ALTERNATIVE USES FOR WASTE PRODUCTS FROM BIOMASS BURNERS

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ABSTRACT

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Key Words: biochar, biomass, biomass burning, biomass uses, combustion, fertilizer, forest industry, nutrient replacement, paper birch, renewable energy, road stabilization, thermal energy, trembling aspen, wood ash, waste products

Woody biomass has become an important source of renewable energy throughout the world. A major issue that has risen from the increased use of combustion technology to produce thermal energy is the large amount of waste products left over from biomass burning. Currently, the majority of waste products from biomass burning, such as ash and biochar, is landfilled. Hence, there is a need to find alternative uses for the waste products from biomass burning to promote its use and increase sustainability. There are several uses of ash inside and outside the forestry industry. Ash can be used to replace nutrients lost during harvesting and can be used to stabilize forest roads. It also serves many functions in the construction industry such as being used as an additive in industrial processes. There are also several limitations and barriers to the use of ash, such as government regulation. This article will discuss the properties, uses and barriers to the use of wood ash.

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1.0. INTRODUCTION

As a result of increasing concerns over climate change and depleting fossil fuels, woody biomass has become an important source of renewable energy and its usage has significantly increased over the past years (Ingwald and Klaus 2009; James et al. 2014; Lauri et al. 2014; Fatehi 2013). Woody biomass is separated into three major categories: mill residue, forest residue and standing timber (Bradley 2010). There are five major processes in which woody biomass can be transformed into heat and energy: direct combustion, cogeneration, co-firing, gasification and liquid biofuels (Wang 2017; James et al. 2014). Some examples of wood combustion technologies used to produce heat and energy include boilers, gasifiers and pellet burners (James et al. 2014).

The forestry industry is an energy-intensive industry, whether it be by the production of pulp and papers, OSB, or lumber (Dahl et al. 2010). However, mills are able to take advantage of the large amounts of biomass waste produced in-house. Most mill residues, such as black liquor, bark, wood chips, and sawdust, can be burned to produce thermal energy to be used at the mills. Therefore, the use of biomass to produce energy in the forestry industry helps improve forest sustainability and reduces the effects of harvesting on the environment by increasing utilization of harvested wood and providing a more environmentally friendly way to produce power for the mills.

However, a major disadvantage in the rising use of wood combustion technologies to produce heat and energy has led to an increase in waste from biomass burning, moreover, an increase in combustion residues such as ash and biochar (Dahl et al. 2010; Ingwald and Klaus 2009; James et al. 2014). Sustainability in the forest industry is increased by reducing waste in all activities, from the forest to the mill. Therefore, there needs to be an increased use for the ash produced by biomass burning.

Currently, most ash produced by biomass burning is taken to landfills where it is disposed of (James et al. 2014). However, landfilling of wood ash from Canadian pulp and paper mills has been slightly decreasing in recent years (Hannam et al. 2018). In 1995, 84% of ash produced was landfilled, while in 2013, landfilling rates fell to 63% (Hannam et al. 2018). Wood ash management practices also vary considerably among provinces. In Alberta, almost half of the ash produced is used for soil amendment (Hannam et al. 2018). On the other hand, in British Columbia, almost all of the ash is landfilled (Hannam et al. 2018). Options for using ash are currently limited by the quality of the ash (James et al. 2014). Increasing the quality of wood ash, researching new applications for wood ash, and improving the current uses of ash can help reduce waste in the forest industry.

2.0. LITERATURE REVIEW

2.1. WOODY BIOMASS

Woody biomass is an important source of energy throughout the world (Lauri et al. 2014). There are three categories of woody biomass: mill residue, forest residue, and standing timber (Bradley 2010). Mill residue includes bark, sawdust, and shavings from pulp mill and sawmill operations. Forest residue consists of tree-tops, branches, and leaves from harvest and thinning activities that are left in the forest or on the roadside following harvest. Standing timber biomass typically consists of trees that are affected by insect or disease or trees that are unmerchantable.

2.2. INDUSTRY USE OF BIOMASS

The evolution of wood combustion technologies such as boilers, gasifiers and wood pellet burners has led to a rapid increase in the utilization of biomass for heat and energy (James et al. 2014). The forest industry has high energy demands throughout all of its processes which can be very cost intensive (Dahl eh al. 2010). In Sweden, the forestry industry uses over 50% of the total energy (Johansson et al. 2002). Increased energy costs and an oil crisis in the 1970's resulted in the Swedish forest industry reducing its dependence on oil by using by-products from processes within the industry to produce energy (Tromborg and Solberg 2010; Johansson et al. 2002).

Many sawmill and pulp mill processes produce vast amounts of burnable residues such as wood residues (i.e. bark, wood chips and sawdust) and other forms of residue such as black liquor from pulp production (Dahl et al. 2010). Sawmills and pulp mills are able to take advantage of these burnable residues by combusting them to produce heat and energy to meet their high demands and reduce costs while promoting sustainability. The thermal energy produced by the burning of on-site biomass is also an environmentally friendly alternative to the use of fossil fuels. Heat from biomass burners is often directed to lumber dry kilns, while the electricity can be used for processing or can be sold to outside markets (Nicholls et al. 2008).

2.2.1. Norbord utilization of biomass

Norbord is a forest certified company based in Toronto, Canada, that manufacturer's Oriented Strand Board (OSB) in 15 mills located across Canada and the United States (Norbord.com). Callidus gasification systems were built at Norbord OSB mills in South Carolina and Alabama, as well as at non-Norbord mills in Arkansas and Canada (Fosgitt 2010). The Callidus gasification systems were built in 1999-2002 to gasify mill wastes to provide thermal heat for steam generation, raw product drying, and combustion of the volatile organic compounds (especially terpene) and other hazardous air pollutants (methanol, formaldehyde, etc.) found in wood dryer exhaust. The system at Norbord's mills consists of three rotary kiln gasifiers coupled to thermal oxidizers that are able to produce a total of up to 300 million BTU per hour of heat. The biomass heat is then used to generate steam. In addition, a small amount of biomass heat is used to heat thermal oil for the OSB press. To preserve the suitability of the ash for agriculture purposes, only clean biomass is used for fuel. The fuel used in the Callidus system at Norbord consists of bark, sawdust, sander dust, chips, crosstie chips, and other residual wood materials. Figure 1 below displays the Callidus gasification system, along with a day's worth of waste from running it.

Figure 1. Norbord's gasification kiln operation (Spring, P. Pers. Comm.).

2.3. WASTE PRODUCTS FROM BIOMASS BURNERS

One of the main issues with using wood combustion technologies such as the Callidus gasification system to produce heat and energy from biomass is finding use for the large amounts of waste products from the process (Dahl et al. 2010; Ingwald and Klaus 2009; James et al. 2014). The burning of biomass produces large amounts of wood ash and biochar. Biochar is a form of waste that is rich in carbon that is produced by biomass pyrolysis under an oxygen-limited environment (Diatta 2016; Weber and Quicker 2018). The gasification process results in nearly equal amounts of ash and biochar (Pan and Eberhardt 2011).

Currently, large amounts of the ash that results from biomass burning is disposed of in landfills (Ingwald and Klaus 2009; James et al. 2014; Pels et al. 2005). In the USA, approximately 3-5 million tonnes of ash is produced annually from primary and secondary wood industries along with the pulp and paper industry (Demeyer et al. 2001). Around 90% of the ash derived from paper industry waste and power generation is sent to landfill (Pan and Eberhardt 2011; Sarenbo 2009). Restrictive environmental regulations had resulted in increased costs of waste disposal, thus, creating greater incentive to find alternative uses for waste products from biomass burning. In order for biomass burning to be environmentally sustainable, biomass ash should be recycled whenever possible (James et al. 2014).

2.4. PROPERTIES OF WOOD ASH

There are two main types of ash produced from biomass burning which include fly ash and bottom ash (Augusto et al. 2008). Fly ash is the lightest fraction of ash (~200μm) that accumulates on the inside of the boiler and ventilation systems of biomass burners (Pitman 2006). Bottom ash is coarser particles of ash. During the incineration of wood and other forms of biomass, the amount of ash produced can range from 2 to 20% of the initial input material (Knapp and Insam 2011). Wood ash has a relatively high pH value, ranging from 8-13. (Augusto et al. 2008). A study by Demeyer et al. (2001) supported this, reporting a range of pH values from 8.9 to 13.5. The pH of wood ash has also been reported to increase up to 40 years after application. The pH value gives it a high acid neutralizing capacity (Augusto et al. 2008) and its high acid neutralizing capacity is a result of the formation of carbonates during the combustion and conditioning processes that take place during biomass burning.

The median value of the neutralizing capacity of ash is around 50%. The calcium carbonate equivalent (CCE) of wood ash has been reported to range from 13.2 to 92.4%, measured across 18 variations of ash samples (Aronsson and Ekelund 2004; Demeyer et al. 2001). The properties of wood ash described above, along with its ability to react easily with water indicates that wood ash has the ability to neutralize acidified soils and surface water. Moreover, wood ash's strong alkaline ability gives it a liming effect that allows it to be used as an alternative to lime or can be used in a mixture of lime and ash.

The major elements found in wood ash include N, P, Ca, Si, Al, K, and Mg (Demeyer et al. 2001; Karltun et al. 2008; Knapp and Insam 2011). The concentrations of macro-elements in wood ash are quite variable. Alkali and alkaline earth elements commonly exist in the form of oxides, hydroxides and carbonates. Si and Al are suggested to be the structural elements of wood ash because they are the least soluble. Ca, Mg, and K are the most acidic soluble elements. K is a very soluble element in wood ash, giving it a high leaching ability (Knapp and Insam 2011). Table 1 summarizes the element concentrations found in wood ash from various sources (Pitmann 2006). Table 2 summarizes the macro element concentrations from specified tree types from various sources.

Table 1. Element concentration in wood ash from various sources - % dry weight.

	Wood residue/bark ash		Paper mill ash	Softwood ash		Hardwood ash	
	Median	Range	Median values	Stem	Bark	Stem	Bark
Ca	13.2	7.4-33.1	16.6	22.4	28.5	19.0	27.1
Fe	1.5	0.3-2.1	0.5	0.8	0.2	0.5	0.6
K	2.9	1.7-4.2	2.6	12.4	9.8	20.4	12.2
Mg	1.5	0.7-2.2	1.1	4.3	2.8	3.6	2.2
Mn	0.7	0.3-1.3	0.3	2.9	1.7	0.8	0.6
Na	0.2	0.2-0.5	0.1	-	-	-	-
P	0.8	0.3-1.4	0.4	2.4	2.8	4.2	3.4
S	0.6	0.4-0.7	0.0	2.3	1.2	2.1	1.1
Al	2.0	1.5-3.2	0.9	-	-	-	-
C	-	-	25.5	-	-	-	-
pH	12.7	11.7-13.1	12.4	-	-	-	-
N	Rarely reported <0.1%						

Data from *Pitman (2006).

Table 2. Element concentrations in wood ash from specified tree types (mg/kg).

Macro element	Al	Ca	Fe	K	Mg	Mn	Na	P	S	Si
Conifers										
Pinus banksiana	33.3	387.0	35.0	22.5	33.2	39.0	23.0	12.2	10.4	74.8
Pinus sylvestris	1.0-18.0	600.0	3.0-15.0	300.0	120.0	70.0	3.0-22.0	30.0	NG	NG
Picea abies	NG	700.0	NG	300.0	90.0	90.0	NG	20.0	NG	NG
Pinus sp	4.7	290.0	5.8	162.5	70.3	40.4	0.6	8.4	10.7	ND
Tsuga heterophylla	11.1	421.0	9.1	25.3	79.0	19.0	8.2	9.2	5.6	46.7
Broadleaves										
Betula sp	0.0	466.0	20.3	36.3	25.3	47.0	9.6	12.6	12.8	14.0
Betula pubescens	3.0	500.0	7.0	400.0	90.0	90.0	7.0	40.0	100.0	90.0
Acer sp	20.1	402.0	11.9	31.9	117.0	27.0	16.3	4.8	5.6	46.3
Populus tremuloides	1.4	212.0	2.6	112.5	35.5	1.4	0.6	11.8	7.0	1.1
Populus sp	3.5	257.0	3.2	79.3	90.9	4.5	23.0	9.5	10.2	ND
Quercus rubra	6.8	366.0	NM	60.8	52.0	14.9	0.8	15.6	18.0	ND
Quercus (white oak)	ND	314.0	0.9	102.5	75.7	1.4	ND	5.6	12.1	1.3

Data from Pitmann (2006).
ND = not detected, NM = not measured, NG = not given

The microelement concentrations found in wood ash are also quite variable and include Fe, Mn, Zn, and Cu (Knapp and Insam 2011). Iron is the most abundant microelement found in wood ash and can be in concentrations of up to 21 g kg^{-1} Fe. Fe is also very insoluble, suggesting it to be a structural component of wood ash and has low reactivity in acid soils. Nitrogen content in wood ash is very low because most of it is vaporized during combustion. Carbon is also present in very low concentrations, usually in the form of charcoal, as a result of incomplete combustion (Knapp and Insam 2011). The trace elements found in wood ash include As, Ba, B, Cd, Cu, Cr, Ag, Mo, Hg, Ni, V, and Zn (Karltun et al. 2008).

There are many factors that cause the variability in properties of wood ash. To begin with, some variation is explained by the composition of the fuel (Karltun et al. 2008). For example, nutrient concentrations in the ash of bark and foliage are between 5 to 10 times higher than the ash of wood originating from the stem (Augusto et al. 2008; Knapp and Inslam 2011). The properties of wood ash can also depend on the plant species and origin of the plant (Knapp and Insam 2011). For example, hardwoods have been found to be more effective fertilizers because they contain higher proportions of macronutrients than softwoods (Pitman 2006). The amount of ash formed varies greatly with the composition of fuel, however, the concentrations of elements in the ash is expected to vary little.

Other factors that influence variations in element concentrations and the properties of wood ash include the type of burner being used, the incineration conditions, potential contamination of the fuel, and storage conditions (Knapp and Inslam 2011). These factors also determine the quality of the ash for different applications (Knapp and Insam 2011). For example, if incineration conditions are poor and as a result incomplete combustion takes place, the amount of charcoal (C) produced causes large variations in the element concentrations per unit weight. A study by Pitman (2006) concluded that burning temperatures need to be between 600° and 900° Celsius to release the maximum amount of nutrients without creating heavy metal concentrations in the ash.

The physical properties of wood ash are also important when determining the environmental impact that wood ash application could have (Aronsson and Ekelund 2004). Coarser particles of ash are found to be less reactive to the environment than finer particles of ash. More than 80% of wood ash is composed of particles less than 1.0 mm in diameter (Demeyer et al. 2001). The unit weight of wood ash is variable and typically ranges from 162 kg/m^3 to a maximum of 1376 kg/m^3 (Subramaniam et al. 2015). Heavy metal concentrations that are known to be harmful to the environment were found to increase with decreasing precipitation, temperature and particle size during combustion by a study on the effects of different combustion techniques on ash properties by Obernberger et al. (2007). Concentrations of K, Na, Cl and S also increased with decreasing particle size (Obernberger et al. 2007).

Since there are elements contained in wood ash that are harmful to the environment, the concentrations of these elements have to be minimized while not taking away the positive characteristics of the ash to make it a beneficial product (Demeyer et al. 2001). This can be done by treating and pre-treating ash using methods that minimize the negative environmental effects. There are three main types of ash that can be produced from biomass burning: fly ash, self-hardened crushed-ash and pelleted or agglomerated ash. Self-hardened and pelleted or agglomerated ash are two types of treatments that take place after combustion to increase the particle size of the ash and make it more stable (Knapp and Insam 2011). Hardening of ash can be done through thermal treatment or by adding a binding material.

Self-hardened crushed-ash and pelleted ash are stabilized forms of ash that results in a more effective liming effect and avoids possible shock effects of high pH (Demeyer et al. 2001). Therefore, stabilized ash would be desired to be used in wood ash applications to the environment to minimize potential risks of contamination. Granulated ash is also easier to spread and releases chemical elements more slowly than fly ash, reducing the risk of high magnitude alkaline flushes to the environment (Pitman 2006; Knapp and Inslam 2011).

2.4.1. Trembling aspen and paper birch

The wood ash samples being tested in this literature are from Southern Yellow Pine collected at Norbord's OSB mill in Alabama. However, the focus of this paper is on finding alternative uses of ash and char produced by gasification of trembling aspen (*Populus tremuloides*) and paper birch (*Betula papyrifera*) biomass at Norbord's northern locations. The Canadian mills burn mostly bark recovered from aspen and some birch, supplemented with purchased wood chips of any local species (Spring, R. Pers. Comm.). The ash content of trembling aspen bark is around 5% (Yemele et al. 2007; Fournier and Goulet 1971). The ash content of paper birch bark is approximately 2.68% (Feng et al. 2014). A study by Hosegood (2010) researched the thermal value of all Northwestern Ontario tree species at different locations along the stem (i.e. the lower bole, lower bark, upper bole, upper bark, branches and leaves). Included in his study was the ash content of the tree species and their components (Table 3).

Table 3. Ash content of tree species and their components in Thunder Bay, ON in percent.

Species	Tree Components					
	Lower Bole	Lower Bark	Upper Bole	Upper Bark	Branch	Leaf
Ab	0.648	9.188	1.049	7.583	3.181	8.072
Bf	0.85	2.665	0.675	2.561	1.927	4.272
Bw	0.229	2.317	0.189	1.867	0.886	2.897
Pj	0.133	1.452	0.669	1.171	0.588	1.965
Po	0.603	3.535	0.483	3.186	1.777	4.603
Sb	0.392	4.584	0.317	2.389	1.662	2.223
Ta	0.346	2.644	0.426	2.316	1.209	3.049

Data from Hosegood (2010).

2.5. CURRENT USES OF WOOD ASH IN THE FOREST INDUSTRY

The figure below displays a brief description of a few of the current uses of ash which include nutrient replacement following harvest in the forest, road stabilization and fertilizer. There are many other uses of ash, however, for the purpose of this literature, it will focus on the uses in forestry.

Table 4. Uses of ash in the forest industry.

Use of ash	Description
Nutrient replacement and fertilizer post-harvest	• Rich in nutrients such as Ca, Mg, and P (James et al. 2014; Sarenbo 2000) • Increases growth and production (Sarenbo 2009) • Mitigates acidification (Aronsson and Ekelund 2008) • Uncommon practice (Sarenbo 2009)
Road stabilization	• Improves strength and decreases deformation (Lagerkvist and Lind 2009) • Strong freezing and thawing properties

2.5.1. Recycling of ash in forest ecosystems

It is suggested that wood ash and biochar could be used as an effective fertilizer in forest ecosystems (Knapp and Insam 2011). When ash is recycled in forests, it can be used to replace nutrient losses from whole tree harvesting because it contains nutrient elements such as calcium, magnesium, and phosphorous (James et al. 2014; Sarenbo 2009). Nutrients are often depleted as a result of whole tree harvesting because it removes the nutrient-rich branches and branches that are otherwise left in other conventional harvesting systems. The use of wood ash as a fertilizer in forest ecosystems is commonly studied in Northern European countries throughout their boreal forests due to extensive whole-tree harvesting (Knapp and Insam 2011). In Sweden, Denmark, and Finland, wood ash has been applied to forests to replace nutrient deficiencies and mitigate the acidification of boreal forests and surface waters resulting from whole-tree harvesting (Aronsson and Ekelund 2008; Karltun et al. 2008). A study by Arvidsson and Lundkvist (2003) found that soil pH of a harvested forest was increased by a 3 Mg ha^{-1} wood ash application in young Norway spruce stands. Concentrations of exchangeable Ca and Mg, along with effective cation exchange capacity were also elevated as a result of the ash treatment (Arvidsson and Lundkvist 2003).

The use of wood ash in the forest industry was encouraged by legislation, landfill directives and waste taxes in the 1990's (Karltun et al. 2008). In Finland, about 100,000 t of wood ash is produced annually, 14% of which is treated and applied in forests equalling around 3000 ha of land. Wood ash treatments can be performed via helicopters or from the ground using harvesting equipment and can be used as a treatment alone or in combination with nitrogen fertilizer (Knapp and Insam 2011; Karltun et al. 2008.).

Wood ash has also been suggested to increase forest growth and wood production in some forests (Sarenbo 2009). In Finland, wood ash is commonly spread on peat land (Karltun et al. 2008). A study performed by Lauhhanen et al. (1997) found that wood ash fertilization on peat soil could project internal rates of return on investment of between 4% and 9% for assessment periods between 44 and 56 years (Karltun et al. 2008). In another study, wood ash was spread on drained pine mires to increase growth and production in Finland (Moilanen et al. 2002). Wood ash fertilization accelerated growth of Scots pine on drained mires by increasing the decomposition rate in litter, vegetation and peat, improving soil fertility and nutrient status of the trees, and improving microbial activity in the soil. Another benefit of treating forest soils with wood ash is that it emulates fire as a natural disturbance (Hannam et al. 2018). However, wood ash treatment was not found to have a significant effect on plant growth in forests low in nitrogen, which is the main limiting element for plant growth on mineral soils in the boreal forest (Knapp and Insam 2011). Another concern with the application of wood ash in forest ecosystems is the risk of heavy metal contamination.

In Finland, the recommended dose of wood ash treatment for upland forests is 2.5-3 t ha^{-1} and 4-8 t ha^{-1} for forested peatlands (Karltun et al. 2008). In Sweden, the Swedish Board of Forestry has established a set of guidelines for recycling wood ash into the forest: the main part of the ash has to originate from the forest fuel, the ash has to be stabilized and pre-treated to avoid damage to soil chemistry, flora and fauna, the ash dose should be based on the amount of base cations removed and have a liming effect, a maximum of 3 t ha^{-1} should be spread through a ten year period, the total amount of heavy metals spread during a rotation period should not exceed the amount removed at harvest and the method, time and dose for ash recirculation should be chosen to minimize leaching and nutrient loss (Karltun et al. 2008).

However, fertilizing forest soils with wood ash is not a very common practice as there are still many limitations and not enough research (Sarenbo 2009). A study on stand productivity on two classes of soil in Nordic countries found that tree growth improvement should only be expected for organic soils and not mineral soils as a result of ash lacking nitrogen (Augusto et al. 2008). The cost of spreading ash on the forest floor along with transportation and treatment costs can also be expensive (Karltun et al. 2008).

2.5.2. Use of ash in road construction

In Sweden, around 50% of ash produced by the forest industry is used in other industries (Sarenbo 2009). For example, ash is used as cement raw meal addition, cement and concrete filler, addition to compost, asphaltic filler, underground mining, civil engineering and other building materials (Lamers et al. 2018). Another use of wood ash is for road construction materials (Zhou et al. 2000; Obernberger and Supancic 2009; Lagerkvist and Lind 2009). Ash is suggested to improve soil strength and reduce deformation. Studies performed in Sweden demonstrated that ash has good cementing properties for stabilizing roads and for deep mixing and soil stabilization (Lagerkvist and Lind 2009).

The chemical properties of wood ash, including its high concentrations of CaO (up to 50%) and lesser amount of MgO (up to 8%), gives it the ability to be used as a substitute for burnt lime, which is used as a binding material for soil stabilization (Obernberger and Supancic 2009). Burnt lime (CaO) is commonly used in soil stabilization and can improve compatibility and ductility properties, increase bearing capacity and insensibility to water, and improve volume stability (Obernberger and Supancic 2009). The addition of wood ash to clay and silt soils should have similar effects to soil properties as the addition of burnt lime.

The substitution of wood ash for burnt lime would also have many advantages. It would reduce the use of non-renewable raw material ($CaCO_3$), reduce negative environmental impacts of the extraction of $CaCO_3$, reduce CO_2 emissions from the calcination of $CaCO_3$, and preserve landfill capacities by recycling wood ash (Obernberger and Supancic 2009). Studies across the world have shown that ash also has good freezing and thawing properties (Lagerkvist and Lind 2009), which is a huge asset when building forestry roads. In recent years, there has been an increasing need for road stabilization due to climate change. Vast amounts of forest roads are threatened by changing bearing capacity and increasing damages to roads from harvesting and hauling activities (Lagerkvist and Lind 2009). The use of ash to stabilize forestry roads could help mitigate the effects of climate change.

A study performed by Zhou et al. (2000) found that the use of fly ash in road stabilization was most effective when applied at a rate of 10% by weight. When applied at a rate of 10% by weight on plastic clay soils, the unconfined comprehensive strength of the soil increased from 260 kPa to more than 490 kPa. They also found that at an application rate of 10% by weight the fly ash was not hazardous to the environment and heavy metal concentrations remained well below regulatory limits.

2.6. USES OF WOOD ASH OUTSIDE THE FOREST INDUSTRY

2.6.1. Use of ash in agriculture

There is a lot of interest in wood ash application within the forest industry, but there are also several applications outside the forest industry. Wood ash is commonly used as fertilizer in forest ecosystems, however, it can also be used for fertilizer in agriculture, a huge industry throughout the world (Knapp and Insam 2011). A major limitation in agriculture around the world is soil acidity, which reduces crop production (Arshad et al. 2012; Haynes and Mokolobate 2001). High acidity in soils results in infertility causing a loss of crop production on highly weathered and leached soils (Haynes and Mokolabate 2001). Issues with soil acidity are common in tropical and temperate regions of the world and have increased due to anthropogenic disturbances. Two major factors limiting the productivity of acidic soils are nutrient deficiencies and the presence of phytotoxic substances. Important nutrients for crop production that are lost with rising acidity include P, Ca and Mg (Haynes and Mokolabate 2001). In addition, phytotoxic substances are introduced, or levels are increased in the soil due to rising acidity, such as include Al and Mn (Haynes and Mokolabate 2001). The presence of phytotoxic substances restricts soil fertility.

Agricultural lime is used in many parts of the world to reduce soil acidity and increase crop yields (Arshad et al. 2012). Wood ash is an effective liming material on acid agricultural soils. In Maine, up to 70,000 tons of wood ash is spread on farmland every year (Griffin 2018). It also promotes plant growth as a result of increased availability of phosphorous, calcium, magnesium, potassium and boron and decreased aluminum and manganese toxicity (Demeyer et al. 2001). Wood ash could be an economically beneficial alternative to the use of agricultural lime in Northwestern America because the use of agricultural lime is limited by its high costs, especially transportation. Most ash-generating mills in Canada are located in northwestern Alberta, which would reduce transportation costs.

A study by Patterson et al. (2004) in central Alberta reported that wood ash increased barley biomass and canola seed yield when the soil was fertilized with 25 t ha^{-1} of wood ash supplemented with a N fertilizer. The study by Arshad et al. (2012) also found that wood ash was a suitable alternative for agricultural lime and moreover found that it was actually superior to it due to its significant amount of phosphorous and other nutrients that agricultural lime lacks. It was as effective at increasing soil pH, nutrients, soil aggregation, and crop yields. However, the liming effect of wood ash compared to lime products is lower when expressed per unit weight (Karltun et al. 2008). For example, three tonnes of wood ash has a liming effect equivalent to about one ton of quicklime, CaO.

2.6.2. Wood ash use in construction and industrial processes

Currently, wood ash is commonly used as a soil supplement in forest and agriculture settings (Subramaniam et al. 2015). A limitation of wood ash application in forest and agriculture ecosystems is that it requires high quality ash to reduce and mitigate negative environmental implications (Knapp and Insam 2011). For example, ashes that contain elevated heavy metal contents should not be used for ecosystem applications and are suggested to be used for other applications. Ashes of lower quality can be used in applications such as construction of roads, surface in landfills, or as additive in industrial processes such as concrete, brick, glass and cement production.

The unit weight of wood ash ranges from 162 to 1376 kg/m^3 and the specific gravity ranges between 2.26 and 2.60, suggesting that it could possibly reduce the unit weight of concrete and cement when used as a supplement material (Subramaniam et al. 2015). A study by Subramaniam et al. (2015) found that there was no significant difference in compressive strength when comparing cement blocks supplemented with less than 20% wood ash and the control block consisting of 100% cement. The compressive strength was found to be highest when supplemented with 15% wood ash, which displayed 9% higher strength than the control. The durability of the cement supplemented with wood ash was also found to be higher than the control due to the ashes ability to decrease water permeability of the cement. The decreased water permeability is a result of the extensive pore refinement of wood ash. Ash can be used as an environmentally friendly substitute for materials that originate from non-renewable resources (Obernberger and Supancic 2009).

2.7. LIMITING FACTORS AND RISKS OF WOOD ASH APPLICATION

Although wood ash does have the potential to benefit forests by providing important nutrients and reducing acidity, it is necessary to evaluate the limiting factors and potential ecological risks wood ash could have on the environment (Augusto et al. 2008). One limiting factor of ash application to forest floors observed in Nordic countries is that it was only effective on improving tree growth on organic soils and not mineral soils. This was a result of mineral soils requiring input of nitrogen, which wood ash lacks. However, improvements to forests on mineral soil with the use of ash application was found to be beneficial when enhanced with nitrogen or when there were deficiencies in K, Ca, or Mg. Therefore, wood ash application could be supplemented with the addition of nitrogen to be more effective on mineral soils. Another factor that limits the use of wood ash as a liming agent is that its liming effect is around one third that of lime products such as quicklime (Karltun et al. 2008).

Another limiting factor of wood ash application is that it may contain harmful amounts of toxic heavy metals such as Cd (Augusto et al. 2008). Other heavy metals found in wood ash include As, Cr, Cu, Hg, Ni, Pb, and Zn (Pitman 2006). Heavy metals in wood ash often originate from the fuel source (Karltun et al. 2008). All woody biomass contains heavy metals in low concentrations that can contaminate soil. However, in the forest context, the bioavailability of the heavy metal contents in wood ash on forest soils was found to be very low (Augusto et al. 2008; Karltun et al. 2008). If the heavy metal concentrations of the wood ash are not greater than the heavy metal concentrations of the woody biomass when exported from the forest, then it should not raise the concentrations when recycled back into the forest (Karltun et al. 2008). Norbord minimizes the risk of heavy metal contamination by not mixing biomass fuel with any other material such as municipal waste, used tires, paints, etc, allowing it to be certified for agricultural uses (Spring, R. Pers. Comm.).

Issues with heavy metal concentrations in wood ash arise when they are influenced by the ash treatment (Karltun et al. 2008). The solubility of the heavy metals may be increased if the alkalinity of the ash is consumed in acid environments such as forest soils, allowing the heavy metals to leach into the soil when the ash is dissolved. The concentration of heavy metals in wood ash may also be increased if the fuel source is contaminated before combustion. High heavy metal concentrations in ash have occurred when produced from surface-treated waste wood and wood treated with industrial preservatives (Knapp and Insam 2011). Thus, it would be recommended to only use biomass strictly from forest harvesting that has not been contaminated when applying it to soil. Heavy metal concentrations in wood ash could also be reduced if the fly ash and bottom ash is separated during the combustion phase because heavy metals such as Zn concentrate in the fly ash.

Most authors support that wood ash contains few harmful elements (Demeyer et al. 2001). A factor that may be more concerning than contamination from noxious elements is the strong increase in soil pH and available K resulting from wood ash addition to soil. With regards to concerns of heavy metal contamination, heavy metal concentration is known to decrease with increasing ash particle size (Demeyer et al. 2001), therefore wood ash application may be restricted to ash types with larger particle size. There is also a risk of nutrient losses and contamination of surface and ground waters after the application of wood ash to forest soils. Without the use of excessive amounts of ash, wood ash application to soils should present no major environmental risks (Demeyer et al. 2001).

Another limitation of wood ash application is that ashes may also contain organic pollutants such as polychlorinated dibenzodioxin, biphenyls, dibenzofuran and polycyclic aromatic hydrocarbons (PAHs) (Knapp and Inslam 2011). Organic pollutants are toxic, mutagenic and carcinogenic pollutants that result from poor combustion of wood. The remobilisation of the organic pollutants is also advanced by the rise in Ph that wood ash application causes.

The process for obtaining regulatory approval to use ash is also challenging and varies greatly (Hannam et al. 2018). For example, the use of wood ash for soil amendment is mostly under provincial or territorial jurisdiction in Canada. Therefore, regulations for ash use vary among provinces. Various government departments administer the use of ash and as a result, ash can be classified differently in each jurisdiction. An environmental impact assessment is often required to get approval to apply ash in the environment and in some provinces an approval process is put in place (Hannam et al. 2018). Currently, the application process to use wood ash is often confusing and time consuming. Landfilling of ash is often the most cost-effective method of disposal and is typically an easier option, creating some disincentive to find ways to use ash.

3.0. CONCLUSION

With increasing use of biomass combustion technology to produce heat and energy throughout the world, there is an increasing demand to find alternative uses of the wood ash waste that is produced from the burning of biomass. Currently, most of the wood ash produced from biomass burning is landfilled. However, there are several beneficial alternatives to the landfilling of ash. One of the greatest opportunities of recycling wood ash is that it originates from the forest industry and it can be recycled back into the industry. Ash is rich in nutrients that are often depleted during harvest and can be recycled in the forest to replace them and can moreover increase the growth and production of the forest. Ash can also be used to stabilize forest roads by improving strength along with freezing and thawing properties.

There are also several uses of wood ash outside the forest industry. Another important industry throughout the world that can benefit from the application of wood ash is agriculture. For example, Norbord sells some of their ash to local farmers (Spring, R. Pers. Comm.). Ash can perform as an effective liming agent and can increase crop growth, increase nutrient levels and decrease soil toxicity. Wood ash can also serve many purposes in construction and industrial processes. For example, it can be used in concrete, brick, glass and cement production. Norbord also sells some ash to a manufacturer of patio stones (Spring, R. Pers. Comm.). There are still some limitations, risks and barriers of wood ash utilization from biomass burning, however, with further research and regulation, the barriers of ash application can be mitigated.

4.0. LITERATURE CITED

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