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A cost analysis of bioenergy-generated ash disposal options in Canada

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Abstract

The burning of wood for bioenergy produces significant amounts of ash residue which requires disposal. We constructed a cost model to evaluate the unit costs of three ash disposal methods in the Canadian context: landfills owned and operated by the bioenergy facility, municipal landfills, and forest site application. The model accounts for costs related to the pre-treatment, transportation, and disposal of ash at a landfill or forest site. Model parameter values were assigned appropriate distributions (based on published literature and industry surveys) and Monte Carlo simulations were employed to produce a range of model outputs for each disposal option. Results indicate that existing landfills (if available for ash disposal) are likely the most cost effective option (median value of \$77/tonne), although applying ash to a forest site is only ~15-20% more costly (median value of \$92/tonne). Indeed the unit cost estimates across disposal options have considerable overlap. This suggests that close examination of firm specific circumstances is highly warranted when choosing a disposal approach – even in the absence of accounting for potential environmental benefits associated with forest-site disposal of ash.

Key Words:

Wood Ash Disposal, Cost Comparison, Landfill Disposal, Forest Application, Canada

Introduction

The use of forest biomass to generate energy is expected to increase as governments aspire to phase out traditional fossil fuels, and the demand for renewably sourced energy grows. While bioenergy production may be beneficial for local economies and reduce greenhouse gas emissions on some scales (Paré et al. 2011; Ter-Mikaelian et al. 2015), the waste-generating side of bioenergy use is often ignored. Bioenergy ash, while rich in nutrients, is not yet re-purposed (as coal ash is) on a large scale in Canada (McKenna pers.com. 2015), and is typically sent to landfills (both in Canada and globally) (Brais et al. 2015; Freire et al. 2015; Hébert and Breton 2009). As the production of bioenergy and ash waste-products increase (Bradburn 2014), the need for landfill capacity to accept ash will escalate as existing landfills reach or exceed their capacities (Khan et al. 2016). This potentially undermines the environmental benefits typically associated with bioenergy projects and adds important financial costs to be considered when assessing the merits of alternative energy options.

The application of ash on recently harvested forest sites is an alternative to the landfill approach and can generate a number of benefits, including: 1) return of nutrients removed from the site during harvest (Nautiyal 1978); 2) reduced soil acidity due to the alkaline nature of the applied ash; 3) potentially improved silvicultural yields (Augusto et al. 2008; Brais et al. 2015; Väätäinen et al. 2011), and 4) expanded lifetime for existing landfills. The forest application of ash is in fact practiced in some European and Scandinavian countries (Huotari et al. 2015), but has gained little traction in Canada, despite historical precedent and agricultural use (Hébert and Breton 2009).

Here we examine financial factors associated with forest-based bioenergy ash disposal in Canada. Specifically, we develop a spreadsheet-based model and estimate the present value unit

costs of three different ash disposal methods: disposal in a landfill owned by the bioenergy facility, disposal in a landfill owned by a local authority (e.g. municipal landfill), and ash application to forest soils. Although the application of bioenergy ash to forest sites has been studied from a variety of perspectives in Europe and Scandinavia (Augusto et al. 2008; Börjesson 2000; Reid and Watmough 2013), very few conclusions can be applied to the Canadian context, a direct result of differences in ash quality, forest management, governance, and environmental factors (Augusto et al. 2008). We also provide what can be interpreted as a break-even silvicultural application price per tonne of ash. This value is simply the difference in the unit costs required to equalize the cost of forest site application with landfill disposal – a useful metric that identifies what the benefits of the forest application would have to be in order to justify forest applications versus the least cost alternative. The choice of this metric is further justified below.

Methods

Model Overview

Our methods of estimating costs are similar to those used by Ramlal et al. (2009) in their net present value (NPV) cost calculations regarding municipal biosolids, and Freeze et al. (1993) manure-spreading cost estimates (see also Adhikari et al. 2005). The calculations presented here examine only the financial costs associated with the three ash disposal options; economic interpretations of benefits that might result from forest ash application are not considered due to the lack of available information at this time. They are the subject of ongoing research.

We developed a spreadsheet-based model, augmented with the @Risk Monte Carlo simulation program (@Risk v7.5, Palisade Co., Ithaca, NY 2016) to investigate the implications

of various uncertainties. The model estimates the financial costs associated with the disposal of ash in: 1) a producer-owned landfill, 2) a local or municipal landfill, and 3) on a forest site. Each disposal option consists of specific cost categories thought to reflect the disposal processes; pre-disposal treatment, transportation, and final disposal costs. These cost parameters are described below and summarized in Table 1. Model outputs include the cost for each process, unit costs in the form of total disposal cost per tonne of ash, and analysis of the key variables associated with each cost estimate. Unit costs are a useful metric for decision-makers who face the task of making their own subjective (and sometimes politically influenced) judgements about benefit values and opportunity costs (McKenney et al. 2014). The following sub-sections provide details about each component. Figure 1 outlines the model process.

Figure 1.

Pre-Disposal

Pre-disposal processing reflects the costs incurred to stabilize the ash and transform it into a more useful, appropriate and/or acceptable form. Untreated ash from combustion facilities is generally not suitable or acceptable for application on most soils in Canada due to its potentially high reactivity (Arvidsson and Lundkvist 2003; Huotari et al. 2015). In addition, the dusty and corrosive nature of untreated ash adds health and safety concerns (Väätäinen et al. 2011). Most stabilization processes convert loose ash into less reactive forms, and reduce handling concerns by increasing particle sizes (Ring et al. 2005). For our purposes, we assume that any ash applied to the forest will be granulated, a process that mixes ash with water, creating a fertilizer-like product (Väätäinen et al. 2011). We also assume that pre-disposal processing is not required for

landfill disposal, given the limited concerns regarding nutrient leaching and harm to underlying soils.

Total cost of the pre-disposal treatment is given by the product of the quantity of ash to be processed, and the treatment fee on a per tonne basis:

$$[1] \text{ Total Pre – disposal Treatment Cost} = Q \times T$$

where Q is the quantity of ash to be disposed of in tonnes in a given year, and T is the cost associated with the selected pre-disposal treatment option (\$/tonne).

Transportation

Depending on the location of the bioenergy facility producing ash and the selected disposal method, transportation costs may represent a considerable proportion of the total cost. Here we consider transportation costs to be the expenses associated with moving the ash from the production facility to the disposal site, inclusive of the fees associated with positioning the transport to receive or to dump ash, loading and un-loading the ash, round trip transportation distance, the number of trips to the disposal site, and road type. Because the disposal method may vary between an easily accessible local landfill to a remote forest site, it is unrealistic to assume that the road type used for transportation to each disposal site remains the same. Standard forestry transportation models (Ljubic 1986; Smith and Tse 1977) typically assume that faster speeds are achieved on well-maintained highways, while forest and gravel roads demand a slower pace, thus incurring higher transportation costs. Transportation costs are calculated as follows:

$$[2] \text{ Transportation Cost} = h ((E + R_{Loaded} + R_{Empty}) \times e)$$

where h is the hourly transportation cost in \$/hour, E is the time spent loading and unloading the ash and positioning the transport in hours, R_{Loaded} and R_{Empty} represent the time travelled by a loaded and unloaded transport over different road classifications respectively, and e is the annual number of trips required to transport the ash. R_{Loaded} and R_{Empty} are further defined below:

[2.1]
$$R_{Loaded} = \left(\frac{D_{Hwy}}{S_{Hwy,L}} \right) + \left(\frac{D_{Primary}}{S_{Primary,L}} \right) + \left(\frac{D_{Secondary}}{S_{Secondary,L}} \right) + \left(\frac{D_{Tertiary}}{S_{Tertiary,L}} \right)$$

where D is the distance travelled on each road classification and S is the speed travelled on each road type and is estimated based on loaded transport speeds. The equation for R_{Empty} is identical, using empty transportation speeds. e , the annual number of trips required to transport the ash, is calculated as:

[2.2]
$$e = \frac{Q}{Truck\ capacity}$$

where *Truck capacity* is the weight of ash the transport vehicle is capable of carrying.

We assume that the majority of the transportation distance between an ash generating facility and an owned landfill would take place on highway or primary roads. Similarly, we anticipate that most of the transportation distance between a production facility and a municipal landfill would take place on highways and higher road classifications. Transportation for forest application is likely to encounter all four types of road classes, with the majority of distance assumed to take place on highway classed roads.

Costs estimates for transportation are similarly structured across all three disposal options; the options are differentiated by the processes and costs associated with disposal in landfills or application on forest soils. Disposal costs for a producer-owned landfill are estimated as the net

present value (NPV) of a combination of construction, maintenance, closure and monitoring costs for a landfill. Disposal in a municipal landfill is expected to incur a tipping fee, as set by the municipality. Application on a forest site requires the use of specialized machinery, which must be transported to and from the site, and testing of the soil and ash for compatibility and regulatory restrictions. The following sections highlight the unique assumptions about the pre-disposal and transportation cost categories made for each disposal option and outline the disposal cost estimates.

Disposal

Disposal in an Ash Producer-owned Landfill

Ash production facilities may not pay a tipping fee when disposal occurs in their own landfill. However, landfilling costs still accumulate as a result of initial construction costs, yearly maintenance costs, and end-of-life closure costs. Our model estimates somewhat simplified lifetime costs for two possible scenarios – the first assuming a new landfill has to be constructed for the sole purpose of receiving the ash waste, the second assuming that the landfill is already in operation and only accepts ash. We use the net present value (NPV) lifetime cost to derive landfill tipping fees (similar to Eilrich et al. 2003), expressed on a per tonne basis. The NPV estimate for a new landfill includes construction and regulatory fees, maintenance costs over the lifetime of the landfill, the costs of closure, and environmental monitoring fees for a period following the end of the useful life of the landfill. Similar costs are incurred by an existing landfill, but minus the initial construction costs, which are considered ‘sunk costs’ that do not influence future decisions (Boardman et al. 2006)).

The total cost of ash disposal in the producer-owned landfill is calculated as:

[3] *Total Owned Landfill Disposal Cost* = $L \times Q$

where L is the per tonne disposal cost in an owned landfill, calculated as follows:

[3.1]
$$L = \frac{\left(\sum_{t=1}^{t_\varphi} \left(\frac{\varphi}{(1+i)^t} \right) + \sum_{t=t_\varphi+1}^{t_\mu} \left(\frac{\mu}{(1+i)^t} \right) + \sum_{t=t_\mu+1}^{t_\omega} \left(\frac{\omega}{(1+i)^t} \right) + \sum_{t=t_\omega+1}^{t_m} \left(\frac{m}{(1+i)^t} \right) \right) \times s}{d}$$

where φ is the cost associated with constructing a landfill (including the cost of obtaining regulatory approval) over t_φ years; μ is the fee associated with day to day operations of the landfill, and is assumed to be incurred annually until the landfill closes at year t_μ . ω are the annual fees associated with closing the landfill and extend until shutdown is completed at year t_ω ; m accounts for the annual costs of maintaining the land after active remediation activities have ceased (i.e., maintaining fencing, monitoring groundwater, etc.) and continue until all regulatory obligations have been met at year t_m ; φ , μ , ω , and m are all expressed on a per hectare basis, and s represents the landfill area in hectares. The total producer-owned landfill disposal cost is divided by the landfill capacity, represented by d , and expressed on a per tonne basis. The year the landfill closes (t_μ) is calculated based on the landfill capacity and annual rate of ash addition in tonnes, and is capped at 50 years:

[3.2]
$$t_\mu = \frac{\text{Landfill Capacity}}{\text{Annual Rate of ash Added}}$$

Ash producer-owned landfill disposal costs incurred over the partial lifetime of the landfill are also discounted to the present. In this case, disposal costs are calculated similar to those described above, but without the term in equation [3.1] that accounts for construction costs as these are considered unrecoverable sunk costs in this scenario (Boardman et al. 2006).

Disposal in a Municipal Landfill

The costs of disposal in a local municipal landfill are estimated as the standard, non-hazardous material tipping fee municipalities typically charge on a per tonne basis. For disposal of ash, an additional regulatory cost has been included in the calculation. This fee reflects the costs (monetary, opportunity and time) that may be encountered by a bioenergy facility while seeking approval for ash disposal from provincial regulators and municipal authorities. Experience within the industry suggests that some municipal authorities require additional investment by the ash producer to upgrade existing municipal landfill facilities prior to disposal. In some cases provincial landfill regulatory practices can also increase unit costs (Basiliko pers.com. 2016, McKenna pers.com. 2015). Thus these costs are likely to vary significantly across the country. Cost of disposal in a municipal landfill is calculated as:

$$[4] \text{ Total Municipal Landfill Cost} = r + (Q \times \tau)$$

where r is the regulatory fee associated with municipal disposal, and τ is the landfill tipping fee. It is assumed that there are no restrictions on the amount of ash that can be deposited in a municipal landfill.

Forest Application

Forest site ash application costs are estimated as a function of the amount of land intended for ash application, equipment costs, application costs, and regulatory/testing fees. The amount of forest land needed is a function of the per hectare amount of ash application, and the total quantity of ash to be applied. Currently, there are no national regulations dictating the amount of application of ash on forest soils, and provincial and territorial approaches to applying wood ash on soils differ significantly (Deschamps 2015). Future regulations may result in more unified provincial and territorial approaches by specifying the allowable quantity of ash applied to forest

soils dependent on various environmental factors (Deschamps 2015) but ultimately this will likely have some variation by jurisdiction.

Land suitable for application of ash is assumed to have been recently clear-cut, given that application on newly forested sites can be expected to be much more costly. We have assumed that numerous adjacent/aggregated parcels of clear-cut land will be used for ash application. For each application site, ash-spreading equipment (similar to agricultural granular fertilizer spreading equipment, (Brais et al. 2015)) must be delivered, un-loaded and loaded, and the soil and ash must be tested for suitability. Equipment transportation costs are estimated assuming the equipment must be transported from the bioenergy facility to the application site and back, accounting for loaded transport speeds on various road classifications. The transportation costs of moving spreading equipment between the actual forest sites have not been included here, given the potential variation in distance between sites. In addition to the transportation costs, a fee for equipment use per tonne per hectare is incurred, and a single regulatory fee is assumed to reflect the costs (financial, opportunity, and time costs) of obtaining approval for ash application from the appropriate authorities. The cost of applying ash to forest soils is calculated as:

$$[5] \text{ Total Forest Application Cost} = [g + (\text{Number of sites} \times \chi) + (A \times Q) + \text{Float costs}]$$

where g is the regulatory cost associated with obtaining approval for ash application, Number of sites is the number of cut-blocks required to apply ash at the selected application rate, χ is the cost of testing both the soil and the ash for compatibility, A is the application cost on a per tonne per hectare basis, representing equipment rental costs, salary and fuel costs for the spreading operation only. Note that the application cost does not include the cost of transporting

the spreading equipment to the cut-block (Nishio pers.com. 2015). *Float Costs* represent the associated cost of transporting the spreading equipment to and from the cut-block sites for forest application. The number of sites is calculated as:

$$[5.1] \text{ Number of sites} = \left(\frac{Q}{\rho}\right) \div \alpha$$

where ρ is the amount of ash application in tonnes per hectare, and α is the average cut-block size. Float costs are calculated as:

$$[5.2] \text{ Float Costs} = (\text{Equipment transport time} + ([\text{Number of sites} \times (\theta + l)]) \times \kappa)$$

where *Equipment transport time* is the time required to transport the spreading equipment to and from the forest application site, θ is the time spent moving the spreading equipment onto the ash application site (hours), l is the time spent loading and unloading the equipment (hours), and κ is the equipment rental cost per hour incurred during transportation to and from the forest application site. *Equipment transport costs* are calculated using Equation [2], with the assumption that both the inbound and outbound transportation trips are calculated based on the loaded speed.

Data and Assumptions

The costs associated with the disposal of ash are unique to every producer and every disposal option. In an effort to account for some of the uncertainty associated with the data we have gathered regarding costs for each option, all model variables have been assigned a distribution of values, based on literature data and discussions with industry and government representatives. As an additional benefit of the use of variable distributions, technical costs that are not explicitly included within the analysis are implicitly captured within the cost ranges. The

variables, their distributions and most likely values are illustrated in Table 1. Table 1 includes data from pulp and paper mills and sawmills. The ash generated at these facilities is subject to the same disposal constraints as ash produced by dedicated bioenergy facilities. Distributional data for some variables are based on datasets that are large enough to identify appropriate distributional shapes; for variables with smaller datasets, maximum, most likely, and minimum values from the literature are used to assign triangular or uniform distributions. That said, it must be recognized that in many respects some costs are subjective (Buchanan 1969) and unknowable except to the individual decision-maker. Each firm will have its own cost circumstances; hence here we provide a set of results based on our own assessment of costs (all expressed in 2014 Canadian dollars). More importantly we provide a framework for similar analyses. The spreadsheet model is available upon request from the senior author.

Table 1.

Sensitivity Analysis

Using the base case data and assumptions discussed above, the cost per tonne of ash for each of the disposal options is estimated as a single most likely value, and as a range of values generated from the distributions assigned to the variables. This is achieved with the @Risk program. The program runs multiple iterations of the model, selecting different parameters for each variable based on the assigned distributions. Table 1 summarizes the range of values used in the sensitivity analyses.

Additionally, we examined three key model assumptions that affect the financial feasibility of wood ash application on forest soils. Referencing the base case distributions, we evaluated changes in pre-disposal treatment costs, adjustments to the acceptable rate of ash application on

forest sites, and changes in the transportation distance between ash producers and forest sites selected for ash application.

Pre-Disposal Treatments

There are few guidelines for the application of ash on forest lands, and no regulations regarding pre-disposal treatments. These treatments could represent a considerable cost when applying ash to forested soils. The base case assumes that the ash will be granulated prior to application, although there are less expensive pre-disposal treatments available. Treatment costs were varied from no-cost (no pre-treatment was required) to a mid-range cost (crushed ash), inclusive of the high-cost base case assumption (granulated ash). Crushed ash is allowed to harden (with the addition of water) into large blocks, and crushed into smaller pieces (Börjesson 2000; Pitman 2006). Granulated ash is generally considered to be of higher quality than crushed ash, and is more costly due to the uniformity of the ash particle sizes and the potential requirement for additional infrastructure.

Forest Soil Ash Application Amount

The per hectare amount of ash application on forest soils is not regulated in Canada, and the quantity of ash that triggers a regulatory response is unknown for most jurisdictions. The initial assumption of 2 tonnes of ash per hectare of forest soil was based on experience from both Canadian and European literature (Arvidsson and Lundkvist 2003; Brais et al. 2015; Jacobson et al. 2014). We varied ash application rates from 2 to 5 tonnes/ha to reflect a likely range of possible application rates in future guidelines. The per hectare amount of ash application influences a number of factors beyond the equipment cost associated with application. If a larger

volume of ash can be applied to the site, less area will be needed to safely apply the ash, and fewer soil tests will have to be conducted.

Transportation Distance to Forest Site

Transportation distances between bioenergy facilities and local landfills are unlikely to be large, and should not vary substantially through time. Alternatively, forest application sites are anticipated to be remote, and transportation distances are likely to change as forest sites are treated with ash, and new forest sites are sought. Transportation distances for forest application were varied between four triangular distributions of $\pm 25\%$ with midpoints of 50 km, 100 km, 250 km, and 500 km to accommodate larger travel distances and the need to travel farther afield to obtain new ash application sites. A transportation distance of 500 km, although unlikely, has been included to highlight the costs associated with extreme transportation distances.

Results

Base Model Outputs

Results from the base model runs indicate that disposal in an ash producer-owned landfill part way through its lifecycle was generally the least costly option, followed by (in order of increasing cost) application of wood ash onto forest soils, ash disposal in a municipal landfill, and construction of a new on-site landfill. Table 2 presents the cost estimates for each disposal option and the break-even price that would be required to make forest application attractive to an ash producer relative to the more traditional landfilling approach. In this case, an ash producer using an existing owned landfill would require an additional \$15/tonne payment before being indifferent between forest application and continued use of the landfill.

Table 2.

Figure 2 illustrates the distribution of the model outputs associated with each disposal option. Of particular note is the range of variation within the cost distributions –the forest disposal option was associated with the least variation and the municipal landfill option was associated with the greatest variation. This variation is driven by the range of parameter input values associated with each disposal option (see Table 1). The contribution of specific model parameters to this variation is examined in the sensitivity analyses below.

Figure 2.

Sensitivity Analysis Results

Figure 3 highlights the most influential variables associated with each disposal option. For a landfill owned and operated by a bioenergy facility, both the discount rate, and the size (area and capacity) of the landfill are key parameters, regardless of whether the landfill is partially through its lifespan, or has yet to be constructed. Not surprisingly, the cost of disposal in a municipal landfill is overwhelmingly dictated by the municipal tipping fee. The cost of pre-disposal treatment (granulation in the base case) strongly influences the final cost of forest application.

Figure 3.

Pre-disposal Treatments

Pre-disposal treatments represent a significant cost for wood ash disposal. When pre-disposal treatment costs are eliminated, ash application on forest sites is the cheapest disposal option (Fig. 4). Total costs for this scenario reflect transportation and application, estimated from

\$6.38 to \$48.17/tonne of ash. Crushing ash as a pre-disposal treatment is also a low cost option, resulting in total costs of approximately \$21.01 to \$67.23/tonne of ash (Fig. 4). In the event that there is no need for pre-disposal treatment, or that crushed ash is sufficient for forest application, forest application is likely to be the most cost effective ash disposal method.

Figure 4.

Forest Soil Ash Application Amount

The impact of increasing the ash application amount from 2 tonnes/ha (in the base case) to 3, 4, and 5 tonnes/ha was minimal. As the per hectare amount of ash application increased, the cost distribution shifted to the left, consistent with the expectation that costs would decline with higher application rates. However, the magnitude of these changes was small, due to the relatively minor contribution that application costs make to total disposal costs (Table 2, Fig. 3).

Transportation Distance to Forest Site

Variation in the transportation distance to the forest sites influenced both the initial ash transport cost, and the cost of transporting ash spreading equipment to and from the forested site. We investigated a range of transportation distances from 50 to 500 km (Fig. 5). As the transportation distance increased, the cost distribution shifted to the right and broadened. This is a result of the combined effect of increasing ash and spreading equipment transport costs, and the increasing proportion of total costs related to transportation.

Figure 5.

Discussion and Concluding Comments

Our findings indicate that, under average conditions, ash disposal in an existing producer-owned landfill is the most economically attractive disposal method. Alternatively, the costs of applying ash on forest sites are only slightly higher than those associated with disposal in an existing producer-owned landfill, suggesting that ash application on forest sites offers a viable alternative to the landfilling approach. Disposal in a municipal landfill and disposal in a newly constructed producer-owned landfill appear to be more costly options. However, given the wide range of outcomes identified here, selection of an appropriate ash disposal option will depend on the unique set of economic factors associated with a given bioenergy production facility.

Furthermore, our findings suggest limited variation in the cost estimates for forest site application when compared to the cost estimates for other disposal methods. The wide range in cost estimates for landfilling practices is a result of the uncertainty associated with landfill parameters and the significant variation observed within the industry. Landfills surveyed typically varied in size, capacity, lifespan and tipping fees. Additional variation in cost estimates stems from construction, maintenance, closure and post-closure monitoring costs. Costs associated with landfills are highly site specific (Eilrich et al. 2003), and therefore vary considerably.

While average costs for forest application were modestly higher (\$15/tonne of ash) than the costs associated with disposal in an existing producer-owned landfill, there are a number of avenues that could be explored to further reduce costs related to forest application. Reducing the costs associated with pre-disposal treatment of the ash would significantly improve the economic attractiveness of forest application. The model assumed that ash from biomass combustion facilities was treated to improve stability and usefulness prior to application on forest sites. Variations in this assumption have highlighted potential cost savings with different approaches to

388 ash pre-disposal treatment. Reductions in the cost of ash treatment would improve the financial
389 feasibility of forest application.

390 Additionally, spreading ash on local forest sites within a certain distance from the ash
391 production facility will ensure that forest site application remains somewhat competitive with
392 landfill disposal options. Based on the assumptions made here, forest application transportation
393 distances can be extended to approximately 100 km prior to increasing total costs such that
394 municipal landfill disposal becomes more financially attractive. Moderate increases in
395 transportation distance result in significant increases in cost due to the compounding effects of
396 transporting ash and spreading equipment.

397 We did not consider costs/losses that may occur when granulated ash is unloaded at the forest
398 disposal site. Depending on the situation, the granulated ash will likely need to be temporarily
399 stored in piles prior to spreading (Kopecky et al. 2014), which could lead to wastage.
400 Alternatively, the granulated ash could be packed in sacks prior to transport (Väätäinen et al.
401 2011); this would likely reduce wastage at time of unloading, but incur costs related to the
402 packaging. While future modelling efforts may attempt to incorporate these considerations, we
403 feel that their overall economic impact is relatively minor and should be contained within the
404 bounds of the sensitivity analysis employed here.

405 Although wood ash application on forest sites is economically feasible under some
406 circumstances, the effects of the regulatory environment cannot be ignored. The regulations that
407 currently govern soil additives vary by province, and are not designed for biomass ash
408 application on forest sites (Deschamps 2015). There is no formal approval process currently
409 available to proponents interested in forest application, and the existing regulatory process are

perceived to be expensive and time consuming (Rutherford, pers.com. 2016). These factors impose significant barriers and may discourage forest site applications. Representative costs of obtaining regulatory approval have been included in the model and are based on discussions with industry.

Disposing of ash in existing producer-owned landfills will continue to be the most cost effective option for ash producers without acknowledgement of the social and environmental costs and benefits associated with landfilling or forest site application. The break-even values calculated to encourage adoption of forest soil ash applications highlight the minimum monetized value (approximately \$15/tonne of ash or more) of environmental services necessary to make ash producers indifferent between traditional disposal methods and forest soil application.

Future research could estimate the monetized value of environmental services accruing from forest soil application of wood ash. Scandinavian literature has suggested that the return of nutrients removed from the forest site during harvest may help to improve silvicultural yields and the application of alkaline ash to acidic soils may increase soil nutrient availability (Augusto et al. 2008; Brais et al. 2015; Staples and Rees 2001; Väätäinen et al. 2011). Additional non-forest benefits may also include extension of existing landfill lifetimes, and delaying the creation of new landfills and their associated social costs.

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523 **Table 1:** Summary of model variables and assigned distributions used in the model.

Variable	Most Likely Values	@Risk Distribution Values	@Risk Distribution	Comments
Quantity of Ash Disposed	1,000 tonnes	-		Model assumes 1,000 tonnes of ash disposed under each option
<i>Pre-disposal Processing</i>				
Crushing	\$18.70	\$12.50 - \$24.90/tonne	Triangular	Börjesson 2000
Granulation	\$73.00	\$49.60 - \$95.80/tonne	Triangular	Börjesson 2000
<i>Transportation</i>				
Truck Capacity	38 tonnes	30 - 54	Triangular	Smith and Tse 1977 and Nishio 2015
Distance (Ash producer owned landfill)	-	1 - 5 km	Uniform	Discussions with industry suggest that producer-owned landfills are typically adjacent to or within 5 km of production facilities
Distance (Municipal landfill)	-	1 - 50 km	Uniform	Distance from the ash production facility to the municipal landfill may vary randomly
Distance (Forest application)	-	1 - 100 km	Uniform	Distance from the ash production facility to the forest application site may vary
Loading Time	0.67 hour	0.33 - 1 hour	Triangular	Nishio 2015
Un-Loading Time	0.17 hour	0.08 - 0.25 hour	Triangular	Nishio 2015
Turn-around Time	0.13 hour	0.08 - 0.17 hour	Triangular	Nishio 2015
Variable Transportation Costs	\$86.80	\$48.60 - \$125.00 per hour	Triangular	Lavoic 1979, Ljiubic 1986, and Nishio 2015
Road Type Speed, Loaded (Highway)	75.00 km/h	50.00 – 100.00 km/h	Triangular	Lavoic 1979, Ljiubic 1986, and Nishio 2015.
Road Type Speed, Loaded (Primary)	62.80 km/h	50.90 – 75.00 km/h	Triangular	Lavoic 1979, Ljiubic 1986, and Nishio 2015.

Road Type Speed, Loaded (Secondary)	44.80 km/h	36.50 – 55.00 km/h	Triangular	Lavoic 1979, Ljiubic 1986, and Nishio 2015.
Road Type Speed, Loaded (Tertiary)	25.20 km/h	18.30- 31.20 km/h	Triangular	Lavoic 1979, Ljiubic 1986, and Nishio 2015.
Road Type Speed, Empty (Highway)	87.50 km/h	75.00 – 100.00 km/h	Triangular	Lavoic 1979, Ljiubic 1986, and Nishio 2015.
Road Type Speed, Empty (Primary)	68.30 km/h	53.80 – 80.00 km/h	Triangular	Lavoic 1979, Ljiubic 1986, and Nishio 2015.
Road Type Speed, Empty (Secondary)	52.10 km/h	42.50 – 62.50 km/h	Triangular	Lavoic 1979, Ljiubic 1986, and Nishio 2015.
Road Type Speed, Empty (Tertiary)	30.70 km/h	24.00 – 37.00 km/h	Triangular	Lavoic 1979, Ljiubic 1986, and Nishio 2015.
Disposal Costs				
<i>Ash producer-owned Landfill Disposal</i>				
Discount Rate	4%	2% - 8%	Triangular	
Pre-Construction Costs	\$300,000	\$200,000 - \$400,000 /landfill	Triangular	Nishio 2015
New Site Construction Costs	\$1,499,260	\$817,778 - \$2,180,741/yr	Triangular	Duffy 2016
Maintenance Costs	\$86,790	\$55,493 - \$118,090/yr	Triangular	Duffy 2016
Remediation Costs	\$920,080	\$477,200 - \$1,362,962/yr	Triangular	Duffy 2016
Post-Closure Costs	\$9,350	\$120 - \$18,580/yr	Triangular	Duffy 2016
Total Landfill Area	19.55 ha	6.10 - 33 ha	Triangular	Based on interviews of random pulp and paper and saw mills across British Columbia, Ontario and Nova Scotia
Total Landfill Capacity	409,667 tonnes	252,000 - 597,000 tonnes	Triangular	Based on interviews of random pulp and paper and saw mills across British Columbia, Ontario and Nova Scotia
Annual Rate of Ash Addition	15,360 tonnes/yr	3,000 - 27,000 tonnes/yr	Triangular	Based on interviews of random pulp and paper and saw mills across British Columbia, Ontario and Nova Scotia

Remaining Storage Lifetime	50 years	-		Lifetime capped to reflect changes in regulation and industry
Landfill Construction Period	1 year	-		Construction period limited to one year for simplicity
<i>Municipal Landfill Disposal</i>				
Regulatory Fees	\$6,000 per landfill	\$0 - \$10,000 per landfill	Triangular	Application fees for environmental compliance approvals under the Environmental Protection Act (Government of Ontario, N.D.) Value range established based on a random sample of 15 municipal landfills from three provinces: British Columbia, Ontario and Nova Scotia
Landfill Disposal Fee	\$99.60 per tonne	\$12.75 - \$220 per tonne	Logistic	
<i>Forest Application</i>				
Average Cut-Block Size	35 hectares	4 - 100 hectares	Triangular	Based on 2002 to 2013 cut-block data from the Ontario Ministry of Natural Resources and Forestry (OMNRF, 2014)
Regulatory Fees	\$7,823.60	\$0 - \$15,000	ExtValueMin	Based on comments from UNBC Aleza Lake Ash Testing Site (Rutherford, pers. com. 2016)
Site Soil Testing	\$76.40 per site	\$35.80 - \$117.00 per site	Triangular	The University of Wisconsin Madison (2012)
Ash Testing	\$39.80 per site	\$35.80 - \$43.90 per site	Triangular	The University of Wisconsin Madison (2012)
Float Equipment Rental Costs	\$112.50 per hour	\$90 - \$135 per hour	Triangular	Nishio 2015
Time spent moving ash spreading equipment onto application site	0.13 hour	0.08 – 0.17 hour	Triangular	Nishio 2015
Float Loading and Off- loading Time	0.21 hour	0.17 - 0.25 hours	Triangular	Nishio 2015
Application Cost	\$4.80 per tonne per ha	\$2.58 - \$8.05 per tonne per ha	Triangular	Based on FPInnovation Ash Application Cost Model, excluding equipment transportation costs (Nishio 2015)

525 **Table 2:** Summary of model results for four wood ash disposal options.

Model Item	Ash producer-owned Landfill Disposal (Partial Life)		Ash producer-owned Landfill Disposal (Full Life)		Municipal Landfill Disposal		Forest Application	
	Low Value	High Value	Low Value	High Value	Low Value	High Value	Low Value	High Value
@Risk Distribution Ranges								
Pre-Disposal Treatment Costs (\$/tonne of ash)	\$0	\$0	\$0	\$0	\$0	\$0	\$50	\$96
Transportation Costs (\$/tonne of ash)	\$1	\$5	\$1	\$5	\$1	\$10	\$1	\$11
Disposal Costs (\$/tonne of ash)	\$23	\$188	\$47	\$281	\$2	\$394	\$4	\$34
Final Cost (\$/tonne of ash)*	\$25	\$190	\$50	\$283	\$5	\$399	\$60	\$128
@Risk Distribution Results								
Median (\$/tonne of ash)	\$77		\$136		\$108		\$92	
Break-even Price (\$/tonne of ash)	\$15		-\$44		-\$16		NA	

526 *Min and Max of @Risk Total Cost Distributions

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Figure Captions

Figure 1: The model outline showcases the cost categories for each of the three disposal options examined.

Figure 2: Distribution of the base case model outputs for four wood ash disposal options.

Figure 3: Influence of primary model variables on base model outputs for four ash disposal options: a) producer-owned landfill, partial lifetime, b) producer-owned landfill, full lifetime, c) municipal landfill, and d) forest application.

Figure 4: Sensitivity analysis results for wood ash disposal under three different pre-disposal treatment options. The base case scenario (the granulation treatment) is shown in solid green.

Figure 5: Sensitivity analysis results for four different assumptions regarding forest site transportation distance. The base case scenario is shown in solid green.

Figure 1.

Figure 2.

549 **Figure 3.**

551 **Figure 4.**

553 **Figure 5.**

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