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Venier, Lisa; Canadian Forest Service,
Allen, Darren; Great Lakes Forestry Centre,
Deschamps, Candace; Canadian Forest Service
Hope, Emily; Great Lakes Forestry Centre
Jull, Michael; University of Northern British Columbia College of Science and Management
Kwiaton, Martin; Ontario Ministry of Natural Resources and Forestry, Centre for Northern Forest Ecosystem Research
Mckenney, Dan; Great Lakes Forestry Centre
Rutherford, Mike; University of Northern British Columbia College of Science and Management
Hazlett, Paul; Great Lakes Forestry Centre |
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Wood ash as a soil amendment in Canadian forests: what are the barriers to utilization?

K.D. Hannam\textsuperscript{a}, L. Venier\textsuperscript{b}, D. Allen\textsuperscript{b}, C. Deschamps\textsuperscript{b}, E. Hope\textsuperscript{b}, M. Jull\textsuperscript{c}, M. Kwiaton\textsuperscript{d}, D. McKenney\textsuperscript{b}, P.M. Rutherford\textsuperscript{c}, P.W. Hazlett\textsuperscript{b,\textsuperscript{*}}

Affiliation & Address:
\textsuperscript{a}University of British Columbia
Okanagan Campus
3187 University Way
Kelowna, BC V1V 1V7

\textsuperscript{b}Natural Resources Canada
Canadian Forest Service
Great Lakes Forestry Centre
1219 Queen Street East
Sault Ste. Marie, Ontario P6A 2E5

\textsuperscript{c}University of Northern British Columbia
3333 University Way
Prince George, BC V2N 4Z9

\textsuperscript{d}Ontario Ministry of Natural Resources
Centre for Northern Forest Ecosystem Research
955 Oliver Rd
Thunder Bay, Ontario P7B 5E1

*Corresponding Author:
P.W. Hazlett
Tel.: +1 705 541 5630
E-mail address: paul.hazlett@canada.ca
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.
Introduction

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

The primary users of bioenergy in Canada are the timber and pulp and paper industries, which generate heat and power for on-site use by combusting the by-products of the manufacturing process (e.g., off-cuts, hog fuel, black liquor; Bradburn 2014). Increasingly, however, the use of forest biomass for energy is diversifying. Many Canadian provinces and territories have implemented policies that promote investment in forest biomass-based energy production. For example, as required under the Environmental Protection Act, Ontario Power Generation (OPG) has phased out coal-fired electricity production and converted the generating stations at Thunder Bay and Atikokan to wood or torrefied pellet combustion (Bradburn 2014; Ontario Power 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; Karltnn 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).
Landfilling is often the most cost-effective method of ash disposal

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

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

Finally, transportation costs include the fees associated with transporting the ash 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 (Karltun 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 (Karltun et al. 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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combustion system, a downdraft gasifier and a wood pellet burner by fractionation.


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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).

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<tr>
<td>pH in H$_2$O</td>
<td>11.3 (8.6 – 13.8)</td>
<td>10.9 (7.5 – 12.9)</td>
</tr>
<tr>
<td>Total C (%)</td>
<td>18.1 (2.7 – 43)</td>
<td>20.4 (0.5 – 51.8)</td>
</tr>
<tr>
<td>Total Inorganic C (%)</td>
<td>2.6 (0.2 – 7.2)</td>
<td>1.7 (0.02 – 3.3)</td>
</tr>
<tr>
<td>Total N (%)</td>
<td>0.2 (0.04 – 0.4)</td>
<td>0.09 (&lt;0.01 – 0.3)</td>
</tr>
<tr>
<td>Total P (g kg$^{-1}$)</td>
<td>6.3 (3.2 – 10.6)</td>
<td>4.9 (0.1 – 11.9)</td>
</tr>
<tr>
<td>Total Ca (g kg$^{-1}$)</td>
<td>153.5 (92.1 – 247.9)</td>
<td>103.7 (3.9 – 211.0)</td>
</tr>
<tr>
<td>Total Mg (g kg$^{-1}$)</td>
<td>14.6 (6.4 – 29.4)</td>
<td>11.8 (0.6 – 33.1)</td>
</tr>
<tr>
<td>Total K (g kg$^{-1}$)</td>
<td>33.1 (13.5 – 90.8)</td>
<td>24.1 (0.8 – 50.8)</td>
</tr>
<tr>
<td>Total S (g kg$^{-1}$)</td>
<td>11.0 (&lt;0.1 – 47.4)</td>
<td>3.8 (&lt;0.1 – 25.9)</td>
</tr>
</tbody>
</table>
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).

<table>
<thead>
<tr>
<th>Category A Compost</th>
<th>Category B Compost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arsenic</td>
<td>13</td>
</tr>
<tr>
<td>Cadmium</td>
<td>3</td>
</tr>
<tr>
<td>Chromium</td>
<td>210</td>
</tr>
<tr>
<td>Cobalt</td>
<td>34</td>
</tr>
<tr>
<td>Copper</td>
<td>400</td>
</tr>
<tr>
<td>Lead</td>
<td>150</td>
</tr>
<tr>
<td>Mercury</td>
<td>0.8</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>5</td>
</tr>
<tr>
<td>Nickel</td>
<td>62</td>
</tr>
<tr>
<td>Selenium</td>
<td>2</td>
</tr>
<tr>
<td>Zinc</td>
<td>700</td>
</tr>
</tbody>
</table>

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).

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

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

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

Different symbols represent individual biomass boilers.
Figure 2a.

![Graph showing total concentration of arsenic, cadmium, molybdenum, and selenium in fly ash, bottom ash, and compost categories.]

Figure 2b.

![Graph showing total concentration of chromium, cobalt, copper, lead, nickel, and zinc in fly ash, bottom ash, and compost categories.]

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