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BIOMASS FLY ASH AS FOLIAR FERTILIZER FOR HYBRID ASPEN TREES: NUTRIENT UPTAKE, GROWTH RESPONSE, AND COMPATIBILITY WITH NITROGEN FERTILIZER

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□ *Biomass ash is an important and potentially useful by-product of the bioenergy industry. As a "proof of concept" for using biomass fly ash as a foliar fertilizer, we tested (i) whether the nutrients in the ash were absorbed by hybrid aspen trees, (ii) whether the ash affected tree growth, and (iii) whether the ash was compatible with nitrogen foliar fertilizer. Four foliar treatments (water [control], ash suspended in water, nitrogen fertilizer solution, and ash suspended in nitrogen fertilizer solution) were evaluated. Several nutrients in the fly ash were absorbed by hybrid aspen both in the greenhouse and in the field; however, this absorption did not significantly affect tree growth in either setting. Nitrogen fertilization was associated with significantly higher tree growth in the greenhouse; inclusion of the fly ash with the nitrogen fertilizer solution did not significantly alter this growth response.*

Keywords: bioenergy, 'Crandon', ethanol, poplars, short-rotation woody crops

INTRODUCTION

When biomass is burned to produce bioenergy, a significant portion of the dry mass may be converted to ash: for example, 0.3–5.2% ash has been reported for various wood fuels, and 3.9–20.3% for various herbaceous residues (Miles et al., 1996). While the value of biomass ash as a soil-applied fertilizer and liming agent is known (Moilanen et al., 2005, 2002; Hytonen, 1998), so too are the difficulties of utilizing dry ash. Achieving uniform coverage is challenging, and windy conditions easily transport the ash from the intended application site. Theoretically, these difficulties may be overcome by mixing the ash with water to form a foliar fertilizer suspension. Though not

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all nutrients are readily absorbed through foliage, several nutrients found in biomass ash (such as potassium, calcium, and iron) can be absorbed this way, perhaps more efficiently than if applied to the soil (Fageria et al., 2009).

In general, foliar fertilization is less well studied than dry fertilization, and to our knowledge has never been reported for a suspension of biomass ash. Thus, the overarching goal of this study was to test the concept of using biomass ash as a foliar fertilizer for the hybrid aspen 'Crandon' (*Populus alba* L. × *P. grandidenta* Michx.), which has demonstrated high yield potential as a bioenergy crop in Iowa (Goerndt and Mize, 2008) as well as the southern portions of Minnesota and Wisconsin (Zalesny et al., 2009). To achieve this goal, the basic characteristics of the ash which are important for foliar applications was evaluated, and then the fly ash as a foliar fertilizer in both greenhouse and field settings was tested.

As a "proof of concept" for using biomass fly ash as a foliar fertilizer, researchers specifically tested the following: (i) whether the nutrients in the ash were absorbed by hybrid aspen trees, (ii) whether the ash affected tree growth, and (iii) whether the ash was compatible with nitrogen foliar fertilizer (which is an important consideration due to the low nitrogen content of ash). The first of these questions was answered via nutrient analyses of trees treated with ash-based foliar fertilizer (ash suspended in water) compared to trees treated with a control (water). Similarly, the second question was answered by comparing the effects of the foliar treatments on tree growth. The third question was answered by comparing the effects of a nitrogen fertilizer solution alone to that of a nitrogen fertilizer solution with ash added (ash suspended in nitrogen fertilizer solution).

MATERIALS AND METHODS

Source and Characteristics of the Ash

The ash for this study was provided by POET, LLC from an ethanol plant which burns biomass at approximately 980°C in a 150,000 pounds per hour (PPH) steam watertube boiler. The ash was produced from a mix of dry and wet wood (60–65% and 35–40%, respectively, on a mass basis), as well as trace amounts of soluble corn biomass. Two types of ash are produced at the plant: wet front ash, which is shaken off the front of the boiler grates during combustion and is doused with water during removal; and dry fly ash, which is recovered after exiting the boiler via the flue. The dry fly ash was selected for this study, due to its lower moisture content and lack of contamination from soil and other foreign objects that may be found in the front ash.

Using a 60g sample, a preliminary evaluation of the particle size distribution of the fly ash was conducted, and each particle size fraction was tested to determine sprayer compatibility (based on clogging of spray equipment nozzles); from this, it was determined that the ash particles $\leq 150\ \mu m$ were

TABLE 1 Nutrient content of the non-compatible (NC) and sprayer-compatible (SC) biomass fly ash

Type	Plant nutrient	NC (%)	SC (%)
Primary nutrients	Total N	0.03	0.01
	P_2O_5	2.43	4.86
	K_2O	3.66	6.01
Secondary nutrients	Ca	6.44	9.09
	Mg	1.71	2.48
	S	0.97	2.44
Micronutrients	Cu	0.01	0.01
	Fe	1.88	1.78
	Mn	0.13	0.13
	Na	2.43	6.22
	Zn	0.05	0.08

sprayer-compatible. On a mass basis, the sprayer-compatible ash comprised 68.8% of the total ash in this initial sample. A larger quantity (13.5 kg) of fly ash was then separated into sprayer-compatible and non-compatible fractions using a 150 μm nylon sieve measuring 20 cm across; approximately 1 kg of ash was sieved (hand-shaken for 3 to 4 minutes) at a time. With this larger sample, it was found that 75.4% of the fly ash was of a sprayer-compatible size.

Both the sprayer-compatible and non-compatible ash fractions were tested for plant nutrient contents (Table 1). Observed nutrient levels were similar to those previously reported for woody biomass ash (Miles et al., 1996). The smaller, sprayer-compatible fraction was enriched in most nutrients, which is consistent with previous research (Dahl et al., 2009; Obernberger et al., 1997). Conductivity of the foliar treatments containing ash was also evaluated, to gauge the risk of damage to the trees due to salinity. The conductivity of the ash treatments used in this study were found to be 3.4 and 2.8 mmhos cm^{-1}, for ash suspended in water and ash suspended in fertilizer, respectively. Conductivity of 2–4 mmhos cm^{-1} is considered problematic for sensitive plant species, and 4–8 mmhos cm^{-1} is considered problematic for most crops (Ayers and Westcot, 1985; Bernstein, 1975); however, it is important to distinguish that these guidelines are based upon irrigation water applied on a frequent (e.g. daily) basis. Less appears to be known about the risks of infrequent (e.g. weekly or monthly) applications of foliar fertilizers having similar conductivity values.

Greenhouse Experiment

To address the questions of interest (absorbance, growth response, and nitrogen fertilizer compatibility), four different foliar treatments were evaluated: (i) a control in which only water was applied to the leaves, (ii) a suspension of fly ash in water, (iii) a nitrogen fertilizer solution, and (iv) a suspension of fly ash in nitrogen fertilizer solution. A 20-0-0 urea-ammonium nitrate (UAN) fertilizer was used as the nitrogen source. For treatments containing ash and/or nitrogen fertilizer, mixtures were prepared in 1 L plastic spray bottles at rates of 7.25 g ash and/or 2.55 g of nitrogen fertilizer per L of water, to approximate the nutrient concentrations recommended for greenhouse applications of commercial foliar fertilizers (e.g. "Folo Spray 20-20-20" from J.R. Simplot Company, Boise, ID, USA). Based on the nutrient analysis previously described for the sprayer-compatible ash, the resulting nutrient concentrations are estimated to be 510 ppm total nitrogen (N), 350 ppm phosphorus pentoxide (P_2O_5) and 435 ppm potassium oxide (K_2O).

Dormant hardwood cuttings (each measuring 10 cm long) of the hybrid aspen 'Crandon' (*P. alba* × *P. grandidentata*) were planted in peat moss in mid-March, 2011. Initial growth and survival were poor due to widespread infection with black stem rot. Based on visual appearance, the healthiest trees were selected for inclusion in the experiment and were transplanted into 236-mL Accelerator® (Nursery Supplies Inc., Chambersburg, PA, USA) containers in mid-April. After transplanting, the trees were watered via subirrigation for 45 minutes two times per day. Initial tree heights were recorded prior to the first foliar treatment on April 21; heights were also recorded prior to each weekly foliar treatment thereafter. Treatments were applied with a spray bottle by saturating the upper and lower surfaces of the leaves.

The initial design consisted of a randomized complete block design, with each of the four foliar treatments represented by eight randomly selected trees per block (32 trees $block^{-1}$), with three blocks (96 trees total). However, over the course of the experiment trees in two of the blocks developed black stem rot, which resulted in highly variable tree growth as well as mortality. As a result, measurements of these two blocks were discontinued after six foliar applications. The experiment was continued with the remaining block of healthy trees (which received a total of nine foliar applications), and was analyzed as a completely randomized design, with eight trees per foliar treatment (32 trees total).

The trees were destructively sampled on 1 July, washed thoroughly under running water to remove any treatment residues, and oven-dried at 60°C to determine the effects of the treatments on the final dry biomass of the shoots (stems + leaves), roots, and cuttings. The plant tissues were ground through a 0.4 mm screen and sent to the U.S. Forest Service Institute for Applied Ecosystem Studies in Rhinelander, WI, for analysis of the nutrients nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sodium (Na). Nitrogen content was determined using a Flash EA1112 N-C analyzer with a model MAS 200 autosampler (Thermo Electron, via CE Elantech, Inc., Lakewood, NJ, USA); P content was determined using a Varian 720 ICP-OES (EPA 200.7 method); and the remaining nutrients (K, Ca, Mg, and Na) were determined via atomic emission (AE) spectroscopy using a Varian Agilent model 240 FS AA unit (Agilent Technologies, Englewood, CO, USA). Due to additional costs for the P analysis, only shoots were analyzed for this nutrient.

The growth and nutrient data were evaluated for treatment effects with analysis of variance (ANOVA) using PROC GLM in SAS (SAS Institute Inc., Cary, NC). The response variables analyzed (covariates in parentheses) included: final tree height (initial tree height), shoot biomass (number of shoots), root biomass (number of shoots), cutting biomass (initial cutting diameter), shoot:root biomass ratio (final tree height), shoot nutrients (shoot biomass), root nutrients (root biomass), and cutting nutrients (cutting biomass). Where treatment effects were statistically significant ($P < 0.05$), multiple comparisons analyses (with Tukey's adjustment) were conducted to determine differences among the adjusted means of the treatments. In addition, statistical contrasts, which pooled observations within nitrogen treatments ("N" and "N+Ash") versus non-nitrogen treatments ("Control" and "Ash"), as well as ash treatments ("Ash" and "N+Ash") versus non-ash treatments ("Control" and "N"), were conducted to further evaluate plant responses to applications of nitrogen and ash.

Field Experiment

For the field study, the second treatment (ash suspended in water) was excluded to allow greater replication of the remaining treatments (control, nitrogen fertilizer solution, and ash suspended in nitrogen fertilizer solution). This decision was based on the results of the greenhouse study (presented in the following section), which demonstrated that (i) a growth response is unlikely to occur without nitrogen fertilizer, and (ii) the ash is likely to be compatible with the nitrogen fertilizer.

Each of the three foliar treatments was randomly assigned to a plot within each of four blocks (12 total plots) at a field site located near the Iowa State University campus in Ames, IA. Each plot measured 4 m × 5 m in area; the inner 2 m × 3 m area was used for biomass measurements, and the 1-m-wide outer perimeter was used for tissue sampling. The plots were marked and cleared of existing vegetation (3-year-old hybrid aspen root sprouts) in mid-May. For the treatments containing ash and/or nitrogen fertilizer, mixtures were prepared in a 15 L Solo® (Solo Inc., Newport News, VA, USA) backpack sprayer at rates of 8.0 g of ash and/or 2.4 g of nitrogen fertilizer L^{-1} of water. Based on the nutrient analysis for the sprayer-compatible ash, the resulting nutrient concentrations are estimated to be 480 ppm total N, 385 ppm P_2O_5, and 480 ppm K_2O, which is similar in magnitude to the greenhouse experiment but more evenly balanced among the primary nutrients. The foliar treatments were applied to the plots at a rate of 1,875 L ha^{-1}. This equated to 3.6, 2.9, and 3.6 kg ha^{-1} yr^{-1} of N, P_2O_5, and K_2O, respectively; although these are modest rates by row-crop standards, research suggests that similarly low fertilizer rates - with directed placement - can significantly increase the growth of young hybrid poplar trees in the field (Guillemette and DesRochers, 2008; van den Driessche, 1999). Monthly foliar applications to the regenerating trees were conducted on 24 June, 17 July, 13 August, and 7 September.

Tissue samples were collected on September 16 by clipping stems (four plot^{-1}) just below the tenth leaf measuring at least 2 cm long, per the Leaf Plastochron Index (LPI) method (Larson and Isebrands, 1971). The samples were washed thoroughly under running water to remove any treatment residues, the leaves were removed from the stems, and the material was oven-dried at 60°C. The tissue samples were then ground through a 0.4 mm screen and sent to the U.S. Forest Service Institute for Applied Ecosystem Studies in Rhinelander, WI, for analysis of nutrients (N, P, K, Ca, Mg, and Na), using the same equipment and methods previously described for the greenhouse experiment. Due to additional costs for the P analysis, only stems were analyzed for this nutrient. Shortly after cessation of growth, the trees in the inner plots were harvested on 20 October and oven-dried at 100°C to determine the final biomass productivity for each plot.

The growth and nutrient data were evaluated for treatment effects with analysis of variance (ANOVA) using PROC GLM in SAS (SAS Institute Inc.). The response variables analyzed (covariates in parentheses) included: percent biomass regrowth (initial biomass [log-transformed]), stem nutrients (sample biomass), and leaf nutrients (sample biomass). Where treatment effects were statistically significant ($P < 0.05$), multiple comparisons analyses (with Tukey adjustment) were conducted to determine differences among the adjusted means of the treatments. In addition, statistical contrasts were conducted ("N" versus "Control"; and, "N+Ash" versus "N") to further evaluate plant responses to the presence of nitrogen and ash in the treatments.

RESULTS

Greenhouse Experiment

The treatments were associated with significant differences ($P < 0.001$) in final tree height following nine foliar applications. Multiple comparisons analysis showed that the treatments containing nitrogen fertilizer significantly increased tree height, both with and without ash (Figure 1). Significant treatment differences ($P < 0.01$) were also observed for shoot biomass, while root and cutting biomass were not significantly affected by the treatments (Figure 2). Multiple comparisons analysis for shoot biomass showed that the treatments containing nitrogen fertilizer significantly increased shoot biomass, both with and without ash. Treatment differences were found to be

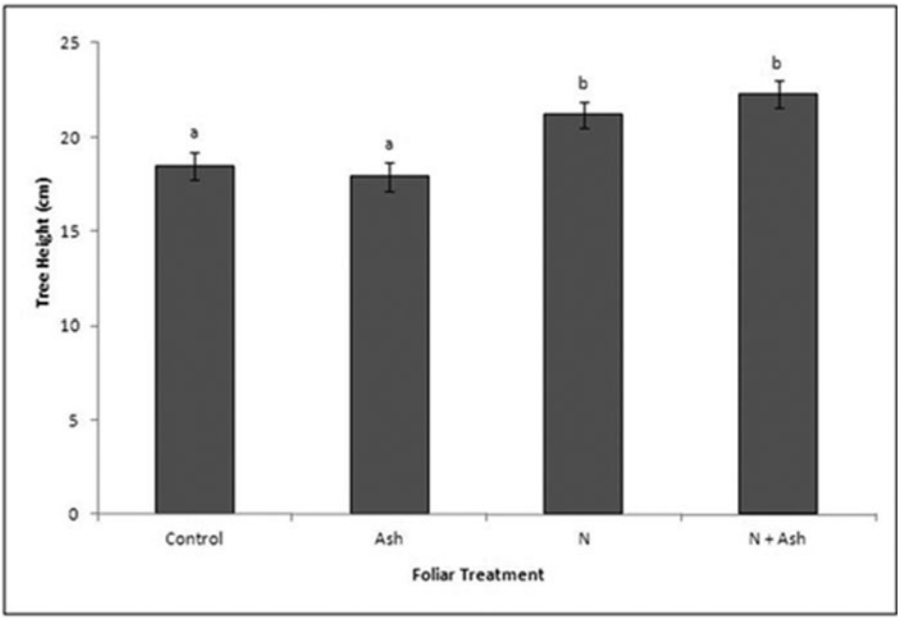

FIGURE 1 Effects of treatments on final tree height (adjusted for initial tree height) after nine foliar applications. Error bars represent +/− 1 standard error of the mean. Statistically significant differences ($P < 0.05$) are represented by different letters above the treatments.

non-significant ($P = 0.82$) for the ratio of shoot:root biomass (not shown). The statistical contrasts confirmed the aforementioned trends for tree height and shoot biomass; in addition, root biomass and cutting biomass were found to be significantly higher for the treatments containing nitrogen fertilizer, whereas the ash treatments did not significantly affect root or cutting biomass (Table 2).

The foliar treatments were associated with significant differences in the plant tissue content of N (shoots), P (shoots), K (roots and cuttings), and Na (shoots, roots, and cuttings), as illustrated in Figure 3. Multiple comparisons analysis for shoot N showed that the nitrogen fertilizer treatments significantly increased shoot N, both with and without ash (Figure 3a). The

TABLE 2 Results of statistical contrasts for tree growth parameters in the greenhouse experiment. Levels of statistical significance are $P < 0.10$ (*), $P < 0.05$ (**), and $P < 0.01$ (***). Where significant for a particular growth parameter, the effects are identified as being associated with an increase (+) or decrease (−) in the concentration of that nutrient in the plant

Contrasts	Height	Shoot biomass	Cutting biomass	Root biomass	Shoot:root ratio
N effect	+	+	+	+	o
Sig.	***	***	*	**	–
Ash effect	o	o	o	o	o
Sig.	–	–	–	–	–

ash alone significantly increased shoot P and root K compared to the control, and when mixed with nitrogen fertilizer the ash significantly increased shoot P and root K compared to the nitrogen fertilizer alone (Figures 3b and 3c). For the cuttings, the nitrogen fertilizer treatments were associated with a significant decrease in K content relative to the control, whereas the ash treatments had no significant effect (Figure 3c). The ash treatments significantly increased the Na content of the shoots, roots, and cuttings, both with and without nitrogen fertilizer, with the exception of the roots in the ash-only treatment (Figure 3f).

Most of these trends were confirmed by the statistical contrasts: significant increases for N (shoots) were found for the nitrogen treatments, and significant increases for P (shoots), K (roots), and Na (shoots, roots, and cuttings) were found for the ash treatments (Table 3). However, shoot N was found to be significantly lower in the ash treatments (whereas multiple comparisons had detected no difference). Additional trends were also identified by the contrasts: N (roots) and Na (roots) were significantly higher in the nitrogen treatments, while P (shoots) and K (cuttings and roots) were significantly lower; and, K (shoots) was significantly higher in the ash treatments, while Ca (shoots) and Mg (shoots and roots) were significantly lower.

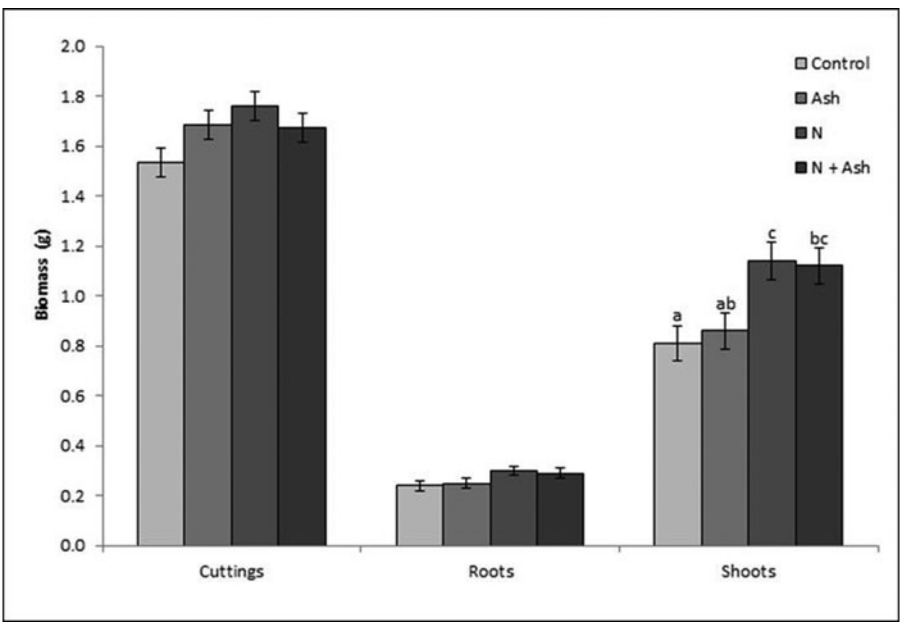

FIGURE 2 Effects of foliar treatments on adjusted mean biomass of cuttings, roots, and shoots after nine foliar applications in the greenhouse. Error bars represent +/− 1 standard error of the mean. Statistically significant differences (P < 0.05) are represented by different letters above the treatments.

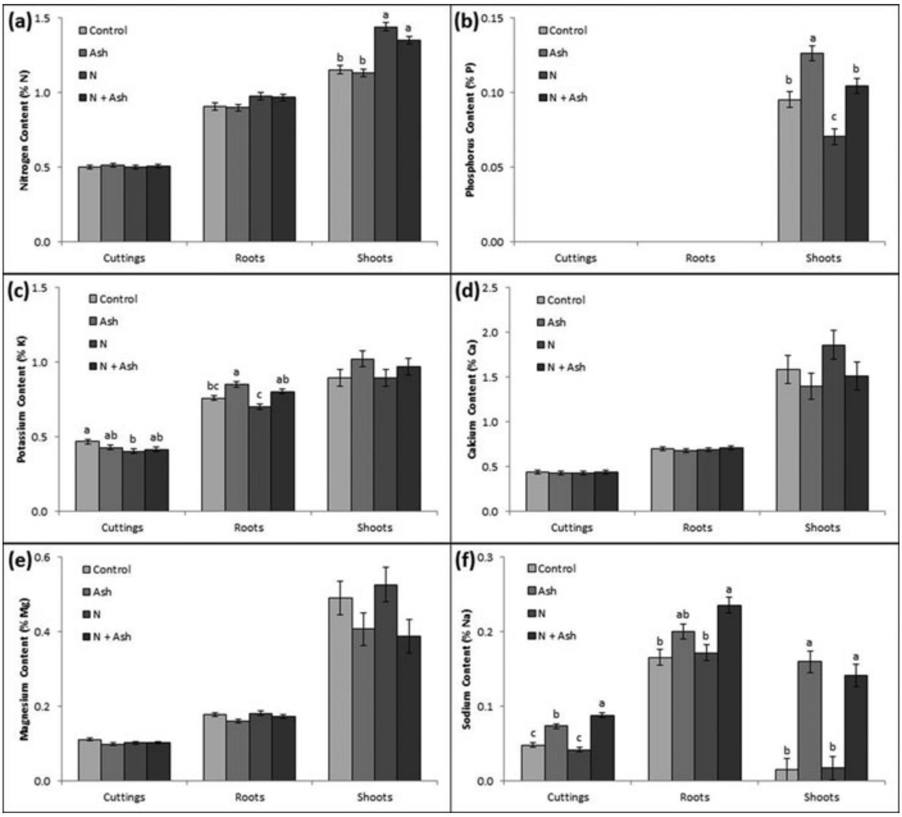

FIGURE 3 Effects of treatments on plant tissue concentrations (adjusted for tissue biomass) of A) nitrogen, B) phosphorus, C) potassium, D) calcium, E) magnesium, and F) sodium, after nine foliar applications in the greenhouse. Error bars represent +/− 1 standard error of the mean. Statistically significant differences ($P < 0.05$) are represented by different letters above the treatments. Cuttings and roots were not analyzed for phosphorus.

Field Experiment

Treatment effects were non-significant ($P = 0.68$) for biomass regrowth (not shown). The foliar treatments were, however, associated with significant

TABLE 3 Results of statistical contrasts for plant tissue nutrients in the greenhouse experiment. Levels of statistical significance are $P < 0.10$ (*), $P < 0.05$ (**), and $P < 0.01$ (***). Where significant for a particular nutrient, the effects are identified as being associated with an increase (+) or decrease (−) in the concentration of that nutrient in the plant. Cuttings and roots were not analyzed for phosphorus

	Shoots						Cuttings						Roots					
Contrasts	N	P	K	Ca	Mg	Na	N	P	K	Ca	Mg	Na	N	P	K	Ca	Mg	Na
N effect	+	-	o	o	o	o	o	na	-	o	o	o	+	na	-	o	o	+
Sig.	***	***	–	–	–	–	–	na	**	–	–	–	**	na	**	–	–	*
Ash effect	-	+	+	-	-	+	o	na	o	o	o	+	o	na	+	o	-	+
Sig.	**	***	*	*	**	***	–	na	–	–	–	***	–	na	***	–	**	***

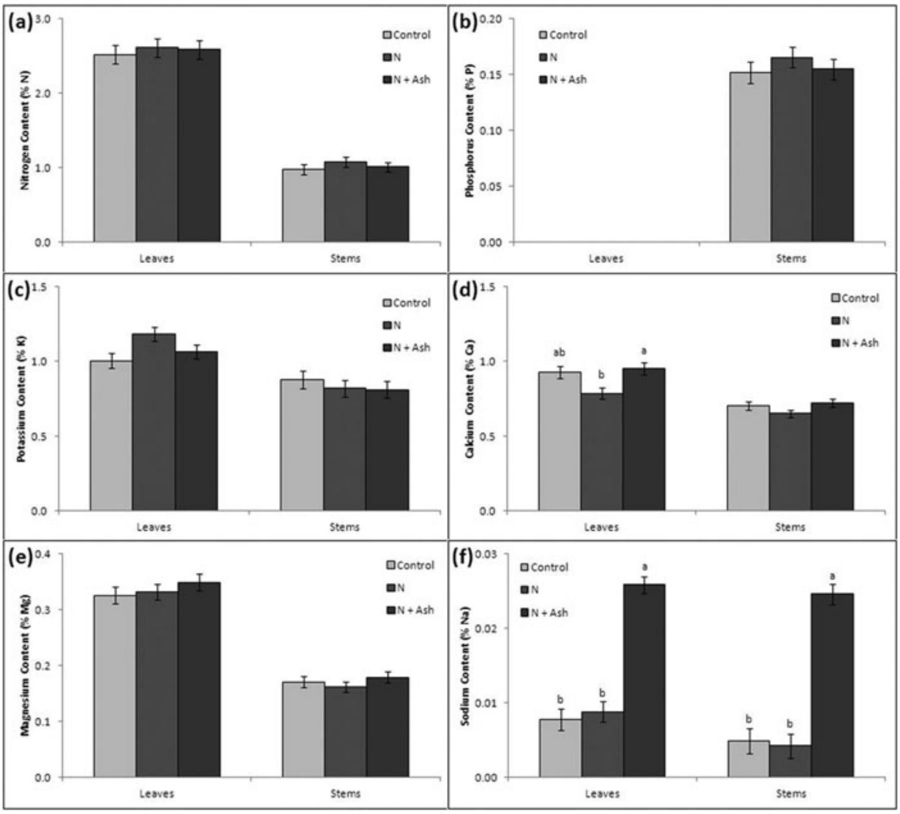

FIGURE 4 Effects of treatments on plant tissue concentrations (adjusted for tissue biomass) of A) nitrogen, B) phosphorus, C) potassium, D) calcium, E) magnesium, and F) sodium, after four applications in the field. Error bars represent +/− 1 standard error of the mean. Statistically significant differences ($P < 0.05$) are represented by different letters above the treatments. Leaves were not analyzed for phosphorus.

differences in the plant tissue content of Ca (leaves) and Na (leaves and stems), as illustrated in Figure 4. Multiple comparisons analysis for leaf Ca showed that the ash with nitrogen fertilizer significantly increased Ca content compared to the nitrogen fertilizer solution alone, but not relative to the control (Figure 4d). For stem and leaf Na, multiple comparisons analysis showed that the ash with nitrogen fertilizer significantly increased Na content, relative to both the control and the nitrogen fertilizer solution alone (Figure 4f).

These trends were confirmed by the statistical contrasts: significant increases for Ca in the leaves and for Na in the stems and leaves were found with the ash with nitrogen fertilizer compared to the nitrogen fertilizer alone (Table 4). Additional trends were also identified by the contrasts: K (leaves) was significantly higher for the nitrogen fertilizer treatment compared to control, while Ca (leaves) was significantly lower; and, Ca (stem) was

TABLE 4 Results of statistical contrasts for the field experiment. Levels of statistical significance are P < 0.10 (*), P < 0.05 (**), and P < 0.01 (***). Where significant, the effects are identified as being associated with an increase (+) or decrease (−) in the parameter. Leaves were not analyzed for phosphorus

	Biomass	Stems						Leaves					
Contrasts	% regrowth	N	P	K	Ca	Mg	Na	N	P	K	Ca	Mg	Na
N effect	o	o	o	o	o	o	o	o	na	+	-	o	o
Sig.	–	–	–	–	–	–	–	–	na	**	**	–	–
Ash effect	o	o	o	o	+	o	+	o	na	o	+	o	+
Sig.	–	–	–	–	*	–	***	–	na	–	**	–	***

significantly higher for the ash with nitrogen fertilizer versus the nitrogen fertilizer alone.

DISCUSSION

Greenhouse Experiment

The results of the greenhouse study show that hybrid aspen trees respond positively to foliar nitrogen fertilization, and that the increased growth does not alter the trees' ratio of shoot:root biomass. This is consistent with previous research showing that fertilization accelerates poplar growth without altering biomass allocation, after accounting for differences in tree size (Coyle and Coleman, 2005). Because the presence of the ash did not reduce the growth effects of the nitrogen fertilizer solution, relative to the nitrogen fertilizer solution alone, the ash appears to be compatible with nitrogen fertilizers derived from UAN. The results also show no effects (positive or negative) of the ash on tree growth. Possible reasons for this include (i) the trees were nitrogen-limited, even with foliar nitrogen applications, which prevented the plants from benefiting from the nutrients in the ash, and/or (ii) hybrid aspen are not highly susceptible to deficiencies of the nutrients found in the ash.

The increases in tissue N associated with the nitrogen fertilizer treatments (see Table 3, Figure 3a) indicate that the growth response described above is due to the uptake of foliar-applied N by the trees. The increases in P, K, and Na associated with the ash treatments indicate that some of the nutrients contained in the ash can be absorbed by the target plants; however, decreases in N, Ca, and Mg in certain plant tissues were also associated with the ash treatments. Similarly, decreases in shoot P were also associated with the nitrogen fertilizer treatments.

Some of these changes in nutrient concentrations may be explained by specific nutritional needs of the plants, coupled with the need to maintain electrochemical balance in the plant tissue. Ferndandez and Eichert (2009)

TABLE 5 Adjusted mean shoot content (% $tree^{-1}$) of individual cations (K, Ca, Mg, Na) and total cations in the greenhouse experiment. Standard deviations and coefficients of variation (CV, %) represent the variability among treatment means

Treatment	Shoot K (% $tree^{-1}$)	Shoot Ca (% $tree^{-1}$)	Shoot Mg (% $tree^{-1}$)	Shoot Na (% $tree^{-1}$)	Total cations (% $tree^{-1}$)
Control	0.89	1.59	0.49	0.01	2.98
Ash	1.02	1.40	0.41	0.16	2.99
N	0.90	1.86	0.53	0.02	3.31
N+Ash	0.97	1.51	0.39	0.14	3.01
St. Dev.	0.06	0.20	0.07	0.08	0.16
CV (%)	6.5	12.3	14.5	95.1	5.2

describe foliar uptake of plant nutrients through pores in the cuticle via the exchange of cations; some cations are absorbed, but in order to maintain electrochemical balance other cations are leached. Here, it would appear the cations K and Na were absorbed, while the cations Ca and Mg were leached. Based on the optimum nutrient levels described for hybrid poplars by Lteif et al. (2008), the hybrid aspen trees in our study were below sufficiency for K, but were within the sufficiency ranges for Ca and Mg; thus, it would appear the trees selectively exchanged cations based on nutritional needs. Sufficiency levels for Na in hybrid poplars were not available in the literature, but the absorbance of Na here may be explained by the ability of Na to substitute for K in certain physiological functions (Subbarao et al., 2003; Wakeel et al., 2011); as previously noted, shoot K was below sufficiency in this experiment. The cation exchange hypothesis is supported by a comparison of individual and total cations in the shoots (Table 5); the total cation content of the shoots was similar among treatments (3.0–3.3%), and was less variable than that of the individual cations, as demonstrated by the lower coefficient of variation (standard deviation of the treatment means as a percentage of the overall mean) for the total cations (5.2%) compared to the individual cations (6.5–95.1%). The highest coefficient of variation (95.1%) was observed for Na, which reflects the ability of hybrid poplars to absorb large quantities of this nutrient when available (Zalesny et al., 2008).

One explanation for the decreases in shoot P associated with the nitrogen treatments and the decreases in shoot N associated with the ash treatments (see Table 3, Figure 3a, Figure 3b) may be that these two nutrients were affecting each other's nutrient-use-efficiencies within the shoots. Specifically, the increases in shoot P resulting from the ash treatments may have increased N-use-efficiency in the shoots, thereby reducing the need to transfer stored N from the cuttings to the shoots. Comparison of the distribution of nitrogen among plant tissues (Table 6) supports this hypothesis; a shift of 1–2% of total plant nitrogen from the cuttings to the shoots was observed for the "Control" treatment compared to "Ash", and for the "N" treatment compared to "N+Ash", while total N (mg $tree^{-1}$) was similar within each of these

TABLE 6 Adjusted mean plant tissue nitrogen (% of total tree nitrogen) and total tree nitrogen (mg tree^{-1}) for hybrid aspen in the greenhouse experiment

Treatment pairings	Shoot N (% total N)	Cutting N (% total N)	Root N (% total N)	Total N (mg tree^{-1})
Control	51.1	37.7	11.2	22.6
Ash	50.2	38.6	11.2	22.5
N	56.3	33.1	10.6	25.6
N+Ash	54.4	34.7	10.9	24.8

pairings. Similarly, the increases in shoot N resulting from the foliar nitrogen treatments may have increased P-use-efficiency in the shoot, which in turn may result in a shift of P from the shoot to other tissues (i.e. cutting or roots). However, because the cost of the P analysis precluded the other tissues from being analyzed for P, this particular hypothesis cannot be evaluated here.

Field Experiment

The results of the field study showed that neither the nitrogen fertilizer nor the ash significantly affected tree growth, nor did the ash significantly alter the effects of the nitrogen fertilizer. Plant tissue N for the control trees fell within the range of sufficiency for hybrid poplars (Lteif et al., 2008); thus, higher N availability in the field soil (compared to the potting media used in the greenhouse study) appears to explain this lack of response to nitrogen fertilizer. Because the trees did not respond to the ash treatment, even with sufficient nitrogen, it appears that hybrid aspen are not highly susceptible to deficiencies of the nutrients found in the ash.

The increases in Ca and Na associated with the ash treatments (see Table 4, Figure 4d, Figure 4f) suggest that some of the nutrients contained in the ash can be absorbed by the target plants. Although the control trees were generally within the ranges of sufficiency for hybrid poplars (Lteif et al., 2008) for most nutrients, Ca and K were near their lower limits for sufficiency. Thus, similar to the greenhouse experiment, it appears nutrient uptake in the field may have been selective and based on nutritional needs, assuming that Na substitutes for K as previously discussed.

In summary, the results of the field experiment suggest that the ash is compatible with nitrogen fertilizer solution and contains nutrients that can be absorbed by the target plants, which is consistent with the results of the greenhouse experiment. However, the absorption of nutrients from the ash did not result in any statistically significant benefits to biomass productivity (even with sufficient levels of N in the plant tissues). This is consistent with findings from willow bioenergy plantations (Park et al., 2004), where increases in leaf litter nutrients were associated with ash applied to agricultural soils but biomass productivity was unaffected.

Targeting crop species that are known to benefit from foliar applications of the nutrients prevalent in the ash (and particularly those nutrients shown here to be available for foliar absorption) should be considered for future testing.

Crop Selection

The effectiveness of foliar fertilizers varies by crop and by nutrient (Fernandez and Eichert, 2009). In general, though, crops are not highly responsive to foliar applications of primary nutrients (Fageria et al., 2009). This stems from the fact that crops often have large requirements for primary nutrients, and application rates for foliar fertilizers are limited to relatively small amounts by (i) the risk of foliar damage associated with high nutrient concentrations, and (ii) the desire of growers to minimize the number of passes through the field with spraying equipment. Because fertilization rates for secondary nutrients and micronutrients are generally smaller than those for primary nutrients, a greater proportion of the crop's requirement can potentially be met with foliar fertilization. Thus, responses to foliar fertilization may be more easily attained, particularly for nutrients having low availability in the soil (as may occur with iron) and/or poor mobility within the plant (as may occur with calcium).

For example, calcium deficiency in fruit trees is treated with approximately 10 kg ha^{-1} yr^{-1} of foliar calcium (for example Neilsen et al., 2005; Raese and Drake, 2006; Rosenberger et al., 2004). Further evaluation of the fly ash as a source of foliar calcium appears to be warranted based on (i) the prevalence of calcium in the fly ash (see Table 1), (ii) the ability of the fly ash to raise calcium levels of plant tissues as demonstrated in the field study (see Table 4), and (iii) the pre-existence of a market for foliar calcium in fruit production. The other nutrients found in the ash are not as likely to be feasible for foliar application due to the high application rates typically required for primary nutrients such as P and K, the apparent lack of markets for Na, and the relatively low levels of the remaining secondary nutrients and micronutrients in this particular ash. However, the nutrient content of biomass ash is known to vary by feedstock (Miles et al., 1996), and by other factors including boiler temperature (Misra et al., 1993); as such, additional work should be done to evaluate the possible foliar fertilizer uses of a wider selection of biomass ashes.

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