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Establishment of poplars in soils amended with fibercake residuals from paper and containerboard production

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Abstract Hybrid poplars (*Populus* sp.) are increasingly implemented in agroforestry systems across the U.S., mainly for their biomass production, carbon allocation, and ecosystem services. While agroforestry systems are usually established on marginal land, soil amendments, such as paper mill fibercake residuals, can provide necessary nutrients such as nitrogen (N) to increase poplar yield. To assess the effects of such amendments on poplar early growth and establishment, three clones (*Populus deltoides* Bartr. ex Marsh × *P. maximowiczii* A. Henry 'DM114'; *P. deltoides* × *P. nigra* L. 'DN170'; *P. nigra* × *P. maximowczii* 'NM2') were grown in a greenhouse for 35 days in soils amended with fibercake residuals from two northern Wisconsin sources (Expera Specialty Solutions, EXP, Rhinelander, WI; Packaging Corporation of America, PCA, Tomahawk, WI). Trees were grown in eleven different soil treatments (one potting mix control, one nursery soil treatment, and nine nursery soil-fibercake blends), with soils mixed according to tillable depth and N application rates. Expera treatments produced 4–30% greater values for growth parameters (excluding root number) and 2% greater values for biomass parameters (excluding root dry mass and root–shoot ratio) than other treatments containing fibercake (i.e., PCA and combined EXP + PCA treatments). Clone 'NM2' produced the greatest values for all parameters tested, while 'DM114' and 'DN170' values were typically intermediate and low, respectively. 'NM2' grown in Expera soils produced the highest values for all parameters, suggesting that 'NM2' has potential for greater early growth and biomass production on agroforestry sites amended with Expera fibercake.

Keywords Paper mill biosolids · *Populus* hybrids · Soil amendments · Industrial byproducts

Introduction

Agroforestry, the combination of agricultural and silvicultural systems, was formally introduced in the early twentieth century as a way to reduce erosion on cultivated lands (Smith 1929; Gold 2017). Since then, numerous additional benefits of the practice have been outlined, both environmental and economic. For example, environmental services provided by agroforestry systems include carbon sequestration,

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enhanced soil fertility, biodiversity conservation, and improved air and water quality (Jose 2009), as well as pest control, pollination/seed dispersal, soil stabilization, increases in net primary production, flood mitigation, and aesthetic/cultural benefits (Kremen 2005). Economic benefits of agroforestry are also abundant; however, the magnitude of the return depends on the species of tree that is implemented. All trees have specific establishment, maintenance, and harvest costs in addition to species-specific market values (which can fluctuate), that dictate end return to the landowner (Lazarus et al. 2015). Ultimately, the end product (e.g., biomass for bioenergy, timber products such as furniture, lumber, and mulch, or edible components such as black walnut, pecan, and elderberry) and its corresponding market dictate the economic benefits derived from an agroforestry system (Gold et al. 2015). The magnitude of economic benefits is also influenced by which agroforestry practice is involved (Peters 2000), i.e., windbreaks, riparian buffers, alley cropping, silvopasture, forest farming, and/or urban food forests.

Regardless of the specific practice, agroforestry systems across the United States (U.S.) are increasing in total area covered. Schoenenberger et al. (2017) reported that 6520 km of windbreaks and 44,130 ha of the other four practices combined were applied in the U.S. during fiscal years 2012–2015 using all United States Department of Agriculture (USDA) Farm Service Agency and Natural Resources Conservation Service conservation programs. These numbers do not include the areas of agroforestry systems established by non-federal entities, such as state and nongovernmental organizations. As global climate change, population growth, and resource degradation threaten ecosystem services and food/energy security, agroforestry systems are likely to continue growing in number and scale (Jose et al. 2012), especially when short rotation woody crops are considered (Lin et al. 2010).

Agroforestry does not require prime agricultural land to succeed; agroforestry systems are commonly established on marginal sites. In fact, agroforestry systems are purported to be successful on land facing a myriad of problems, including those related to natural degradation (e.g., wind and water erosion of soil, wildfires) and human-caused degradation (e.g., deforestation, land-use change, decline in soil fertility due to chemical fertilizers or overuse of land) (Le Houérou 1993; Acharya and Kafle 2009; Xu et al. 2012; Djanibekov et al. 2018; Pande et al. 2018). As a result, ensuring maximum production of crops and trees on such land can be challenging. Tree, crop, and livestock species must be selected that can not only survive but produce the largest possible yield as well. Some characteristics of interest during the selection process are: light utilization and the effects of shading (Lin et al. 2001; Pang et al. 2019); rooting traits such as competitiveness, distribution, and density (Schroth 1995); species compatibility, value, marketability, survival, and growth rate (Gold et al. 2015).

Hybrid poplars (*Populus* sp.) meet many of these selection criteria and are therefore commonly used in agroforestry systems. Poplars are known for their rapid growth, extensive root systems, and ease of vegetative propagation (Stanton et al. 2014). In particular, poplar productivity potential has been reported to range from 4 to 13 dry Mg ha^{-1} year^{-1}, sometimes even exceeding 20 dry Mg ha^{-1} year^{-1} in the Midwestern U.S. (Zalesny et al. 2009, 2016). Because their growth is so rapid (rotation length of less than 20 years), poplars are also referred to as short rotation woody crops (SRWCs) and are grown in biomass/bioenergy production systems (Zalesny et al. 2011). Further, poplars grow well on marginal land, so much so that they are extensively implemented in phytotechnology systems, i.e., systems that use plants to clean up contaminated soil and water (Tsao 2003). Poplars have been successfully used to remediate inorganic [e.g., heavy metals (Sebastiani et al., 2004), salts (Zalesny et al. 2008), nitrates (Zalesny et al. 2006)] and organic contaminants [e.g., explosives (Thompson et al. 1998), volatile organic compounds (Ma et al. 2004), petroleum hydrocarbons (Zalesny et al. 2005b), pesticides (EPA 2005), and veterinary antibiotics (Lin et al. 2010)]. Recently, poplars have become a major component in agroforestry systems across the U.S., and the world (Guevara-Escobar et al. 2007; Nerlich et al. 2013; Gamble et al. 2014). The benefits of poplars in agroforestry systems are plenty. Poplars provide biomass production for renewable energy, production of wood-based products, carbon allocation, windbreaks, and increased water/soil/air quality (Christersson 2008; Schoeneberger et al. 2017). Nevertheless, poplars, as with any other species, must go through a selection process in order to enhance genotype-by-environment interactions.

Once particular poplar genotypes are selected for an agroforestry system, site managers must determine how to maximize their economic and environmental returns. While poplars thrive on marginal lands, some soil conditions, like nitrogen (N) deficiency, can decrease productivity if fertilization does not occur. Traditional chemical fertilization methods are both costly (Lazarus et al. 2015) and environmentally unsound. One alternative for increasing soil N is to incorporate industrial byproducts such as fibercake residuals into the soil. Fibercake residuals (also known as paper mill biosolids) are solid wastes mainly composed of organic matter and nutrients generated during the pulping of wood and are collected during the treatment of mill wastewater (Mohammed et al. 2012). The U.S. pulp and paper industry alone produces over 4.8 million metric tons of such residuals each year (NCASI 1999). Essential plant nutrients contained in the residuals include N, phosphorus (P), and potassium (K), among others like calcium (Ca) (Lteif et al. 2007). Research has documented the positive effects of industrial residuals such as composted sewage sludge (Lombard et al. 2011), boiler ash (Cavaleri et al. 2004), and biochar (Thomas et al. 2018) on SRWC plantations, however, literature linking solid fibercake residuals with poplar production is very limited (Marron 2015). Thus, there is a need to assess the effects of fibercake residual soil amendments on poplar trees grown for agroforestry systems. The residuals have the potential to not only increase poplar yield, but also to close the loop of waste production in the paper and containerboard industry.

The objectives of the current study were to assess the early growth and establishment of three hybrid poplar clones grown in soils amended with fibercake residuals. Further, we sought to determine the most effective soil-fibercake combinations for future nursery and field production, and biomass-producing agroforestry systems. To do so, we collected data 35 days after planting on height, diameter, leaf area, number of leaves, number of roots, belowground biomass, aboveground biomass, and root–shoot ratio, and tested for differences among genotypes, soil-fibercake treatments, and their interactions.

Materials and methods

Fibercake properties

Fibercake residuals were collected from two sources in northern Wisconsin. Expera Specialty Solutions (Rhinelander, WI, USA) (known as Ahlstrom-Munksjö after completion of this study) provided residuals from papermaking, while Packaging Corporation of America (PCA) (Tomahawk, WI, USA) provided residuals from the production of containerboard (i.e., the outer layers and fluted center layer of corrugated containers). Both residual byproducts were combined primary (wood fiber) and secondary (bacterial biomass) blended residuals. The Expera fibercake was known to release available-N while the PCA residual was known to immobilize N when applied to agricultural sites (Rogers et al. 2018).

All fibercake residuals were transported to the USDA Forest Service, Northern Research Station, Institute for Applied Ecosystem Studies (Rhinelander, WI, USA). Packaging Corporation of America residuals were stored outside under a tarp to eliminate moisture accumulation through precipitation. Expera residuals were stored indoors in sterile, air-tight covered 3.8-L buckets after being air-dried for 48 h. The residuals were stored differently due to differences in chemical composition, specifically the release of available-N. Since the Expera fibercake contains fresh bacteria and actively releases N, it needed to be dried to prevent N release via denitrification. Packaging Corporation of America fibercake contains stabilized dead bacteria and does not actively release N, and therefore was stored outside.

The two fibercake residuals had differing characteristics, where PCA fibercake had smaller grains, while Expera fibercake had large clods. For this reason, Expera fibercake was first ground in a Thomas-Wiley Laboratory Mill Model 4 (Arthur H. Thomas Co., Philadelphia, PA, USA) without a screen to break up the large clods. Then, both fibercakes were sifted through 2 mm sieve until a homogenized particle size was achieved. In addition to the fibercake products, we also used nursery soils collected at the USDA Forest Service, Rhinelander Experimental Forest (Rhinelander, WI, USA) and potting mix (Jolly Gardener PRO-LINE C/G, Amherst Junction, WI, USA). The nursery is the site of future out-planting using these fibercake residuals, and the potting mix served as a control.

Nursery soil and potting mix were also sifted through the 2 mm sieve.

Experimental design and plant materials

Eleven soil treatments were tested, including one potting mix control, one treatment of nursery soils, and nine nursery soil-fibercake blends that were mixed based on expected N uptake of the trees and Wisconsin Department of Natural Resources regulations for field N loading (Table 1). Nursery soils were collected to a depth of 61 cm from the Rhinelander Experimental Forest Eastern Unit (45.634539°N, − 89.479117°W) and are classified as Keweenaw–Sayner–Vilas complex (Soil Survey Staff 2020). There were three blends of nursery soil mixed with Expera residuals, three blends with PCA residuals, and a three-component blend of nursery soil + Expera + PCA. Soil concentrations for each treatment were based on our maximum effective tilling depth of 15.2 cm (i.e., all percentages of treatment constituents were based on a 15.2 cm depth in the field). Standard application procedures for PCA typically involve applying no more than 10.2 cm of fibercake to a site. Therefore, the three PCA-nursery soil treatments were based on fibercake depths of 2.5, 5.1, and 10.2 cm. Expera treatments, on the other hand, were calculated to achieve application rates of 50, 100, and 200 kg available N ha^{-1} based on the methods of Coleman et al. (2004). Concentration values for the nursery soil + Expera + PCA combination treatments were based on the Expera rates for available N. Soil concentrations for all treatments were calculated volumetrically to achieve desired application rates and proportions and mixed manually (Table 1). The sieved soil treatments were then transferred into 10.16- × 10.16- × 30.48-cm CP412CH Treepots (Stuewe and Sons, Inc., Tangent, OR, USA). Three subsamples of each treatment, along with the two fibercake sources described above, were sent to the University of Wisconsin Soil and Forage Analysis Laboratory (Marshfield, WI, USA) for analysis of macronutrients [i.e., total carbon (C), N, P, K, Ca, magnesium (Mg), sulfur (S)], micronutrients [i.e., boron (B), copper (cu), iron (Fe), Manganese (Mn), sodium (Na), zinc (Zn)], nitrate–N (NO_3–N),

Table 1 Proportions of papermaking fibercake residuals from expera specialty solutions (EXP; Rhinelander, WI), containerboard fibercake residuals from packaging corporation of America (PCA; Tomahawk, WI), and nursery soils from the USDA forest service, rhinelander experimental forest (NURS; Rhinelander, WI) used for two- and three-component blends, as well as nursery soils and a standard potting mix control (POTT) used for soil treatments to test the early growth and biomass production of three hybrid poplar clones (*Populus deltoides* Bartr. ex Marsh × *P. maximowiczii* A. Henry ‘DM114’; *P. deltoides* × *P. nigra* L. ‘DN170’; *P. nigra* × *P. maximowczii* ‘NM2’)

Soil treatment		EXP (%)	PCA (%)	NURS (%)
EXP1	EXP + NURS	2	0	98
EXP2	EXP + NURS	4	0	96
EXP3	EXP + NURS	8	0	92
PCA1	PCA + NURS	0	17	83
PCA2	PCA + NURS	0	33	67
PCA3	PCA + NURS	0	67	33
COM1	EXP + PCA + NURS	2	65	33
COM2	EXP + PCA + NURS	4	63	33
COM3	EXP + PCA + NURS	8	58	33
NURS	NURS	0	0	100
POTT	POTT	100% potting mix control		

Soil concentrations for each treatment were based on a maximum effective tilling depth of 15.2 cm. Standard application procedures for PCA typically involve applying no more than 10.2 cm of fibercake to a site. Thus, the three PCA treatments were based on fibercake depths of 2.5 (PCA1), 5.1 (PCA2), and 10.2 (PCA3) cm. Given active mobilization of nitrogen (N) in the soil, EXP treatments were based on application rates of 50 (EXP1), 100 (EXP2), and 200 (EXP3) kg available N ha^{-1}, according to Coleman et al. (2004)

ammonium–N (NH_4–N), and total Kjeldahl nitrogen (TKN). Electrical conductivity (EC) and chloride (Cl^-) were analyzed at the USDA Forest Service, Northern Research Station, Institute for Applied Ecosystem Studies (Rhinelander, WI, USA). Soil chemical properties of each treatment are listed in Table 2.

Three hybrid poplar genotypes (*Populus deltoides* Bartr. ex Marsh × *P. maximowiczii* A. Henry 'DM114'; *P. deltoides* × *P. nigra* L. 'DN170'; *P. nigra* × *P. maximowczii* 'NM2') were tested. Whips were collected during dormancy from Hugo Sauer Nursery (45.634387°N, − 89.464089°W) (Rhinelander, WI, USA) and processed into cuttings 12.7 cm in length, with at least one bud in the top 2.54 cm of each cutting. Before planting, cuttings were soaked in water to a height of 6.35 cm for 48 h. Cuttings were planted in the CP412CH Treepots with an individual soil volume of 2.27 L and were irrigated with well-water according to demand. Trees were grown for 35 days in a greenhouse with a 16-h photoperiod and daytime and nighttime temperatures of 24 °C and 20 °C, respectively. Trees were arranged in a split-plot design with three random block effects, eleven fixed soil treatment whole plots, and three fixed clone sub-plots. Five trees per treatment × clone interaction were tested in each block, resulting in a total of 495 trees tested. Effects of potential greenhouse gradients were mitigated by arranging the clones in randomized complete blocks.

At 35 days of growth, tree height was measured from the point of attachment between the primary stem and the original cutting to the tip of the apical bud. Diameter was measured 1.5 cm above the point of attachment, reducing error caused by stem swell. Leaf area was measured on leaves from the third, sixth, and ninth Leaf Plastochron Index (i.e., LPI 3, 6, 9) (Larson and Isebrands 1971) from each tree using a LI-COR 3000 Leaf Area Meter (LI-COR Inc., Lincoln, NE, USA). Prior to data analyses, areas of the leaves were bulked on an individual-tree basis. Trees were harvested, washed, and separated into: roots, cuttings, stems, and leaves. Number of roots and number of leaves per tree were counted. All tissues were dried in an oven at 55 °C until constant mass was achieved. Root–shoot ratio was then calculated as the ratio of belowground biomass (root dry mass) to aboveground biomass (dry mass of stems + leaves).

Statistical analysis

All data were tested using analyses of variance (ANOVA) and analyses of means (ANOM) according to SAS® (PROC GLM; PROC ANOM; SAS Institute, INC., Cary, North Carolina, USA) using a split-plot design with three random block effects, eleven fixed soil treatment whole plots, three fixed clone sub-plots, and five trees per treatment × clone interaction. The block × clone interaction for root–shoot ratio had a probability value equal to $P = 0.2686$; thus, this term was pooled with the error term to test clone and treatment × clone effects. The block × clone interaction had $P > 0.25$ for all other growth parameters and, therefore, no pooling was conducted for those parameters. Analyses of covariance (ANCOVA) were conducted to test for potential effects of cutting dry mass, which was significant ($P < 0.05$) for all parameters. Therefore, all means were adjusted for cutting dry mass. Fisher's protected least significant difference (LSD) was used to separate means of main effects at a probability level of $P < 0.05$.

Results

Poplar growth parameters

The treatment × clone interaction was significant for height ($P < 0.0001$) (Table 3). Height ranged from 10.9 ± 0.9 ('DN170' COM3) to 29.0 ± 0.9 cm ('NM2' EXP3), with an overall mean of 17.5 ± 0.9 cm (Fig. 1). Clone 'NM2' produced the greatest height across treatments, with trees 59% and 93% taller than those of 'DM114' and 'DN170', respectively. EXP, PCA, and COM treatments reduced height 0%, 14%, and 16% compared to NURS and 9%, 24%, and 26% compared to POTT, respectively. Both EXP1 and EXP3 produced greater height than NURS, but POTT produced the tallest trees overall. Treatments containing Expera fibercake produced trees with height 14% greater than PCA treatments and 16% greater than combination treatments. There were similar trends in clonal responses to treatments, with EXP treatments producing tree height 25%, 7%, and 4% greater than PCA treatments and 27%, 7%, and 7% greater than combination treatments for 'NM2', 'DM114', and 'DN170', respectively.

Table 2 Chemical properties of two fibercake residual sources (EXP; PCA) and nursery soils (NURS) mixed for two- and three-component blends, as well as potting mix control (POTT) used as soil treatments to test the early growth and biomass production of three hybrid poplar clones (*Populus deltoides* Bartr. ex Marsh × *P. maximowiczii* A. Henry 'DM114'; *P. deltoides* × *P. nigra* L. 'DN170'; *P. nigra* × *P. maximowczii* 'NM2'). See Table 1 for a description of soil treatments

Treatment	P (mg kg^{-1})	K (mg kg^{-1})	S (mg kg^{-1})	B (mg kg^{-1})	Cu (mg kg^{-1})	Mn (mg kg^{-1})	Na (mg kg^{-1})	Zn (mg kg^{-1})	Cl (mg kg^{-1})	NO_3-N (mg kg^{-1})	NH_4-N (mg kg^{-1})
EXP	3786.7 ± 46.3	1536.7 ± 38.4	3583.3 ± 46.3	12.6 ± 1.2	57.9 ± 9.8	67.5 ± 0.5	373.1 ± 2.8	130.8 ± 1.5	634.5 ± 17.2	6.8 ± 0.2	137.1 ± 7.8
PCA	973.3 ± 29.6	546.7 ± 23.3	1460.0 ± 35.1	15.8 ± 2.0	40.2 ± 5.2	433.8 ± 18.5	393.3 ± 44.8	98.5 ± 4.3	117.3 ± 4.2	3.5 ± 0.0	12.7 ± 0.3
EXP1	406.7 ± 8.8	616.7 ± 59.3	126.7 ± 6.7	0.0 ± 0.0	5.3 ± 0.4	246.0 ± 13.5	32.6 ± 2.2	21.9 ± 0.7	23.6 ± 1.2	7.5 ± 0.1	19.7 ± 3.2
EXP2	376.7 ± 23.3	610.0 ± 17.3	120.0 ± 5.8	0.0 ± 0.0	5.3 ± 0.1	301.4 ± 103.4	35.0 ± 4.3	20.4 ± 0.3	29.3 ± 6.6	6.9 ± 0.1	26.3 ± 1.5
EXP3	396.7 ± 8.8	616.7 ± 8.8	136.7 ± 3.3	0.0 ± 0.0	5.3 ± 0.1	233.2 ± 23.7	33.3 ± 1.0	21.8 ± 0.4	32.1 ± 2.4	7.4 ± 0.1	34.6 ± 4.0
PCA1	370.0 ± 5.8	600.0 ± 11.5	126.7 ± 3.3	0.0 ± 0.0	5.1 ± 0.0	216.3 ± 17.7	39.6 ± 1.2	21.5 ± 0.3	19.5 ± 1.4	5.1 ± 0.1	6.6 ± 0.1
PCA2	350.0 ± 11.5	593.3 ± 17.6	123.3 ± 6.7	0.0 ± 0.0	5.3 ± 0.8	187.9 ± 6.3	54.7 ± 1.0	21.5 ± 1.1	16.3 ± 0.9	2.6 ± 0.5	5.5 ± 0.8
PCA3	510.0 ± 58.6	620.0 ± 23.1	403.3 ± 89.7	3.0 ± 0.9	11.5 ± 2.3	266.6 ± 33.4	192.5 ± 32.2	37.9 ± 5.0	31.5 ± 7.9	1.7 ± 0.0	7.4 ± 0.3
COM1	640.0 ± 90.7	593.3 ± 8.8	650.0 ± 175.2	6.2 ± 1.2	17.7 ± 3.5	274.3 ± 26.0	229.6 ± 49.4	49.2 ± 8.8	48.1 ± 4.6	2.0 ± 0.1	8.8 ± 0.9
COM2	510.0 ± 43.6	606.7 ± 23.3	380.0 ± 55.7	3.0 ± 0.2	10.0 ± 1.0	245.1 ± 10.9	169.2 ± 16.3	34.9 ± 2.2	54.2 ± 6.1	1.9 ± 0.1	11.3 ± 0.7
COM3	696.7 ± 116.1	656.7 ± 52.4	666.7 ± 160.5	3.8 ± 1.6	17.1 ± 4.5	284.8 ± 25.6	230.9 ± 41.8	49.3 ± 8.7	75.4 ± 8.3	2.1 ± 0.1	13.1 ± 1.1
NURS	373.3 ± 8.8	856.7 ± 282.4	116.7 ± 3.3	0.0 ± 0.0	4.9 ± 0.2	199.5 ± 16.3	30.4 ± 3.9	19.6 ± 1.0	17.2 ± 2.1	6.9 ± 0.0	6.4 ± 0.4
POTT	500.0 ± 50.3	6596.7 ± 611.7	1576.7 ± 235.7	6.8 ± 1.6	15.5 ± 1.9	196.2 ± 30.0	709.5 ± 43.3	34.9 ± 2.5	55.8 ± 1.5	476.0 ± 20.1	4.1 ± 0.9

Treatment	C (g kg^{-1})	N (g kg^{-1})	Ca (g kg^{-1})	Mg (g kg^{-1})	Fe (g kg^{-1})	TKN (g kg^{-1})	C:N (dS m^{-1})	pH (dS m^{-1})	EC (dS m^{-1})
EXP	294.3 ± 7.9	27.1 ± 0.3	17.9 ± 0.2	1.7 ± 0.0	2.2 ± 0.1	27.2 ± 0.6	10.9 ± 0.2	7.3 ± 0.1	20.3 ± 0.1
PCA	245.7 ± 5.6	6.8 ± 0.3	26.5 ± 0.6	2.1 ± 0.1	4.1 ± 0.1	7.9 ± 0.1	36.2 ± 1.0	7.4 ± 0.1	9.3 ± 0.2
EXP1	17.6 ± 0.7	1.3 ± 0.1	2.1 ± 0.1	1.7 ± 0.0	9.9 ± 0.2	1.4 ± 0.1	13.7 ± 0.9	6.2 ± 0.1	0.6 ± 0.0
EXP2	18.6 ± 0.8	1.4 ± 0.1	1.8 ± 0.1	1.6 ± 0.1	9.4 ± 0.5	1.2 ± 0.1	13.3 ± 0.0	6.3 ± 0.1	0.7 ± 0.2
EXP3	18.7 ± 1.4	1.6 ± 0.1	1.8 ± 0.0	1.7 ± 0.0	10.0 ± 0.4	1.4 ± 0.1	12.0 ± 0.6	6.6 ± 0.1	0.8 ± 0.1
PCA1	17.3 ± 1.0	1.3 ± 0.1	1.9 ± 0.0	1.7 ± 0.0	9.3 ± 0.3	1.4 ± 0.1	13.1 ± 0.7	6.5 ± 0.1	0.6 ± 0.0
PCA2	22.8 ± 0.9	1.5 ± 0.1	2.3 ± 0.1	1.8 ± 0.1	9.3 ± 0.3	1.5 ± 0.0	15.2 ± 0.3	6.5 ± 0.1	0.7 ± 0.1
PCA3	53.3 ± 1.7	2.0 ± 0.1	7.5 ± 1.8	1.7 ± 0.0	7.3 ± 0.1	2.3 ± 0.1	27.2 ± 1.1	7.1 ± 0.0	3.3 ± 0.2
COM1	59.4 ± 5.7	2.3 ± 0.1	10.2 ± 2.7	2.0 ± 0.2	7.0 ± 0.4	2.4 ± 0.1	25.7 ± 1.5	7.3 ± 0.1	2.7 ± 0.3
COM2	46.5 ± 8.1	1.9 ± 0.2	6.0 ± 0.7	1.7 ± 0.1	7.6 ± 0.2	2.7 ± 0.1	23.7 ± 1.7	7.1 ± 0.0	3.8 ± 0.5
COM3	59.2 ± 2.8	2.3 ± 0.1	9.6 ± 2.1	1.9 ± 0.1	6.9 ± 0.2	2.9 ± 0.1	25.7 ± 0.6	7.1 ± 0.0	4.4 ± 0.6
NURS	16.7 ± 0.6	1.4 ± 0.0	1.8 ± 0.1	1.7 ± 0.1	9.2 ± 0.6	1.3 ± 0.1	11.9 ± 0.5	6.3 ± 0.1	0.6 ± 0.0
POTT	233.6 ± 13.1	5.9 ± 0.5	11.8 ± 0.8	16.8 ± 1.3	11.3 ± 0.9	3.9 ± 0.1	40.0 ± 1.0	6.0 ± 0.2	17.4 ± 0.9

Chemical properties: total carbon (C), nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulfur (S), boron (B), copper (cu), iron (Fe), manganese (Mn), sodium (Na), zinc (Zn), chloride (Cl^-), nitrate (NO_3–N), ammonium–N (NH_4–N), total Kjeldahl nitrogen (TKN), carbon:nitrogen ratio, and electrical conductivity (EC)

Table 3 Probability values from analyses of variance in a study testing the establishment of three hybrid poplar clones (*Populus deltoides* Bartr. ex Marsh × *P. maximowiczii* A. Henry 'DM114'; *P. deltoides* × *P. nigra* L. 'DN170'; *P. nigra* × *P. maximowczii* 'NM2') grown in soils amended with fibercake residuals from paper and containerboard production. Significant effects are bolded. See Table 1 for a description of soil treatments

Trait	Source of variation		
	Treatment	Clone	Treatment × Clone
Height	**< 0.0001**	**< 0.0001**	**< 0.0001**
Diameter	0.1655	**0.0006**	0.8152
Leaf area	**< 0.0001**	**0.0003**	**0.0106**
Number of leaves	**0.0004**	**0.0005**	0.2982
Number of roots	**0.0053**	0.0546	0.0986
Stem dry mass	**< 0.0001**	**0.0022**	**< 0.0001**
Leaf dry mass	**< 0.0001**	**0.0008**	**< 0.0001**
Aboveground dry mass[a]	**< 0.0001**	**0.0010**	**< 0.0001**
Root dry mass	0.1277	**0.0015**	**0.0057**
Total dry mass	**< 0.0001**	**0.0010**	**< 0.0001**
Root–shoot ratio	0.1117	**< 0.0001**	**0.0040**

[a] Aboveground dry mass = stem + leaf dry mass

The treatment × clone interaction was significant for leaf area ($P = 0.0106$) (Table 3). Leaf area ranged from 35.2 ± 4.0 ('DN170' PCA3) to 97.6 ± 4.1 cm^2 ('NM2' POTT). The overall mean for leaf area was 58.3 ± 4.1 cm^2 (Fig. 1). Similar to height, clone 'NM2' produced trees with the greatest leaf area that was 50% and 81% larger than that of 'DM114' and 'DN170', respectively. Also like height, treatments containing Expera fibercake produced trees with 30% and 21% greater leaf area than PCA and combination treatments, respectively. Only POTT produced greater leaf area than all fibercake treatments at 4%, 29% and 21% greater than EXP, PCA, and COM treatments, respectively. EXP3 produced the greatest leaf area out of all eleven treatments, and PCA3 the smallest. Clonal responses to treatments were congruent with those of height. EXP treatments produced trees with leaf area 39%, 15%, and 31% greater than PCA treatments and 31%, 8%, and 20% greater than combination treatments for 'NM2', 'DM114', and 'DN170', respectively.

Although the treatment × clone interaction was not significant for diameter ($P = 0.8152$), this growth parameter was governed by the clone main effect ($P = 0.0006$) (Table 3). 'NM2' had the largest diameter (3.13 ± 0.03 cm) that was 7% and 25% greater than 'DM114' and 'DN170', respectively. All three clones were significantly different from each other ($P = 0.0006$), while clone 'DN170' produced diameters 14% lower than the overall mean, and clone 'NM2' produced diameters 10% higher than the overall mean.

Leaf number was governed by the treatment ($P = 0.0004$) and clone ($P = 0.0005$) main effects (Table 3). Treatment POTT produced the highest average count which was 12% higher than the overall mean, while treatment PCA2 produced the lowest average count that was 11% lower than the overall mean (Fig. 2). In general, treatments containing Expera fibercake produced trees with 11% higher leaf counts than PCA treatments and 4% higher than combination treatments. None of the treatments differed significantly from the overall mean. On the other hand, leaf numbers of 'NM2' were 15% higher than the mean ($P = 0.0005$) and leaf numbers of 'DN170' were 19% lower than the mean ($P = 0.0005$). Clone 'NM2' had the highest average leaf count that was 13% and 37% greater than that of 'DM114' and 'DN170', respectively.

Root number was governed only by the treatment main effect ($P = 0.0053$) (Table 3). Treatment NURS produced the highest average root number and COM2 the lowest at 19% greater and 16% lower than the mean, respectively (Fig. 2). Treatments containing

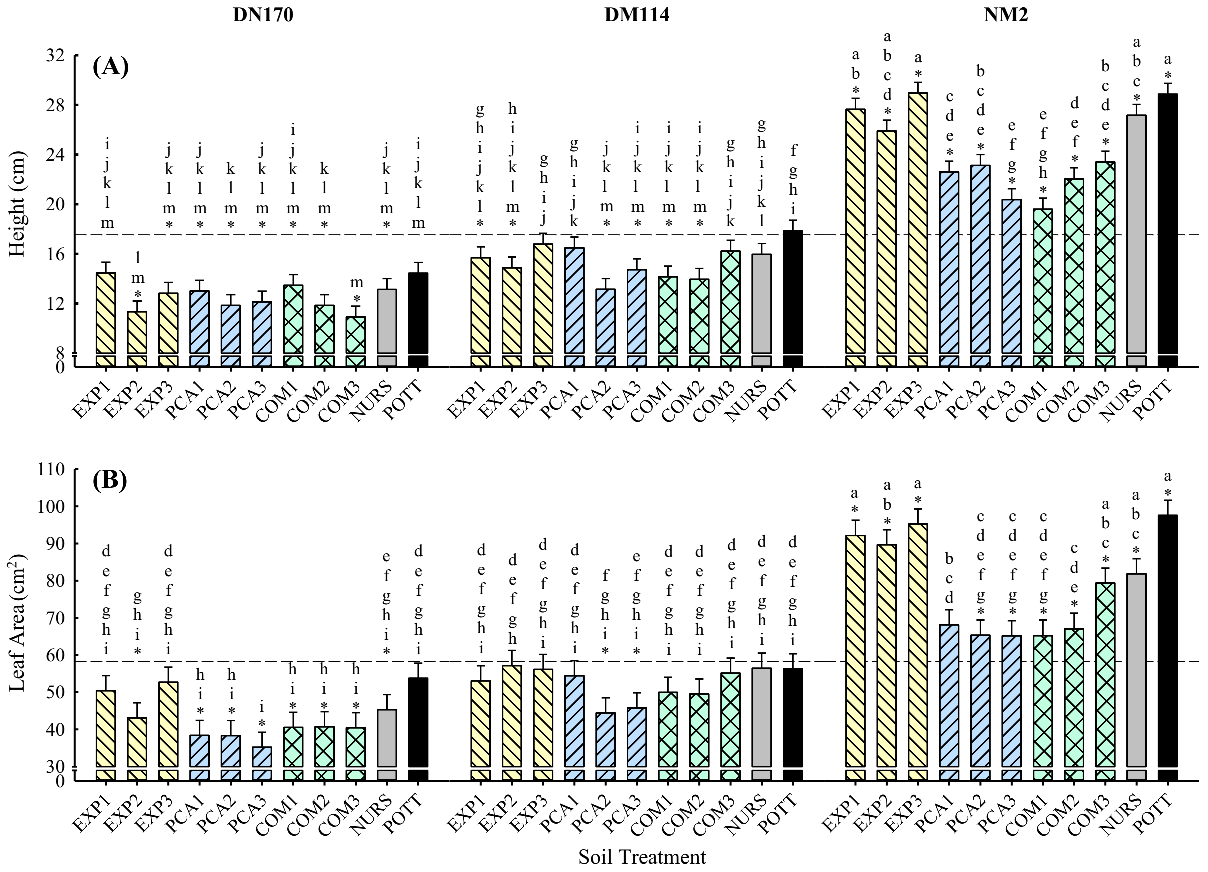

Fig. 1 Mean (± one standard error) height (**a**) and leaf area (**b**) of three hybrid poplar clones (*Populus deltoides* Bartr. ex Marsh × *P. maximowiczii* A. Henry 'DM114'; *P. deltoides* × *P. nigra* L. 'DN170'; *P. nigra* × *P. maximowczii* 'NM2') grown in soils amended with papermaking fibercake residuals from Expera Specialty Solutions (EXP; Rhinelander, WI), containerboard fibercake residuals from Packaging Corporation of America (PCA; Tomahawk, WI), and nursery soils from the USDA Forest Service, Rhinelander Experimental Forest (NURS; Rhinelander, WI) used for two- and three-component blends, as well as nursery soils and a standard potting mix control (POTT). See Table 1 for a description of soil treatments. The overall mean is indicated with a dashed line, and means differing from the overall mean at $P < 0.05$ are indicated with asterisks. Bars with the same letters are not different at $P < 0.05$

PCA fibercake produced 6% higher root number than both Expera and combination treatments. None of the treatments differed significantly from the overall mean (Fig. 2).

The treatment × clone interaction was significant for stem, leaf, and aboveground (stem + leaf) dry mass ($P < 0.0001$) (Table 3) (Supplemental Figure 1). Aboveground dry mass ranged from 5.4097 ± 0.0538 ('DN170' PCA1) to 6.4729 ± 0.0549 g ('NM2' EXP1) with an overall mean of 5.7402 ± 0.0541 g (Fig. 3). 'NM2' produced trees with the greatest aboveground dry mass at 9% and 12% greater than 'DM114' and 'DN170', respectively ($P < 0.0001$). EXP1 produced the most aboveground dry mass out of all eleven treatments, and COM2 the least. Differences in aboveground dry mass among treatments were not as pronounced as those for height and leaf area. EXP treatments produced the greatest aboveground dry mass, but only 2% greater than both PCA and COM treatments. EXP treatments reduced aboveground dry mass 1% compared to both NURS and POTT, while PCA and COM produced a 3% reduction compared to both NURS and POTT. Within treatments, the clonal response was such that EXP treatments produced 6% and 5% greater aboveground dry mass than PCA and combination treatments, respectively, for 'NM2'. 'DM114' and 'DN170' did not follow this trend, wherein aboveground dry mass for PCA, EXP, and

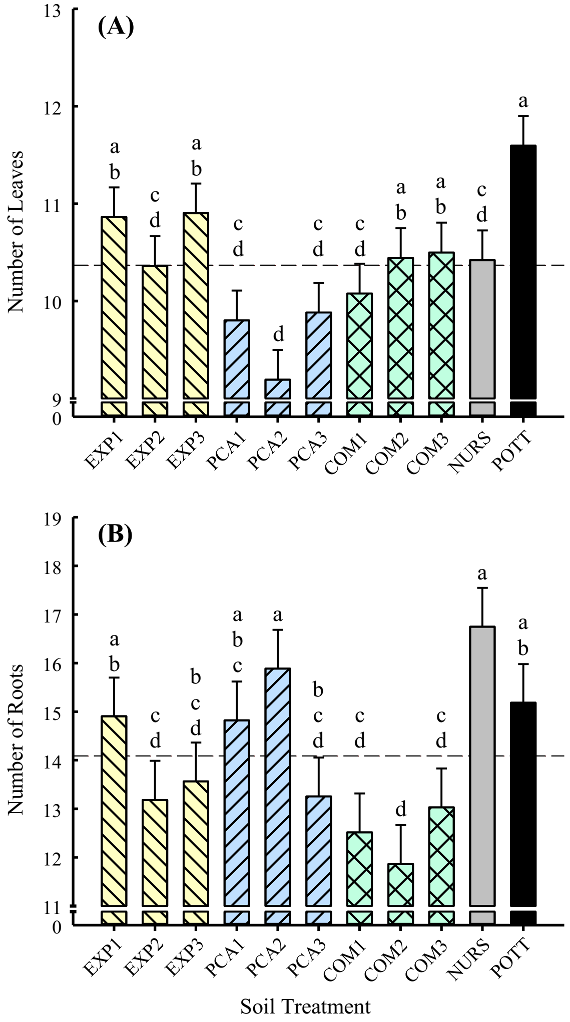

Fig. 2 Mean (± one standard error) number of leaves (**a**) and number of roots (**b**) across three hybrid poplar clones (*Populus deltoides* Bartr. ex Marsh × *P. maximowiczii* A. Henry 'DM114'; *P. deltoides* × *P. nigra* L. 'DN170'; *P. nigra* × *P. maximowczii* 'NM2') grown in soils amended with papermaking fibercake residuals from Expera Specialty Solutions (EXP; Rhinelander, WI), containerboard fibercake residuals from Packaging Corporation of America (PCA; Tomahawk, WI), and nursery soils from the USDA Forest Service, Rhinelander Experimental Forest (NURS; Rhinelander, WI) used for two- and three-component blends, as well as nursery soils and a standard potting mix control (POTT). See Table 1 for a description of soil treatments. The overall mean is indicated with a dashed line, and means differing from the overall mean at $P < 0.05$ are indicated with asterisks. Bars with the same letters are not different at $P < 0.05$

COM treatments were within 1% of each other (Fig. 3).

Root dry mass was also governed by the treatment × clone interaction ($P = 0.0057$) (Table 3). Root dry mass ranged from 0.0203 ± 0.0163 ('DM114' EXP3) to 0.2070 ± 0.0164 g ('NM2' PCA1) with a mean of 0.0675 ± 0.0164 g (Fig. 3). Overall, 'NM2' produced the greatest root dry mass at 121% and 130% greater than 'DM114' and 'DN170', respectively. Unlike other growth parameters, for which EXP treatments produced the greatest values, root dry mass was greatest for treatments with PCA, which were 42% and 44% greater than EXP and COM treatments, respectively. NURS and POTT produced greater root dry mass than all treatments except PCA treatments, which were 17% and 14% greater, respectively. EXP1, PCA1, and PCA2 all produced root dry mass greater than NURS and POTT, with PCA1 the greatest overall, and EXP2 the lowest overall. Clonal responses to treatment had similar trends for two of the three clones. Root dry mass for PCA treatments was 49% and 90% greater than Expera treatments and 67% and 36% greater than combination treatments for 'NM2' and 'DM114', respectively. On the other hand, for 'DN170', EXP treatments produced the greatest dry root mass at 5% and 13% greater than PCA and COM treatments, respectively (Fig. 3).

The treatment × clone interaction was significant for total dry mass (root + stem + leaf) ($P < 0.0001$) (Table 3), with values ranging from 5.4480 ± 0.0602 ('DN170' COM2) to 6.6068 ± 0.0614 g ('NM2' EXP1), and a mean of 5.8077 ± 0.0606 g (Fig. 4). 'NM2' produced 10% and 13% greater total dry mass than 'DM114' and 'DN170', respectively. EXP1 produced the greatest total biomass out of all eleven treatments and COM2 produced the lowest. EXP treatments produced 2% greater total dry mass than both PCA and COM treatments. While NURS and POTT produced greater total dry mass than treatments containing fibercake, all differences were less than 4%. Within treatments, clonal responses were similar to that of aboveground dry mass. 'NM2' had 5% and 6% greater total dry mass in EXP treatments compared to PCA and COM treatments, respectively, while all three types of treatments were within 1% of each other for 'DM114' and 'DN170' (Fig. 4).

The treatment × clone interaction was significant for root–shoot ratio ($P = 0.0040$) (Table 3). Root–shoot ratio ranged from 0.0036 ± 0.0025 ('DM114'

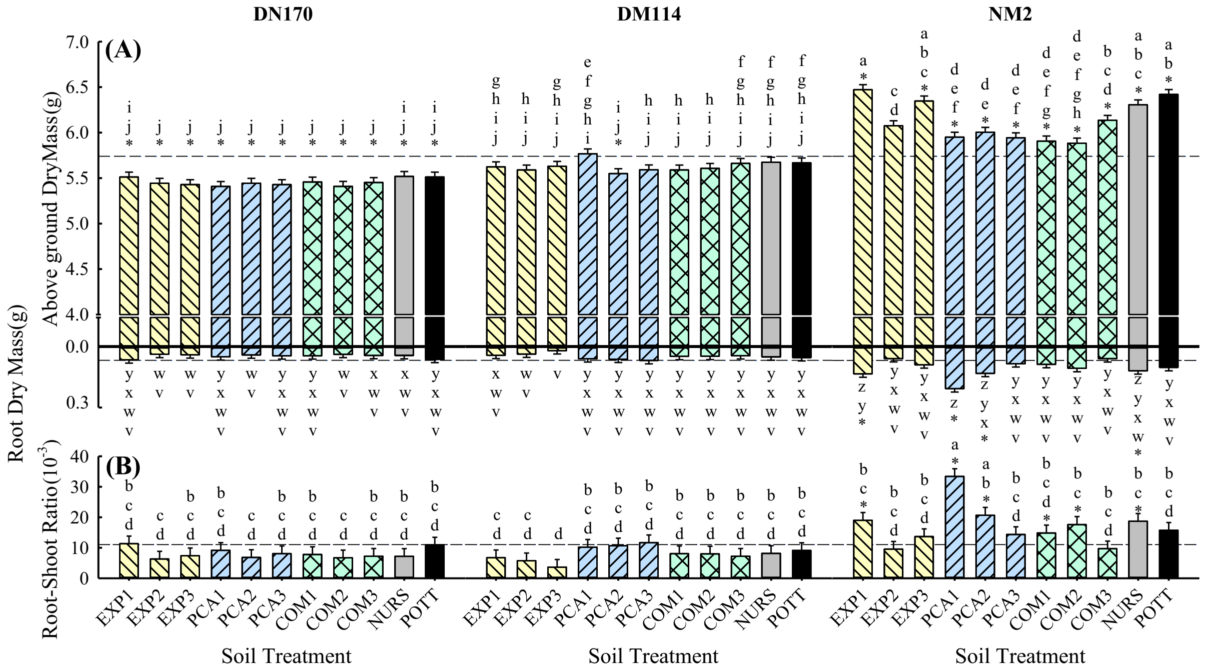

Fig. 3 Mean (± one standard error) aboveground and root dry mass (**a**) and root–shoot ratio (**b**) of three hybrid poplar clones (*Populus deltoides* Bartr. ex Marsh × *P. maximowiczii* A. Henry 'DM114'; *P. deltoides* × *P. nigra* L. 'DN170'; *P. nigra* × *P. maximowczii* 'NM2') grown in soils amended with papermaking fibercake residuals from Expera Specialty Solutions (EXP; Rhinelander, WI), containerboard fibercake residuals from Packaging Corporation of America (PCA; Tomahawk, WI), and nursery soils from the USDA Forest Service, Rhinelander Experimental Forest (NURS; Rhinelander, WI) used for two- and three-component blends, as well as nursery soils and a standard potting mix control (POTT). See Table 1 for a description of soil treatments. The overall mean is indicated with a dashed line, and means differing from the overall mean at $P < 0.05$ are indicated with asterisks. Bars with the same letters are not different at $P < 0.05$

EXP3) to 0.0334 ± 0.0025 ('NM2' PCA1) (Fig. 3). The overall mean was 0.0111 ± 0.0025. 'NM2' produced an average root–shoot ratio that was 110% greater than both 'DM114' and 'DN170'. Like dry mass, EXP1, PCA1, and PCA2 all produced greater root–shoot ratios than all other treatments, including NURS and POTT, while EXP2 produced the lowest. Similar to root dry mass, PCA treatments produced the greatest root–shoot ratio, 50% and 43% greater than that of EXP and COM treatments, respectively. Additionally, PCA treatments produced larger values than NURS and POTT (22% and 16% greater, respectively), and were the only treatments to do so. Within treatments, clonal responses were such that PCA treatments produced root–shoot ratio 62% and 102% greater than EXP treatments and 63% and 40% greater than COM treatments for 'NM2' and 'DM114', respectively. 'DN170' did not show the same trends; EXP treatments exhibited the largest root–shoot ratio at 4% and 15% greater than PCA and COM treatments, respectively (Fig. 3).

Discussion

Globally, poplars have been successfully established in agroforestry systems such as riparian buffers, shelterbelts, silvoarable systems, and forest or homestead gardens (Newman and Gordon 2018). Poplar-based agroforestry systems exhibit environmental benefits such as increased soil organic carbon (Gupta et al. 2009), reduced N and P losses in runoff (Nerlich et al. 2013), and carbon sequestration (Winans et al. 2015). Poplars also produce large quantities of biomass (5.4–30.0 Mg ha^{-1}year^{-1}), and biomass-agroforestry systems are prescribed in shelterbelts, alley cropping, and riparian buffer strips (Holzmueller and Jose 2012). Applying soil amendments such as

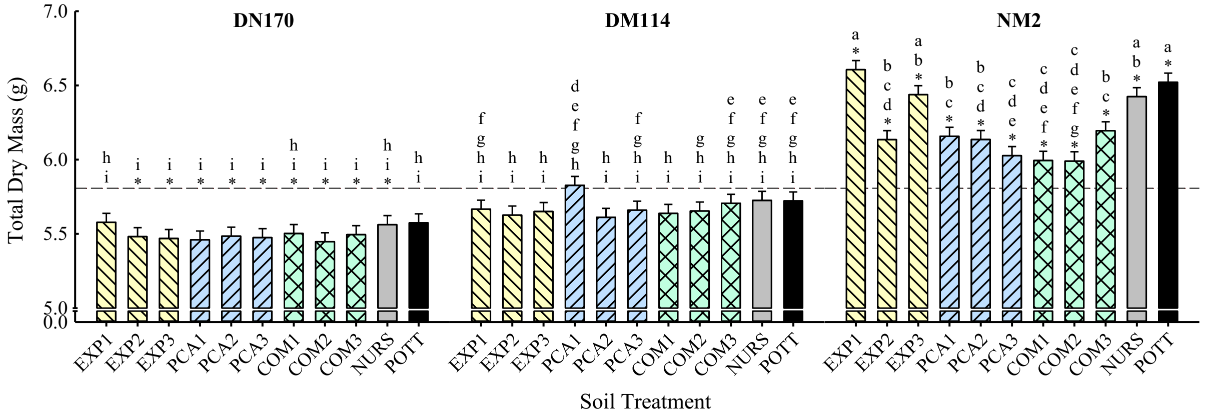

Fig. 4 Mean (± one standard error) total dry mass of three hybrid poplar clones (*Populus deltoides* Bartr. ex Marsh × *P. maximowiczii* A. Henry 'DM114'; *P. deltoides* × *P. nigra* L. 'DN170'; *P. nigra* × *P. maximowczii* 'NM2') grown in soils amended with papermaking fibercake residuals from Expera Specialty Solutions (EXP; Rhinelander, WI), containerboard fibercake residuals from Packaging Corporation of America (PCA; Tomahawk, WI), and nursery soils from the USDA Forest Service, Rhinelander Experimental Forest (NURS; Rhinelander, WI) used for two- and three-component blends, as well as nursery soils and a standard potting mix control (POTT). See Table 1 for a description of soil treatments. The overall mean is indicated with a dashed line, and means differing from the overall mean at $P < 0.05$ are indicated with asterisks. Bars with the same letters are not different at $P < 0.05$

fibercake residuals to poplar-based agroforestry systems has the potential to increase environmental and economic returns by maximizing tree growth and biomass. Utilizing fibercake also closes the loop of waste generation in the paper and containerboard production industry. Therefore, we sought to determine the most effective fibercake treatment(s) for future nursery and field production of hybrid poplar clones, and later, for biomass-producing agroforestry systems.

In general, the treatment × clone interaction governed growth and biomass traits, with the exceptions of diameter, leaf number, and root number. Out of all treatments containing fibercake, those with Expera fibercake generally produced the greatest parameter values for both growth and biomass parameters. From a clonal perspective, clone 'NM2' produced the greatest values for all parameters tested, while 'DM114' and 'DN170' values were typically intermediate and low, respectively. This may owe to the generalist nature of 'NM2', which has been reported to exhibit enhanced productivity across a wide range of site and/or soil treatment conditions (Netzer et al. 2002; Zalesny et al. 2009; Rogers et al. 2019). Further, the combination of Expera treatments with the 'NM2' clone (the EXP × 'NM2' interaction) produced the highest values for all parameters compared to treatment × clone interactions of other treatments containing fibercake, which suggested that 'NM2' has potential for greater early growth and biomass production on agroforestry sites amended with Expera fibercake.

Industrial byproducts are promoted as effective soil amendments for reclaimed mine sites (Haering et al. 2000), urban soils (Scharenbroch et al. 2013), and as nutrient sources for crops (Khaleel et al. 1981) and trees (Lombard et al. 2011). Although little information exists on the effects of solid fibercake from paper and containerboard production as a soil amendment, reported benefits of liquid paper mill sludge include increases in soil organic matter, physical properties, water holding capacity, and cation exchange capacity (Camberato et al. 2006), as well as increased tree growth (Lteif et al. 2007). In our study, treatments produced various results of the poplar growth parameters, but treatments containing Expera fibercake surpassed other treatments for a majority of the parameters. Expera treatments, on average, produced between 4 and 30% greater values for growth parameters (excluding root number) and 2% greater values for biomass parameters (excluding root dry mass and root–shoot ratio) than other treatments containing fibercake (i.e., PCA treatments and COM treatments). Particularly, EXP1 and EXP3 consistently produced large values for the poplar growth parameters across treatments. These observed trends of greater poplar growth in EXP treatments are likely due to concentrations of available N in the different fibercake treatments. Expera fibercake readily releases N for use by plants, whereas PCA fibercake immobilizes N, and releases it slowly over time. The addition of available N likely increased production, as it has been shown to increase growth (Brown and van den Driessche 2005) and light-saturated net photosynthesis rates and chlorophyll content of leaves (Cooke et al. 2005). In our study, EXP1 (50 N; 50 kg available N ha^{-1}) outperformed EXP3 (200 N; 200 kg available N ha^{-1}) for aboveground dry mass, total dry mass, root dry mass, and root–shoot values. These results corroborate those of Coleman et al. (2004), who reported that the 50 N, 100 N, and 200 N treatments all enhanced growth similarly in *Populus deltoides*, and that application rates of 100 N and 200 N exceeded the demands of the trees. EXP3 did produce the second greatest height overall, but was only marginally greater than EXP1 (within 2%). Similar results were found in a poplar fertilization study; stem volume (a function of basal area and height) was not significantly larger in treatments with the greatest N (Guillemette and DesRochers 2008).

Conversely, treatments containing PCA fibercake produced low to intermediate values for every trait except those involving roots. PCA1 produced trees with the largest root dry mass and root–shoot ratio values out of all treatments, and root number values higher than every treatment except NURS. This may be due to fibercake composition; pure PCA fibercake had 542% greater Mn than pure Expera fibercake (Table 2). Although trees were not planted in pure fibercake, Mn was still much higher within PCA treatments. Manganese has been shown to influence carbohydrate partitioning in plants; its deficiency causes reduced root length and suppression of lateral root formation (Marschner 1995), which could have been the case in treatments not containing PCA fibercake. Increased rooting in PCA treatments may also be due to the higher C:N ratio of PCA fibercake compared to Expera (Table 2). In Norway spruce [*Picea abies* (L.) H. Karst.] and Scots pine (*Pinus sylvestris* L.), higher C:N ratios were positively correlated with fine root biomass (Helmisaari et al. 2007). Ericsson et al. (1996) similarly reported that a decrease in a mineral nutrient, particularly N, produces an increased root–shoot ratio. Inversely, lower C:N ratios have shown to increase shoot growth and decrease root growth, thus decreasing root–shoot ratio in crops (Brouwer 1962) and herbaceous plants (Saarinen 1998; Müller et al. 2000). Liu and Dickman (1992) corroborated these results and reported that higher N concentrations led to increased aboveground partitioning of resources, and therefore lower root–shoot ratios in poplars. Rhizospheric microbial communities are also greatly affected by the C:N ratio of the soil/substrate within which they reside, and can influence the biomass partitioning of associated plants. Differing C:N ratios have been shown to alter microbial community structure of forest soils, particularly regarding the proportions of fungal and bacterial biomass (Wan et al. 2015). High C:N ratios present in papermill residuals, like the PCA fibercake in our study, can increase competition for N among microbes, and can eventually lead to N depletion of the soil (Larsen and McCartney 2000), thereby contributing to decreased shoot growth and increased root growth of associated plants (Ericsson et al. 1996). In our study, the C:N ratio and low available N in PCA fibercake may have led to the high belowground biomass production of trees grown in PCA-amended treatments, while the lower C:N ratio of Expera fibercake may have caused the corresponding high aboveground biomass production. While out of the scope of this study, further research is warranted that characterizes the microbial populations and their dynamics among the poplar-fibercake treatments.

Synergistic effects from combining the fibercakes were not observed; combination treatments did not produce high values for any of the tested growth parameters. Rather, COM treatments produced some of the lowest overall values for multiple parameters. Variations in poplar growth performance among fibercake treatments, like those reported here, support the need for careful selection and application of fibercake residuals as soil amendments to optimize poplar growth and biomass production. Additionally, further research assessing the long-term performance of poplar clones grown in Expera and PCA fibercake treatments in the field could provide valuable information regarding the productivity potential of different clone and fibercake treatment combinations, which could be used to inform management decisions. For example, Expera could be monitored for decreases in effectiveness as available N changes over time, while

PCA may exhibit the opposite effects as its available N is slowly released over time.

In conclusion, we found that while all three clones belong to different genomic groups, this much variation was not expected (Zalesny et al. 2005a). We assert that 'NM2' utilized additional resources from the fibercake amendments more efficiently than the other two clones. Others have documented the vigorous production of 'NM2' under plantation conditions (Miller 2018; Nielsen et al.2014), but information regarding enhanced nutrient uptake from biosolids or fibercake is not available. Further research involving a more extensive variety of clones is needed to determine the most effective treatment × clone interactions for fibercake-amended, poplar-based agroforestry systems.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest associated with this research or publication.

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