untreated fly ash	
E. Townships – poplar	QC	2015	Humo-Ferric to Ferro-Humic Podzols	3 to 6 years	hybrid <i>Populus</i>	15 Mg ha ⁻¹ untreated bottom ash	
E. Townships - maple	QC	2015	Humo-Ferric to Ferro-Humic Podzols	Uneven aged	<i>Acer saccharum</i>	20 Mg ha ⁻¹ untreated bottom ash	

*No longer maintained

†Recently harvested

‡All values are expressed on a dry weight basis except for the E. Townships sites, which are expressed on a fresh weight basis

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Table 5. Maximum wood ash dosage rates in Europe and Canada

Canada		Europe	
Alberta	45 Mg ha ⁻¹ lifetime ⁻¹ on agricultural soils (Alberta Environment 2002)	Austria	2 Mg ha ⁻¹ 20 years ⁻¹ (V. Bruckman, Austrian Academy of Sciences, personal communication, December 2017).
CCME	200 Mg ha ⁻¹ 45 years ⁻¹ (Canadian Council of Ministers of the Environment 2005).	Denmark	3 Mg ha ⁻¹ 10 years ⁻¹ ; 3 applications 75 years ⁻¹ (M. Ingerslev, University of Copenhagen, personal communication, December 2017).
Québec	88 Mg ha ⁻¹ 20 years ⁻¹ (Hébert 2015).	Lithuania	3-7 Mg ha ⁻¹ rotation ⁻¹ , depending on site type (Varnagirytė-Kabašinskiene 2012).
		Sweden	6 Mg ha ⁻¹ rotation ⁻¹ (S. Anderson, Swedish Forest Agency, personal communication, January 2018).

Figure captions:**Figure 1.**

Differences in the concentrations of ten trace elements, calculated using pairs of fly and bottom ashes generated in seven Canadian biomass boilers. Each symbol represents a pair of fly and bottom ash samples. Values that fall above the zero line indicate trace elements that were more concentrated in fly ash; values that fall below the zero line indicate trace elements that were more concentrated in bottom ash. Few mercury data were available so they are not presented. (Source: AshNet - Ash Chemistry Database <http://cfs.nrcan.gc.ca/projects/140>).

Figure 2.

Average trace element concentrations in fly and bottom ashes generated from a range of feedstocks, boilers and provinces across Canada. Values are means ($\pm$ standard deviation) of 7 to 9 samples of fly ash and 12 to 16 samples of bottom ash. Few mercury data were available so they are not presented. Dashes represent the trace element limits applied to wood ash in many Canadian provinces/territories (Source: AshNet - Ash Chemistry Database <http://cfs.nrcan.gc.ca/projects/140>; Canadian Council of Ministers of the Environment, 2005).

Figure 1.

Figure 2a.

Figure 2b.