Uptake of Macro- and Micro-Nutrients into Leaf, Woody, and Root Tissue of *Populus* after Irrigation with Landfill Leachate

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This research was funded by Iowa State University—Department of Natural Resource Ecology and Management, U.S. Forest Service—Northern Research Station, and a Grant-in-Aid of Research from Sigma Xi, the Scientific Research Society. The authors are grateful to Neil Nelson for continual support throughout the project. The authors acknowledge the following people for assistance during field, greenhouse, and laboratory work: Edmund Bauer, Patricia Bauer, Daniel Baumann, Bruce Birr, David Coyle, Jennifer Crozier, Raymond Lange, JoAnne Lund, Paula Marquardt, and Nicanor Saliendra. Also, the authors appreciate review of earlier versions of the manuscript from: Gary Bafluelos, Edmund Bauer, Jud Isebrands, Neil Nelson, Thomas Schmidt. Robert van den Driessche, and two anonymous reviewers.

Journal of Sustainable Forestry, Vol. 27(3) 2008
Available online at http://www.haworthpress.com

doi:10.1080/10549810802256262

ABSTRACT. Information about macro- and micro-nutrient uptake and distribution into tissues of Populus irrigated with landfill leachate helps to maximize biomass production and understand impacts of leachate chemistry on tree health. We irrigated eight Populus clones (NC 13460, NCI4O18, NC14104, NC14106, DM115, DN5, NM2, NM6) with fertilized (N, P, K) well water(control) or municipal solid waste landfill leachate weekly during 2005 and 2006 in Rhinelander, Wisconsin, USA. During Aug. 2006, we tested for differences in total N, P, K, Ca, Mg, S, Zn, B, Mn, Fe, Cu, Al, and Pb concentration in preplanting and harvest soils; and in leaf, woody (stems+branches), and root tissue. Other than N, leachate did not increase the soil concentration of elements relative to preplanting levels. There was broad genotypic variation for tissue concentrations, with clone-specific uptake for most elements. Nitrogen, P, K, Ca, Mg, S, B, and Mn concentrations were greatest in leaves and least in woody tissue, while those of Fe, Cu, and Al were greatest in roots and least in leaves and woody tissue. Overall, successful uptake of nutrients without impacts to tree health validated the use of landfill leachate as an irrigation and fertilization source for Populus.

KEYWORDS. Sustainable intensive forestry, phytoaccurnulation, waste management, hybrid poplar, *Populus deltoides*, *P. nigra*, *P. maximowiczii*, *P. trichocarpa*

Using *Populus* for environmental benefits requires selection of genotypes that are matched to local environments and specific contaminants (Isebrands & Karnosky, 2001; Zalesny & Bauer, 2007b). The intensive management of Populus requires irrigation and fertilization to increase biomass production (Brown & van den Driessche, 2002; Coyle & Coleman, 2005; DesRochers, van den Driessche, & Thomas, 2006). Landfill leachate used as an irrigation and fertilization source may supply water and elemental nutrient requirements to *Populus* trees (i.e., poplars) grown in short rotation woody crop (SRWC) systems at a lower cost than traditional sources (Shrive, McBride, & Gordon, 1994; Erdman & Christenson, 2000; Zalesny & Bauer, 2007a). However, leachate chemistry varies due to waste materials received at the facility and seasonal changes in waste decomposition (Shrive et al., 1994; Kjeldsen et al., 2002). Therefore, it is necessary to evaluate leachate chemistry in order to determine its potential nutritive value to the trees, especially as it relates to providing fertilization rates for optimal biomass production (Fung, Wang, Altman, &Hutterman, 1998; Stephens, Tyrrel, & Tiberghien, 2000).

There are few reports about the specific plant tissue responses to macro- and micro- nutrients available in landfill leachate. Thus, to maximize environmental benefits it is necessary to incorporate the knowledge of *Populus* species and clones in SRWC systems for remedial benefits with the uptake and distribution of macro- and micro-nutrients (Mirck, Isebrands, Verwijst, & Ledin, 2005). Overall, there is a need to compare growth and tissue concentration of field-grown *Populus* trees irrigated and fertilized with landfill leachate versus those grown under traditional water and nutrient regimes. Understanding macro- and micro-nutrient accumulation and distribution in leaf, woody, and root tissue of *Populus* irrigated with landfill leachate is important for maximizing biomass production during a growing season, along with understanding the phytotoxic impacts of excessive levels of nutrients on tree health, soil health, and groundwater quality.

This study expands on our previous work evaluating the selection of clonal material (Zalesny, Zalesny, Wiese, & Hall, 2007a), growth and biormass production (Zalesny, Zalesny, Coyle, & Hall, 2007b), and salt accumulation (Zalesny, Zalesny, Wiese, Sexton, & Hall, 2007c) of *Populus* clones irrigated with landfill leachate. However, uptake of nutrients into the trees was not evaluated in those studies. Therefore, the primary objective of the current study was to test the uptake and distribution of rmacro- and micro-nutrients into leaf, woody (stems+branches), and root tissue of eight *Populus* genotypes that were irrigated with fertilized (N, P, K) well water (control) or municipal solid waste landfill leachate for two growing seasons. Our hypotheses were that clones would respond differently to water and leachate irrigation, and that tissue concentrations of macro- and micro-nutrients in leaf, woody, and root tissues would vary among clones. This information is necessary for sustainable SRWC management, because there is a general lack of knowledge about elemental nutrient concentration in the tissues of Populus genotypes when irrigated with landfill leachate in the field.

MATERIALS AND METHODS

Zalesny et al. (2007b) provided details about site description, clone selection, tree establishment, experimental design, and treatment application. In summary, the study was conducted at the Oneida County Landfill located 6 km west of Rhinelander, Wisconsin, USA (45.6° N, 89.4° SW). Temperature, precipitation, and growing degree days across the experimental period were described previously (Zalesny et al., 2007b). The landfill soils are classified as mixed, frigid, coarse loamy Alfic Haplorthods (Padus Loam, PaB), with 0 to 6% slopes, and are considered well to moderately well drained with loamy deposits underlain by stratified sand and gravel glacial outwash.

Eight *Populus* clones were selected from 25 original genotypes, based on above- and below-ground traits, after being irrigated with leachate in a series of greenhouse experiments that constituted three phyto-recurrent selection cycles (Zalesny et al., 2007a). The clones and their parentages (i.e., genomic groups) were: NC13460, NC14018 ([*P. trichocarpa* Torr. & Gray × *P. deitoides* Bartr. ex Marsh] × P. deltoides 'BC_1'); NC14104, NC14106, DM115 (*P. deltoides* × *P. maximowiczii* A. Henry 'DM'); DN5 (*P. deltoides* × *P. nigra* L. 'DN'); and NM2, NM6 (*P. nigra* × *P. maximowiczii* 'NM'). Although *P. maximowiczii* is currently classified as a subspecies of *P. suaveolens* Fischer, we have retained the species nomenclature for *P. maximowiczii* (Japanese poplar) that has been previously used in the *Populus* literature (Eckenwalder, 1996; Dickmann, 2001).

Shoots were collected during dormancy from stool beds established at Hugo Sauer Nursery in Rhinelander. Hardwood cuttings, 20 cm long, were prepared during January 2005, with cuts made to position at least one primary bud not more than 2.54 cm from the top of each cutting. Cuttings were stored at 5°C and soaked in water to a height of 15 cm for 3 d before hand-planting with a dibble bar (straight rod, 2 cm in diameter, with a T handle) on June 14, 2005. Prior to planting, the soil was tilled to a depth of 30 cm. Cuttings were planted in a split plot design with eight blocks, two irrigation treatments (whole plots), and eight clones (sub plots) at a spacing of 1.2 × 2.4 m (i.e., 3,472 trees ha^{-1} Clones were arranged in randomized complete blocks in order to minimize effects of any potential environmental gradients. Two border rows of clone NM2 were established on the perimeter of the planting and between treatment whole plots to reduce potential border effects (Hansen, 1981).

Water (control) from a nonimpacted well located 100 m from the study area was applied three times at a rate of 3.8 L $tree^{-1}$ to all cuttings via hand irrigation during an establishment period of 14 d. Following establishment, trees were hand irrigated with either fertilized water or municipal solid waste landfill leachate, using a low-flow distribution nozzle connected to a garden hose. Fertilizer (N, P, and K) was added to the control treatment during each irrigation application at a rate equal to that of the leachate to eliminate fertilization effects of these macronutrients.

The 2005 weekly application rate was 3.8 L tree^{-1} (23.1 mm ha^{-1} assuming an irrigated soil surface area of 0.16 m^2 per tree). Given eight applications, a total of 1.9 kL of each treatment was applied across the growing season. Drip irrigation was used to apply treatments during 2006. The treatment application rate for 2006 was increased to 22.7 L tree^{-1} (34.6 mm ha^{-1} assuming an irrigated soil surface area of 0.66 m^2 per tree) because of root system development and increased water usage as the trees developed. Given twelve applications, a total of 17.4 kL of each treatment was applied across the growing season. To prevent substantial leaching from the experimental plot, application of treatments was adjusted based on precipitation events. Irrigation was postponed if greater than 0.5 cm of rainfall occurred within 2 d prior to scheduled watering or was expected to occur with a 40% chance or greater for 2 d following scheduled watering.

Sampling and Measurements

Well Water (Control) and Municipal Solid Waste Landfill Leachate

Water and leachate from the same source as the irrigation treatments were sampled from the Oneida County Landfill during April and October of 2005 and 2006. The water and leachate chemistry was analyzed (Northern Lake Service, Inc., Crandon, Wisconsin, USA) using approved United States Environmental Protection Agency methods. The leachate was brown in color and had a putrid odor. The concentrations of the following elements in the water and leachate are given in Table 1: *macronutrients*—nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulfur (S); *micronutrients*—zinc (Zn), boron (B), manganese (Mn), iron (Fe), copper (Cu); *beneficial nutrients*—aluminum (Al), lead (Pb). The rate per application of these elements, expressed on a kg ha^{-1} basis, is provided in Table 2. Given the complexity of the data, beneficial nutrients were included with micronutrients throughout the manuscript for simplicity of data presentation and interpretation. Zalesny et al.. (2007c) provided information about pH, electrical conductivity, biological oxygen demand, and chemical oxygen demand. Heavy metals and volatile organic compounds were not detectable in the leachate analysis, and therefore, not a concern with respect to plant establishment and development.

Soil

Using a 5-cm diameter hand auger, nine soil samples at a depth of 0 to 30 cm were collected from each irrigation treatment plot one day before

TABLE 1. Elements in well water (control) and leachate from the Oneida County Landfill (Rhinelander, Wisconsin, USA) during the 2005 and 2006 growing seasons

Element	Concentration (mg L^{-1})[a]			
	2005		2006	
	Control	Leachate	Control	Leachate
N	480.0	597.5 ± 86.3	660.0	685.0 ± 25.0
P	1.5	1.9 ± 0.1	3.7	3.0 ± 0.7
K	400.0	450.0 ± 23.8	420.0	450.0 ± 30.0
Ca	Na[b]	na	11.00	25.0
Mg	na	na	4.50	150.0
S	nd[c]	nd	nd	2.6 ± 2.6
Zn	na	na	1.20	0.08
B	na	5.1 ± 0.1	0.07	12.5 ± 0.5
Mn	na	0.5 ± 0.1	0.02	0.25 ± 0.13
Fe	na	7.7 ± 6.3	0.65	5.0 ± 3.0
Cu	na	na	0.12	0.02
Al	na	na	nd	0.1
Pb	na	0.3 ± 0.3	0.01	nd

[a]Data are means ± one standard error (n = 2), except for N, P, and K in the control treatment both years, that were based on April leachate analyses, and additional values in 2006 (n = 1).
[b]Not available.
[c]Not detectable.

planting (June 13, 2005) and harvesting (August 17, 2006). For each date, soil from three sampling points was bulked, and three bulked samples were sent to the University of Wisconsin Soil & Plant Analysis Laboratory (Madison, Wisconsin, USA) for analysis of total P, K, Ca, Mg, S, Zn, B, Mn, Fe, Cu, AI, and Pb concentration using inductively coupled plasma optical emission spectrometry (ICP-OES). Total N concentration of the samples was analyzed at the Institute for Applied Ecosystem Studies (Rhinelander, Wisconsin, USA) using a Flash EA1112 N-C analyzer (Thermo Electron, via CE Elantech, Inc., Lakewood, New Jersey, USA) with a model MAS 200 autosampler. The soil concentrations of these elements are given in Table 3.

Plant Tissues

All trees were destructively harvested in two stages on August 18, 2006. First, the above ground portion of each tree was cut at 10 cm above

TABLE 2. Rate per application of elements in well water (control) and leachate from the Oneida County Landfill (Rhinelander, Wisconsin, USA) during the 2005 and 2006 growing seasons

Element	Rate per application (kg ha^{-1})[a]			
	2005		2006	
	Control	Leachate	Control	Leachate
N[b]	114.00	141.91	227.00	235.60
P	0.36	0.45	1.27	1.03
K	95.00	106.88	144.45	154.77
Ca	Na[c]	na	3.78	8.60
Mg	na	na	1.55	51.59
S	nd[d]	nd	nd	0.88
Zn	na	na	0.41	0.03
B	na	1.21	0.02	4.30
Mn	na	0.12	0.01	0.09
Fe	na	1.83	0.22	1.70
Cu	na	na	0.04	0.01
Al	na	na	nd	0.03
Pb	na	0.07	0.00	nd

[a]2005—8 applications total, rate based on an application volume of 3.8 L tree^{-1} and an irrigated soil surface area of 0.16 m^2 tree^{-1}• 2006—12 applications total, rate based on an application volume of 22.7 L tree^{-1} and an irrigated soil surface area of 0.66 m^2 tree^{-1}•
[b]Nitrogen, P, and K fertilizer additions to the control treatment both years were based on April leachate analyses.
[c]Not available.
[d]Not detectable.

the soil surface, and leaf and woody (stems + branches) components were separated and dried at 70°C to a constant mass. Second, root systems were excavated using a mechanized tree spade that removed a uniform, conical volume of soil (diameter × depth = 0.28 m^3) for each tree. Root systems were washed and dry mass was determined identically to shoot components. Leaf, woody, and root samples for each irrigation treatment × clone interaction were sent to A & L Great Lakes Laboratories, Inc. (Fort Wayne, Indiana, USA) for analysis of total P, K, Ca, Mg, S, Zn, B, Mn, Fe, Cu, AI, and Pb concentration (ICP-OES), while total N concentration was analyzed at the Institute for Applied Ecosystem Studies as with soil N.

TABLE 3. Elements in the soil before planting and at whole-tree harvest after irrigating for the 2005 and 2006 growing seasons with well water (control) and leachate from the Oneida County Landfill (Rhinelander, Wisconsin, USA)

Element	Concentration (mean ± standard error, n = 3)[a]			LSDo.o5
		Harvest		
	Preplanting	Control	Leachate	
N	1.44 ± 0.34 b	1.37 ± 0.59 b	3.45 ± 0.22 a	1.43
P	3.55 ± 0.23 a	0.30 ± 0.01 b	0.35 ± 0.01 b	0.45
K	0.83 ± 0.01 a	0.08 ± 0.00 b	0.10 ± 0.01 b	0.02
Ca	4.81 ± 0.24 a	1.49 ± 0.36 c	2.88 ± 0.13 b	0.90
Mg	1.99 ± 0.00 a	1.38 ± 0.08 c	1.73 ± 0.06 b	0.19
S	1.36 ± 0.09 a	0.01 ± 0.00 b	0.01 ± 0.00 b	0.19
Zn	48.00 ± 4.04 a	2.55 ± 0.09 b	5.30 ± 0.00 b	8.08
B	8.00 ± 0.00 a	1.00 ± 0.00 c	2.15 ± 0.03 b	0.06
Mn	0.20 ± 0.01 a	0.10 ± 0.01 b	0.19 ± 0.02 a	0.04
Fe	10.98 ± 0.36 a	5.41± 0.41 c	7.43 ± 0.36 b	1.31
Cu	16.00 ± 1.15 a	11.03 ± 1.56 b	15.33 ± 0.66 a	4.09
Al	16.61 ± 0.70 a	6.12 ± 1.12 c	10.08 ± 0.52 b	2.83
Pb	3.66 ± 0.04 a	1.86 ± 0.59 b	0.80 ± 0.10 b	1.19

Note. Means for each element followed by different letters were different (LSDoo5).
[a]N, P, K, Ca, Mg, S, Mn, Fe, and Al (g kg^{-1}); Zn, B, Cu, and Pb (mg kg^{-1}).

Data Analysis

Soil elemental data were analyzed using analyses of variance (PROC GLM; SAS Institute, Inc., 2004), according to a completely random design with a fixed main effect for soil sample (preplanting, harvest control, and harvest leachate).

Tissue elemental data were analyzed using analyses of variance (PROC GLM; SAS Institute, Inc., 2004), according to a split split plot design with a random block effect and fixed main effects for irrigation treatment (whole plot), clone (sub plot), and plant tissue (sub sub plot). Where appropriate, nonsignificant ($P > .25$) interaction terms that included the block main effect were pooled into a common error term to increase precision of F tests (Zalesny, Riemenschneider, & Hall, 2005). Given the fixed main effects in both models, means were evaluated rather than variances. Fisher's protected least significant difference (LSD) was used to compare means of soil and tissue data.

RESULTS

Soil

There were four general trends in the soil concentration of macro- and micro-nutrients before planting and at the time of harvest for fertilized well water (control) and leachate irrigation treatments (Table 3): (a) the soil N concentration was greatest for leachate irrigation, while preplanting and control levels did not differ from one another; (b) the soil P, K, S, Zn, and Pb concentration was greatest before planting, while control and leachate levels did not differ from one another; (c) the soil Ca, Mg, B, Fe, and Al concentration was greatest before planting and least for the control irrigation; (d) the soil Mn and Cu concentration was greatest and similar before planting and after leachate irrigation.

Macronutrients (N, P, K, Mg, Ca, S)

Clone main effects were significant for N, P, K, Ca, and S (Table 4). The irrigation × clone interaction was significant for N, Ca, and S. Likewise, the tissue main effect was significant for all macronutrients. The irrigation × tissue interaction was significant for the following macronutrients: P, Mg, and S. The P concentration was significantly greatest for leaf tissue and least in the woody tissue (Figure 1A). The leaf and woody P concentration was greater with water irrigation than leachate, while trees of the leachate treatment exhibited greater P in the roots. The Mg concentration was significantly greatest for the combination of leachate irrigation and leaf tissue (Figure 1B). The control × leaf and leachate × root interactions were similar to one another yet greater than the remaining irrigation × tissue combinations.

The clone × tissue interaction was significant for the following macronutrients: N, P, Ca, Mg, and S (Table 4). The concentration of N, P, Ca, and Mg was greatest in the leaves, with the least amount allocated to the woody tissue (Figure 2). There was broad variation among and within genomic groups for N, P, Ca, and Mg concentration in the tissues. The BC_I clones ((*P. trichocarpa* × *P. deltoides*] × *P. deltoides*) and clone DN5 (*P. deltoides* × *P. nigra*) exhibited greater concentrations ofN and P in the leaves than those of the DM (*P. deltoides* × *P. maximowiczii*) and NM (*P. nigra* × *P. maximowiczii*) genomic groups (Figure 2A; Figure 2B). Clone NC14018 had a significantly greater amount of N and P in the leaves than NC13460. The woody N and P concentration was similar among genomic groups. There was more P in the woody tissue of NM2

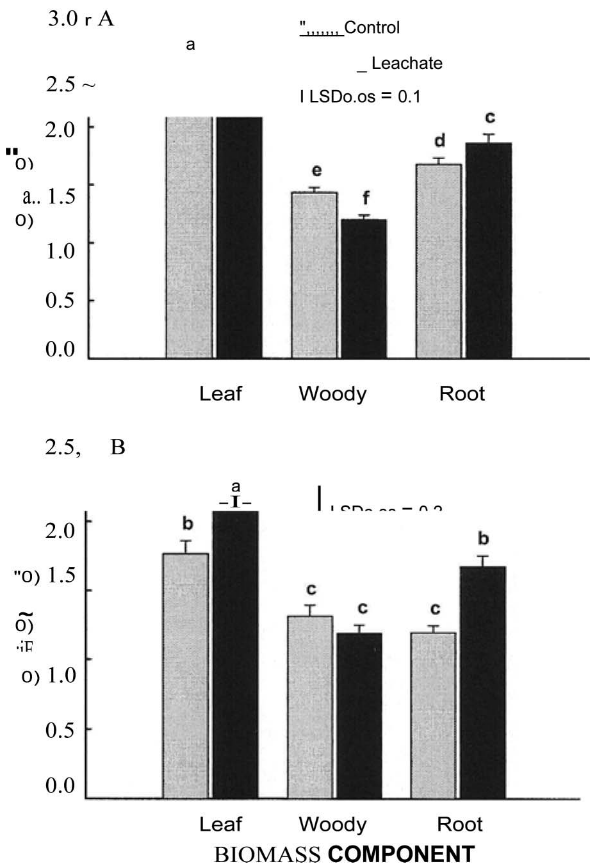
TABLE 4. Probability values from analyses of variance comparing the concentrations across two irrigation treatments (I; well water [control] and landfill Leachate), eight *Populus* clones (C; see Materials and Methods for descriptions), and three tissues (T; leaf, woody, and root). Significant values are in bold

	Source of Variation[a]						
Element	I	C	I × C	T	I × T	C × T	I × C × T
N	0.0577	**0.0133**	**0.0424**	**< 0.0001**	0.2112	**< 0.0001**	0.2158
P	0.4275	**0.0008**	0.6780	**0.0001**	**< 0.0001**	**0.0044**	0.3201
K	0.0560	**0.0506**	0.2325	**< 0.0001**	0.4040	0.0969	0.0995
Ca	0.9737	**0.0255**	**0.0477**	**< 0.0001**	0.1368	**< 0.0001**	0.1393
Mg	0.0998	0.0822	0.9289	**0.0003**	**0.0043**	**< 0.0001**	0.0730
S	0.1171	**< 0.0001**	**0.0257**	**< 0.0001**	**< 0.0001**	**< 0.0001**	**0.0479**
Zn	0.0665	0.1909	0.3906	0.0919	0.5748	0.6067	0.9755
B	**0.0059**	0.4481	0.5567	**0.0002**	**< 0.0001**	0.8133	0.7613
Mn	**0.0320**	**0.0239**	0.2333	**< 0.0001**	**< 0.0001**	**0.0060**	0.7443
Fe	**0.0036**	0.5035	0.5972	**< 0.0001**	**< 0.0001**	0.8528	0.6017
Cu	0.0782	**< 0.0001**	**0.0220**	**< 0.0001**	**< 0.0001**	**< 0.0001**	0.4852
Al	**0.0019**	0.6829	0.4097	**< 0.0001**	**< 0.0001**	0.8559	0.2032
Pb	0.6983	0.6535	0.6856	0.0608	0.0641	0.2046	0.0902

[a]The experimental layout in the field included eight blocks (i.e., replications). For simplicity, the block main effect and interaction terms including the block factor are not included in the table.

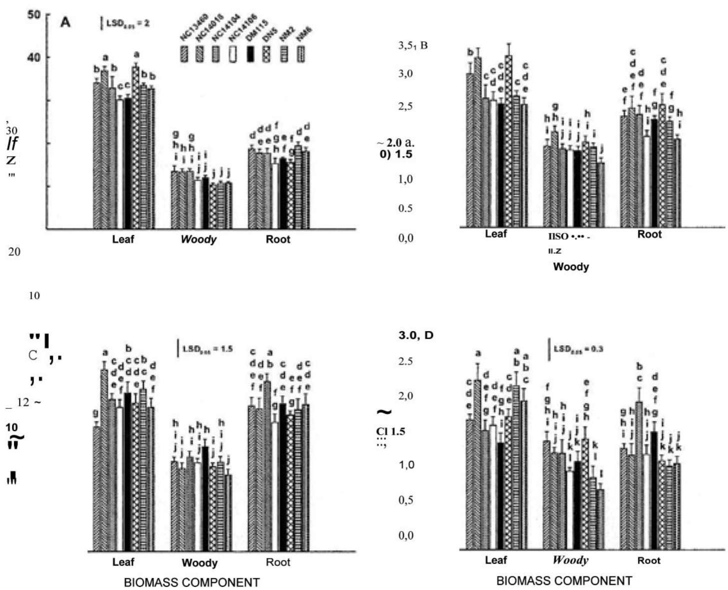
versus NM6. Root N concentration was similar among genomic groups and clones, with the exception of NC14106 and DN5 that had less N than the other genotypes. The BC_I genomic group and DN5 had greater root P concentration than the DM and NM genotypes, which resulted from significantly less P in the roots of NC14106 and NM6. Furthermore, the DM and NM clones, along with DN5, exhibited similar leaf Ca concentration to one another, while the BC_I clones varied (Figure 2C). Clone NC14018 exhibited significantly greater Ca in the leaves than NC13460. Differences for woody Ca concentration were negligible for genomic groups and clones. Root Ca concentration was uniform across genomic groups, despite variation among the DM genotypes. Clone NC14104 exhibited the greatest root Ca concentration, while NC14106 had the least amount of Ca in the roots. Moreover, the NM genomic group exhibited the greatest leaf Mg concentration, while the other genomic groups exhibited similar Mg levels in the leaves (Figure 2D). Clone NC14018

FIGURE 1. Concentration of phosphorus (A) and magnesium (B) in the leaf, woody, and root tissue across eight *Populus* clones when irrigated with well water (control) or landfill leachate for two growing seasons. Error bars represent one standard error of the mean (n_P = 24; n_{Mg} = 48). Bars labeled with the same letter were not different, according to Fisher's protected least significant difference (LSD).



had significantly greater leaf Mg concentration than NC13460. The BC[1] and DM clones, along with DN5, exhibited greater woody Mg concentration than the NM genotypes. No differences existed among clones within genomic groups. The DM clones exhibited greater root Mg concentration

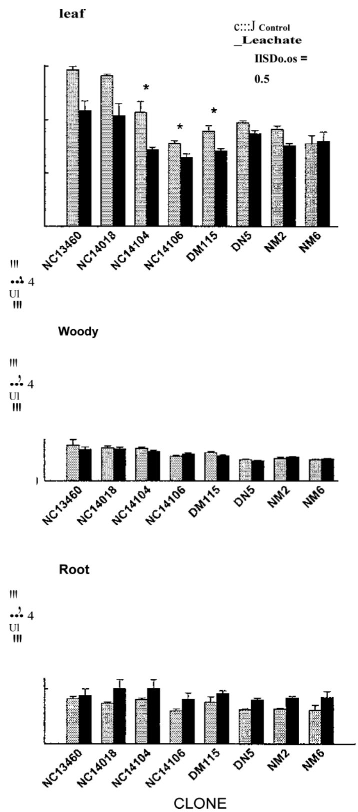
FIGURE 2. Concentration of nitrogen (A), phosphorus (B), calcium (C), and magnesium (D) in the leaf, woody, and root tissue of eight *Populus* clones across two irrigation treatments (well water [control] and landfill leachate). Error bars represent one standard error of the mean ($n_N = n_P = 6$; $n_{Ca} = n_{Mg} = 12$). Bars labeled with the same letter were not different, according to Fisher's protected least significant difference (LSD).



than those of the other genomic groups, while also differing among one other. Clone NC14104 had the greatest root Mg concentration and NC14106 the least.

The irrigation × clone × tissue interaction influenced the distribution of S in leaf, woody, and root tissue (Table 4). Sulfur levels were greatest in the trees irrigated with water, along with being most concentrated in the leaf tissue and least concentrated in the woody tissue (Figure 3). Leaf S concentration was dissimilar for genomic groups, with the following ranking from greatest to least S concentration: BC_1, DM, clone DN5, and NM. All clones exhibited greater leaf S concentration with water versus leachate, except for clone DN5 and NM6 which did not differ. The S concentration in woody tissue was not different among genomic groups and clones. Similarly, except for clone NC14018 which had greater root S

FIGURE 3. Concentration of sulfur for each combination of irrigation treatment (well water [control] and landfill leachate), *Populus* clone, and tree tissue (leaf, woody, and root). Error bars represent one standard error of the mean (n = 3). Asterisks denote treatment differences within a clone, according to Fisher's protected least significant difference (LSD).



concentration with leachate irrigation versus water, differences among irrigation × clone combinations for roots were negligible.

Micronutrients (Zn, B, Mn, Fe, Cu) and Beneficial Nutrients (Al, Pb)

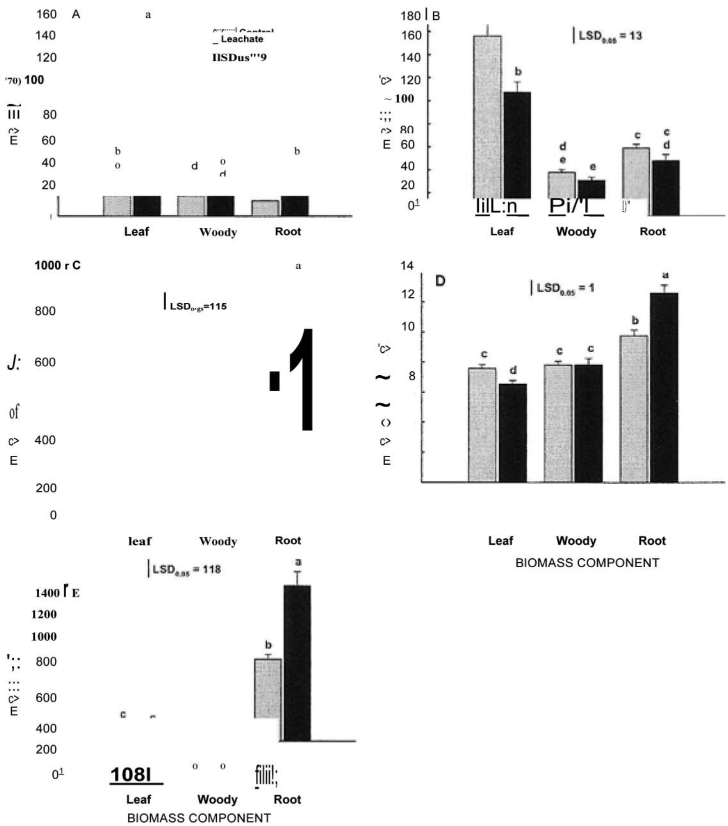
Irrigation treatments were significant for B, Mn, Fe, and AI, while clone main effects were significant for Mn and Cu (Table 4). The irrigation × clone interaction was significant for Cu. Likewise, the tissue main effect was significant for all micronutrients, except Zn and Pb. The irrigation × tissue interaction was significant for the following micronutrients: B, Mn, Fe, Cu, and Al (Table 4). The B concentration was significantly greatest for leaf tissue with leachate irrigation (Figure 4A). Additionally, the leachate treatment increased root B concentration relative to the water irrigation. The Mn concentration was greatest in the leaves and least in the woody tissue (Figure 4B). The leaf Mn concentration was significantly greater for water irrigation versus leachate. The root Fe concentration was significantly greater than in the leaf and woody tissue, and the leachate irrigation increased the root Fe concentration over the control (Figure 4C). The concentration of Cu and Al in leaf, woody, and root tissue showed similar trends as that of Fe (Figure 4D; Figure 4E).

The clone × tissue interaction was significant for the following micronutrients: Mn and Cu (Table 4). There was broad variation among and within genomic groups for Mn and Cu concentration in the tissues. The concentration of Mn was greatest in the leaves, with the least amount allocated to the woody tissue. Clones within the BC_l, DM, and NM genomic groups exhibited broad variation in leafMn concentration. Of the BC_l genotypes, clone NC14018 had greater leaf Mn levels than NC13460, while NC14104 and NC14106 had the greatest and least leaf Mn concentration, respectively, of the DM clones. Likewise, NM6 had significantly greater leaf Mn levels than NM2. Genomic group differences for woody and root Mn concentration were negligible. Clone NC14018 had greater root Mn concentration than NC13460. Furthermore, the concentration of Cu was greatest in the roots, with the least amount allocated to the leaves. Genomic group differences for leaf and woody Cu concentration were negligible. However, the leaf Cu concentration of NC13460 was greater than NC14018, while the woody Cu concentration of NC14106 was greater than NC14104. The BC_l genomic group exhibited significantly greater root Cu concentration than all other genomic groups. Clone DM115 had more Cu in the roots than NC14106.

DISCUSSION

Overall, based on the first 2 years of plantation development, there was broad variation in phytoaccumulation of macro- and micro-nutrients into leaf, woody, and root tissue of *Populus* when irrigated with municipal solid waste landfill leachate or nonfertilized water (Table 5). The leachate

FIGURE 4. Concentration of boron (A), manganese (B), iron (C), copper (D), and aluminum (E) in the leaf, woody, and root tissue across eight *Populus* clones when irrigated with well water (control) or landfill leachate for two growing seasons. Error bars represent one standard error of the mean ($n_B = 24$; $n_{Mn} = n_{Fe} = n_{Cu} = n_{Al} = 48$). Bars labeled with the same letter were not different, according to Fisher's protected least significant difference (LSD).



was not detrimental to tree health, which validated its use as an irrigation and fertilization source for the trees. These 2-year results are important for maximizing biomass production during initial establishment, as well as, serving as a basis for understanding negative impacts of phytotoxic amounts of any nutrient on long-term environmental sustainability (e.g., tree

TABLE 5. Percent of each element distributed among total leaf, woody, and root tissue across eight *Populus* clones irrigated with well water (control) and leachate from the Oneida County Landfill (Rhinelander, Wisconsin, USA) during the 2005 and 2006 growing seasons

Element	Control			Leachate		
	Leaf	Woody	Root	Leaf	Woody	Root
N	64	24	12	61	28	11
P	54	34	12	52	34	14
K	53	32	15	56	31	13
Ca	53	30	17	51	34	15
Mg	51	37	12	53	33	14
S	73	18	9	67	22	11
Zn	38	46	16	38	49	13
B	61	31	8	78	15	7
Mn	72	17	11	69	22	9
Fe	41	22	37	30	15	55
Cu	39	42	19	34	46	20
Al	27	10	63	17	9	74
Pb	27	47	26	30	55	15

health, soil health, and groundwater quality). In this study, N, P, and K were equalized across treatments to reduce fertilization effects and thereby isolate the effects of the other leachate constituents.

Macronutrients (N, P, K, Mg, Ca, S)

Urea ($[NH_2]_2$) CO) was used as the N source for the water irrigation treatment in the current study, while the leachate analyses showed N came from NH_4 and No_3– sources. *Populus* trees have utilized both NH_4 and No_3– forms of N, but have shown a preference for NH_4 (Dickmann, Isebrands, Blake, Kosola, & Kort, 2001). Similarly, *P. tremuloides* Michx. seedlings have utilized both NH_4 and $N0_3$– sources of fertilizer; however, there were interactions between pH and fertilizer source. DesRochers, van den Driessche, & Thomas (2003) reported that NH_4 was more available at high pH and No_3 was more available at low pH. They speculated that the broad ecological range of *P. tremuloides* may be partly attributed to its successful use of both sources of N fertilization (DesRochers et al., 2003).

The four parental *Populus* species (*P. trichocarpa, P. deltoides, P. nigra*, and *P. maximowiczii*) of the clones tested in the current study have broad geographic ranges that likely contributed to the ability of the genotypes to utilize different N sources.

At harvest (mid-August), the N concentration across tissues and clones in the control treatment ranged from 9.34 to 38.61 g kg^{-1}, with a mean of 21.58 ± 2.09 g kg^{-1} (2.16%), while the leachate treatment ranged from 10.70 to 36.87 g kg^{-1}, with a mean of 20.25 ± 1.82 g kg^{-1} (2.03%). The foliar N concentration of the control (3.5%) and leachate (3.2%) treatments were greater than the optimal amount recommended for poplar clones (3%) in mid-July in northern Wisconsin (Hansen, McLaughlin, & Pope, 1988), and that of 2.3% to 2.8% N reported for a *P. trichocarpa* × *P. deltoides* (TD) hybrid in British Columbia, Canada (van den Driessche, 2000). However, our leachate application rate in 2006 (236 kg N ha^{-1}) exceeded the range of recommended optimal N fertilization rates (85 to 185 kg N ha^{-1}) for the North Central United States (Hansen et al., 1988; Hansen, 1994; Stanturf, van Oosten, Netzer, Coleman, & Portwood, 2001). More specifically, Coleman, Friend, and Kern (2004) reported 2-year-old *P. deltoides* 'D105' grown in Rhinelander, Wisconsin, USA, acquired a maximum of 120 kg N ha^{-1} yr^{-1} from native and applied N sources, with trees receiving application rates of 50 and 100 kg N ha^{-1} yr^{-1} exhibiting near-optimal growth. The excess N applied in the current study likely contributed to luxury consumption of N into leaves. Similarly, DesRochers et al. (2006) reported 3.2% N in the leaves of one *P. balsamifera* L. (B) × *P. simonii* Carr. (S) hybrid '33 cv. P38P38' and two *P. deltoides* (D) × *P.* × *petrowskyana* (P) hybrids '24 cv. Walker' '794 cv. Brooks6' receiving 16 g N $tree^{-1}$, which was similar to that applied in 2006 in the current study (15.6 g N $tree^{-1}$). Likewise, leaf N concentration after one growing season of two TD clones (49–177,15–29), one DT clone (*P. deltoides* × *P. trichocarpa 'DTAC-T)*, and one TM clone (*P. trichocarpa* × *P. maximowiczii* '286–43') receiving 250 kg N ha^{-1} ranged from 2.6% to 4.1% (Brown & van den Driessche, 2005).

Our mid-August measurement (taken prior to leaf fall) of 3.2 to 3.5% N in leaf tissue indicated substantial late season N availability for plant processes. Leaf nutrient cycling is an important mechanism for deciduous trees, with more than 50% of N exported to woody and root tissues prior to leaf senescence (Dickmann et al., 2001). Baker and Blackmon (1977) reported seasonal changes in foliar, woody, and root N content for *P. deltoides*, with the greatest decrease in leaf N occurring prior to leaf fall. In late May, they measured 92% of tissue N in the leaves and 8% in the woody tissues (roots not reported), while tissue N allocation in late September was 53% (leaves), 15% (woody), and 32% (roots). Their N distribution in November was 15% (leaves), 35% (woody), and 50% (roots). Overall, the leaf nutrient distributional changes were attributed to internal cycling processes and not shifts in biomass allocation (Baker & Blackmon). Additionally, foliar N concentrations peaked in July (2.9%) and declined (1.5%) at leaf abscission, given N export to woody and root tissue (Baker & Blackmon).

Furthermore, in our study the soil N concentration at harvest was 2.5 times greater than preplanting levels, indicating quantities were applied that exceeded tree uptake. Given the possibility of N leaching into the groundwater, excess N and other nutrients in the leachate of future studies could be managed through dilution with water to reduce the concentration of elements that may have harmful effects on the soil and water.

Although the P application rate was equalized in the water and leachate treatments, differences existed within the irrigation treatment × tissue interaction. There was more P in the leaf and woody tissue of the water treatment, while the greatest root P concentration was with leachate irrigation. The optimal range of plant P is from 0.1% to 0.5%; however, levels of 0.15% P have been deficient for *Populus* (van den Driessche, 1999; Brown & van den Driessche, 2005). Baker and Blackmon (1977) reported decreasing leaf P concentrations from 0.23% in May to 0.12% in November. In late September, total tree P allocated to tissues was 32% (leaves), 21% (woody), and 47% (roots), while such allocations in November were 11% (leaves), 33% (woody), and 56% (root). These decreases in leaf P have been attributed to internal cycling processes that redistributed nearly 30% of P for future plant growth (Dickmann et al., 2001). DesRochers et al. (2006) reported differences in leaf P allocations among three N fertilization treatments (0, 8, and 16 g N tree^{-1}) for *Populus* clones 33 cv. P38P38, 24 cv. Walker, and 794 cv. Brooks6, with 0 g N tree^{-1} (0.20%) being greater than with 16 g N tree^{-1} (0.18%). The irrigation in the current study was most similar to their 16 g N tree^{-1} treatment; however, our leaf P levels were greater in both water (0.25%) and leachate (0.22%) treatments. Likewise, the stem P concentration for water (0.15%) and leachate (0.12%) irrigation in the current study substantiated that of poplar clones Beaupre and Trichobel (0.15%) that were irrigated with effluent and sewage sludge for three growing seasons (Moffat, Armstrong, & Ockleston, 2001). Furthermore, the soil P concentration before planting was 12 times greater than the harvest control plot and 10 times greater than the harvest leachate plot, which likely resulted in the soil providing additional P for plant uptake that was deficient in the irrigation treatments. Overall, the reduction of soil P contributes to ecological sustainability, especially in areas with elevated levels of lake and river enrichment.

Trees require the secondary macronutrients (Mg, Ca, and S) for growth and development at quantities that are similar to P. The Mg application rate in the current study was not equalized in the water and leachate irrigation treatments. Thus, there were differences for irrigation × clone and irrigation × tissue interactions. The leachate Mg concentration was 33 times greater than the water concentration. Greater leaf and root Mg levels were exhibited with leachate, while the stem Mg concentration was greatest with water. However, when irrigated with either treatment, distribution of Mg was greatest in the leaves and least in the root tissue (Table 5). Similarly, Baker and Blackmon (1977) reported September Mg allocations in *P. deltoides* of 58% (leaves), 25% (woody), and 17% (roots), while those in November were 41% (leaves), 35% (woody), and 24% (root). Our stem Mg concentrations with water (0.13%) and leachate (0.12%) treatments were similar to TD *Populus* clones Beaupre (0.11%) and Trichobel (0.09%) that were irrigated with effluent and sewage sludge for three growing seasons (Moffat et al., 2001). Furthermore, the soil Mg concentration at preplanting differed from harvest levels, with the water treatment utilizing the greatest amount of soil Mg. There was a 31% reduction of Mg in the control soils over the 2 years in the current study.

Additions were not made to the water treatment to equalize Ca; therefore, Ca concentration in the leachate was twice that of the water treatment. The distributional trends of Ca in the current study (Table 5) (i.e., greatest in the leaves and least in the root tissue) were similar to those of Baker and Blackmon (1977), who measured 50% (leaves), 35% (woody), and 10% (roots) in September and 39% (leaves), 31% (woody), and 30% (roots) in November. DesRochers et al. (2006) reported differences in leaf Ca allocations among three N fertilization treatments (0, 8, and 16 g N tree^{-1}) for *Populus* clones 33 cv. P38P38, 24 cv. Walker, and 794 cv. Brooks6, with 16 g N tree^{-1} (0.19%) exhibiting the greatest leaf Ca concentration. The irrigation in the current study was most similar to their 16 g N tree^{-1} treatment; however, our leaf Ca levels of 0.13% were equal for water and leachate treatments. Our stem Ca concentrations with water (0.71%) and leachate (0.76%) treatments were greater than TD *Populus* clones Beaupre (0.61 %) and Trichobel (0.59%) that were irrigated with effluent and sewage sludge for three growing seasons (Moffat et al., 2001). Furthermore, the soil Ca concentration at preplanting differed from harvest levels, with the water treatment utilizing the greatest amount of soil Ca. There was a 69% reduction of Ca in the control soils and 40% reduction in the leachate soils during the 2- year field study.

The S concentrations in the water and leachate were inadequate for optimal plant growth. However, the soil provided additional S and maintained overall plant tissue concentrations in leaf (0.37%), woody (0.16%), and root (0.10%) tissue within the general range of 0.1% to 0.5%. The soil S concentration was reduced by 99% in both treatments versus the preplanting value.

Micronutrients (Zn, B, Mn, Fe, Cu) and Beneficial Nutrients (Al, Pb)

Boron concentration differed for all water- and leachate-irrigated tissues, with the greatest levels in the leaf tissue. Although this study did not detect differences among clones for B tissue concentration, the DM genomic group (*P. deltoides* × *P. maximowiczii*) had the greatest amount of B in all tissues. Furthermore, clone DM115 had the greatest leaf concentration (172.33 mg B kg^{-1}), NC14106 had the greatest stem concentration (27.67 mg B kg^{-1}), and NC14104 had the greatest root concentration (43.33 mg B kg^{-1}). Likewise, Banuelos et al. (1999) reported higher concentrations of B in the leaves than stems of eight *Populus* hybrids belonging to three genomic groups (TD, DN, TN) when irrigated with 5 mg B L^{-1} at an electrical conductivity of 7 mS cm^{-1}, which was similar to our findings of the greatest leaf B concentrations at leachate salinity of 9.4 mS cm^{-1}. The concentration of B remaining in the soil (water, 1.0 mg B kg^{-1}; leachate, 2.0 mg B kg^{-1}) after two seasons of irrigation with the water (1.0 mg B L^{-1}) and leachate (12.5 mg B L^{-1}) decreased significantly relative to preplanting levels (8.0 mg B kg^{-1}).

Manganese had greater concentration in leaf tissue of trees irrigated with water versus leachate, despite that the leachate contained 12 times greater Mn in solution. The pattern for Mn was similar for each treatment, with significantly greater concentration in leaves versus roots and in roots versus woody tissue. This is a similar response to three DN clones (DN17, DN182, DN34) and two NM clones (NM2, NM6) irrigated with leachate, whereby the greatest Mn concentration was partitioned in leaf and stem tissue (Zalesny & Bauer, 2007a). The above ground concentration of Mn ranged from 100 to 350 mg kg^{-1}, with a mean of 220 mg kg^{-1} (Zalesny & Bauer, 2007a), which was ten times greater than Beaupre and Trichobel (19.4 mg $k^{-1}g$ each) (Moffat et aI., 2001) but consistent with that reported in the current study that ranged from 119 to 218 mg Mn kg^{-1}, with a mean of 166 mg Mn kg^{-1}. Furthermore, both irrigation treatments reduced the preplanting Mn level in the soil of the respective plot at harvest. The harvest soil concentration for the water treatment had a significant 50% decrease in soil Mn, indicating plants were able to extract and utilize stored Mn, which generally is more available for plant uptake in acidic soils (Foth, 1990). The leachate additions of Mn to the soil, along with tree uptake, resulted in the leachate soil Mn concentration being unchanged.

The root Fe concentration differed between the water (330.48 mg kg^{-1}) and leachate (838.67 mg kg^{-1}) treatments, which was intuitive given that there was nearly 8 times greater Fe in the leachate than the water. The woody Fe concentration of the water (82.33 mg kg^{-1}) and leachate (60.79 mg kg^{-1}) treatments in the current study was similar to that reported by Moffat et al. (2001) for two *Populus* clones: Beaupre (83.4 mg Fe kg^{-1}) and Trichobel (93.3 mg Fe kg^{-1}). Furthermore, the soil Fe concentration at preplanting differed from harvest levels. There was a 51% reduction of Fe in the control soils and 32% reduction in the leachate soils during the 2-year field study, indicating the trees were able to utilize soil Fe.

Irrigation treatments differed for the concentration of Cu in the leaves and roots, with the greatest amount of Cu allocated to the root tissue of leachate-irrigated trees (11.89 mg Cu kg^{-1}) versus water-irrigated trees (9.59 mg Cu kg^{-1}). The leaf tissue of the water treatment had greater Cu (7.71 mg kg^{-1}) than the leachate (6.52 mg kg^{-1}), which was similar to a leaf Cu concentration of 6.00 mg kg reported for three DN and two NM clones irrigated with landfill leachate (Zalesny & Bauer, 2007a), but greater than 1.8 to 3.6 mg Cu kg^{-1} for a TD clone (van den Driessche, 1999). Furthermore, soils for the water treatment at harvest showed a significant 31% decrease in soil Cu concentration, indicating plants were able to extract and utilize stored Cu from the soil, which generally is more available for plant uptake in acidic soils (Foth, 1990). The leachate additions of Cu to the soil, along with plant removal, left the leachate soil Cu concentration unchanged.

Aluminum concentrations were significantly different for root tissue, with the mean for the leachate irrigation (1069.05 mg Al kg^{-1}) being 191% of the root concentration of the water treatment (559.23 mg Al kg^{-1}). Aluminum availability from irrigation was limited. Laboratory analyses detected a very small quantity in the leachate and nothing in the well water. However, the preplanting soil had 16.61 mg Al kg across both treatment plots. Therefore, Al was available to all trees, especially given the low pH of the soil (5.7 ± 0.2) that increased the availability of Al for plant uptake. The preplanting and harvest soil analyses for water and leachate differed for Al concentration. The water treatment had a 63% decrease and the leachate treatment a 39% decrease in soil AI, indicating soil Al was available for uptake and the plants were able to utilize it for growth and development.

CONCLUSION

Biomass production of *Populus* is generally increased with irrigation and fertilization (Brown & van den Driessche, 2002; Coyle & Coleman, 2005; DesRochers et aI., 2006), with adequate water supply necessary for overall productivity (Dickmann, Nguyen, & Pregitzer, 1996). Landfill leachate offers an opportunity to supply water and plant nutritional benefits at a lower cost than traditional sources (Duggan, 2005). However, routine evaluation of leachate throughout the rotation is necessary to correct for any relevant changes in leachate chemistry that might affect plant health (Shrive et al., 1994; Kjeldsen et al., 2002). Such evaluation may elucidate the need for the addition of nutrients that are deficient, such as P, or for dilution to compensate for toxicity of specific elements. This study was conducted at a heterogeneous landfill site that was highly disturbed and that exhibited elevated concentrations of many macro- and micro-nutrients in the soil before planting. However, after two years of plantation development, leachate irrigation did not increase the concentration of any element over that found in the plot prior to leachate treatment, with the exception of N that did accumulate in the soil over preplanting values. Although rotation-age effects are unknown at this time, there was effective uptake of inorganic elements required for plant growth without detrimental impact to tree health or overall sustainability of the SRWC system, which validated the use of landfill leachate as an irrigation and fertilization source for the trees.

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FIGURE 1. Concentration of phosphorus (A) and magnesium (B) in the leaf, woody, and root tissue across eight *Populus* clones when irrigated with well water (control) or landfill leachate for two growing seasons. Error bars represent one standard error of the mean (n_P = 24; n_{Mg} = 48). Bars labeled with the same letter were not different, according to Fisher's protected least significant difference (LSD).

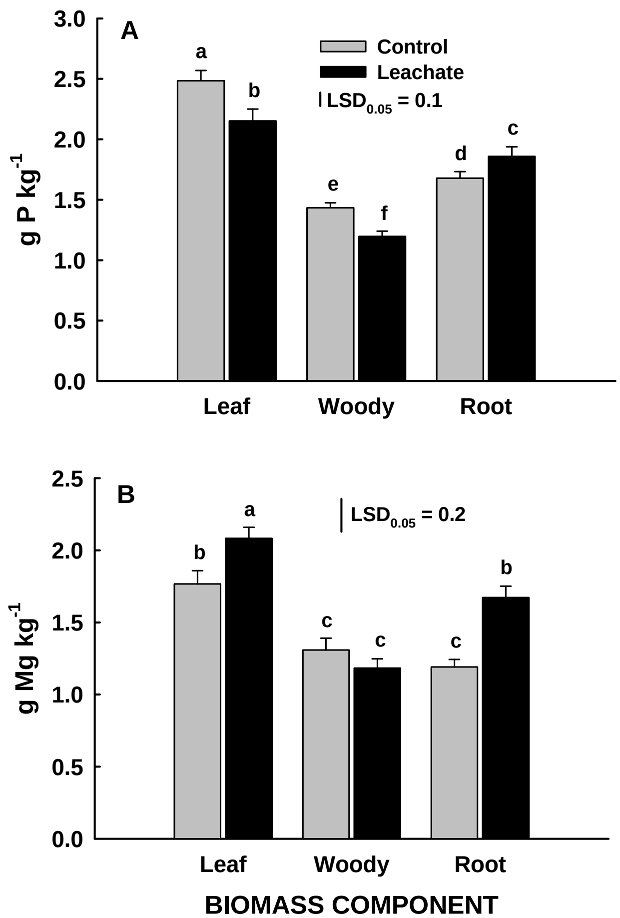

FIGURE 2. Concentration of nitrogen (A), phosphorus (B), calcium (C), and magnesium (D) in the leaf, woody, and root tissue of eight *Populus* clones across two irrigation treatments [well water (control) and landfill leachate]. Error bars represent one standard error of the mean ($n_N = n_P = 6$; $n_{Ca} = n_{Mg} = 12$). Bars labeled with the same letter were not different, according to Fisher's protected least significant difference (LSD).

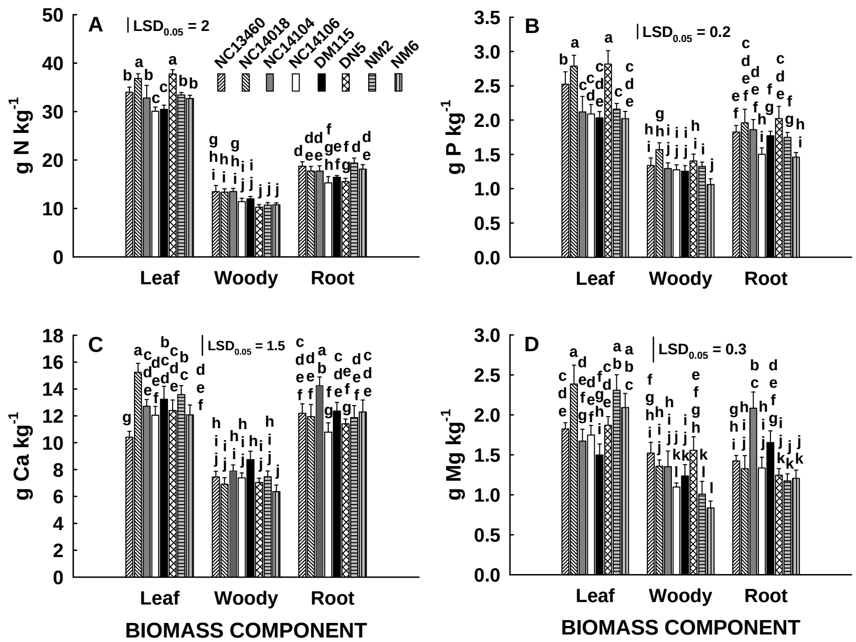

FIGURE 3. Concentration of sulfur for each combination of irrigation treatment [well water (control) and landfill leachate], *Populus* clone, and tree tissue (leaf, woody, and root). Error bars represent one standard error of the mean (n = 3). Asterisks denote treatment differences within a clone, according to Fisher's protected least significant difference (LSD).

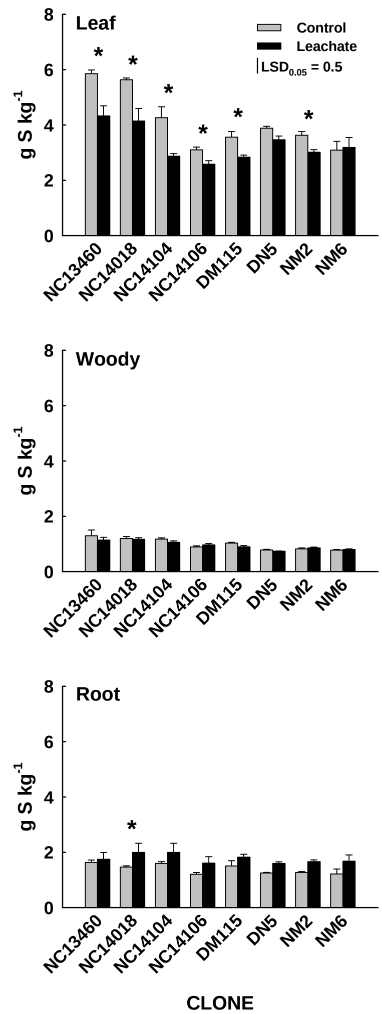

FIGURE 4. Concentration of boron (A), manganese (B), iron (C), copper (D), and aluminum (E) in the leaf, woody, and root tissue across eight *Populus* clones when irrigated with well water (control) or landfill leachate for two growing seasons. Error bars represent one standard error of the mean (n_B = 24; $n_{Mn} = n_{Fe} = n_{Cu} = n_{Al}$ = 48). Bars labeled with the same letter were not different, according to Fisher's protected least significant difference (LSD).

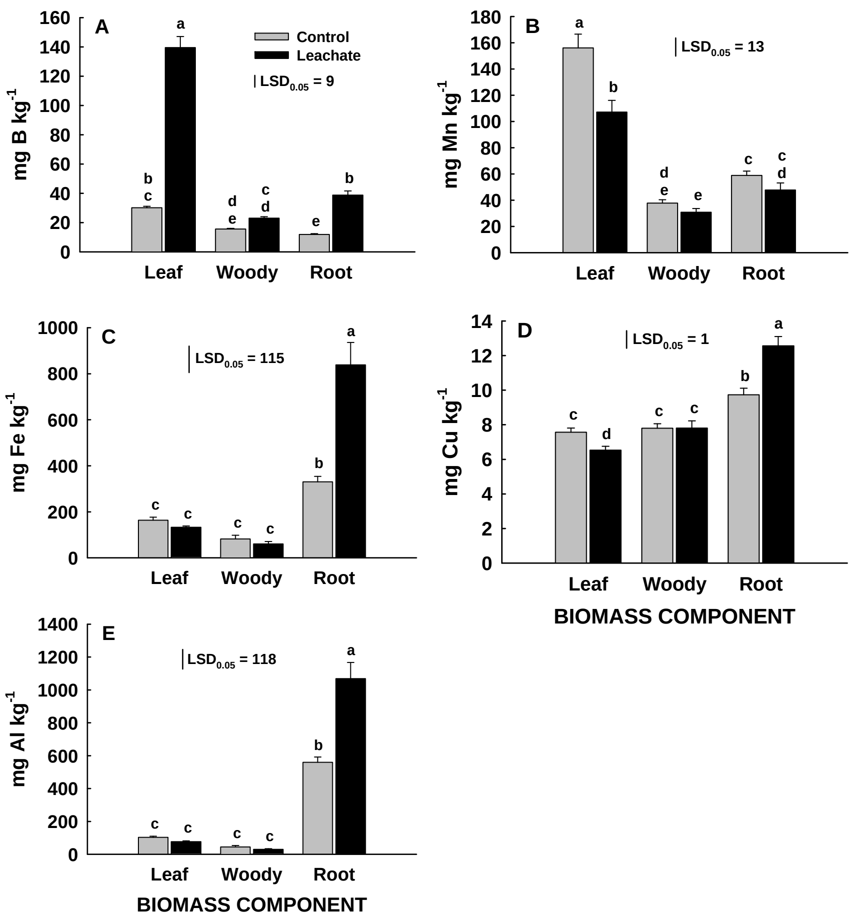

FIGURE 5. Concentration of manganese (A) and copper (B) in the leaf, woody, and root tissue of eight *Populus* clones across two irrigation treatments [well water (control) and landfill leachate]. Error bars represent one standard error of the mean (n = 12). Bars labeled with the same letter were not different, according to Fisher's protected least significant difference (LSD).