Is the beneficial use of wood ash environmentally beneficial? A screening-level life cycle assessment and uncertainty analysis

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Abstract
In this paper, a screening-level life cycle assessment (LCA) approach is used to compare the potential environmental benefits and tradeoffs of different management options for wood ash, namely, agricultural land application, forest soil amendment, use in forest roads, use in concrete and mortar, and landfilling. Uncertainty analyses are used to evaluate the generalizability of the results obtained. Although decisions regarding the selection of a beneficial use option are site-specific and depend on available local markets and wood ash characteristics, this study shows that it is possible to draw a few general conclusions from the application of LCA. All beneficial use (BU) options showed lower environmental indicator scores than those associated with landfilling, in addition to net potential environmental benefits. From an environmental perspective, results suggest that, only in a few situations, beneficially using wood ash might not produce potential net environmental benefits but would still be preferred over landfilling, and in a very few cases, landfilling would be preferred over a BU option. For instance, net environmental benefits may be compromised if wood ash needs to be transported over long distances before it can be beneficially used. Out of the four BU options evaluated, the use of wood ash in concrete to replace Portland cement showed the greatest potential environmental benefits. However, the application of wood ash on agricultural or forest land showed greater environmental benefits than the use in concrete in cases where both its liming and fertilizing potentials are assumed to be achieved at the same time.

Keywords
beneficial use, forest products, industrial ecology, life cycle assessment (LCA), uncertainty analysis, wood ash

1 | INTRODUCTION

Considerable quantities of solids are generated annually as by-products from the manufacturing of pulp, paper, and other forest products, including wood ash. More than 60% (American Forest & Paper Association & National Council for Air and Stream Improvement, 2018) of wood and coal ash combined in North America is still disposed of in landfills. The increased difficulty and costs associated with permitting, constructing, and operating new landfills, in addition to the desire to achieve a more circular manufacturing process, has caused many in the industry to focus their attention on reducing waste streams and extending the life of their current landfills. Efforts are being made by the forest products industry to find more environmentally and economically attractive alternative beneficial uses for these by-products. For instance, wood ash can be used as a substitute for lime in agricultural or silvicultural applications. Like other beneficial uses, land application generally costs less than landfilling over its lifetime and can extend the life of company-owned landfills. Other possible beneficial uses for wood ash include use as compost feedstock, in soil...
stabilization, and as an additive in various construction applications. Very little information comparing the potential environmental benefits and tradeoffs of various management options for wood ash is available.

To fully understand the potential environmental benefits and tradeoffs of different management options for wood ash, it is necessary to examine their full life cycle impacts. The few relevant life cycle assessments (LCAs) available in the literature have focused on either comparing the benefits of using wood ash as a replacement of materials in the context of a specific application or evaluating one or two beneficial use options against landfilling in site-specific contexts. None of these assessments have compared multiple and distinct management options for wood ash in a way that allows for robust decision-making based on environmental impact information. For instance, Bergman and Suer (2011) used LCA to compare the use of wood fly ash with the use of gravel in forest roads. The authors did not compare the use of wood ash in forest roads with other beneficial uses or landfilling, da Costa, Quinteiro, Tarelho, Arroja, and Dias (2019) assessed the potential impacts of using wood ash in construction materials (cement mortar, adhesive mortar, concrete blocks, and bituminous asphalts) using LCA, and compared this beneficial use option to landfilling, da Costa, Quinteiro, Tarelho, Arroja, and Dias (2020) assessed the potential impacts of using wood ash as liming and fertilizing agent, and compared this beneficial use option to landfilling. Tosti, van Zomeren, Pels, Damgaard, and Comans (2019) compared the use of wood fly ash as secondary cementitious material in cement mortar to a reference landfill scenario. No consideration was given to other beneficial use options. Toller, Kärman, Gustafsson, and Magnusson (2009) compared two beneficial use options for wood ash, namely road construction and as a nutrient resource on forest land, to landfilling. The focus of the study was on the implications for one specific operation, making it difficult to assess the general applicability of the results.

In this paper, we use a screening-level LCA approach and uncertainty analyses to compare the potential environmental benefits and tradeoffs of different management options for wood ash, namely agricultural land application, forest soil amendment, use in forest roads, use in concrete and mortar, and landfilling in the context of its production by North American forest products facilities. The objective of the study was to support decision-making in the selection of adequate management options. As such, the choice of beneficial use options was based on interest expressed by North American facilities as well as on data availability.

## 2 | METHODS

We applied a screening-level LCA methodology by using solely information readily available from the literature or public databases (i.e., no primary data) to compare different management options (i.e., landfilling and beneficial uses) for wood ash. More specifically, literature was used to define wood ash composition (e.g., nutrients, metals, carbon), for the quantities of material substituted from the use of wood ash, and for transportation distances. Public databases were used to model the environmental loads of the different unit processes involved in the comparison. In cases where an assumed parameter or data source was found to be significant for the results, this parameter was tested in a sensitivity analysis.

### 2.1 | System boundaries, functional unit, and approach to multifunctionality

As illustrated in Figure 1, two types of product systems are compared for wood ash management: (a) “disposal” type (DIS) consisting of one product system in which wood ash is disposed of in a landfill (DIS: Landfilling), and (b) “beneficial use” type (BU) consisting of four product systems in which wood ash is applied on agricultural land (BU1: Agric.), used as forest soil amendment (BU2: ForSoil), used in forest roads (BU3: ForRoad), and used in concrete or mortar (BU4: Concrete, mortar considered in sensitivity analysis). The functional unit is the management of 1 tonne of wood ash. The beneficial use product systems also fulfill additional functions of liming (in the case of BU1: Agric.), nutrient enhancement (in the case of BU2: ForSoil), road stabilization (in the case of BU3: ForRoad) and binding (in the case of BU4: Concrete). To compare management options on an equal basis, their functions need to be made equivalent. This has been achieved by expanding the system boundary to include the unit processes to manufacture the avoided products fulfilling these additional functions. Here system expansion was used because it was the approach to multifunctionality that best address the objective of the study and not with the intention of applying a consequential approach to LCA. Average data were used.

For each management option, the system boundary starts at the point where the ash is generated, as part of forest product manufacturing. Upstream unit processes are not included because they exist irrespective of how wood ash is managed. The system boundary encompasses the unit processes involved in the transportation of wood ash to the use site (where applicable), and the management and handling of wood ash as well as unit processes avoided by beneficially using wood ash (where applicable).

### 2.2 | Life cycle inventory

#### 2.2.1 | Wood ash characterization

Wood ash characterization in terms of carbon, nutrients, and metals is based on an extensive review of existing literature (National Council for Air and Stream Improvement, 2017). Fly, bottom, and combined ash are considered as a single category defined by the median, minimum and maximum values found in the literature for each of the available environmental parameters (e.g., carbon, nutrient, or heavy metals, and metals contents).
Characteristics of bottom and fly ash are also evaluated separately using sensitivity analysis. Detailed wood ash characterization can be found in Supporting Information S1.

### 2.2.2 Landfilling

In North America, landfilling is still the main management option for wood ash from forest products manufacturing facilities. Landfilling emissions were based on ecoinvent’s residuals landfilling model (Doka, 2008a) updated with wood ash composition data compiled for this study and mentioned in the previous section. In the base case, landfilling was assumed to occur onsite (i.e., no transportation). However, uncertainty analyses include a maximum distance traveled for wood ash to landfill of 50 km, by truck, to reflect cases were wood ash would not be landfilled on site. Transportation emissions were modeled using the DATASMART database (Long Trail Sustainability [LTS], 2019). DATASMART is a North American focused dataset, based on a combination of US LCI v.1.60 and ecoinvent v.2.2 data, modified specifically to be representative of North American operations.

### 2.2.3 Agricultural land application

Soils may be naturally acidic or become more acidic over time depending on how land is managed and the buffering capacity of the soil, which depends on the type of parent materials. The use of nitrogen fertilizers, wet weather, intensive crop rotation, and low organic matter content can also contribute to the acidification of the soil. Applying wood ash can help counteract this reduction in soil pH.

The liming effect of wood ash was evaluated based on literature and compared to that of agricultural lime (see list of references evaluated in Supporting Information S2). As such, it was assumed that, on average, 1 metric tonne (t) of wood ash would displace 600 kg of agricultural lime (min: 200 kg, max: 1,400 kg). Environmental loads from application of wood ash to agricultural land were based on the ecoinvent model and the DATASMART database (Doka, 2008b; LTS, 2019) using the ash composition compiled for this study. Average transportation distance from the

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**FIGURE 1** Simplified system boundary for wood ash management options

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| Functional unit studied | DIS: Landfilling | BU1: Agric. | BU2: ForSoil | BU3: ForRoad | BU4: Concrete |
|-------------------------|------------------|------------|--------------|--------------|--------------|
| Management process      | Landfilling      | Application on agricultural land | Application on forest soil | Use in forest roads | Use in concretes or mortars |
| Beneficial use function | Liming           | Nutrient enhancement | Road stabilization | Binding or aggregate |
| Production and use of avoided product(s) | Application on agricultural land | Application on forest soil | Use in forest roads | Use in concretes or mortars |
|                         | 600 kg CaCO₃ | 33.0 kg K₂O | 2,450 kg gravel | 1,000 kg Portland cement |

*Truck: 75%, 179 km; Rail: 21%, 1,008 km; Barge: 4%, 1,387 km.*
forest product manufacturing facility to the application site was assumed to be 100 km (min: 10 km, max: 200 km). It was assumed that lime would be transported to the field over 100 km by truck (United States Department of Transportation & United States Department of Commerce, 2015). The environmental loads associated with the production, transportation and application of agricultural lime where modeled using the corn field data of the DATASMART database (i.e., “Lime, agricultural, corn production/ha/RNA”).

The base case assumes that wood ash is primarily used for its liming ability, that is, to increase the pH of the soil within a range that would enhance crop yield because it seems this is its main use in North America. However, wood ash is also a source of several macro- and micronutrients necessary for plant growth. While the fertilizing effect was not considered in the base case, the achievable fertilizing effect was tested by conducting a sensitivity analysis. Assumptions regarding fertilizing effects are discussed in the next section.

### 2.2.4 Forest soil amendment

Wood ash can be used, in place of commercial fertilizers, to return nutrients lost from forest ecosystems during harvesting. Environmental loads for the unit processes involved in applying ash to agricultural land were used as proxies for those used in forest land application. Average transportation distance to the forest site was assumed to be 130 km by truck based on a review of existing North American data (min: 90 km, max: 300 km). The quantity of commercial fertilizers being displaced was calculated using the phosphorus and potassium content of wood ash (see Supporting Information S1) and information from the available literature on the bioavailability of these nutrients in ash in relation to that of commercial fertilizers (Naylor & Schmidt, 1989; National Council for Air and Stream Improvement, 2000; Pitman, 2006). As such, it was assumed that applying 1 tonne of ash to forest soil would displace, on average, 15.5 kg P₂O₅ (min: 0 kg, max: 135 kg) and 33.0 kg K₂O (min: 0 kg, max 389 kg). P₂O₅ and K₂O fertilizers were selected based on data availability. The environmental loads associated with the production and application of commercial fertilizers were modeled using the DATASMART database. Transportation distance and modes for commercial fertilizers [179 km by truck (75%), 1,038 km by rail (21%) and 1,387 km by boat (4%)] were estimated using data from the U.S. Commodity Flow Survey (United States Department of Transportation & United States Department of Commerce, 2015). The potential liming effect was not considered in the base case for this beneficial use option but was tested by conducting a sensitivity analysis (see 2.2.3).

### 2.2.5 Use in forest roads

Wood ash has been used as an aggregate material in road construction and soil stabilization applications. In this beneficial use option, ash is used instead of gravel in forest roads. The ash to gravel ratio used in the analysis is based on the work by Bergman and Suer (2011). Accordingly, it was assumed that 1 tonne of ash would displace 2,450 kg of gravel. The difference in metal leaching due to the use of gravel and that associated with the use of wood ash is based on work conducted by Nordmark et al. (2014). Differences in mobile equipment used to apply gravel versus wood ash in road construction were neglected. Distance from mill to forest was assumed to be 130 km (min: 90 km, max: 300 km) and 40 km for transporting gravel to the forest site (United States Department of Transportation & United States Department of Commerce, 2015). The environmental loads from unit processes involved in the production of gravel and in transportation were derived from the DATASMART database.

### 2.2.6 Use in concrete or mortar

Wood ash can also be used as an ingredient in the manufacturing of construction materials (e.g., concrete). In this beneficial use option, we assume wood ash is used in place of Portland cement in concrete with no additional sieving and grinding. Ash is assumed to be transported by truck over 240 km to the construction site, while the average distance travelled for transporting Portland cement is assumed to be 170 km (United States Department of Transportation & United States Department of Commerce, 2015). Differences in metal leaching and unit processes for using ash in place of Portland cement are neglected. Based on information from the literature, a substitution ratio of 1 metric tonne (t) of ash per metric ton of cement (max: 1.5 t ash/t cement) is assumed (Barbosa, Lapa, Dias, & Mendes, 2013; Elinwa, Ejeh, & Mamuda, 2008; Garcia & Sousa-Coutinho, 2013; Maschio, Tonello, Piani, & Furlani, 2011).

In the sensitivity analysis, the assumption is that wood ash displaces cement in mortar and not in concrete. The use of ash in mortar requires additional grinding and sieving to match the sizes of the materials that will be replaced. An energy consumption of 11.9 kW h/t is assumed for ash grinding and 2.2 kW h/t for ash sieving (da Costa et al., 2019). A North American (average of United States and Canada) electricity grid is assumed. The analysis also tests the scenario where wood ash displaces silica sand instead of Portland cement. All unit processes involved with the use of silica sand and Portland cement and with transportation are modeled using the DATASMART database.

### 2.3 Life Cycle Impact Assessment

A Life Cycle Impact Assessment (LCIA) was undertaken using the TRACI 2 impact assessment method (Bare, 2011), which includes the following impact categories: ozone depletion, global warming, smog, acidification, eutrophication, respiratory inorganics, fossil fuel depletion, human toxicity (carcinogenics), human toxicity (non carcinogenics), and ecotoxicity. In TRACI, the characterization factors for the three toxicity impact categories are based on the USETox model (Rosenbaum et al., 2008). These factors were not used to undertake quantitative comparisons between
management options but only to flag the potential toxicity risk. Indeed, as recognized by Rosenbaum et al. (2008), these characterization factors are only suitable for identifying the main substances with potential risk of being toxic and for which more analyses would be required.

2.4 | Contribution and uncertainty analyses

For each management option and impact category contribution, analyses were undertaken to compute the quantitative contribution of groups of unit processes to the indicator scores.

Monte Carlo simulations (1,000 runs) were run to analyze how the results would be affected by the uncertainty in model input data. For foreground parameters for which it was possible to determine minimum and maximum values, a triangular distribution was assumed. In all other cases, the ecoinvent pedigree approach was used using lognormal distributions (Weidema et al., 2013). Uncertainty in the background data and LCIA method was not considered because there was no readily available data to do so.

Uncertainty analyses were used in a variety of ways. First, the uncertainty in each of the management option indicator scores ($IS_i$) was evaluated in order to compute the range of variation of these scores. Then, we also used uncertainty analysis to estimate the probability that (a) a beneficial use option results in a lower environmental score than landfilling ($IS_{BU} < IS_{DIS}$), (b) a beneficial use option results in potential net environmental benefits ($IS < 0$), and (c) a beneficial use option results in a lower indicator score than another beneficial use option ($IS_{BUi} < IS_{BUj}$).

2.5 | Sensitivity analyses

A first set of sensitivity analyses was defined based on the contribution of the different unit processes to each of the indicator scores and on the results of the uncertainty analyses:

- S1: Minimum transportation distance for use in forest roads is 130 km with an average of 215 km (originally min: from 90 to 300 km with average distance at 130 km, see Section 2.2.5);
- S2: Agricultural land application also displaces fertilizers (vs. only lime, see Section 2.2.3);
- S3: Use as forest soil amendment also displaces lime (vs. only fertilizers, see Section 2.2.4);
- S4: Wood ash is used in mortar instead of concrete (see Section 2.2.6); and
- S5: Wood ash is used in mortar instead of concrete, displacing silica sand instead of Portland cement (see Section 2.2.6).

A second set of sensitivity analyses was also defined to address the differences in bottom ash (S6) and fly ash (S7) (see Section 2.2.1).

3 | RESULTS

3.1 | Interpretation of the results

In this paper, impact category results for each of the management options are normalized to those of landfilling and calculated as follows:

$$IS_i = \frac{ICR_{i,M&T} - ICR_{i, Avoided}}{ICR_{Dis}}$$

where, for each impact category, $IS_i$ is the normalized indicator score for management option $i$; $ICR_{i,M&T}$, the impact category result of the unit processes associated with the management and transportation of wood ash in management options $i$; $ICR_{i, Avoided}$, the impact category result of the unit processes associated with the production, use and transportation of the avoided product(s) in management option $i$, and $ICR_{Dis}$, the impact category result of landfilling. $IS_{i,M&T} - IS_{i, Avoided}$ is the (unnormalized) indicator score of a management option $i$.

An indicator score was computed for each of the impact categories. As such, for a given impact category, the results can be interpreted as follows:

- $IS_i < 100\%$ (or $< -100\%$ in the case of the global warming indicator): the indicator score of the beneficial use option is lower than that of landfilling;
- $IS_i > 100\%$ (or $> -100\%$ in the case of the global warming indicator): the indicator score of the beneficial use option is higher than that of landfilling;

1 The global warming impact category results for landfilling is negative because carbon is stored in landfills. Because we are comparing different management options, carbon that is stored in one option but not in another one represent a benefit.
• IS$_i$ < 0%: the indicator score of the unit processes associated with the management and transportation of wood ash is lower than the indicator score of the unit processes associated with the production, use and transportation of the avoided product(s) (i.e., the beneficial use option results in potential net environmental benefits); and
• IS$_i$ > 0%: the indicator score of the unit processes associated with the management and transportation of wood ash is higher than the indicator score of the unit processes associated with the production, use and transportation of the avoided product(s) (i.e., the beneficial use option results in a potential net environmental impact).

Note, in this paper, we use "net potential benefit" to mean a potential positive effect on the environment, and "net impact" to mean a potential negative effect on the environment.

### 3.2 Comparison of beneficial use options

Figure 2 (see detailed data in Supporting Information S1) presents the indicator scores (IS) for the various management options for wood ash and the level of uncertainty associated with these scores. The range of uncertainty of the indicator scores for the various management options is significant. This is further explored in the next section.

The smallest difference is observed between the management options for the following impact categories: ozone depletion (OD), eutrophication (EU) and fossil fuel depletion (FFD) indicators. For the global warming (GW), smog (Sm), acidification (Ac) and respiratory inorganics (Res) impact categories, all BU options generally present a lower indicator score than landfilling. Other authors also typically find that alternative management options for wood ash result in lower environmental score than landfilling (da Costa et al., 2019, 2020; Toller et al., 2009; Tosti et al., 2019).

Our findings also indicate potential net benefit from all beneficial use options for these indicators. The net environmental benefits are explained by the fact that the environmental load of producing, transporting and using the avoided product is greater than that associated with managing wood ash through that beneficial use option (see Contribution Analyses in Supporting Information S2). This finding is consistent with existing literature (e.g., da Costa et al., 2019).

Finally, Figure 2 shows that use in concrete followed by agricultural land application seems to be the most promising options from an environmental standpoint.

![Figure 2](image.png)

**FIGURE 2** Normalized environmental scores of management options for wood ash (IS, normalized indicator score; OD, ozone depletion; GW, global warming; Sm, smog; Ac, acidification; Eu, eutrophication; Res, respiratory inorganics; FFD, fossil fuel depletion). Underlying data used to create this figure can be found in Supporting Information S1.
3.3 | Uncertainty analyses

Results from the Monte Carlo simulations are presented in Table 1. The table shows, for each of the impact categories:

1. An estimation of the probability that the indicator score of a beneficial use option is lower than that of landfilling ($IS_i < IS_{DIS}$);
2. An estimation of the probability that the indicator score of a beneficial use option is lower than 0 ($IS_i < 0$, net environmental benefits); and
3. An estimation of the probability that the indicator score of a beneficial use option is lower than that of another ($IS_i < IS_j$).

3.3.1 | Comparing BU options to landfilling

Results in Table 1 show that all beneficial use options will likely result in lower indicator scores than landfilling (i.e., that the potential environmental impact associated with the beneficial use options is lower than that of landfilling) for all impact categories. There is a very small probability that the use of wood ash in forest roads (BU3) would result in higher scores than landfilling with respect to the smog, acidification and fossil fuel depletion categories. The Monte Carlo simulation did not allow determination of the factors contributing to the uncertainty around the indicator scores, but it is possible to speculate from the results of the contribution analyses (see Supporting Information S2) that longer transportation distances for wood ash might be one cause of the higher environmental scores obtained.

3.3.2 | Evaluating the potential net environmental benefit

Table 1 shows that agricultural land application (BU1), forest soil amendment (BU2) and use in concrete (BU4) likely result in a potential net environmental benefit for all impact categories, meaning that the avoided environmental load would be greater than the direct environmental load from managing and transporting wood ash. Use in forest roads (BU3) is likely to show a potential net environmental impact under certain conditions with respect to the smog, acidification, eutrophication and fossil fuel depletion impact categories. These results may be explained by the longer distances wood ash will have to travel to reach the BU application sites.

3.3.3 | Comparing BU options together

Results in Table 1 show that, overall, use in forest roads (BU3) is the least beneficial option under almost all conditions and for all indicators (all associated probabilities that another beneficial use option has lower indicator score are at, or very close to, 100%).

**TABLE 1** Result of the Monte Carlo simulations

| Estimation of the probability* that $IS_i < x$ | OD | GW | Sm | Ac | Eu | Res | FFD |
|---------------------------------------------|----|----|----|----|----|-----|-----|
| 1. Comparing BU options to landfilling      |    |    |    |    |    |     |     |
| $IS_{BU1} < IS_{DIS}$                       | 100%| 100%| 100%| 100%| 100%| 100%| 100%|
| $IS_{BU2} < IS_{DIS}$                       | 100%| 100%| 100%| 100%| 100%| 100%| 100%|
| $IS_{BU3} < IS_{DIS}$                       | 100%| 100%| 81.6%| 95.8%| 100%| 100%| 99.2%|
| $IS_{BU4} < IS_{DIS}$                       | 100%| 100%| 100%| 100%| 100%| 100%| 99.9%|
| 2. Evaluating the potential net environmental benefit |
| $IS_{BU1} < 0$                              | 100%| 100%| 100%| 100%| 100%| 100%| 100%|
| $IS_{BU2} < 0$                              | 100%| 100%| 99.7%| 99.9%| 100%| 100%| 99.7%|
| $IS_{BU3} < 0$                              | 100%| 100%| 39.2%| 71.1%| 98.8%| 100%| 53.9%|
| $IS_{BU4} < 0$                              | 100%| 100%| 100%| 100%| 100%| 100%| 97.7%|
| 3. Comparing BU options together            |    |    |    |    |    |     |     |
| $IS_{BU4} < IS_{BU1}$                       | 19.5%| 65.1%| 99.3%| 93.7%| 80.4%| 80.0%| 8.0% |
| $IS_{BU4} < IS_{BU2}$                       | 11.0%| 99.4%| 72.9%| 93.9%| 0.9% | 68.3%| 6.2% |
| $IS_{BU4} < IS_{BU3}$                       | 100%| 100%| 100%| 100%| 100%| 100%| 96.9%|
| $IS_{BU1} < IS_{BU2}$                       | 22.4%| 97.6%| 35.2%| 71.1%| 0.6%| 51.5%| 26.6%|
| $IS_{BU1} < IS_{BU3}$                       | 100%| 100%| 100%| 100%| 100%| 100%| 100% |
| $IS_{BU2} < IS_{BU3}$                       | 100%| 99.9%| 100%| 100%| 100%| 100%| 100% |

Abbreviations: IS, indicator score; OD, ozone depletion; GW, global warming; Sm, smog; Ac, acidification; Eu, eutrophication; Res, respiratory inorganics; FFD, fossil fuel depletion; BU, beneficial use; DIS, disposal in a landfill (DIS: Landfilling); BU1, application on agricultural land; BU2, use as forest soil amendment; BU3, use in forest roads; BU4, use in concrete or mortar. The estimation is provided by the percent of Monte Carlo simulation runs for which $IS_i < IS_j$.  

* The estimation is provided by the percent of Monte Carlo simulation runs for which $IS_i < IS_j$. 
TABLE 2  Result of the sensitivity analyses S1 to S5

| #   | Estimation of the probability that IS\textsubscript{i} < x\textsubscript{i} | OD   | GW   | Sm   | Ac   | Eu   | Res  | FFD   |
|-----|---------------------------------------------------------------|------|------|------|------|------|------|-------|
| S1  | IS\textsubscript{BU3} < IS\textsubscript{DIS}                | 100% | 100% | 61.1%| 87.9%| 100% | 100% | 97.4% |
|     | IS\textsubscript{BU3} < 0                                    | 100% | 100% | 14.1%| 41.6%| 96.3%| 100% | 23.1% |
| S2  | IS\textsubscript{BU4} < IS\textsubscript{BU1}                | 0%   | 26.7%| 15.9%| 25.4%| 0.1% | 6.7% | 0%    |
| S3  | IS\textsubscript{BU4} < IS\textsubscript{BU2}                | 0%   | 99.4%| 93.9%| 90.4%| 0%   | 68.3%| 0%    |
| S4  | IS\textsubscript{BU4} < IS\textsubscript{BU1}                | 19.7%| 66.3%| 98.6%| 92.7%| 80.3%| 82.5%| 6.8%  |
| S5  | IS\textsubscript{BU4} < IS\textsubscript{BU1}                | 0.2% | 0%   | 99.3%| 93.7%| 0%   | 80.4%| 0%    |
|     | IS\textsubscript{BU4} < IS\textsubscript{BU2}                | 0.1% | 99.4%| 93.9%| 90.4%| 0%   | 68.3%| 0%    |
|     | IS\textsubscript{BU4} < IS\textsubscript{DIS}                | 100% | 99.9%| 40.4%| 43.4%| 100% | 98.5%| 86.3% |
|     | IS\textsubscript{BU4} < 0                                    | 99.9%| 100% | 13.9%| 20.7%| 100% | 51.7%| 35.6% |

Abbreviations: S, sensitivity analysis; IS, indicator score; OD, ozone depletion; GW, global warming; Sm, smog; Ac, acidification; Eu, eutrophication; Res, respiratory inorganics; FFD, fossil fuel depletion; BU, beneficial use; DIS, disposal in a landfill; BU1, application on agricultural land; BU2, use as forest soil amendment; BU3, use in forest roads; BU4, use in concrete or mortar. Base case results are shown within brackets.

Use in concrete (BU4) is the most likely BU option to show potential environmental benefit with respect to the global warming, smog, acidification and respiratory inorganics categories.

Forest soil amendment (BU2) is the most likely to show the greatest benefits with respect to the ozone depletion and fossil fuel depletion impact categories but, as shown in Figure 2, the difference between the beneficial use options is less significant for these indicators. Nonetheless, agricultural land application (BU1) is generally likely to produce greater environmental benefits than forest soil amendment (BU2) (higher probability) with respect to global warming and acidification.

3.4 | Sensitivity analyses

Results of sensitivity analyses S1 to S5 are depicted in Table 2. S1 confirms that transportation distance for wood ash is an important variable to determine whether use of wood ash in forest roads (BU3) has a lower environmental impact for a given category compared to landfilling, and potential net environmental benefits. This is consistent with findings from da Costa et al. (2019) that showed that transportation of ash was an important variable in the environmental profile of its use for construction material. S2 and S3 show that if both the liming and fertilizing characteristics of wood ash are considered in the LCA for agricultural land application (BU1) and forest soil amendment (BU2), then these BU options would likely be better environmental choices than use of ash in concrete (BU4) (all associated probabilities that BU4 is better are very low < 27%). S4 shows that the incremental energy required to use wood ash in mortar compared to its use in concrete (BU4) is not sufficient to change its ranking compared to other management options. Finally, S5 shows that using wood ash to displace silica sand instead of Portland cement significantly reduces the environmental benefits that can be achieved by using wood ash as a substitute to other materials in concrete. Furthermore, displacing silica sand with wood ash in concrete may even result in higher indicator scores than landfilling with respect to the acidification and smog categories because the associated benefits would not be enough to offset emissions involved in wood ash transportation.

In a second set of sensitivity analyses for which the detailed results are presented in Supporting Information S2, we evaluated the effect of considering bottom and fly ashes separately, not as combined material. From an LCA perspective, discriminating between fly and bottom ash makes a difference in the results for impact categories and BU options sensitive to the composition of wood ash. For instance, compositional ash data suggest that there would be more carbon sequestration in fly ash; however, carbon sequestration would occur in landfills nevertheless. Results presented in Supporting Information S2 show that, overall, discriminating between fly and wood ash would not change the ranking of beneficial use options.

3.5 | Toxicity indicators

Detailed results for the toxicity indicators are presented in Supporting Information S2. As discussed previously, these results should be interpreted carefully. Similarly from results obtained by Toller et al. (2009) and da Costa et al. (2020), our results suggest an increased environmental risk from using wood ash in agricultural land and forest soil applications than disposing it in a landfill mainly with regard to the “Human health - Non-carcinogens” and “Ecotoxicity” indicators. In particular, the zinc content of ash shows potential implication for these indicators. Copper may also be a substance of interest with respect to the “Ecotoxicity” indicator. The analysis showed that the beneficial use of bottom ash resulted in a lower risk than the beneficial use of fly ash with respect to “Carcinogens,” “Non-carcinogens,” and “Ecotoxicity” indicators. This observation is explained
by the fact that certain metals are highly volatile at high combustion temperatures (e.g., mercury and selenium), and a portion can condense on fly ash particles in the postcombustion zone.

Although a variety of substances seem to contribute to the three toxicity indicators in the case of using wood ash in forest road, at the net the effect is likely marginal because of what is being avoided. For instance, in the case of the ecotoxicity indicators, the vanadium and barium contents of ash seems to be the main contributors but this contribution is somewhat offset by zinc releases to water that would occur in the processes involved in producing the gravel. However, because of the level of uncertainty associated with this indicator, it is very difficult to conclude on the overall ecotoxicity score of this management options. In the case of use in concretes, any emissions associated with the use of the ash seem to be offset by avoiding emissions from producing the concrete.

**4 | DISCUSSION**

Wood ash characteristics are key in determining the technical viability of the beneficial use options considered by a facility. In North America, application of wood ash to forest land is less common than agricultural land application due to a variety of factors, including uncertain response of trees to wood ash in light of growth cycles longer than those associated with agricultural crops, competing understory vegetation, wood species, climate, soil type and pH, and complex nutrient dynamics. The proportions of silica, alumina, iron oxide, and alkaline-earth and alkali oxides in wood ash, which primarily depend on combustion conditions and wood species, can affect the degree to which wood ash can be used as a substitute material for cement in concrete mixes. High carbon content can also be a factor making the use of wood ash in concrete more difficult. Environmental considerations associated with metal levels in wood ash may limit its use in some applications. However, research shows that heavy metals are not fully bioavailable (Pan & Eberhardt, 2011), and at the concentration levels present in wood ash and controlled agronomic rates ash is typically applied on land, the potential for an adverse environmental effect is minimal (Meyers & Kopecky, 1998; Moilanen et al., 2006; Patterson, 2001).

**5 | CONCLUSIONS**

This research proposes an approach to incorporate additional considerations for selecting a management option for wood ash by addressing the general environmental benefits and tradeoffs of multiple beneficial use options, and the uncertainty associated with wood ash characteristics, transportation, and use. Overall, all BU options showed lower environmental indicator scores than those associated with landfiling as well as net potential environmental benefits, provided that fossil fuel-based materials can be substituted. We identified a few conditions in which beneficial use of wood ash might not produce potential net environmental benefits; however, these beneficial use options would still be better management approaches than landfiling and there are very few conditions in which a beneficial use option might be worse than landfiling from an environmental perspective. Results show that use of wood ash in concrete to replace Portland cement is the beneficial use option with the greatest potential environmental benefits because of the environmental load associated with manufacturing Portland cement. However, the use of wood ash in agricultural land applications and as a forest soil amendment showed to be more promising than use in concrete applications, provided that both the liming and fertilizing characteristics of wood ash can be achieved at the same time or if wood ash displaces silica sand instead of Portland cement when used in concrete mixes. Agricultural land application and forest soil amendment show tradeoffs between environmental indicators due to the relative environmental load of producing commercial lime compared to that of producing commercial fertilizers. Use of wood ash in forest roads showed the least promise as a beneficial use option from an environmental perspective but would still be a better option than landfiling in most site-specific situations. In the end, decisions regarding beneficial use of wood ash are going to be facility specific. They will depend on the local markets available and wood ash characteristics.

**CONFLICT OF INTEREST**

The authors declare no conflict of interest.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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