



## Potential use of wood ash in South African forestry: a review

Gerhardus P Scheepers & Ben du Toit

To cite this article: Gerhardus P Scheepers & Ben du Toit (2016) Potential use of wood ash in South African forestry: a review, *Southern Forests: a Journal of Forest Science*, 78:4, 255-266, DOI: [10.2989/20702620.2016.1230716](https://doi.org/10.2989/20702620.2016.1230716)

To link to this article: <http://dx.doi.org/10.2989/20702620.2016.1230716>



Published online: 16 Sep 2016.



Submit your article to this journal [↗](#)



Article views: 10



View related articles [↗](#)



View Crossmark data [↗](#)



Citing articles: 1 View citing articles [↗](#)

## Potential use of wood ash in South African forestry: a review

Gerhardus P Scheepers and Ben du Toit\*

Department of Forestry and Wood Science, Stellenbosch University, Stellenbosch, South Africa

\* Corresponding author, email: [ben@sun.ac.za](mailto:ben@sun.ac.za)

The use of landfills as a disposal method for wood ash is costly, environmentally detrimental and is pitted against increasingly stern environmental regulations. Literature has shown that wood ash has the potential to be used as a forest fertiliser and the effects tend to be highly site-specific. Wood ash contains a combination of carbonates, hydroxides and other calcium-containing minerals that are responsible for the liming effect observed following application to soils. In addition, it contains significant magnesium and potassium concentrations, but little nitrogen and sulphur. The phosphorus availability of wood ash varies considerably and in effect can limit soil phosphorus uptake and may affect subsequent nutrient balance in plants. Short-rotation forestry practices and whole-tree harvest systems can induce periodic or persisting nutrient deficiencies and acidify the soil. This may affect the ability of a site to sustain adequate nutrient levels over successive rotations. Utilising wood ash as a soil amendment can offset or correct some nutrient deficiencies and imbalances induced by intensively managed plantation forests. This review covers the international literature on ash applications to forest land, including the effect of ash-beds remaining after slash burning (as a useful analogy for the effects of wood ash on soil properties and tree growth). The results show that ash applications to forest land can be done safely and can potentially stimulate microbial activity and improve pine and eucalypt growth. Safe ash application rates should be determined after consideration of (1) soil buffer capacity and ash alkalinity (expressed as calcium carbonate equivalence) and (2) an evaluation of the concentrations of heavy metals existing in soils and present in the available ash, particularly from cadmium, chromium, lead and arsenic.

**Keywords:** environmental risk, forestry, liming effect, soil acidification, wood ash

### Introduction

The production of paper and pulp related materials produce by-products such as fly ash, bottom ash and biomass ash. The ash produced is sourced from energy and recovery boilers in pulp mills and energy boilers in saw mills. Currently, the various ash residues of South African pulp mill are commonly disposed of in landfills. Tightening environmental regulations and rising disposal costs have placed increased pressure on pulp and paper companies to further investigate alternative disposal methods (Demeyer et al. 2001). This review assesses the possibility of introducing pure wood ash, produced in sawmills and papers mills, to plantation forest soils. The effects of various source materials, production conditions and ash types are covered leading up to potential implementations in South Africa. It furthermore considers the potential effects of wood ash on soil nutrient concentrations, soil microbial populations, ecosystem health and tree growth. In this review, pure wood ash produced from slash burning is used as an analogy for the possible changes in soil chemistry and tree growth if wood ash additions were made to South African soils. Wood ash can be used as a potential forest fertiliser under certain conditions (Goodwin and Burrow 2006; Pitman 2006; Kuokkanen et al. 2009).

The implementation of intensified harvesting systems (e.g. shorter rotations and whole-tree harvesting) may lead to nutritional deficiencies in subsequent rotations. Removal of biomass from sites that are already deficient or marginally deficient in nutrients can further aggravate the deficiency (Compton and Cole 1991; Saint-André et al. 2008). Du Toit and Scholes (2002) showed considerable soil nitrogen (N), potassium (K) and calcium (Ca) nutrient losses resulting from wood harvesting and firewood collection; the authors additionally found that increased management intensity resulted in larger nutrient losses, but that nutritional stability would depend on the soil buffering ability of the site. Similarly, Dovey (2009) found that forest productivity and harvesting intensity were the main drivers for nutrient losses from the forest system. The removal and burning of slash in *Eucalyptus grandis* stands show reduced N, phosphorus (P), K, Ca and magnesium (Mg) soil content relative to slash-retained sites, and N, K and Ca losses have to be managed to ensure nutritional sustainability (du Toit 2003). The planting of short-rotation crops such as eucalypts can lead to soil nutrient depletion as a result of the high nutrient demand and uptake capacity of the species (Gonçalves et al. 2008a). Intensive silvicultural management operations,

such as whole-tree harvesting, slash burning and shortened rotations, can affect the ability of the site to supply a balanced set of nutrients to subsequent rotations. Burning of slash following harvest operations results in increased short-term nutrient availability and changes in short-term nutrient dynamics (du Toit and Dovey 2005; Smith and du Toit 2005; du Toit et al. 2008). Du Toit (2003) showed variable degrees of P, K, Ca and Mg losses in South African *E. grandis* plantations ensuing from harvesting and slash-burning operations. He additionally stated these losses could cumulatively add up to more substantial losses if rotations are not managed properly and thus lead to increased topsoil acidification. Similarly, a review by Titshall et al. (2013) identified harvest residue management, ground-based mechanised harvest operations and to a smaller degree fertilisation as high disturbance activities. The authors recommend a more precautionary approach be taken with regard to soil compaction from harvest equipment, soil organic carbon (C) and nutrient losses from intensive biomass removal and residue management practices to prevent any negative long-term impacts on afforested sites. Titshall et al. (2013) concluded that South African soils appear to be resilient to forest management practices, but that there are a range of factors that need to be considered to maintain site nutritional sustainability.

## Sources and properties of wood ash

### Wood ash sources and forms

The form and nature of wood ash is determined by several factors, such as the physical and chemical nature of the material burnt, the plant parts making up the material (stem, leaves and bark), co-combustion with other fuel sources (such as coal) and combustion conditions (Demeyer et al. 2001). Wood ash can be produced by a range of conditions and for each production process the chemical and physical properties can vary greatly. Sawmills produce wood ash by burning stem-wood off-cuts produced during timber processing in boilers and off-cuts can be combined with other fuels for the generation of power. The nature of the wood ash is then determined by the ratio of the stem-wood to the other fuel sources. Pulp and paper companies can dry sludge produced from the paper production process and use it to fuel the boilers. In addition, the companies can combine it with other materials such as coal for fuelling boilers or energy production. Sawmills and pulp/paper mills can import biomass, such as bark, leaves and branches, from external sources and burn the material as biofuel for energy production.

Combustion temperature is an important factor that affects the chemical properties and quantity of wood ash produced. The wood ash production process and the effect of temperature variations are well documented by Etiégni and Campbell (1991); these authors found that the degree of nutrients released by the combustion process is associated with the temperature. In addition, Pitman (2006) suggests biomass be burnt between 500 and 900 °C for maximum nutrient preservation and minimum heavy metal content in wood ash.

Wood ash is broadly divided into either fly ash or bottom ash, based on where the ash is collected from after the

combustion process (Santalla et al. 2011). Fly ash is captured in boiler emissions in filters, flue gas desulphurisation and electrostatic precipitators, whereas bottom ash (or boiler ash) is the combustion residue that remains in the furnace after combustion. Fly ash consists of fine particulates and precipitated volatiles, typically with a high specific surface area, whereas bottom ashes tend to be coarser in texture. As a result, fly ash typically contains greater nutrient concentrations, has an increased reactivity and nutrients are released and available for plant uptake more rapidly following application.

Wood ash is largely applied to land in three forms; loose, crushed and granulated. Granulation methods are documented in Kellner and Weibull (1998) and Väätäinen et al. (2011). It is essential to factor in particle size during application if wood ash is to be used as a potential soil ameliorant; small particle sizes and powdery-textured ash could easily result in losses during transport and application in windy conditions. More importantly, loose wood ash can potentially induce a shock-effect on the soil by rapidly raising the soil pH, thus increasing the risk of over-liming. The granulation methods described by Kellner and Weibull (1998) and Väätäinen et al. (2011) can effectively be used to adjust application rates to safer quantities (Pitman 2006), and reduce potential harm to soil biota and vegetation stemming from potential over-application (Jacobson 2003).

### Physicochemical properties of wood ash

#### Physical properties

Particle size varies considerably and is largely dependent on the degree of biomass combustion. Etiégni and Campbell (1991) studied the physical and chemical properties of wood ash and the effect of combustion temperature. These authors found an average wood ash particle size of 230 µm; a range for the particle size was not given. Ribeiro et al. (2010) observed particle sizes in the range of 0.040–2 000 µm for wood ash produced in a pulp mill boiler.

The specific surface area of wood ash affects the adsorption properties of wood ash. Kilpimaa et al. (2013) found that wood ash and C residues with larger specific surface areas have increased adsorption properties; this was also associated with the pore size that affects the type of molecules that can be adsorbed on the surface. Loose wood ash has a larger specific surface area and displays a higher rate of leaching, thus the supplied nutrients are more easily leached from the soil body. Leaching can be reduced by altering the physical form of the wood ash through granulation or pelleting (Knapp and Insam 2011). Rajamma et al. (2009) reported wood fly ash specific surface area values of 40.29 m<sup>2</sup> g<sup>-1</sup> and 7.92 m<sup>2</sup> g<sup>-1</sup> from fly ash samples sourced from a thermal and a co-generation power plant. The larger specific surface area was attributed to a higher degree of irregularity in particle shapes and porosity (Rajamma et al. 2009; Cheah and Ramli 2011).

Wood ash is typically hydrophilic, and can thus absorb and retain water. This property can potentially increase the water-holding capacity of soils treated with wood ash, and as a result increase the moisture and nutrient availability in soils (Etiégni et al. 1991; Goodwin and Burrow 2006; Pitman 2006; Santalla et al. 2011).

### Chemical properties

Wood ash has a high acid-neutralising capacity and induces a liming effect (Etiégni et al. 1991; Demeyer et al. 2001; Jacobson 2003; Pitman 2006; Kuokannen et al. 2009; Lévai et al. 2009). Etiégni and Campbell (1991) recognised two neutralising points, the first from hydroxides and second from carbonates. A significant proportion of the chemical composition of wood ash contains a mixture of oxides, silicates, hydroxides and carbonates, and the solubility of some of these carbonates and hydroxides induce the liming effect after wood ash applications (Mandre 2006). Risse and Harris (2011) analysed the  $\text{CaCO}_3$  content for 37 industrial wood ash samples and reported an average of 43% and a range of 22–92%. In addition, these authors reported an average pH value of 10.4 and a range spanning pH 9 to 13.5. The calcium carbonate equivalence (CCE) of wood ash is a measure of the acid-neutralising capacity of the ash, relative to pure calcium carbonate (Ohno and Erich 1993). The CCE varies significantly and is a product of the combustion temperature, tree species and material burnt. Muse and Mitchell (1995) reported an average CCE of 38% for 19 boiler ash samples. Lerner and Utzinger (1986) reported CCE values of 88% for *Prunus avium* (black cherry). Mitchell and Black (1997) reported CCE values in the range of 25–70% for industrial boiler ash.

The degree of combustion and temperature greatly affects the elemental concentrations in wood ash. Carbonates and bicarbonates become more prevalent at combustion temperatures less than 500 °C and oxides above 1 000 °C in industrial wood-fuelled boilers (Etiégni et al. 1991). In addition, these authors found that the highest macronutrient concentrations are retained at temperatures of 500–800 °C. Misra et al. (1993) studied the wood ash composition of five tree species (*Pinus ponderosa*, *Populus tremuloides*, *Quercus alba*, *Quercus rubra* and *Liriodendron tulipifera*) as a function of furnace temperature and found that  $\text{CaCO}_3$  and  $\text{K}_2\text{Ca}(\text{CO}_3)_2$  became more prevalent at 600 °C and  $\text{CaO}$  and  $\text{MgO}$  at 1 300 °C. Calcium is the most abundant element found in wood ash and several sources (Table 1) show that Ca concentrations can range from 94 900–317 400  $\text{mg kg}^{-1}$  for wood ash produced from different source materials. Potassium, sodium (Na), zinc (Zn) and carbonate ( $\text{CO}_3^{2-}$ ) concentrations decrease with increased combustion temperatures and metal ion concentrations increase or remain constant (Etiégni et al. 1991; Misra et al. 1993; Pitman 2006). In addition, the amount of organic matter in wood ash is a function of combustion temperature. Higher combustion temperatures improve exchange properties and the surface area of charcoal (Glaser et al. 2002). Guerrini et al. (2000) suspected the presence of charcoal could explain the high OM content occasionally found in wood ash. The organic matter increase from charcoal does not necessarily contribute to the nutrient content of wood ash and can be low at times (Park et al. 2004).

The effect of wood ash on plant growth is governed by soil properties and application rates and can potentially replace or partially replace almost all nutrients (with the exception of N) that are removed per rotation from whole-tree harvesting and other agricultural activities (Pitman 2006; Lévai et al. 2009). Wood ash macronutrient

concentrations vary greatly. The quantity of C and N in wood ash is generally low, due to oxidation forming gaseous compounds during combustion (Demeyer et al. 2001). The K found in wood ash is readily soluble and is easily leached by water (Etiégni et al. 1991; Ulery et al. 1993). Risse and Harris (2011) reported mean N, P and K concentrations, taken from the analyses of 37 wood ash samples, of 0.15%, 0.53% and 2.60%, respectively. Mean N, P and K concentration ranges were 0.02–0.77%, 0.10–1.40% and 0.10–13.0%, respectively. In pelleted form, P is readily soluble and can improve soil fertility (Kuokannen et al. 2009). Elliot and Mahmood (2006) found that P availability can range from 30% to 70% in wood ash. The inherently low levels of P in wood ash, combined with a moderately low plant-available fraction, means that wood ash might not be able to supply the soil with sufficient P when used as a fertiliser source. The chemical make-up of wood ash is highly variable depending on the origin of the material. Additional macronutrient concentrations for a range of wood ash sources relative to limestone can be seen in Table 1.

Siddique (2008) reported mean iron (Fe), Zn and manganese (Mn) concentrations for wood ash produced from woody materials in the range of 5 900–6 100  $\text{mg kg}^{-1}$ , 380–420  $\text{mg kg}^{-1}$  and 2 440–2 750  $\text{mg kg}^{-1}$ , respectively. Copper (Cu) and aluminium (Al) concentration ranges were 41–46  $\text{mg kg}^{-1}$  and 4 000–4 500  $\text{mg kg}^{-1}$ . The variations of macro- and micronutrient concentrations in wood ash can also be attributed to the section or part of the tree that is burnt. Elemental concentrations produced from the combustion of bark and leaves have concentrations 5–10 times greater than that of stem wood (Pitman 2006; Ozolinčius et al. 2007).

Biotoxic effects of wood ash are through direct effects of toxic elements or induced through excess alkalinity or leaching of mobile elements to water sources (Aronsson and Ekelund 2004). Land application of pulp and paper manufacturing residuals can be done without compromising groundwater quality; residuals have to be mixed properly and applied at acceptable rates. A potential risk of P surface run-off remains after wood ash additions and could lead to contamination of water sources (Patterson 2001). A three-year study based on the effect of wood ash application on water quality in a drainage basin indicated small increases in  $\text{K}^+$ ,  $\text{SO}_4^{2-}$  and  $\text{Cl}^-$  concentrations and phytoplankton biomass. Similar tank experiments based on the immediate effects of wood ash on water quality exhibited increases in water pH, alkalinity, conductivity, P and Ca concentrations and a decrease in phytoplankton biomass (Aronsson and Ekelund 2004). Williams et al. (1996) stated that the application of wood ash may have a slow downward transmission into soil horizons and has little effect on soil water. These authors studied the effects of bottom ash from bark boilers on forest and water chemistry in the USA. Application rates of 11, 22 and 44  $\text{Mg ha}^{-1}$  were made per rotation and groundwater samples showed little changes; the only significant changes were noted for  $\text{Ca}^{2+}$ ,  $\text{K}^+$  and sulphate. Groundwater remained unaffected for all application rates and was within the standards set for consumption.

Fly ash produced from the combustion of pure material, in the absence of a co-fired material such as coal, will result

**Table 1:** Total elemental concentrations of several wood ash sources and limestone. Adapted from Demeyer et al. (2001), Alakangas (2005), Siddique (2008) and Risse and Harris (2011)

Element	Ashes of wood and bark (mg kg <sup>-1</sup> )		Ashes of paper and pulp (mg kg <sup>-1</sup> )		Industrial wood ash (%)	Wood material (mg kg <sup>-1</sup> )	Wood material (mg kg <sup>-1</sup> )		Limestone (%)
							Bottom ash	Fly ash	
	Etiégni et al. (1991)	Huang et al. (1992)	Ohno and Erich (1993)	Muse and Mitchell (1995)	Risse and Harris (2011) <sup>a</sup>	Siddique (2008)	Alakangas (2005)		Risse and Harris (2011)
Organic carbon	–	–	–	247 000	–	–	–	–	–
Nitrogen	600	900	–	4520	0.15 (0.02–0.77)	–	–	–	0.01
Phosphorus	14 000	6 900	1 800	3 000	0.53 (0.10–1.40)	–	–	–	0.06
Potassium	41 300	28 600	10 300	13 300	2.6 (0.10–13)	–	–	–	0.13
Calcium	317 400	109 400	94 900	120 000	15 (2.50–33)	–	–	–	31
Magnesium	22 500	16 200	6500	7 730	1 (0.10–2.50)	–	–	–	5.10
Sulphur	4 455	6 800	–	–	–	–	–	–	–
Sodium	3 400	1 600	6 700	1 410	0.19 (0–0.54)	–	–	–	0.07
Iron	19 500	3 300	14 300	6 260	0.84 (0.20–2.10)	5 900–6 100	–	–	0.29
Zinc	700	794	423	183	233.0 (35.1–1 250)	380–420	15–1 000	40–700	113
Manganese	6 693	3 470	3 300	2 600	0.41 (0–1.30)	2 440–2 750	2 500–5 500	6 000–9 000	0.05
Copper	145	78	151	67	70 (37–207)	41–46	15–300	200	10
Aluminium	23 650	1 300	82 100	12 500	1.6 (0.50–3.20)	4 000–4 500	–	–	0.25
Molybdenum	114	–	61	15	19 (0–123)	5.6–6.7	–	–	–
Boron	8	127	–	95	123 (14–290)	–	–	–	–
Lead	130	66	32	72	65 (16–137)	29–35	15–60	40–1 000	55
Nickel	47	12	65	16	20 (0–63)	6–8	40–250	20–100	20
Chromium	86	14	1036	75	57 (7–368)	12–14	60	40–250	6
Cobalt	–	4	–	14	–	–	0–7	3–200	–
Cadmium	21	3	<1	2	30 (0.20–26)	5.5–6.1	0.4–0.7	6–40	0.70
Barium	–	–	549	588	–	220–300	–	–	–
Arsenic	–	–	–	–	6 (3–10)	42–53	0.2–0.3	1–60	–
Mercury	–	–	–	–	1.9 (0–5)	0.05–0.08	0–0.4	0–1	–
Selenium	–	–	–	–	0.9 (0–11)	0.53–0.64	–	5–15	–
Vanadium	–	–	–	–	–	–	10–120	20–30	–
Silver	–	–	–	–	–	0.2–0.4	–	–	–
<b>Other chemical properties</b>									
CaCO <sub>3</sub>					43 (22–92)				100
pH					10.4 (9–13.5)				9.9
Total solids (%)					75 (31–100)				100

<sup>a</sup> Mean and range values from Risse and Harris (2011) taken from 37 ash samples

in a cleaner ash with reduced heavy metal concentrations and toxic compounds. Bottom ash, also known as boiler ash, is less reactive and contains lower nutrient concentrations and lower heavy metal concentrations. The application of bottom ash ensures a longer and gradual release of nutrients and significantly reduces the risk of heavy metal contamination. Bottom ash is better suited to be used as a soil amendment relative to fly ash (Pitman 2006; Cassidy and Ashton 2007; Santalla et al. 2011). Fly ash can contain possible high levels of damaging toxins and heavy metals, but it can be used as a soil ameliorant if leaching potentials of toxic elements are known (Kuokannen et al. 2009). A review by Pitman (2006) on the use of wood ash in forestry emphasised that fly ash contains increased cadmium (Cd), chromium (Cr), Cu, lead (Pb) and arsenic (As) concentrations and is not suitable for application. Concentrations of Cd, Cr and Pb can range from 5.5 to 6.1 mg kg<sup>-1</sup>, 12 to 14 mg kg<sup>-1</sup> and 29 to 35 mg kg<sup>-1</sup>, respectively (Siddique 2008) (Table 1). Herselman (2007) established that several South African soils have high naturally occurring concentrations of Cr, nickel (Ni) and Pb. It is crucial that the naturally

occurring heavy metals concentration of a soil is known before wood ash applications are made to it.

High application rates of wood ash may be detrimental to the environment due to the presence of Cd (Patterson 2001). Patterson (2001) additionally stated that if ingested, Cd can induce liver and kidney damage due to bioaccumulation of this metal in plant and animal tissues. Relative to coal ash, wood ash may contain lesser quantities of potentially hazardous components such as As, Cd and selenium (Se), and is better suited to be used as a soil ameliorant (Elliot and Mahmood 2006; Bird and Talberth 2008). Literature reviewed by Patterson (2001) revealed the solubility of heavy metals and trace elements from wood ash, such as Cd and Zn, can increase as soil pH values decrease below 6.5. In addition, the solubility of both elements can increase substantially once pH values are reduced to below 5.5–6.0. The solubility and chemical properties of Cd are, to a large degree, determined by the form (stability) of the wood ash and the resultant changes in soil pH induced by the liming effect. Cadmium can be adsorbed by clay minerals, carbonates and hydrous oxides of Fe or Mn. Furthermore, it

can be precipitated as a carbonate, hydroxide or phosphate (McLean and Bledsoe 1992). McLean and Bledsoe (1992) specified that under acidic soil conditions Cd solubility increases and little adsorption takes place by colloids, hydrous oxides and organic matter. At soil pH values greater than 6, Cd is adsorbed in the soil solid phase or is precipitated (concentrations in solution are thus reduced). It is essential that the reaction of Cd under diverse soil conditions is understood, as many South African forest soils have pH values lower than 5. Similar findings were made by Lévai et al. (2009); the solubility of heavy metals in wood ash is low and, as a result, root uptake is hindered. The presence of Cd in wood ash may decrease colonisation of ectomycorrhizae and microbial activity (Aronsson and Ekelund 2004). Aronsson and Ekelund (2004) recommend extreme caution be followed if wood ash additions are made to soils; the mobility of Cd, Al and caesium (Cs) could result in environmental harm and it is crucial that wood ash is analysed prior to application. In conclusion, these authors recommend wood ash applications be site-specific in contrast to general guidelines for wood ash application to forests.

Wood ash may contain several dioxins and furans (Matysik et al. 2001; Elliot and Mahmood 2006; Pitman 2006) and harmful organic compounds such as polychlorinated dibenzo-*p*-dioxins and polychlorinated dibenzofurans (Matysik et al. 2001). Dioxins and furans are formed as a product of burning salt-laden woody material and the presence of chloride determines the concentration of chlorinated organics in ash (Elliot and Mahmood 2006). Variability in dioxin and furan concentrations are additionally determined by boiler operating conditions, temperatures and fuel salt content (Demeyer et al. 2001; Elliot and Mahmood 2006). The application of wood ash at rates exceeding 10 t ha<sup>-1</sup> may lead to possible toxicity, but contamination from radionuclides, heavy metals and dioxins in wood ash is insignificant and would likely not affect ecosystem function (Pitman 2006). Pitman (2006) additionally found that leaching of dioxins and furans from wood ash is improbable, due to the absorbent behaviour of wood ash. This suggests that both compounds persist in the soil if introduced into the soil by means of wood ash applications.

Boiler systems co-fired with charcoal or by-products produced from the paper production process will greatly affect wood ash composition, depending on the degree of combustion and the nature of the co-fired materials. Heavy metal concentrations and the occurrence of toxic compounds such as dioxins and furans may increase substantially and limit the amount of ash that can be applied and the possibility of using of the material as a soil ameliorant. From the studied literature, the availability of these hazardous elements and compounds vary significantly; this accentuates the importance of site classification and wood ash characterisation in advance of wood ash applications. The purity of the material burnt greatly affects the ability of the produced wood ash to be re-introduced back into the soil body.

## Application of wood ash to forest soils

### Ash form

Wood ash applications can greatly improve the physical properties of forest soils, especially on sandy sites

(Goodwin and Burrow 2006). The effects of applying wood ash as a soil ameliorant is predominantly governed by application rate and soil type (Pitman 2006). Wood ash form at application is crucial as each form has a distinct chemical composition; a higher grade of product preparation (from a loose to granulated texture) yields lower Ca and increased P concentrations (Pitman 2006). The risk of heavy metal contamination, N-leaching, root damage and potential damage to soil biota and vegetation is greatest in loose form and at high application rates (Jacobson 2003). Loose wood ash releases Ca, K and Na more rapidly than granulated or crushed wood ash (Pitman 2006). The reactivity and potential damage can be reduced by stabilising the product; this is achieved by changing the product from a loose to crushed or granulated texture.

### Effects on soil properties

#### Effects on soil reaction, N and P

The application of wood ash can increase soil pH and decrease soil exchangeable acidity (Demeyer et al. 2001; Mandre et al. 2004; Mandre 2006; Pitman 2006; Perucci et al. 2008; Kuokannen et al. 2009; Saarsalmi et al. 2012). Soil mineralogy, soil electrical charge and buffer capacity greatly affect the increase in soil pH resulting from lime (and hence also ash) applications. Large increases in forest soil pH brought by the application of liming materials may lead to nutrient imbalances or a decrease in nutrient availability, followed by a subsequent decline in tree growth. For example, Schönau and Herbert (1982, 1983) and Herbert (1983) documented significant decreases in eucalypt stand growth following lime applications in excess of 5 Mg ha<sup>-1</sup>. Significant growth decreases were noted for lime applications of 10 Mg ha<sup>-1</sup> and Schönau and Herbert (1982, 1983) suggested that moderate lime application rates were better suited to acid soils, and that the maximum application rate of 10 Mg ha<sup>-1</sup> reduced growth and/or showed no significant growth responses (Wattle Research Institute 1977).

In cases where pH and Ca content are increased to high levels (pH > 8), it can result in the reduction of plant-available P in soils, due to the precipitation of sparingly soluble Ca-phosphates (Bohn et al. 1979; Fox et al. 1981; Plante 2006). Reduced and variable P availabilities were also reported by Elliot and Mahmood (2006) and Etiégni et al. (1991). Etiégni et al. (1991) concluded that P availability is at a maximum for a soil with a pH of 6.0–7.0 and decreases at pH over 8.0. The application of wood ash may increase plant-available P and K, but the effect is brief (Ohno and Erich 1994). These authors studied the effects of wood ash on P and K availability and reported increases in plant-available P and K for the first 25 weeks and a gradual decline thereafter.

The application of wood ash on nutrient-poor sandy soils can lead to increased soil pH, increased K and Ca concentrations, decreased N and P concentrations, and potential nutrient imbalances (Mandre et al. 2004). Mandre et al. (2004) studied the effects of 2.5, 5 and 10 Mg ha<sup>-1</sup> wood ash applications on *Picea abies* (Norway spruce) at the age 4 years. Literature reviewed by Goodwin and Burrow (2006) stated that the alkalinity of wood ash could increase N volatilisation from urea fertilisers as a result of soil pH

increases from wood ash additions. This can be explained by the well-documented generation of alkalinity upon urea hydrolysis and the subsequent conversion of ammonium to volatile ammonia, as explained by Bohn et al. (1979) and Tan (2011). Schwenke et al. (2012) investigated the relationship between the degree of N volatilisation and the application of different N formulations (urea and ammonium sulphate) at different times of the year. The authors showed that an increase in soil pH can increase the loss of N, if urea was used as an N source, together with several other contributing factors, such as temperature, crop canopy and soil moisture content.

The application of 11 Mg ha<sup>-1</sup> of wood ash to 67-year-old *Pinus pinaster* stands, under Mediterranean climatic conditions, increased the leaching of base cations and P, and affected soil C and N dynamics (Gómez-Rey et al. 2013). Gómez-Rey et al. (2013) observed the effects of loose and pelleted wood ash applications on nutrient leaching, nutrient dynamics and fertility. Shortly after application, increased leaching of base cations and P was observed, which resulted in increased soil nutrient availability and reduced soil acidity. This was more prevalent with loose ash relative to the pelleted form. Increased base cation losses were attributed to rapid solubilisation of salt compounds and carbonates in the ash, and the accompanying mobile anions resulted in leaching (Plante 2006). In addition, Gómez-Rey et al. (2013) found that P dissolution was attributed to the increase in soil pH and, as a result, the precipitation of Al and Fe phosphates. Phosphates were more susceptible to leaching due to their anionic form. Carbon and N dynamics were affected by a combination of wood ash and an additional N source; increased carbon dioxide (CO<sub>2</sub>) fluxes were reported for the duration of the experiment, signalling increased microbial activity.

Gómez-Rey et al. (2013) observed leaching of base cations and soil P along with changes in soil C and N dynamics from wood ash applications at a depth of 10 cm from the soil surface. Saarsalmi et al. (2001) studied the effects of wood ash on soil chemical properties of forest soils on two contrasting wet and dry sites, planted with *Pinus sylvestris* and *Picea abies*. Results indicated a pH increase of 0.6–1.0 in the humus layer and 0.2–0.3 increase in the mineral soil 16 years after application. No significant increases in soil pH were recorded seven years after application for the mineral soil. The findings of Saarsalmi et al. (2001) provide further understanding with regard to the slow downward transmission of wood ash in certain soils; the reaction of wood ash is more likely to take place in the humus and topsoil layer. Williams et al. (1996) reported minor changes in elemental concentrations at a soil depth of 45 cm following wood ash applications and concentrations returned to initial levels (control treatments) within a period of 60 weeks.

#### *Effects on base cations and trace elements*

Wood ash used as a soil ameliorant can provide the soil with micronutrients such as Zn and B (Patterson 2001). Increases in soil pH following wood ash additions can increase soil exchangeable Ca, Mg and K and decrease exchangeable Al and Fe (Naylor and Schmidt 1989).

The application of 11 t ha<sup>-1</sup> of wood ash on an N-limited sandy soil (Arenosol) led to increased leaching of base cations shortly after application in loose and pelleted form, indicating that leaching is more prevalent in loose ash (Gómez-Rey et al. 2013). These authors studied the effects of wood ash application on nutrient leaching, soil C and N dynamics and fertility in a *Pinus pinaster* stand. Loose wood ash applications increased the leaching of Ca, Mg, Na and K in the 0–10 cm soil layer and resulted in increased nutrient availability and reduced soil acidity at a depth of 10 cm from the soil surface. Wood ash incubation studies conducted by Ohno and Erich (1994) indicated a 10-fold increase in divalent Ca and Mg cation concentrations after four weeks. After a 72-week period, Ca and Mg concentrations were 15 and 22 times higher, respectively, than the control. The substantial increases were attributed to the steep increase in soil pH due to the neutralising effect caused by wood ash additions and can be explained by the release of Ca, Mg, K and Na from the ash.

Research by Saarsalmi et al. (2012) reported similar findings; elevated concentrations of Ca, Mg and K in the wood ash + nitrogen fertilisation trials were found up to 30 years after application. These authors showed that wood ash applications combined with N fertiliser decreased exchangeable acidity in the organic layer up to 15 years after fertilisation. In addition, the authors reported increases in cation exchange capacity (CEC), base saturation and soil pH in the 5–10 cm and 0–5 cm mineral layers. A similar study by Saarsalmi et al. (2001), based on the effects of wood ash applications on soil properties in Scots pine and Norway spruce stands, found that wood ash applications increased the CEC of the soil on all sites. Ash applications of 3 t ha<sup>-1</sup> were made on the experimental area and soil and mineral samples were collected at 7 and 16 years after application. Increases in CEC and base saturation, and decreases in exchangeable Al were observed in all soil layers. The application of combined pulp/paper residuals and wood ash on *E. grandis* plantations can result in Ca:K soil imbalances after two years, and as a result induce acute foliar K deficiency (Guerrini et al. 2000). These authors recommended applying a K source to offset this potential imbalance. Evidence supporting these findings has also been obtained from soils under ash beds that remained after slash burning in plantation forests.

#### *Microbial biomass and communities*

Microbial communities are highly responsive to soil pH changes (Saarsalmi et al. 2012). Wood ash applications combined with an additional N source can potentially increase soil C and N microbial biomass and C mineralisation rate, and subsequently lead to increased CO<sub>2</sub> production when applied to acidic soils (Saarsalmi et al. 2012). These authors studied the effects of wood ash and urea N fertiliser on soil chemical properties, soil microbial biomass and stand growth. Separate and combined applications of 1, 2.5 and 5 Mg ha<sup>-1</sup> of wood ash and N were made to *Pinus sylvestris* stands and were then monitored for 30 growing seasons. The authors concluded that wood ash in combination with an N source affects soil chemical properties, C and N cycling, and microbial processes for a considerable period, 30 years in this study. Similar results

were found in earlier work by Saarsalmi et al. (2010). The effects of wood ash and agricultural lime on certain ectomycorrhizal fungal species do not vary greatly over times (Erland and Söderström 1990). These authors studied the effects of liming on ectomycorrhizal fungal species on *Pinus sylvestris* seedlings and found variable seedling growth within treatments, but only a single ectomycorrhizal species (*Paxillus involutus*) was affected by the increased soil pH, which resulted in increased infection of *Pinus sylvestris* seedlings. No significant differences were found for the wood ash and agricultural lime treatments. Residuals that have high C content could additionally result in N immobilisation by soil microbial activity; micro-organisms utilise N to offset their internal C:N ratio (Matysik et al. 2001; Goodwin and Burrow 2006).

Wood ash applications on acidic and N-rich peat soils can increase the cellulose decomposition rate and bacterial populations and, as a result, increase the soil respiration rate (Pitman 2006). Wood ash applications can increase ectomycorrhizal mycelial populations following application (Hagerberg and Wallander 2002). These authors studied the impact of intensive harvesting and wood ash applications on external ectomycorrhizal mycelial populations and found that wood ash amendments can increase ectomycorrhizal fungal biomass by approximately 2.4 times in a 13-month period. No significant effects were observed for the control and intensively harvested plots. Increases were observed in autumn, thus implicating seasonality as a determining factor for the effects of wood ash on ectomycorrhizal populations. A review by Pitman (2006) on the use of wood ash in forestry revealed that increases in soil respiration without changes in soil fungal biomass have been observed. Soil respiration increases were attributed to increased soil pH and increased mineralisation of organic matter by soil biota. A literature review conducted by Demeyer et al. (2001) found that different wood ash application rates do not necessarily affect the microbial community when compared with fire treatments (fire significantly reduced microbial biomass). Wood ash and fire treatments were established in Scots pine trials and fungi were more severely affected by high wood ash application rates than bacteria. Aronsson and Ekelund (2004) recommends the use of a more stabilised form of wood ash, such as a pelleted form to avoid potential damage on organisms and shock effects induced by high pH changes.

#### *Charcoal content*

Charcoal contains a high C:N ratio and could potentially reduce N mineralisation and subsequently N uptake in plants (Steiner et al. 2008). This could be attributed to the fact that charcoal contains highly resistant C molecules; these molecules provide a poorly decomposable C substrate. This results in decreased C mineralisation of soil carbon and a subsequent reduction in C cycling in the soil (Liang et al. 2010). The increased nutrient content, retention capacity and reduced leaching are products of the slow biological oxidation of charcoal, which leads to the formation of carboxylic groups that provide cation exchange sites. The oxidation of charcoal thus produces organo-mineral complexes that lead to increases in CEC. Research has shown that charcoal is slowly mineralised into the

soil environment (Glaser et al. 2002). The combustion of biomass material produces mixed wood ash and can contain traces of charcoal. The presence of charcoal in wood ash facilitates the slow release of nutrients, can aid in avoiding the risk of depletion of forest soil nutrients and potentially act as a long-term source of nutrients and organic matter (Santalla et al. 2011). Santalla et al. (2011) studied the effects of mixed wood ash application on *Pinus radiata*, applied independently and with an additional P source four years after application. It was found that the presence of charcoal could reduce P availability. Charcoal can absorb organic and inorganic P in its pores, which leads to the formation of sparingly soluble phosphates, although phosphates are subsequently released into the soil (Laird et al. 2010).

#### *Heavy metal concentrations*

Wood ash contains variable concentrations of heavy metals and could potentially harm the environment as well as humans and several animal and plant species living in it. Heavy metals and trace elements, such as boron (B), Zn, Cd, Se, cobalt (Co), mercury (Hg), Pb, Ni, Cr and Cu have been reported by Demeyer et al. (2001), Patterson (2001), Aronsson and Ekelund (2004), Elliot and Mahmood (2006), Pitman (2006), Bird and Talberth (2008) and Saarsalmi et al. (2012). The presence of heavy metals and other possible contaminants are acknowledged by all authors, but discrepancies are prevalent regarding their concentrations and reactivity. Heavy metal content increases from bottom to fly ash and bottom ash is thus better suited for land application (Demeyer et al. 2001; Elliot and Mahmood 2006).

Saarsalmi et al. (2012) found no evidence of increased Cd concentrations in the organic layer, and Cd and Pb concentrations were not affected by the application of wood ash. In similar trials in Finland, increased Cd levels were reported, but the increases were negligible and ranged within naturally occurring Cd levels. A review by Pitman (2006) states the adsorption of Cd into soils is governed by soil pH, organic matter, and Fe and Mn hydrous oxide content. Wood ash with high Cd concentrations has a significantly reduced leaching potential due the capacity of wood ash to bond with hydrous Mn oxides and hydrous Fe oxides (Pitman 2006); wood ash contains significant concentrations of Mn and bottom ash concentrations can range from 2 500–5 500 mg kg<sup>-1</sup> (Alakangas 2005).

In summary, it is clear that the effects of wood ash amendments on the growth of forest flora, fungi and soil fauna may vary considerably. The range of responses revealed in studies are due to abiotic factors, site fertility, wood ash properties, different time scales of various studies (Aronsson and Ekelund 2004), initial soil pH and soil buffer capacity.

#### **Effects on tree growth**

Tree growth responses following wood ash applications are not well documented, but positive and negative responses have been recorded (Demeyer et al. 2001). Saarsalmi et al. (2012) found that wood ash applications of 1, 2.5 and 5 Mg ha<sup>-1</sup>, co-applied with urea-N fertiliser, can increase pine forest basal area increment up to 30 years after



application on a N-poor sandy soil. Scots pine trials were established in northern Finland and were fertilised with three wood ash application rates of 1, 2.5 and 5 Mg ha<sup>-1</sup>, resulting in an increase in growth for the study period. The application of a combination of wood ash and paper sludge to *E. grandis* stands on three predominantly sandy soils in Brazil (an oxisol, a sandy oxisol and an entisol) showed increases in volume increment in the range of 38–64% at 3 years of age. By 5 years of age, plots treated with wood ash on an oxisol showed increased volumes in the range of 31–75% relative to plots treated with only chemical fertiliser. The soils used in the experiments all had a substantial sand content (Guerrini et al. 2000). Similar trials in Brazil documented a positive growth response following ash applications to a 6.5-year-old *E. grandis* stand, at rates of 0 to 25 Mg ha<sup>-1</sup>. However, ash application rates that exceeded 15 Mg ha<sup>-1</sup> did not yield additional increases in growth (Gonçalves and Moro 1995). The positive growth response from the wood ash applications may have been attributed to the increased soil availability of P, K and B following application, as documented by Demeyer et al. (2001). Several sources indicated that positive growth responses can be expected from wood ash applications, but reduced growth is also probable. Mandre et al. (2004) found that wood ash applications on nutrient-poor sandy soils can result in reduced height growth in *Pinus abies* at application rates exceeding 5 t ha<sup>-1</sup>, but greater root biomass and stem growth can be achieved at low ash application rates in the range of 2.5–5 t ha<sup>-1</sup>. The application of wood ash to N-deficient or less fertile sites may result in reduced growth responses relative to wood ash treatments combined with a supplementary N source on more fertile sites (Jacobson 2003).

### Nutritional sustainability in South African soils

Within an ecosystem nutrients occur in various nutrient pools; these nutrient pools are comprised of above- and belowground biomass, the forest floor and the soil. Soil nutrient pools can broadly be divided into two categories, namely readily available and potentially available pools. Major inputs to these pools are atmospheric deposition, N-fixation, fertilisation and weathering. Processes resulting in loss of nutrients from these pools are erosion, weathering, harvesting, volatilisation and fire (du Toit et al. 2014). Nutritional sustainability of plantation soils largely depends on the size of the bioavailable pool (du Toit and Scholes 2002). These authors showed that larger nutrient pools increase the buffering ability of soil against short-term nutrient changes induced by forest management practices, and concluded that the degree of site disturbance is largely determined by the intensity of nutrient removal and site fertility. Ackerman et al. (2013) stated that reduced stand productivities can be expected on sensitive soils as a result of residue management disturbing short-term nutrient pools.

Full-tree harvest systems, coupled with slash burning, can potentially induce nutrient deficiencies due to slash removal (aboveground biomass). South African literature indicates the risk of reduced site productivity and nutrient depletion if sound management practices are neglected or additional nutrients are not supplied to the soil (du Toit et

al. 2010; Dovey et al. 2011). This shows that wood ash can potentially be used as an alternative to substitute or mitigate some of these nutrient losses.

### Wood ash application in South Africa

The effects of pure wood ash applications on South African soils are not well documented and little research has been done on this subject. However, the commonly practiced and relatively well-documented effects of slash burning (du Toit and Dovey 2005; Smith and du Toit 2005; du Toit et al. 2008) on South African plantation forests may provide a useful analogy giving insight into potential responses that may be expected from application of wood ash to the soil. It is also recognised that slash burning does introduce a heat component that could affect soil behaviour and responses. Nonetheless, the similarity in the nature of wood ash that is produced from biomass combustion and that from slash burning provides a best-available evaluation of likely impacts of wood ash applications to forest soils.

More importantly, before wood ash applications can be considered in South Africa, the cost implications have to be evaluated. The costs associated with moving the wood ash from the mill and lastly applying it to the forest soil greatly influences the reality for implementing such a project. Little literature could be assimilated to assess the economic viability of wood ash applications, but certain key factors, such as transportation and application costs, are essential. The costs of disposing wood ash on landfills plus the costs of replacing depleted nutrients have to exceed the collective costs of loading, transporting and applying the wood ash on plantation forests. In addition, the amount of wood ash that the soil can potentially accommodate will be a finite quantity. A complete financial analysis is recommended before companies consider this notion.

### Ash from slash burning as analogy

Forests are dynamic systems whereby nutrients are taken-up and recycled continuously (Laclau et al. 2003). Slash burning is the process of reducing forest residues produced at harvesting and mobilising it to prepare the site for future establishment. Burning of forest residues can result in substantial nutrient losses stemming from erosion, oxidation, volatilisation and leaching (Hart 1985; Giardina et al. 2000; Gonçalves et al. 2008b; Kauffman et al. 2009).

Residue management on South African plantation forests is an integral part of silvicultural operations; bark, woody components and branches are broadcasted and left to decompose, or broadcasted and burnt during site preparation. The burning of slash temporary releases a large amount of nutrients and as a result increases growth (Giardina et al. 2000; du Toit and Dovey 2005; du Toit et al. 2008; Gonçalves et al. 2008b). Similar to slash-burning operations, the wood ash produced from the combustion of biomass material in boilers can contain reasonable amounts of nutrients (Table 1). Due to the similarities, the potential effects of wood ash on soil properties and tree growth is described by comparing it to the effects of slash ash on soil properties and tree growth. In addition, it allows for some degree of understanding of what to

expect from wood ash applications to South African soils. The big difference concerning wood ash applications and slash burning is the heat component. The heat released from slash burning significantly affects the soil chemical changes and the nutrient losses that originate from high-intensity fires; this component is absent from wood ash applications. Du Toit et al. (2010) specified that biomass removal (whole-tree harvesting) and slash burning from plantations can be unsustainable over several rotations. Ash application creates the possibility of re-introducing nutrients removed from forest operations back into the soil. This could be a viable method of improving sustainability, but within its own set of limitations. Depending on the source of the wood ash, it may contain dangerous concentrations of heavy metals, dioxins and furans. In addition, the risk of over-liming and resultant soil changes may also threaten soil biota and nutrition.

The effects of slash or residue management on soil chemical and biological processes are well documented in South African and international literature.

### Legal requirements of land application of wood ash

Legislation states that the Minister of Agriculture has the authority to register any new agricultural substances for agricultural development if the proposed substance does not hold legal implications (complies with the limits set by the law) and poses a threat to biosecurity (Department of Environmental Affairs 2013a). Current legislation does not allow the use of pulp and paper residues as a fertilising agent or soil ameliorant due to reasons stated previously; however, the use of wood ash (exclusively bottom ash from a pure source) is not specified. It is essential to gain a comprehensive understanding regarding the classification of organic wastes, hazardous materials, compost and fertiliser according to South African legislation. The National Environmental Management: Waste Act (Act No. 59 of 2008) defines bottom ash as a level 2, Major Waste Type, or more specifically a Hazardous Waste. Bottom ash is disposed of in a landfill. The same act defines fertiliser as any substance proposed to be used for improving or maintaining plant growth or soil productivity (Department of Environmental Affairs 2013b). The National Environmental Management: Waste Act (Act No. 59 of 2008) defines a by-product as a material produced as part of a process intended to manufacture another substance or product and retains properties of the original source or virgin material (Department of Environmental Affairs 2013b). Wood ash is produced as a by-product of pulp and paper mills, but the chemical composition is determined by a range of conditions. A review by Pitman (2006) on the potential use of wood ash in forestry states Cd, As, Hg and Pb concentrations should not be problematic if bottom ash is used. With conservative wood ash application rates, there is virtually no environmental risk, provided pure woody material is used (Demeyer et al. 2001) and the buffer capacity of the soil is not exceeded. The allocation of certain organic materials, particularly pure bottom ash, as a potential fertiliser source is ambiguous according to current South African law. The South African Department of Environmental Affairs' National Environmental Management: Waste Act, 2008

(Act No. 59 of 2008) provides detailed heavy metal and metalloid soil screening values that can be used to ensure compliance with the law. South Africa does not currently have the required guidelines for land applications of wood ash and therefore have to rely on legislation meant for other purposes.

The ambiguity of current South African legislation requires further insight and strategies regarding this matter. If the South African forestry industry were to adopt the notion of pure wood ash applications on plantation soils, several essential characteristics and concepts need to be incorporated into the planning and implementation phase.

### Conclusion

Wood ash is one of the main by-products of tree biomass combustion produced in pulp and paper mills, sawmills and numerous boiler systems. It contains a range of macro- and micronutrients in moderate to high concentrations, but little or no N and S. Several studies have shown that wood ash applied with supplemental N sources can greatly improve the growth in eucalypt and pine trees. Risks to the environment resulting from the presence of heavy metals, dioxins and furans can be avoided by not using excessive application rates, using ash derived from the burning of uncontaminated tree residues, and/or ensuring a complete chemical analysis of wood ash is done and the current soil metal content is considered when application rates are planned. The risks are substantially lower if pure wood ash, free of possible contaminants, is used. The effects of wood ash on soil microbial activity varies; literature has shown that wood ash can lead to microbial biomass increases, but decreases and no effects can be expected and is essentially a product of soil type. The presence of heavy metals can lead to possible water contamination, but the risk is minimised with sufficiently conservative application rates and downward transmission of heavy metals is reduced significantly at higher pH values. Wood ash application rates defined as excessive or adequate vary significantly according to the literature, and this accentuates the importance of site-specific applications. The findings of Schönau and Herbert (1982, 1983) showed that moderate lime application rates of approximately 5 t ha<sup>-1</sup> can increase eucalypt stand growth and that over-liming can significantly decrease growth. Scheepers (2014) reported a mean CCE of 73.5% for three wood ash samples, taken from a single saw mill at different time intervals in KwaZulu-Natal. Therefore, wood ash applications in the range of 1 t ha<sup>-1</sup> (sands with a low buffer capacity) to a maximum of 5 t ha<sup>-1</sup> (acid clayey soils with a higher buffer capacity) are likely to be safe. This estimate is based on (1) buffer capacity tests done for the coastal Aeolian sands (Scheepers 2014), (2) the CCE of wood ashes (Scheepers 2014; Mitchell and Black 1997), (3) the negative results obtained when soils were over-limed in experiments by Schönau and Herbert (1982, 1983) and (4) the fact that some soils of South Africa have high naturally occurring heavy metal concentrations (Herselman 2007). Applications rates that exceed 5 t ha<sup>-1</sup> can potentially increase heavy metal concentrations to dangerous levels that might harm human life and biodiversity.

The disposal of wood ash on landfills in South Africa is costly and damaging to the environment. Several reviewed sources have shown wood ash can potentially be safely disposed on plantation soils and more importantly, can replace some of the nutrients removed from whole-tree harvesting systems. The induced liming effect can potentially alleviate acidic soil conditions and improve pine and eucalypt growth, provided that the soil pH is not increased excessively. Forest growth and soil chemical responses to wood ash additions are likely to be site-specific. The diverse and at times opposing results obtained from international literature is indicative of the effect that factors such as climate, tree genotype, soil characteristics and residue composition can have on the response to wood ash fertilisation.

## References

- Ackerman P, Ham C, Dovey S, du Toit B, de Wet J, Kunneke A, Seifert T, Meincken M, von Doderer C. 2013. State of the art of the use of forest residue for bioenergy in southern Africa. *ICFR Bulletin Series* no. 03/2013. Pietermaritzburg: Institute for Commercial Forestry Research.
- Alakangas E. 2005. Properties of wood fuels used in Finland. Project report PRO2/P2030/05 (Project no. C5SU00800). Jyväskylä: Technical Research Centre of Finland, VTT Processes.
- Aronsson KA, Ekelund NGA. 2004. Biological effects of wood ash application to forest and aquatic ecosystems. *Journal of Environmental Quality* 33: 1595–1605.
- Bird M, Talberth J. 2008. Waste stream reduction and re-use in the pulp and paper sector. Unpublished report. Washington State Department of Ecology Industrial Footprint Project. Santa Fe, New Mexico: Centre for Sustainable Economy.
- Bohn HL, McNeal BL, O'Connor GA. 1979. *Soil chemistry*. New York: Wiley.
- Cassidy P, Ashton S. 2007. Ash content. In: Hubbard W, Biles L, Mayfield C, Ahton S (eds), *Sustainable forestry for bioenergy and bio-based products: trainer's curriculum notebook*. Athens, GA: Southern Forest Research Partnership. pp 201–202.
- Cheah CB, Ramli M. 2011. The implementation of wood waste ash: review paper. *Resources, Conservation and Recycling* 55: 669–685.
- Compton JE, Cole DW. 1991. Impact of harvest intensity on growth and nutrition of successive rotations of Douglas-fir. *Forest Research Institute Bulletin* 161: 151–161.
- Demeyer A, Voundi Nkana JC, Verloo MG. 2001. Characteristics of wood ash and influence on soil properties and nutrient uptake: an overview. *Bioresource Technology* 77: 287–295.
- Department of Environmental Affairs. 2013a. National Environmental Management: Waste Act, 2008 (Act no. 59 of 2008). Available at <http://cer.org.za/wp-content/uploads/2014/02/natl-norms-and-stds-for-remediation-of-contaminated-land-and-soil-quality.pdf> [accessed 18 September 2014].
- Department of Environmental Affairs. 2013b. The National Organic Waste Composting Strategy: draft strategy report. Pretoria: Department of Environmental Affairs.
- Dovey SB. 2009. Estimating biomass and macronutrient content of some commercially important plantation species in South Africa. *Southern Forests* 71: 246–261.
- Dovey SB, du Toit B, de Clercq W. 2011. A comparison of soil moisture relations between standing and clear felled plots with burnt and unburnt harvest residue treatments of a clonal eucalypt plantation on the Zululand Coastal Plain, South Africa. *Water SA* 37: 483–494.
- du Toit B. 2003. Effects of site management operations on the nutrient capital of a eucalypt plantation system in South Africa. *Southern African Forestry Journal* 199: 15–25.
- du Toit B, Dovey SB. 2005. Effects of site management on leaf area, early biomass development, and stand growth efficiency of a *Eucalyptus grandis* plantation in South Africa. *Canadian Journal of Forest Research* 35: 891–900.
- du Toit B, Dovey SB, Smith CW. 2008. Effects of slash and site management treatments on soil properties, nutrition and growth of a *Eucalyptus grandis* plantation in South Africa. In: Nambiar EKS (ed.), *Site management and productivity in tropical plantation forests: proceedings of workshops in Piracicaba (Brazil) 22–26 November 2004 and Bogor (Indonesia) 6–9 November 2006*. Bogor: Center for International Forestry Research. pp 63–77.
- du Toit B, Gush MB, Pryke JS, Samways MJ, Dovey SB. 2014. Ecological impacts of biomass production at stand and landscape levels. In: Seifert T (ed.), *Bioenergy from wood: sustainable production in the tropics*. Dordrecht: Springer. pp 211–236.
- du Toit B, Scholes MC. 2002. Nutritional sustainability of *Eucalyptus* plantations: a case study at Karkloof. *South African Forestry Journal* 199: 15–25.
- du Toit B, Smith CW, Little KM, Boreham G, Pallet RN. 2010. Intensive, site-specific silviculture: Manipulating resource availability at establishment for improved stand productivity: a review of South African research. *Forest Ecology and Management* 259: 1836–1845.
- Elliot A, Mahmood T. 2006. Beneficial uses of pulp and paper power boiler ash residues. *TAPPI Journal* 5(10): 9–16.
- Erland S, Soderstrom B. 1990. Effects of liming on ectomycorrhizal fungi infecting *Pinus sylvestris* L. I. Mycorrhizal infection in limed humus in the laboratory and isolation of fungi from mycorrhizal roots. *New Phytologist* 115: 675–682.
- Etiégni L, Campbell AG. 1991. Physical and chemical characteristics of wood ash. *Bioresource Technology* 37: 173–178.
- Etiégni L, Campbell AG, Mahler RL. 1991. Evaluation of wood ash disposal on agricultural land. I. Potential as a soil additive and liming agent. *Communications in Soil Science and Plant Analysis* 22: 243–256.
- Fox RL, Saïdy NA, Yost RS. 1981. Liming in the tropics: variable-charge soils may be highly buffered. *Illustrated Concepts in Tropical Agriculture* no. 24. Honolulu: University of Hawaii.
- Giardina CP, Sanford RL Jr, Dockersmith IC, Jaramillo VJ. 2000. The effects of slash burning on ecosystem nutrients during the land preparation phase of shifting cultivation. *Plant and Soil* 220: 247–260.
- Glaser B, Lehmann J, Zech W. 2002. Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal - a review. *Biology and Fertility of Soils* 35: 219–230.
- Gómez-Rey MX, Madeira M, Coutinho J. 2013. Soil C and N dynamics, nutrient leaching and fertility in a pine plantation amended with wood ash under Mediterranean climate. *European Journal of Forest Research* 132: 281–295.
- Gonçalves JLM, Moro L. 1995. Uso da cinza de biomassa florestal como fonte de nutrientes em povoamentos puros de *Eucalyptus grandis*. *IPEF* 48/49: 28–37 (in Portuguese with English abstract).
- Gonçalves JLM, Stape JL, Laclau J, Bouillet J, Ranger J. 2008a. Assessing the effects of early silvicultural management on long-term site productivity of fast-growing eucalypt plantations: the Brazilian experience. *Southern Forests* 70: 105–118.
- Gonçalves JLM, Wichert MCP, Gava JL, Serrano MIP. 2008b. Soil fertility and growth of *Eucalyptus grandis* under different residue management practices. Nambiar EKS (ed.), *Site management and productivity in tropical plantation forests: proceedings of workshops in Piracicaba (Brazil) 22–26 November 2004 and Bogor (Indonesia) 6–9 November 2006*. Bogor: Center for

- International Forestry Research. pp 51–62.
- Goodwin E, Burrow AM. 2006. Effects of application of mill-generated primary sludge and boiler ash on Loblolly pine survival and growth. In: Connor KF (eds), *Proceedings of the 13th Biennial Southern Silvicultural Research Conference, Memphis, Tennessee, February 28–March 4 2005*. General Technical Report SRS–92. Asheville, NC: US Department of Agriculture, Forest Service, Southern Research Station. pp 135–138.
- Guerrini IA, Moro L, Lopes MAF, Boas RLV, Benedetti V. 2000. Application of wood ash and pulp and paper sludge to *Eucalyptus grandis* in three Brazilian soils. In: Henry CL, Harrison RB, Bastian RK (eds), *The forest alternative: principles and practice of residuals use*. Seattle: College of Forest Resources, University of Washington. pp 127–131.
- Hagerberg D, Wallander H. 2002. The impact of forest residue removal and wood ash amendment on the growth of the ectomycorrhizal external mycelium. *FEMS Microbiology Ecology* 39: 139–146.
- Hart R. 1985. The questionable practice of slash burning. Part II: environmental effects and alternatives. *NCAP News* 5(4). Available at <http://www.forestlanddwellers.org/Smoke/SlashBurningPart2.pdf> [accessed 28 July 2014].
- Herbert MA. 1983. The response of *Eucalyptus grandis* to fertilising with nitrogen, phosphorus, potassium and dolomitic lime on a Mispah soil series. *South African Forestry Journal* 124: 4–12.
- Herselman JE. 2007. The concentration of selected trace metals in South African soils. PhD thesis, University of Stellenbosch, South Africa.
- Huang H, Campbell AG, Folk R, Mahler RL. 1992. Wood ash as a soil additive and liming agent for wheat: field studies. *Communications in Soil Science and Plant Analysis* 12: 25–33.
- Jacobson S. 2003. Addition of stabilized wood ashes to Swedish coniferous stands on mineral soils – effects on stem growth and needle nutrient concentrations. *Silva Fennica* 37: 437–450.
- Kauffman JB, Hughes RF, Heider C. 2009. Carbon pool and biomass dynamics associated with deforestation, land use, and agricultural abandonment in the Neotropics. *Ecological Applications* 19: 1211–1222.
- Kellner O, Weibull H. 1998. Effects of wood ash on bryophytes and lichens in a Swedish pine forest. *Scandinavian Journal of Forest Research* 13: 76–85.
- Kilpimaa S, Kuokkanen T, Lassi U. 2013. Characterization and utilization potential of wood ash from combustion process and carbon residue from gasification process. *BioResources* 8: 1011–1027.
- Knapp BA, Insam H. 2011. Recycling of biomass ashes: current technologies and future research needs. In: Insam H, Knapp BA. (eds), *Recycling of biomass ashes*. Berlin: Springer-Verlag. pp 1–16.
- Kuokkanen M, Kuokkanen T, Stoor T, Niinimäki J, Pohjonen V. 2009. Chemical methods in the development of eco-efficient wood-based pellet production and technology. *Waste Management and Research* 27: 561–571.
- Laclau J, Deleporte P, Ranger J, Bouillet J, Kazott G. 2003. Nutrient dynamics throughout the rotation of *Eucalyptus* clonal stands in Congo. *Annals of Botany* 91: 879–892.
- Laird DA, Fleming P, Davis DD, Horton R, Wang B, Karlen DL. 2010. Impact of biochar amendments on the quality of a typical mid-western agricultural soil. *Geoderma* 158: 443–449.
- Lerner BR, Utzinger JD. 1986. Wood ash as soil liming material. *Horticultural Science* 21: 76–78.
- Lévai L, Veres S, Gajdos E, Marozsán M, Bákonyi N, Tóth B. 2009. Possibilities in plant nutrition. In: Marić S, Lončarić ZL (eds), *Proceedings of the 44th Croatian and 4th International Symposium on Agriculture, 16–20 January 2009, Opatija, Croatia*. Osijek: Poljoprivredni fakultet Sveučilišta Jurja Strossmayera u Osijeku. pp 556–560.
- Liang BQ, Lehmann J, Sohi S, Thies JE, O'Neill B, Trujillo L, Gaunt J, Solomon D, Grossman J, Neves EG, Luizao FJ. 2010. Black carbon affects the cycling of non-black carbon in soil. *Organic Geochemistry* 41: 206–213.
- Mandre M. 2006. Influence of wood ash on soil chemical composition and biochemical parameters of young Scots pine. *Estonian Journal of Ecology* 55: 91–107.
- Mandre M, Korsjukov R, Ots K. 2004. Effect of wood ash application on the biomass distribution and physiological state of Norway spruce seedlings on sandy soils. *Plant and Soil* 265: 301–314.
- Matysik MA, Gilmore DW, Mozaffari M, Halbach TR. 2001. Application of wood ash, biosolids, and papermill residuals to forest soils – a review of the literature. *Staff Paper Series* no. 1531–23. St Paul: Department of Forest Resources, College of Natural Resources and Minnesota Agricultural Experiment Station, University of Minnesota.
- McLean JE, Bledsoe BE. 1992. Behavior of metals in soils. 540/S-92/018. Washington, DC: US Environmental Protection Agency. Available at <http://nepis.epa.gov/> [accessed 2 August 2014]
- Misra MK, Ragland KW, Baker, AJ. 1993. Wood ash composition as a function of furnace temperature. *Biomass and Bioenergy* 4: 103–116.
- Mitchell CC, Black ED. 1997. Land application of boiler wood ash in the south-eastern United States. In: Rechcigl JE, MacKinnon HC (eds), *Agricultural uses of by-products and wastes. ACS Symposium Series* 668. Washington, DC: American Chemical Society. pp 204–225.
- Muse JK, Mitchell CC. 1995. Paper mill boiler ash and lime by-products as soil liming materials. *Agronomy Journal* 87: 432–438.
- Naylor LM, Schmidt E. 1989. Paper mill wood ash as a fertiliser and liming material: field trials. *TAPPI Journal* 72(6): 199–108.
- Ohno T, Erich MS. 1993. Incubation-derived calcium carbonate equivalence of papermill boiler ashes derived from sludge and wood Sources. *Environmental Pollution* 79: 175–180.
- Ohno T, Erich MS. 1994. Phosphorous and potassium availability in wood ash-amended soils: an incubation study. *Technical Bulletin* 154. Maine: Maine Agricultural and Forest Experiment Station, University of Maine.
- Ozolinčius R, Buožytė R, Varnagirytė-Kabašinskienė I. 2007. Wood ash and nitrogen influence on ground vegetation cover and chemical composition. *Biomass and Bioenergy* 31: 710–716.
- Park BB, Yanai RD, Sahm JM, Ballard BD, Abrahamson LP. 2004. Wood ash effects on soil solution and nutrient budgets in a willow bioenergy plantation. *Water, Air, and Soil Pollution* 159: 209–224.
- Patterson S. 2001. The agronomic benefit of pulp mill boiler wood ash. MSc thesis, University of Lethbridge, Alberta, Canada.
- Perucci P, Monaci E, Onofri A, Vischetti C, Casucci C. 2008. Changes in physico-chemical and biochemical parameters of soil following addition of wood ash: a field experiment. *European Journal of Agronomy* 28: 155–161.
- Pitman R. 2006. Wood ash use in forestry – a review of the environmental impacts. *Forestry* 79: 563–588.
- Plante AF. 2006. Soil biogeochemical cycling of inorganic nutrients and metals. In: Paul EA (ed.), *Soil microbiology, ecology, and biochemistry* (3rd edn). Burlington: Elsevier. pp. 389–430.
- Rajamma R, Ball RJ, Tarelho LAC, Allen GC, Labrincha, JA, Ferreira VM. 2009. Characterisation and use of biomass fly ash in cement-based materials. *Journal of Hazardous Materials* 172: 1049–1060.
- Ribeiro ASM, Monteiro RCC, Davim EJR, Fernandes MHV. 2010. Ash from pulp mill boiler—characterisation and vitrification. *Journal of Hazardous Materials* 179: 303–308.

- Risse M, Harris G. 2011. Biopower. In: Boundy B, Diegel SW, Wright L, Davis SC (eds), *Biomass energy data book* (4th edn). Oak Ridge: Oak Ridge National Laboratory. Available at [http://cta.ornl.gov/bedb/pdf/BEDB4\\_Chapter3.pdf](http://cta.ornl.gov/bedb/pdf/BEDB4_Chapter3.pdf) [accessed 25 October 2013].
- Saarsalmi A, Mälkönen E, Piirainen S. 2001. Effects of wood ash fertilisation on forest soil chemical properties. *Silva Fennica* 35: 355–368.
- Saarsalmi A, Smolander A, Kukkola M, Arola M. 2010. Effect of wood ash and nitrogen fertilisation on soil chemical properties, soil microbial processes, and stand growth in two coniferous stands in Finland. *Plant and Soil* 331: 329–340.
- Saarsalmi A, Smolander A, Kukkola M, Moilanen M, Saramäki J. 2012. 30-Year effects of wood ash and nitrogen fertilization on soil chemical properties, soil microbial processes and stand growth in a Scots pine stand. *Forest Ecology and Management* 278: 63–70.
- Saint-André L, Laclau J-P, Deleporte P, Gava JL, Gonçalves JLM, Mendham D, Nzila JD, Smith C, du Toit B, Xu DP et al. 2008. Slash and litter management effects on *Eucalyptus* productivity: a synthesis using a growth and yield modelling approach. In: Nambiar EKS (ed.), *Site management and productivity in tropical plantation forests: proceedings of workshops in Piracicaba (Brazil) 22–26 November 2004 and Bogor (Indonesia) 6–9 November 2006*. Bogor: Center for International Forestry Research. pp 173–189.
- Santalla M, Omil B, Rodríguez-Soalleiro R, Merino A. 2011. Effectiveness of wood ash containing charcoal as a fertiliser for a forest plantation in a temperate region. *Plant and Soil* 346: 63–78.
- Scheepers GP. 2014. The effect of wood ash on the soil properties and nutrition and growth of *Eucalyptus grandis* x *urophylla* grown on a sandy coastal soil in Zululand. MSc thesis, Stellenbosch University, South Africa.
- Schönau APG, Herbert MA. 1982. Relationship between growth rate and foliar concentrations of nitrogen, phosphorus and potassium for *Eucalyptus grandis*. *South African Forestry Journal* 120: 19–23.
- Schönau APG, Herbert MA. 1983. Relationship between growth rate, fertilizing and foliar nutrient concentrations for *Eucalyptus grandis*. *Fertilizer Research* 4: 369–380.
- Schwenke G, Perfrement A, Manning B, MacMullen G. 2012. Nitrogen volatilisation losses - how much N is lost when applied in different formulations at different times. Grains Research and Development Corporation Update Paper. Available at <http://www.grdc.com.au/Research-and-Development/GRDC-Update-Papers/2012/03/Nitrogen-volatilisation-losses-how-much-N-is-lost-when-applied-in-different-formulations-at-different-times> [accessed 12 September 2013].
- Siddique R. 2008. *Waste materials and by-products in concrete*. Berlin: Springer.
- Smith CW, du Toit B. 2005. The effect of harvesting operations, slash management and fertilisation on the growth of a *Eucalyptus* clonal hybrid on a sandy soil in Zululand, South Africa. *Southern African Forestry Journal* 203: 15–26.
- Steiner C, Glaser B, Teixeira WG, Lehmann J, Blum WEH, Zech W. 2008. Nitrogen retention and plant uptake on a highly weathered central Amazonian ferralsol amended with compost and charcoal. *Journal of Plant Nutrition and Soil Science* 171: 893–899.
- Tan KH. 2011. *Principles of soil chemistry* (4th edn). Boca Raton: CRC Press.
- Titshall L, Dovey S, Rietz D. 2013. A review of management impacts on the soil productivity of South African commercial forestry plantations and the implications for multiple-rotation productivity. *Southern Forests* 75: 169–183.
- Ulery AL, Graham RC, Amrhein C. 1993. Wood-ash composition and soil pH following intense burning. *Soil Science* 156: 893–899.
- Väättäinen K, Sirparanta E, Räisänen M, Tahvanainen T. 2011. The cost and profitability of using granulated wood ash as a forest fertilizer in drained peatland forest. *Biomass and Bioenergy* 35: 3335–3341.
- Wattle Research Institute. 1977. *Report for 1976–77 (Thirtieth year)*. Pietermaritzburg: University of Natal.
- Williams TM, Hollis CA, Smith BR. 1996. Forest soil and water chemistry following bark boiler bottom ash application. *Journal of Environmental Quality* 25: 955–961.