Abstract.

EWALD, ALEXANDER LEE. Productivity and Profitability for Poplar on Fertile and Marginal Sandy Soils with Different Fertilization and Planting-Density Treatments. (Under the direction of Dr. Elizabeth Guthrie Nichols.)

Energy feedstock viability depends on crop yields, production costs, and market prices. This study evaluated the productivity and profitability of four well-performing *Populus* clones under three different fertilization regimens and two planting densities at three sites in coastal sandy soils of North Carolina, USA. A randomized split-split plot design was established in March 2015 at two sites with marginal soils (Clinton A and B) and another site with fertile soils (Williamsdale). At each site, eighteen plots were planted with four highly productive *Populus* clones from prior clonal trials in the same region. Nine plots were planted at a density of 2,500 and 5,000 trees ha^{-1}, respectively, within which three replicate plots were fertilized at 0, 113, and 225 kg nitrogen ha^{-1} in late spring of 2015. Survival, tree height, diameter at breast height (DBH), disease, and predation were measured each fall with leaf area index (LAI) and foliar nitrogen (%) measured in mid-summer. Survival was excellent for *P. deltoides x P. deltoides* clones (140 and 356) and *Populus deltoides x Populus maximowiczii* (230). Survival was comparatively poor for *P. trichocarpa x P. deltoides* (185), particularly in fertilized plots at the lower planting density, but lower survival did not always result in lower tree volumes. Tree volume index was significant for the interactions of site*planting density*fertilization and site*clone*fertilization for both years. At all three sites, *P. deltoides x P. deltoides* clones produced the greatest volume per tree, regardless of planting density or fertilization; fertilized plots produced the most tree volume on fertile soils but not marginal soils. Pests and disease incidence were greater for *P. trichocarpa x P. deltoides* (185) which had lower survival, foliar nitrogen, and volume at all sites. LAI and foliar nitrogen were weakly correlated to volume yields. Estimated biomass yields were not profitable at current market prices for genotype, site, or treatment, but yields could be profitable if market values increased by $27 to $44 USD/t for higher and lower planting densities, respectively.

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Productivity and Profitability for Poplar on Fertile and Marginal Sandy Soils with Different Fertilization and Planting-Density Treatments.

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Approved By:

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Biography.

Alexander Lee Ewald was born on July 27th, 1992 outside of Plymouth, MN, where he spent much of his childhood playing and fishing outdoors. From an early age, he recognized his love for nature and knew it would travel with him throughout his professional career. After receiving his high school diploma from Charlotte Catholic High School in 2010 he attended North Carolina State University for his undergrad and received his Bachelor of Science in Environmental Technology and Management. He also received two minors, one in Environmental Toxicology and another in Sustainable Materials and Technology. While enrolled at North Carolina State University he began working for the Department of Forestry and Environmental Resources, predominantly within their bioenergy initiatives.

This work, under the help and advisement of Dr. Elizabeth Guthrie Nichols, propelled him directly into graduate school in 2015 for a Master of Science in Natural Resources at North Carolina State University. He continues to work within the Department of Forestry and Environmental Resources, advancing the research trials of short-rotation woody forestry, while simultaneously studying hydrology. He hopes that he will one day be able to merge his passion for the outdoors with his project and research management skills he obtained throughout his collegiate career. His primary research interests include renewable energies, water resource management, and fisheries. In his spare time, he enjoys following his favorite football and baseball teams, backpacking across the world, and fishing.

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Title: Productivity and Profitability for Poplar on Fertile and Marginal Sandy Soils with Different Fertilization and Planting-Density Treatments.

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Research Highlights:

- *P. deltoides x P. deltoides* clones yielded the greatest tree volume regardless of site, fertilization, or planting density
- Tree volumes were the largest with lower fertilization rates on marginal soils
- Tree volumes were the largest with higher fertilization rates on fertile soils
- Profitability requires a market value increase for all clones of $27 to $44 USD/t for high and low planting densities, respectively.

Keywords

Populus, volume, fertilization, planting density, LAI, foliar nitrogen, marginal soils

Introduction.

The Energy Independence and Security Act (EISA) of 2007 mandates an increase in biofuels use, from 9.0 billion gallons in 2008 to 36 billion gallons in 2022, which would equate to one-fifth of current gasoline and diesel consumption in the United States (US) [Capehart, 2016]. The EISA also requires that a certain percentage of the renewable fuel blended into transportation fuels must be cellulosic biofuel, biomass based diesel, and advanced biofuel [EPA, 2010]. In recent years, corn based ethanol has been used in the US, primarily as an additive to traditional fossil fuels, to meet oxygenate standards designed to improve air quality [Capehart, 2016]. With more than 5.4 billion bushels of corn used for ethanol in the US, accounting for approximately 41% of the corn produced, the demand for field corn has increased dramatically to meet the EISA standards [Hay, 2015]. Continued expansion of ethanol or other biofuel crop production will rely on converting acreage not currently in production, shifting acreage from other crops to corn (which has high water and nutrient demand), and increasing feedstock productivity on existing acreage [Malcolm *et al.*, 2009]. Increased corn based ethanol production raises environmental concerns for erosion, high fertilization rates, nutrient run-off, and the use of agricultural food-crop lands for energy production [Larson *et al.,* 2010, Hill *et al.,* 2006].

One opportunity to expand bioenergy production in the US, while minimizing environmental concerns, is to develop second generation feedstocks such as tall grasses, *Panicum* and *Miscanthus,* and short rotation woody crops (SRWC) such as *Populus* or *Salix* [Lowrance *et al.,* 2010]. When compared to annual crops, woody species grown in short rotation have higher energy densities, lower transportation costs, and reduced needs for annual inputs such as fertilizer [Balatinecz *et al.,* 2001, Tyndall *et al.,* 2011]. Of the SRWC produced in the USA, poplars (*Populus spp.,*) are among the most commonly analyzed bioenergy crops due to their high productivity and decades of genetic improvement [Zalesny *et al.,* 2011]. Recent national, international, and state policies on renewable energy have resulted in increased bioenergy markets in the southeastern USA. Currently, the southeastern USA exports the most wood pellets to Europe due to abundant material inventory, manufacturing proximity, and accessible shipping ports [Ghezehei *et al.,* 2015, Sikkema *et al.,* 2011]. Increased wood pellet market growth, 11% per year, and projected green ton production, 43 million tons by 2025, will catalyze the need for more non-contentions lands and sustainable feedstock supplies to meet market and energy demands [Matzenberger *et al.*, 2015, FORISK Consulting, 2016].

Poplars have been studied in silviculture experiments for well over 100 years, with some of the first seedlings commercially planted in the Pacific Northwest in the late 1800's [Berguson *et al.,* 2009, Hansen *et al.,* 1983]. Recently, the USA Department of Energy has focused on poplars as a feedstock for liquid fuels [Balatinecz *et al.*, 2001]. Prior clonal studies have shown that poplar trees, when intensively cultured as a SRWC, can produce substantial amounts of biomass [Zalesny *et al.,* 2011, Hansen *et al.,* 1983, Miller *et al.,* 2016, Shifflett *et al.,* 2014, Ghezehei *et al.,* 2015, Coyle *et al.,* 2006]. Ecosystem demography models have estimated the potential yields of poplar plantations across the temperate regions of the United States ranging between 10 and 18 Mg ha^{-1} yr^{-1} (dry weight) [Wang *et al.,* 2013]. However, growth projections for poplars are heavily dependent on climate, soil condition, clonal parentage, fertilization rates, and planting densities [Wang *et al.,* 2013, Miller *et al.,* 2016].

Poplars planted at low densities are less expensive to install, produce larger individual trees than the poplars planted at high densities, but yield lower total biomass production than high density plantations [Fang *et al.,* 2000]. Planting density for poplars can typically range from 1,000 and 2,500 stems ha^{-1} to 5,000 and 20,000 stems ha^{-1} [Hinchee, 2011]. When poplars are planted at high densities, they can increase almost exponentially before “crown closure” [Fang *et al.,* 2000, Amichev *et al.,* 2010]. Determining the optimal planting density depends on the biological and nutrient limitations of a site such as climate, precipitation, and soil quality [Hinchee, 2011]. Because density influences the amount of biomass produced on a “per tree” and “per hectare” basis, the market use and value of the biomass is important to site establishment, rotation lengths, and profitability for landowners.

There are concerns that SRWCs will compete with agriculture or conventional forestry for land use [Capehart, 2016, Mehmood *et al.,* 2016]. Consequently, lands that have poor soil or undesirable characteristics (marginal) will be an important resource for SRWC production in the USA and globally [Mehmood *et al.,* 2016]. Abandoned and degraded lands could be utilized to produce 10 to 52% of current liquid fuel consumption if under SRWC production [Mehmood *et al.,* 2016, Campbell *et al.,* 2008]. However, these lands often have lower quality soils with limited fertility [Finzi *et al.,* 2007], and poplar biomass yields often decline significantly on marginal soils [Liu *et al.,* 1992, Truax *et al.,* 2012, Dipesh *et al.,* 2017]. One study reported poplar biomass yields of 22.4 m^3 ha^{-1} yr^{-1} on fertile soils but low yields of 1.1 m^3 ha^{-1} yr^{-1} on marginal soils [Truax *et al.,* 2012]. Matching fertilizer application rates to crop needs is an essential component to optimize yields, minimize nutrient leaching, and enhance economic returns [Crouse, 2016, Flynn, 2014].

Several studies have focused on finding the optimal nitrogen fertilizer application rate for *Populus* across a variety of different site-specific variables [Coyle *et al.,* 2013, Brown *et al.,* 2005]. Studies conducted in Canada and Spain evaluated nitrogen fertilization rates, ranging from 60 to 250 kg N ha^{-1}, and found that optimum nitrogen fertilization rates are site specific and dependent on genotype [Brown *et al.,* 2005, Lasa *et al.,* 2016]. In the southeastern USA, Coyle *et* *al.*, (2013) evaluated poplar growth response on marginal soils fertilized within 0 to 210 kg ha^{-1} yr^{-1} of nitrogen (for eight years) and observed that optimal *Populus* growth occurred with less than 150 kg N ha^{-1} yr^{-1} and that growth response differed by genotype.

Advancing woody feedstocks for bioenergy production requires economic profitability for landowners [Long *et al.*, 2013]. Poplars and other fast-growing tree stands can be economically feasible when costs are minimized and revenues are maximized [Ghezehei *et al.*, in review]. Stand costs are minimized by effective stand establishment and management, especially the suppression of weed competition. Subsidization improves the economic viability of SRWC stands, [El Kasmioui *et al.*, 2013, Ghezehei *et al.*, in review] yet, revenues are maximized through the enhancement of productivity and increase of feedstock prices. In the southeastern USA, prices of bioenergy feedstocks are comparatively low. Bioenergy feedstock values may rise if robust bioenergy markets develop, which would necessitate understanding of what agronomic management practices, such as planting density, rotation length, and fertilization, yield the best economic returns from poplar genotypes [Ghezehei, *et al.*, 2017].

This study evaluated the interactive effects between fertilization, site conditions, and planting densities on poplar yields for four productive poplar clones. Over the last eight years, clonal trials across the three main physiographic regions of North Carolina have shown genotype-specific performance for site specific conditions of *Populus* [Shifflett *et al.*, 2014, Shifflet *et al.*, 2016, Ghezehei *et al.*, 2015, Ghezehei in review]. Higher productivity has been observed when poplars were irrigated with nutrient-rich waters [Shifflett *et al.*, 2014] and at greater planting densities for non-irrigated and fertilized trials [Ghezehei *et al.*, 2015]. The economic profitability of poplar favors lower density plantings without fertilization or irrigation to match the current wood market economics of pine and unmanaged hardwood forests. This study focused on poplar productivity yields and economic returns under two planting densities and two fertilization regimes using fertile and marginal coastal sandy soils. Genotype response to growth, the incidence of disease and pests, foliar nitrogen content, and leaf area index were also evaluated across sites and treatments. Additionally, economic returns were evaluated based on estimated biomass yields at two, six, and eight years for current and potential market prices.

Materials and Methods.

P. deltoides x P. deltoides (140 and 356), *Populus deltoides x Populus maximowiczii* (230), and *P. trichocarpa x P. deltoides* (185) clones were established at coastal sites that vary in soil quality (Table 1). Williamsdale has soils of the Noboco loamy fine sand series (siliceous, subactive, thermic Oxyaquic Paleudults) which are highly productive, fertile soils [USDA, 2016]. The two sites in Clinton NC are marginal soils, [USDA, 2016] Clinton A is composed of Wagram loamy sand soils (kaolinitic, thermic Arenic Kandiudults) and Clinton B is composed of an Orangeburg loamy fine sand soils series (kaolinitic, thermic Typic Kandiudults). All three sites had prior crops; corn for Williamsdale and sorghum for Clinton. Prior to planting poplar, the sites were planted with a winter wheat cover crop in fall 2014 and routinely mowed. The experimental design was a split-split plot design with three blocks, one representing each site. Fertilization level was the main plot factor with planting density and clone as the split-split plot factors. The plots were fertilized at three different levels (0, 113, and 225 kg N ha^{-1}), accounting for six plots per fertilization rate. Half of the plots were planted at a density of 2,500 trees ha^{-1} and the other half at 5,000 trees ha^{-1}. Each plot was planted with four replicates of each clone. Thus, there are three replicates of each plot in randomization, at each fertilization level and spacing, at each site (Figure S-1 and S-2). Additional cuttings were planted as borders around the perimeter of each plot to reduce border effects [Zavitkovski, 1981].

Site preparation began in February of 2015 when soils were subsoiled then banded with a 30 cm band of 41% glyphosate (4.67 L ha^{-1}) and 37.4% pendimethalin (9.35 L ha^{-1}) solution along the rip-lines for weed control prior to planting. *Populus* cuttings were purchased from ArborGen, LLC (Ridgeville, SC) soaked for 24 hours prior to planting, and planted as 25 cm non-rooted cuttings in March 2015. A nitrogen fertilizer (15-0-0) (YaraLiva Calcinit) was applied by hand in a 0.6 m radius around the individual trees within the fertilized plots in April 2015. All trees were banded with glyphosate/pendimethalin approximately five times per growing season for weed control. Non banded areas were maintained by mowing once a month. All sites were treated for *Chrysomela scripta* Fabricius infestation with Carbaryl™, applied by hand-sprayer in the early summer of year one and mist blower in early and mid-summer of year two. Soil samples were collected in the spring of 2015 at a depth of 15 cm for each of the unfertilized plots, and combined by site. The soils were analyzed using the Mehlich III method at Waters Agricultural Laboratory (Warsaw, NC).

All trees were inventoried for diameter at breast height (DBH) and total height to the apical bud in the late fall after the first and second year of growth. All height (m) measurements were collected using a Crain CMR series measuring rod (Crain Enterprises, Inc., Memphis, TN, USA) and DBH measurements were taken at a height of 130 cm using Lufkin Executive Thin Line DBH tape (Apex Tool Group, Cleveland, OH, USA). Multiple shoots were measured per tree for height and DBH in order to determine total tree volume. The presence of *Melampsora* rust, deer damage, and leaf damage by *Chrysomela scripta* Fabricius were inventoried in July 2016 by scoring the presence or absence of damage. Leaf Area Index (LAI) measurements were

Table 1. Climate and site characteristics for Clinton A, Clinton B, and Williamsdale, in North Carolina, U.S.A.

	Clinton A	**Clinton B**	**Williamsdale**
Soil Quality	marginal	marginal	fertile
Soil Series [c]	Wagram loamy sand	Orangeburg loamy sand	Noboco loamy sand
Mean Annual Rainfall (mm) [a, b]	1,371	1,371	1,480
Elevation (msl) [a]	50.6	50.6	17.0
Mean Annual T (C) [a, b]	16.7	16.7	16.7
Mean Daily Humidity (%) [a, b]	71.9	71.9	73.4
Mean Daily Water Available to Plant (cm^3/cm^3 Soil) [a, b]	0.18	0.18	0.20
Soil pH [d]	6.2	6.1	6.0
Cation Exchange Capacity (Meq/100g) [d]	2.3	2.1	6.9
Soil P Content (kg ha^{-1}) [d]	504	605	1,011
Soil K Content (kg ha^{-1}) [d]	131	112	410
Soil Mg Content (kg ha^{-1}) [d]	102	92	308
Soil Ca Content (kg ha^{-1}) [d]	559	517	1,630
Soil NO^-_3 Content (kg ha^{-1}) [d]	3.7	2.5	4.1
Prior Crop	sorghum	sorghum	corn

[a] Climate data provided by the State Climate Office of North Carolina;

[b] December 2014 – December 2016; [c] Data provided by USDA Web Soil Survey; [d] Collected at a depth of 15 cm;

taken in July of the second growing season using a LAI-2000 LI-COR Plant Canopy Analyzer (LI-COR, Lincoln, Nebraska, USA). Two cross-calibrated sensors were connected to the same data logger to measure below-canopy measurements and to capture full solar radiation in open areas but only during the absence of direct sunlight. Each tree was measured then averaged by clone in each plot. A 25% view cap was used to mask user shadow for those LAI field measurements. Foliar percent nitrogen samples were collected in the second growing season in July by compositing four individual leaves taken from each tree at each ordinal direction and increased in height, for a total of 16 leaves per clone per plot. All foliar samples were analyzed at Waters Agricultural Laboratory (Warsaw, NC, USA).

To estimate aboveground volume, a volume index was calculated using $V = H \times D^2$, where V is volume in cubic decimeters, H is height in decimeters, and D is DBH in decimeters [Avery *et al.*, 2002]. All individual aboveground tree volumes were analyzed using a two-way analyses of variance (ANOVA) in accordance with a split-split plot design with $\alpha = 0.05$ (PROC GLM or PROC MIXED,) (SAS, Cary, NC, USA). Volume, survival, LAI, foliar nitrogen, *Melampsora* rust, deer damage, and leaf damage by *Chrysomela scripta* Fabricius were evaluated for significance within the different levels of planting density, clone, site, and fertilization rate. The first and second year measurements added any multiple shoots together for total volume per tree.

Field precision was determined by duplication of field measurements for height, DBH, LAI, and foliar N. Relative percent difference, or RPD, was calculated for duplicate measurements and averaged for mean RPD per metric. The mean RPD of height and DBH was $0.8 \pm 0.6\%$ and $1 \pm 3\%$ respectively with $n = 62$ duplicate measurements or 7.2% of the total trees measured. The mean RPD of LAI measurements was 5.3 ± 5.6 % for $n = 46$ duplicate measurements or 21.2% of total trees measured. The mean RPD for percent foliar nitrogen was 16 $\pm$ 12% for n = 25 duplicate measurements or 11.5% of total samples collected.

Economic viability of the stands was examined using net present value (NPV). Mean annual increment (MAI) was calculated based on aboveground wood volume indices of treatments at the end of second year by converting them to actual volumes using the equation by Shelton *et al.*, (1982) and multiplying the outcome by poplar wood density [World Agroforestry Centre, 2012] and 1.7 (to obtain wet biomass). Stand revenues were determined based on the delivered price for FOB Mill of hardwood pulpwood of $27.56 USD/t (Timber Mart-South, TMS) (region 2, first quarter of 2014), MAIs and rotation lengths, which included two, six and eight years. Stand establishment and maintenance costs included chemical weed suppression, sub-soiling, cover crops, pesticide applications and associated labor and material costs. Harvest and transport costs were determined based on (TMS) for coastal North Carolina, assuming the harvested biomass was hauled for an average hauling distance (52 for North Carolina, TMS) using a 40-tonne net log truck with a diesel consumption of 2.13 km/liter (5 miles per gallon). Diesel price (assumed) and poplar-seedling of $0.62/liter and $0.30/seedling [ArborGen, 2014] were used. No costs of land rent or property taxes were included.

Results and Discussion.

Genotype response to planting-density for non-fertilized soils.

The four *Populus* clones selected for this study had demonstrated superior growth and survival compared to other *Populus* genotypes as a function of genetics and site quality for sandy coastal soils [Shifflet *et al.,* 2014, Shifflett *et al.,* 2016, Ghezehei in review]. For non-fertilized treatments at each site, there was no apparent genotype advantage for tree volume by planting density (Figure 1, Table S-1 and S-2). There were genotype differences in mean tree volume by clone by site, specifically, between fertile and marginal soils for the first and second years of growth (Table 3, Table S-3, ANOVA, $\alpha = 0.05$). The two *P. deltoides x P. deltoides* clones (140 and 356) had greater mean tree volumes on fertile soils (Williamsdale) compared to marginal soils (Clinton A and B) regardless of planting density (Figure 1). *Populus deltoides x Populus maximowiczii* (clone 230) had greater mean tree volumes on fertile soils at the higher planting density, and *P. trichocarpa x P. deltoides* (185) had similar mean tree volumes at both planting densities for all three sites (Figure 1). At all three sites, increasing the planting density to 5,000 trees ha^{-1} yielded similar mean tree volumes to 2,500 trees ha^{-1} (Figure 1; ANOVA) and doubled per hectare yields (Table 2) for both marginal and fertile soils.

Genotype response to fertilization and planting-density.

Genotype was significant for tree volume in fertilized soils across all sites, and the strongest significant interaction effects were site*planting density*fertilization and site*clone*fertilization (Table 3, ANOVA, $\alpha = 0.05$, $R^2 = 0.77$). For fertile soils at Williamsdale, both fertilization rates significantly increased mean tree volume for all four clones at the lower planting density when compared to non-fertilized soils (Figure 1). Only *P. deltoides x P. deltoides* clones (140 and 356) produced significantly greater mean tree volumes for both planting densities. As shown in Table 2, cumulative tree volumes increased for both fertilization rates, sometimes as much as 50%, regardless of planting density for fertile soils.

For marginal soils, fertilization did not significantly increase mean tree volumes, regardless of planting densities or fertilization rates, except for one clone, *Populus deltoides x*

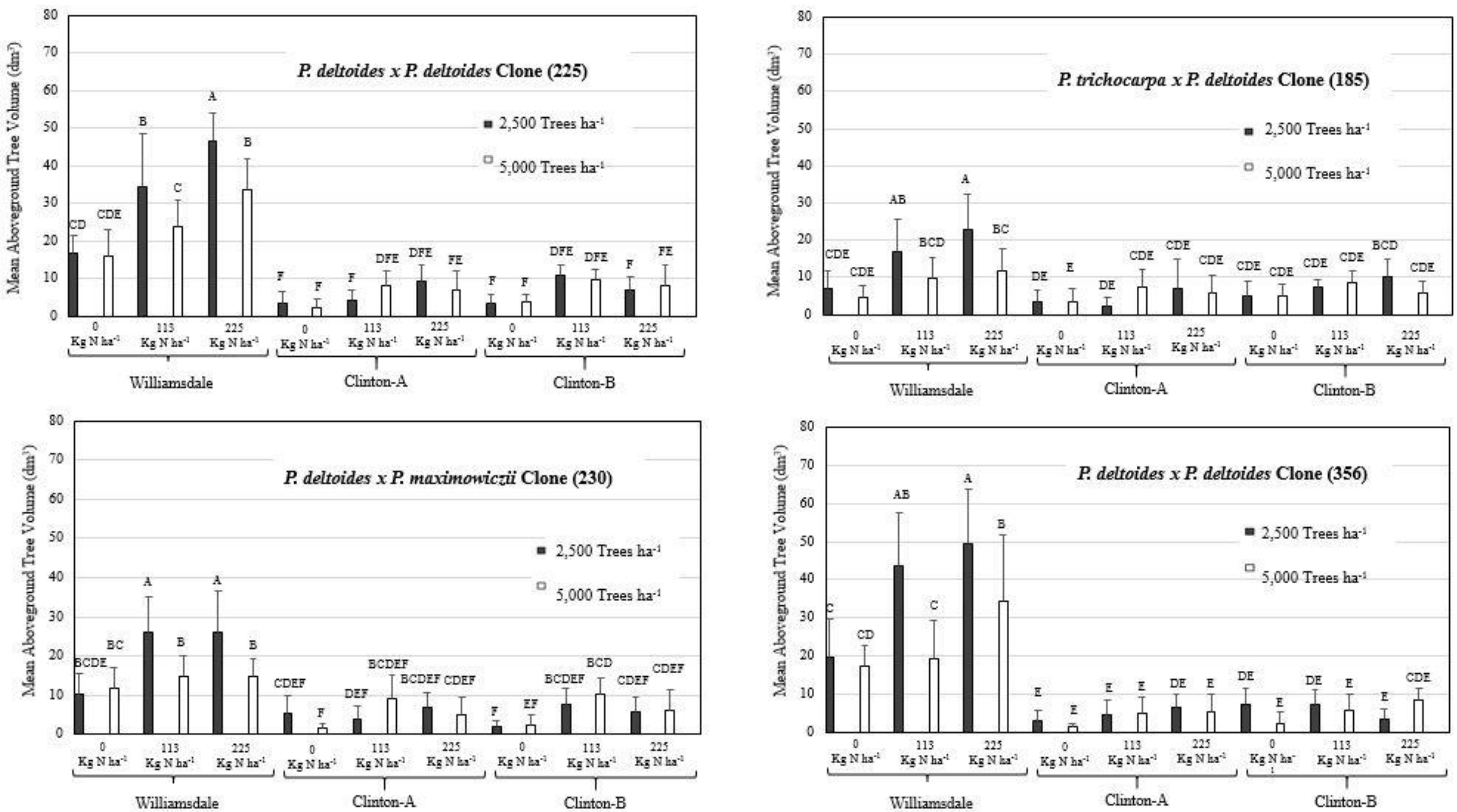

Figure 1. Mean aboveground tree volume (dm^3) (volume index) for each *Populus* clone by site, fertilization treatment, and planting density. Error bars denote one standard deviation of the mean per treatment. Different letters denote significant differences ($\alpha = 0.05$, ANOVA) but do not reflect every significant comparison.

Table 2. Cumulative aboveground tree volume per hectare (actual volume) and estimated wet and dry biomass for *Populus* by planting density after two years of growth.

Site	Fertilization (kg N/ha)	Total Volume (m^3/ha)	Wet Biomass (Mg/ha)	Dry Biomass (Mg/ha)	Total Volume (m^3/ha)	Wet Biomass (Mg/ha)	Dry Biomass (Mg/ha)
		at 2,500 trees ha^{-1}			at 5,000 trees ha^{-1}		
Williamsdale	0	33	16	7.9	65	31	16
Williamsdale	113	48	23	11	73	35	17
Williamsdale	225	51 [a]	24 [a]	12 [a]	85 [a]	41 [a]	20 [a]
Clinton A	0	25	12	6.0	46	22	11
Clinton A	113	25	12	5.9	56 [a]	27 [a]	13 [a]
Clinton A	225	28 [a]	14 [a]	6.6 [a]	55	25	13
Clinton B	0	26	12	6.5	49	24	12
Clinton B	113	29 [a]	14 [a]	6.9 [a]	58 [a]	28 [a]	14 [a]
Clinton B	225	27	13	6.4	55	26	13

[a] Greatest volume of biomass at given site.

Populus maximowiczii (clone 230), which had greater mean tree volumes at 5,000 trees ha^{-1} and 113 kg N ha^{-1} (Figure 1). As shown in Table 2, the lower fertilization rate increased cumulative tree volumes as much as the higher fertilization rate and even higher for trees planted at 5,000 trees ha^{-1}. These volume yields were similar to cumulative tree volumes for fertile soils without fertilization. Fertilization of marginal soils at the lower planting density were not as productive as 5,000 trees ha^{-1} (Table 2), and volume increases to fertilization and planting density was less dramatic for marginal soils versus fertile soils. For marginal soils, fertilization was less impactful as planting densities to increase volume yields similar to fertile soils without fertilization. The site specific response of poplar productivity is not surprising and is well documented for coastal sandy soils [Shifflett *et al.*, 2014, Shifflett *et al.*, 2016, Ghezehei *et al.*, 2016]. Miller *et al.* (2016) reported that the majority of the variability in poplar growth responses was due to site effects, while genotype accounted for 23% of growth variability. This study also reported that 14% of the genotype variation was attributed to poplar's strong genotype by environment interactions which suggests that growth yields can be improved by using poplar genotypes uniquely suited to site conditions. Results from this study support this finding that specific genotypes responded to treatments by site (Table 3, ANOVA, $\alpha = 0.05$).

Estimated biomass yields shown in Table 2 for non-fertilized, fertile soils are similar to prior findings (Miller *et al.*, 2016, Dillen *et al.*, 2012, Fang *et al.*, 2000, Zalesney *et al.*, 2016 Shifflett *et al.*, 2016, Ghezehei *et al.*, 2016]. Many of these studies observed biomass yields ranging from 4.0 to 13.0 dry Mg ha^{-1} yr^{-1}, with some yields exceeding 20.0 dry Mg ha^{-1} yr^{-1} in older stands, when genotypes were matched to specific adaptation zones [Zalesney *et al.*, 2016]. In our study, dry biomass yields of approximately 6.0 Mg ha^{-1} on marginal soils without fertilization (at 2,500 trees ha^{-1} after two years of growth) were greater than recent reports of 1.1

$m^3\ ha^{-1}\ yr^{-1}$ h dry biomass for marginal soils [Truax *et al.*, 2012]. For this study, nitrogen fertilization consistently improved yields on fertile soils but not marginal soils. Studies addressing the site specific response of poplars to fertilization have reported improved yields with fertilization [Christersson *et al.*, 2006] and no improvement with fertilization [Vande Walle *et al.*, 2007]. The variable response of clones to fertilization between fertile and marginal soils may result from soil quality differences of sites. For this study, the cation exchange capacity (CEC) was significantly lower in marginal soils versus fertile soils (Table 1). Lower CEC can result in rapid loss of nutrients due to leaching, particularly when fertilizer is applied in a single application to sandy soils [Sonon *et al.*, 2014].

Productivity Relative to Incidence of Pests and Disease.

Productivity depends upon tree survival and tree health, particularly tree response to predation, weed control, and disease [Truax *et al.*, 2012, Vande Walle *et al.*, 2007, Fang *et al.* 2000, Miller *et al.*, 2016]. Planting density, site, and fertilization rates were not significant for survival (Table S-4, ANOVA, $\alpha = 0.05$) in contrast to other studies [Navarro *et al.*, 2016, Coyle *et al.*, 2006, Ghezehei *et al.*, 2015, Dipesh *et al.*, 2017]. Survival for non-fertilized plots was excellent for all four clones at 93% or greater (Table S-1 and S-2) regardless of planting density and sites. Survival among fertilized plots was not consistent among clones, particularly the *P. trichocarpa x P. deltoides* (185) clone, showing variable survival from 62% to 83% depending on planting density and site. The *P. deltoides x P. deltoides* (140 and 356) and *P. deltoides x P. maximowiczii* (230) clones had greater survival variability on marginal soils regardless of planting density as well as the highest productivity on fertile soils regardless of planting density. However, lower clonal survival rates did not always result in significantly lower tree volumes for fertilized plots.

Table 3. ANOVA results of *Populus* aboveground tree volume (volume index) (dm^3) at Clinton A, Clinton B, and Williamsdale after two growing seasons ($\alpha = 0.05$).

Effect	DF	Type III SS	Mean Square	F Value	Pr > F [a]
Site	2	47,911	23,955	628	<.0001
Planting Density	1	1,746	1,746	45.8	<.0001
Site*Planting Density	2	3,569	1,784	46.8	<.0001
Clone	3	4,924	1,641	43.0	<.0001
Site*Clone	6	10,198	199	44.6	<.0001
Planting Density*Clone	3	296	98	2.59	0.0516
Site*Planting Density*Clone	6	299	49	1.31	0.2497
Fertilization	2	8,998	4,499	118	<.0001
Site*Fertilization	4	5,628	1,407	36.9	<.0001
Planting Density*Fertilization	2	355	177	4.66	0.0098
Site*Planting Density* Fertilization [b]	4	2,251	562	14.7	<.0001
Clone*Fertilization	6	959	159	4.20	0.0004
Site*Clone*Fertilization [b]	12	1,390	115	3.04	0.0003
Planting Density*Clone* Fert	6	451	75	1.98	0.0667
Site*Planting Density*Clone* Fert	12	462	38	1.01	0.4353

[a] Pr > F values lower than $\alpha = 0.05$ are significant; [b] Strongest significant interaction effects; $R^2 = 0.7780$.

Mean tree volumes for *P. trichocarpa x P. deltoides* (185) on marginal soils were not significantly different than the other clones for fertilized treatments (Figure 1).

Disease and predation also impacts poplar productivity [Shifflett *et al.*, 2016, Verlinden *et al.*, 2013]. *Melampsora* rust, *Chrysomela scripta* Fabricius, and deer damage was observed at all three sites for all clones. *Melampsora* rust was the most prevalent across all of the sites, yet, the presence of *Melampsora* rust differed significantly among sites and clones (Table S-5, $R^2 = 0.45$, ANOVA, $\alpha = 0.05$). The fertile soils at Williamsdale had the highest rate of *Melampsora* rust (82%) compared to the marginal soils sites (20 % for Clinton A and 22% for Clinton B) perhaps due to prior *Populus* studies at the Williamsdale (est. 2012). All clones had *Melampsora* rust incidence above 34%, yet, *P. trichocarpa x P. deltoides* (185) clone had a significantly higher presence of *Melampsora* rust (51%) across all sites. Covarelli *et al.*, (2012) reported that site and genotype were important factors for scoring *Melampsora* rust damage in Italy. Planting density and fertilization rate did not significantly influence the presence of *Melampsora* rust in this study, but, planting density did affect the presence of *Chrysomela scripta* Fabricius (Table S-6, ANOVA, $\alpha = 0.05$). The planting density of 5,000 trees ha^{-1} had 42% higher rates of *Chrysomela scripta* Fabricius beetle damage than the planting density of 2,500 trees ha^{-1}. All clones exhibited beetle damage incidence greater than 38%; *P. trichocarpa x P. deltoides* (185) clone had a significantly higher incidence of damage at 50%. Fertilized trees at 113 kg N ha^{-1} had more beetle damage (52%) than no fertilization (33.6%) or 225 kg N ha^{-1} (44.5%) for all clones across the three sites. There were no unprotected trees in this study, however, Coyle *et al.*, (2008) reported that trees protected against *Chrysomela scripta* Fabricius had significantly greater height, diameter, and stem volume than unprotected trees. The presence of deer damage was approximately 1% across all sites and was not significant to tree health in this study (Table S-7, ANOVA, $\alpha = 0.05$).

Productivity, LAI, and Foliar N.

Biomass production in forest stands is directly related to amount of solar radiation intercepted by the foliage or leaf area which is correlated to growth [Ceulemans *et al.,* 1993, Waring *et al.,* 2016, Ridge *et al.,* 1986]. Leaf area index (LAI) measurements indicated that site, clone, planting density, and fertilization rate were significant (Table S-8, ANOVA, $\alpha = 0.05$), but there was not a strong correlation between LAI and tree volume (Table S-9, $R^2 = 0.12$) in contrast to prior studies [Ceulemans *et al.,* 1993, Ridge *et al.,* 1986]. The lack of correlation strength observed in this study most likely reflects the influence of site, clone, planting density, and fertilization variables, of which, site accounts for the largest amount of variability. The LAI (1.85 m^2 m^{-2}) for all trees on fertile soils (Williamsdale) was greater than the LAIs for marginal soils (1.64 m^2 m^{-2} for Clinton A and 1.35 m^2 m^{-2} for Clinton B) after two years of growth. *P. deltoides x P. deltoides* (356) had a significantly lower LAI (1.39 m^2 m^{-2}) than the other three clones (1.80 m^2 m^{-2}) (Figure S-3) although this clone yielded greater tree volumes. The higher planting density of 5,000 trees ha^{-1} had a lower average LAI (1.56 m^2 m^{-2}) than the lower planting density of 2,500 trees ha^{-1} (1.67 m^2 m^{-2}) in contrast to Fang *et al.,* (2000).

Limited nutrient availability can limit growth in SRWC plantations and prior studies have shown increased biomass yields with nitrogen fertilization [Pope *et al.,* 1988, Christersson *et al.,* 2006, Miller *et al.,* 2016 Shifflet *et al.,* 2016, Ghezehei *et al.,* 2015]. Foliar nitrogen (%) analyses can indicate whether nutrient concentrations are sufficient for metabolic requirements for tree [Lteif *et al.,* 2008]. This study found that site, clone, planting density, and fertilization rates significantly affected foliar N (Table S-10; ANOVA, $\alpha = 0.05$, $R^2 = 0.44$). Site had the largest influence on foliar nitrogen variability. Among unfertilized trees, foliar N was significantly higher at Williamsdale (1.97%) than the two Clinton sites (1.84% at Clinton A and Clinton B). There was also a significant difference in foliar N between genotypes; the *P. deltoides x P. deltoides* (140) clone had the highest foliar N (1.95%) while the *P. trichocarpa x P. deltoides* (185) clone had the lowest foliar N (1.80%). Fertilization and planting density did not have a significant influence on genotype, and while statistically significant, the correlation of foliar N to tree volume was weak (Table S-9, $R^2 = 0.10$).

The influence of fertilization on foliar N content varies among published literature. Pope *et al.,* (1988) reported that fertilization can be an important factor to foliar N poplar content on certain soil series. Previous studies have shown much stronger correlations ($R^2 = 0.21$ for height and $R^2 = 0.35$ for DBH) between volume and foliar N concentrations than observed in this study [Lteif *et al.*, 2008, Wilson *et al.,* 2013]. Foliar N concentrations increased by approximately 5% in the fertilized treatments on fertile soils (Williamsdale), regardless of planting density or clone. However, foliar N concentrations decreased by approximately 3% in the fertilized treatments of marginal soils, regardless of planting density or clone, which may reflect nitrogen availability due to poor soil quality such as CEC. Wilson *et al.,* (2013) observed that fertilized trees had higher foliar N but that nitrogen leachate increased with the fertilizer application rate. Thus, increased fertilization rates may not yield expected increases in poplar growth and foliar N, potentially due to soil processes such as microbial competition, leaching, and adsorption [Wilson *et al.,* 2013].

Economic Profitability.

At current regional market prices ($27.56 USD/t), estimated biomass yields based on volume productivity were not economically feasible regardless of rotation length, genotype, site, or treatment (Table 4 and 5). A study conducted in Germany concluded that biomass yields of 7-8 Mg ha^{-1} yr^{-1} of dry poplar biomass were not profitable, even in markets supportive of SRWC forestry [Schweier *et al.*, 2013]. In this study, biomass yields ranged from 6 Mg ha^{-1} to 20 Mg ha^{-1} (after 2 years of growth), yet estimated NPV were not positive even for clones that produced the most biomass (P. *deltoides x P. deltoides*, 140 and 356) and had the highest NPV at all sites.

The lack of genotype impact on profitability is particularly evident when evaluating break-even prices, which are the market prices needed to simply recoup establishment and maintenance costs (Tables 4 and 5). Break-even prices were lower for higher-density plantings at longer rotation lengths for all clones, treatments, and sites. For fertile soils, where fertilization resulted in significantly improved biomass yields, break-even prices were not changed substantially from non-fertilized soils at any rotation length due in part to weed control costs. Although break-even prices were lower at higher planting densities, the additional biomass gained per hectare at the planting density of 5,000 trees ha^{-1} was negated by the greater planting costs for more cuttings for fertile soils. Marginal soils had lower break-even prices for all treatments and planting densities compared to fertile soils because of lower weed control costs on marginal soils. Profitability appears possible only at eight year rotations at higher density plantings for all sites (~ $55 USD/t) (Table 5).

The barriers of profitability were the establishment costs for higher density plantings at all sites and weed control costs for fertile soils. The results of this study suggest that more stringent weed control is needed rather than fertilization for fertile soils whereas fertilization is needed for

Table 4. Net present value (NPV) (at $27.56 USD/t) and breakeven price ($/t) after two, six, and eight years of growth years for *P. deltoides x P. deltoides* (140 and 356), *P. trichocarpa x P. deltoides* (185), and *P. deltoides x P. maximowiczii* (230) at a tree density of 2,500 trees ha^{-1}.

Williamsdale (fertile soils; 2,500 trees ha^{-1})

Clone	**2nd Year NPV ($/ha)**	**2nd Year Breakeven Price ($/t)**	**6th Year NPV ($/ha)**	**6th Year Breakeven Price ($/t)**	**8th Year NPV ($/ha)**	**8th Year Breakeven Price ($/t)**
0 kg N ha^{-1}						
140 DD	-1,905	206.81	-1,659	86.22	-1,561	72.74
185 TD	-1,908	217.29	-1,667	89.92	-1,571	75.69
230 DM	-1,853	212.30	-1,513	88.16	-1,378	74.29
356 DD	-1,849	205.48	-1,500	85.74	-1,362	72.37
113 kg N ha^{-1}						
140 DD	-1,948	192.90	-1,764	81.29	-1,691	68.83
185 TD	-1,925	209.02	-1,698	87.00	-1,608	73.37
230 DM	-1,932	202.50	-1,720	84.69	-1,636	71.53
356 DD	-1,918	188.35	-1,678	79.68	-1,583	67.55
225 N kg ha^{-1}						
140 DD	-1,912	185.45	-1,663	78.66	-1,564	66.73
185 TD	-1,914	206.98	-1,667	86.27	-1,569	72.79
230 DM	-1,862	202.23	-1,522	84.59	-1,387	71.45
356 DD	-1,850	188.60	-1,488	79.77	-1,344	67.62

Table 4. Continued

Clinton A (marginal soils; 2,500 trees ha^{-1})

Clone	2nd Year NPV ($/ha)	2nd Year Break Even Price ($/t)	6th Year NPV ($/ha)	6th Year Break Even Price ($/t)	8th Year NPV ($/ha)	8th Year Break Even Price ($/t)
0 kg N ha^{-1}						
140 DD	-1,785	204.53	-1,628	85.41	-1,565	72.10
185 TD	-1,773	204.53	-1,592	85.41	-1,520	72.10
230 DM	-1,789	205.36	-1,637	85.70	-1,577	72.34
356 DD	-1,785	204.53	-1,628	85.41	-1,565	72.10
113 kg N ha^{-1}						
140 DD	-1,801	204.88	-1,656	85.53	-1,598	72.20
185 TD	-1,791	207.65	-1,627	86.51	-1,562	72.98
230 DM	-1,792	204.93	-1,629	85.55	-1,565	72.21
356 DD	-1,796	205.80	-1,641	85.86	-1,579	72.46
225 kg N ha^{-1}						
140 DD	-1,786	200.12	-1,619	83.85	-1,553	70.86
185 TD	-1,796	202.59	-1,646	84.72	-1,587	71.56
230 DM	-1,794	202.45	-1,640	84.67	-1,579	71.52
356 DD	-1,786	203.69	-1,618	85.11	-1,551	71.87

Table 4. Continued

Clone	2nd Year NPV ($/ha)	2nd Year Break Even Price ($/t)	6th Year NPV ($/ha)	6th Year Break Even Price ($/t)	8th Year NPV ($/ha)	8th Year Break Even Price ($/t)
Clinton B (marginal soils; 2,500 trees ha^{-1})						
0 kg N ha^{-1}						
140 DD	-1,714	197.11	-1,562	82.78	-1,501	70.01
185 TD	-1,691	196.43	-1,498	82.54	-1,421	69.82
230 DM	-1,705	198.08	-1,536	83.13	-1,470	70.28
356 DD	-1,710	194.53	-1,550	81.87	-1,487	69.28
113 kg N ha^{-1}						
140 DD	-1,711	190.73	-1,537	80.53	-1,468	68.22
185 TD	-1,706	193.52	-1,523	81.51	-1,451	69.00
230 DM	-1,727	193.91	-1,583	81.65	-1,526	69.11
356 DD	-1,712	194.68	-1,539	81.92	-1,471	69.33
225 kg N ha^{-1}						
140 DD	-1,714	195.15	-1,553	82.09	-1,489	69.46
185 TD	-1,710	193.33	-1,539	81.45	-1,472	68.95
230 DM	-1,709	197.17	-1,536	82.81	-1,468	70.03
356 DD	-1,719	198.07	-1,567	83.12	-1,506	70.28

Table 5. Net present value (NPV) (at $27.56 USD/t) and breakeven price ($/t) after two, six, and eight years of growth years for *P. deltoides x P. deltoides* (140 and 356), *P. trichocarpa x P. deltoides* (185), and *P. deltoides x P. maximowiczii* (230) at a tree density of 5,000 trees ha^{-1}.

Williamsdale (fertile soils; 5,000 trees ha^{-1})

Clone	2nd Year NPV ($/ha)	2nd Year Breakeven Price ($/t)	6th Year NPV ($/ha)	6th Year Breakeven Price ($/t)	8th Year NPV ($/ha)	8th Year Breakeven Price ($/t)
0 kg N ha^{-1}						
140 DD	-2,561	149.21	-2,120	65.84	-1,945	56.53
185 TD	-2,514	157.14	-1,987	68.64	-1,778	58.76
230 DM	-2,454	150.96	-1,818	66.46	-1,566	57.02
356 DD	-2,630	149.18	-2,315	65.83	-2,190	56.52
113 kg N ha^{-1}						
140 DD	-2,607	144.64	-2,234	64.22	-2,087	55.24
185 TD	-2,593	152.53	-2,194	67.01	-2,036	57.46
230 DM	-2,593	150.08	-2,196	66.15	-2,038	56.77
356 DD	-2,579	147.83	-2,156	65.35	-1,987	56.14
225 kg N ha^{-1}						
140 DD	-2,576	140.06	-2,146	62.60	-1,975	53.95
185 TD	-2,567	153.05	-2,120	67.20	-1,943	57.61
230 DM	-2,543	150.17	-2,054	66.18	-1,860	56.80
356 DD	-2,474	139.57	-1,857	62.43	-1,612	53.81

Table 5. Continued

Clinton A (marginal soils; 5,000 trees ha^{-1})						
Clone	2nd Year NPV ($/ha)	2nd Year Break Even Price ($/t)	6th Year NPV ($/ha)	6th Year Break Even Price ($/t)	8th Year NPV ($/ha)	8th Year Break Even Price ($/t)
0 kg N ha^{-1}						
140 DD	-2,477	150.77	-2,184	66.39	-2,068	56.97
185 TD	-2,444	151.56	-2,089	66.67	-1,948	57.19
230 DM	-2,449	151.15	-2,104	66.52	-1,967	57.07
356 DD	-2,484	151.50	-2,202	66.65	-2,091	57.17
113 kg N ha^{-1}						
140 DD	-2,462	147.68	-2,125	65.30	-1,991	56.10
185 TD	-2,469	148.12	-2,145	65.46	-2,016	56.22
230 DM	-2,490	146.36	-2,204	64.83	-2,090	55.72
356 DD	-2,445	150.12	-2,077	66.16	-1,931	56.78
225 kg N ha^{-1}						
140 DD	-2,468	148.25	-2,147	65.50	-2,019	56.25
185 TD	-2,490	149.23	-2,209	65.85	-2,098	56.53
230 DM	-2,469	149.11	-2,151	65.80	-2,024	56.50
356 DD	-2,466	149.35	-2,141	65.89	-2,013	56.57

Table 5. Continued

Clone	2nd Year NPV ($/ha)	2nd Year Break Even Price ($/t)	6th Year NPV ($/ha)	6th Year Break Even Price ($/t)	8th Year NPV ($/ha)	8th Year Break Even Price ($/t)
	Clinton B (marginal soils; 5,000 trees ha^{-1})					
0 kg N ha^{-1}						
140 DD	-2,393	146.30	-2,083	64.81	-1,959	55.71
185 TD	-2,361	145.19	-1,993	64.42	-1,846	55.39
230 DM	-2,368	147.11	-2,011	65.10	-1,870	55.94
356 DD	-2,385	147.66	-2,061	65.29	-1,933	56.09
113 kg N ha^{-1}						
140 DD	-2,377	142.93	-2,022	63.62	-1,881	54.76
185 TD	-2,391	143.78	-2,062	63.92	-1,931	55.00
230 DM	-2,411	143.09	-2,117	63.67	-2,000	54.80
356 DD	-2,368	145.31	-1,996	64.46	-1,849	55.43
225 kg N ha^{-1}						
140 DD	-2,386	143.19	-2,052	63.71	-1,919	54.83
185 TD	-2,408	145.18	-2,115	64.41	-1,999	55.39
230 DM	-2,389	145.02	-2,060	64.36	-1,930	55.35
356 DD	-2,384	145.16	-2,045	64.41	-1,911	55.38

marginal soils to enhance productivity. Because volume yields were significant to genotype and fertilization at all three sites, these findings highlight the importance of selecting the right clones (or species) for site specific conditions and site management practices. This is especially true on marginal lands where biomass yields are hindered. These findings agree with prior economic analyses for poplar in coastal sandy soils [Ghezehei *et al.* 2015] and highlight the importance of selecting the right poplar genotype for sites, management, and planting density in order to optimize productivity with costs to achieve economic feasibility.

Conclusion.

Appropriate genotype selection, fertilization, and planting density can provide substantial biomass yields for poplars in coastal sandy soils. This study demonstrated that fertilization of *Populus* on marginal lands can improve volume yields similar to volume yields observed on non-fertilized, fertile soils; however, volume yields were significantly greater on fertilized, fertile soils. The influence of genotype was specific to fertilization, disease, pest, and foliar nitrogen response on fertile and marginal soils. Higher levels of fertilization did not necessarily correlate to higher volume yields on marginal soils. The *P. deltoides x P. deltoides* (140 and 356) clones produced The highest mean aboveground volume on marginal soils and substantially greater yields on fertile soils at the high fertilization rate. At current market prices, profitability was not feasible even for high volume yields of fertilized, fertile soil. Higher density plantings increased total volume yields per hectare for fertile and marginal lands and provided the most likely path to profitability at eight year rotation lengths. The economic viability of poplar for SRWC will require site specific management practices and genotype selection practices between fertile and marginal soils, as well as, significant increases of market prices.

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APPENDIX.

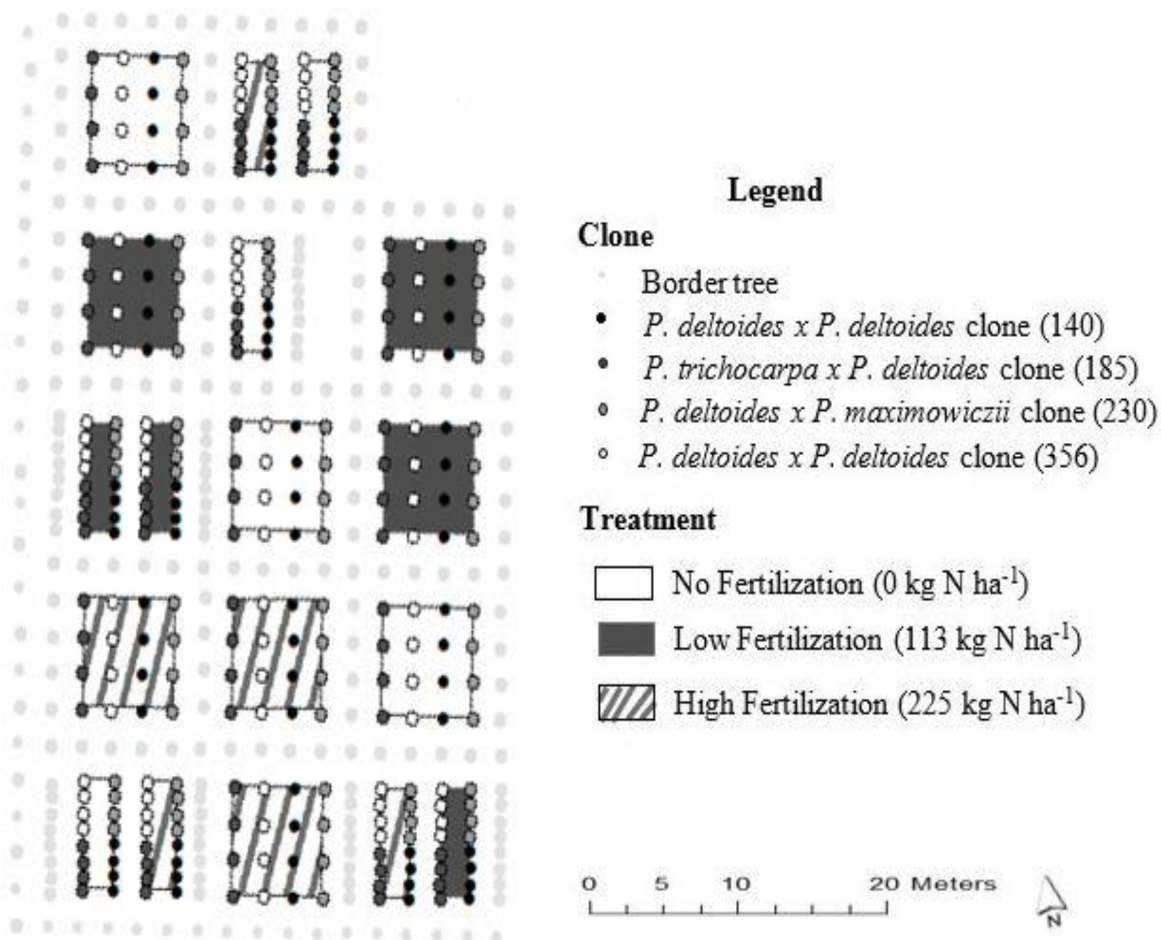

Figure S-1. Site map of randomized, split-split plot study at Williamsdale on fertile soils.

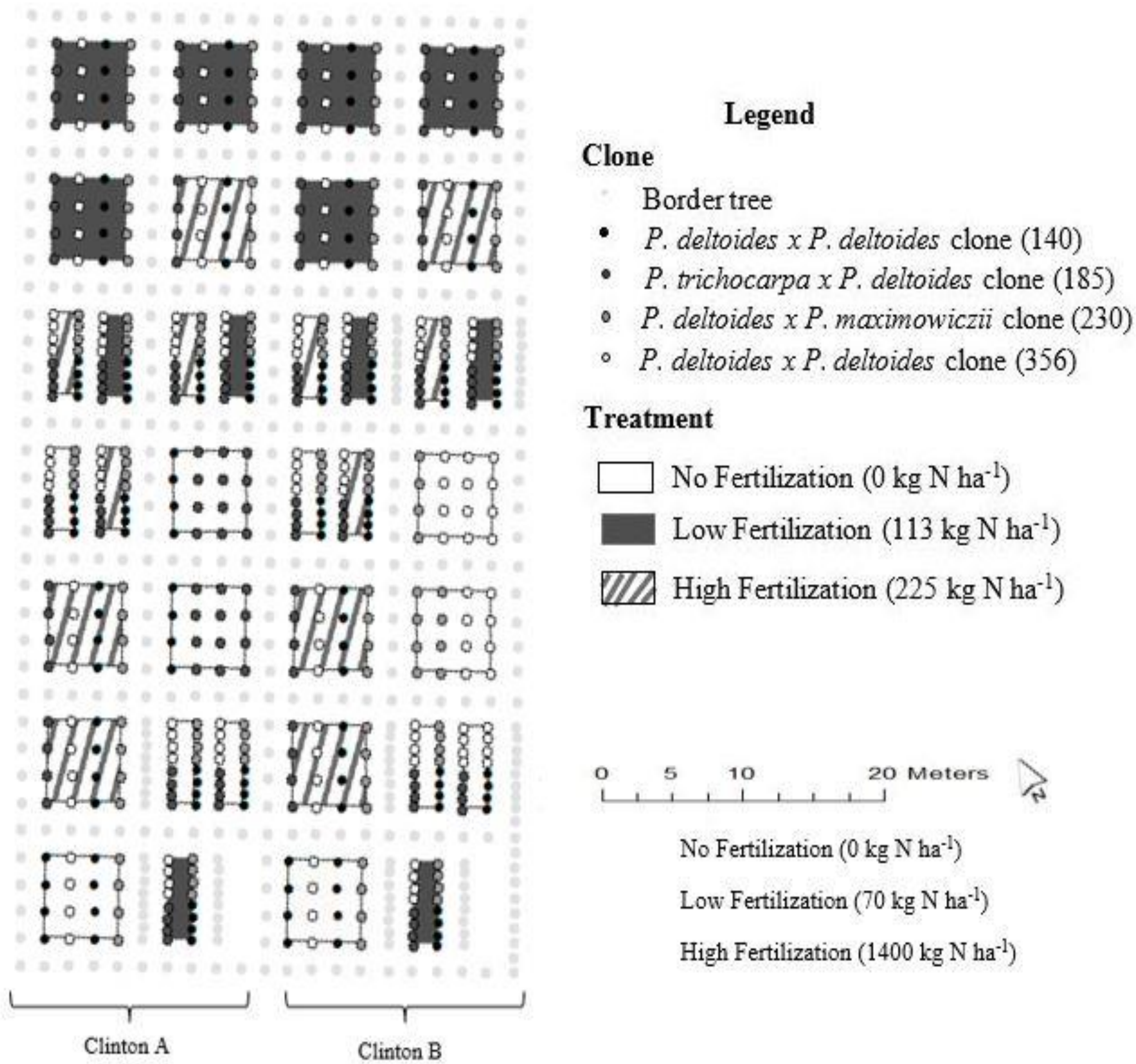

Figure S-2. Site map of randomized, split-split plot studies, Clinton A and Clinton B, on marginal soils which are separated by a row of border trees (planted at 2,500 trees ha^{-1}) running vertically through the poplar plantation.

Table S-1. Survival and productivity metrics after two years of growth for *P. deltoides x P. deltoides* (140 and 356), *P. trichocarpa x P. deltoides* (185), and *P. deltoides x P. maximowiczii* (230) at a tree density of 2,500 trees ha^{-1}. Metrics are mean values $\pm$ one standard deviation (SD) of aboveground tree volume, height, diameter at breast height (DBH), LAI, and foliar nitrogen (%) Clones are listed in order of high to low tree volume within each treatment at each site.

Williamsdale (fertile soils; 2,500 trees ha^{-1})

Clone	Survival (%)	Volume (dm^3)	SD	Height (m)	SD	DBH (cm)	SD	LAI (m^{2}m^{-2})	SD	Foliar N (%)	SD
0 kg N ha^{-1}											
356 DD	100	19.8	0.9	6.5	0.8	5.0	1.0	1.3	0.2	2.0	0.1
140 DD	100	16.7	0.4	6.7	0.7	4.9	0.5	1.2	0.2	2.1	0.1
230 DM	92	10.2	0.5	5.3	0.9	4.1	1.1	1.2	0.3	2.0	0.2
185 TD	75	6.8	0.4	5.0	0.8	3.3	0.7	1.4	0.2	2.0	0.2
113 kg N ha^{-1}											
356 DD	100	43.6	1.3	8.0	0.8	7.1	0.6	2.5	0.1	2.1	0.1
140 DD	100	34.4	1.4	7.6	1.6	6.7	1.3	2.2	0.1	2.2	0.1
230 DM	100	26.1	0.9	6.8	0.5	5.8	0.8	2.7	0.1	2.0	0.3
185 TD	67	17.0	0.8	5.9	0.6	5.2	1.2	2.5	0.2	2.1	0.2
225 N kg ha^{-1}											
140 DD	100	46.6	0.7	7.8	0.3	7.7	0.6	1.9	0.4	2.2	0.2
356 DD	100	27.0	1.0	6.6	0.9	5.9	1.1	2.2	0.6	2.1	0.1
230 DM	100	26.1	1.0	6.5	0.8	5.8	1.1	1.8	0.3	2.1	0.2
185 TD	100	23.0	0.9	6.6	0.6	5.2	1.1	2.2	0.6	2.1	0.6

Table S-1. Continued

Clinton A (marginal soils; 2,500 trees ha^{-1})

Clone	Survival (%)	Volume (dm^3)	SD	Height (m)	SD	DBH (cm)	SD	LAI (m^2m^{-2})	SD	Foliar N (%)	SD
0 kg N ha^{-1}											
230 DM	100	5.2	0.4	4.2	1.9	2.6	1.7	1.9	0.8	1.9	0.2
140 DD	100	3.5	0.3	3.9	1.1	2.5	1.2	1.2	0.5	2.0	0.2
185 TD	92	3.2	0.3	3.7	1.3	2.3	1.3	1.8	0.9	2.1	0.1
356 DD	92	2.9	0.3	3.5	1.1	2.3	1.2	1.3	0.6	1.8	0.4
113 kg N ha^{-1}											
140 DD	92	4.4	0.4	3.9	0.7	2.9	0.4	1.4	0.5	1.7	0.2
356 DD	92	4.4	0.2	4.0	0.9	3.0	1.1	1.0	0.3	1.7	0.3
230 DM	92	3.9	0.3	3.8	0.8	2.8	1.2	1.6	0.4	1.8	0.2
185 TD	83	2.2	0.2	3.4	1.0	2.0	1.1	1.5	0.5	1.3	0.3
225 kg N ha^{-1}											
140 DD	100	9.1	0.4	4.7	0.4	4.2	0.8	1.5	0.4	2.1	0.3
230 DM	92	7.0	0.3	4.5	0.6	3.5	1.0	2.2	0.2	1.9	0.0
185 TD	67	6.9	0.7	4.2	1.0	3.1	1.4	2.1	0.4	1.8	0.1
356 DD	83	6.7	0.3	4.3	0.5	3.6	0.8	1.4	0.3	2.0	0.2

Table S-1. Continued

Clinton B (marginal soils; 2,500 trees ha^{-1})

Clone	Survival (%)	Volume (dm^3)	SD	Height (m)	SD	DBH (cm)	SD	LAI (m^2m^{-2})	SD	Foliar N (%)	SD
0 kg N ha^{-1}											
356 DD	100	7.1	0.4	4.9	0.7	3.5	1.0	0.9	0.3	1.8	0.2
185 TD	75	4.8	0.4	4.4	1.4	2.8	1.2	1.2	0.3	1.7	0.3
140 DD	100	3.3	0.2	4.0	0.9	2.6	0.9	0.9	0.3	1.7	0.2
230 DM	100	1.9	0.1	3.3	1.0	2.0	0.9	1.0	0.2	1.8	0.2
113 kg N ha^{-1}											
140 DD	92	10.8	0.2	5.3	0.4	4.5	0.5	1.2	0.4	1.6	0.1
230 DM	92	7.7	0.4	4.8	0.3	3.7	0.8	1.5	0.3	1.6	0.1
185 TD	58	7.2	0.2	5.1	0.5	3.7	0.4	1.8	0.5	1.6	0.3
356 DD	92	7.2	0.3	4.7	0.9	3.6	1.2	1.0	0.1	1.9	0.1
225 kg N ha^{-1}											
185 TD	67	10.0	0.4	5.0	0.7	4.0	1.0	2.1	0.1	1.8	0.1
140 DD	100	6.7	0.3	4.8	0.7	3.5	0.8	1.0	0.1	1.9	0.1
230 DM	75	5.7	0.3	4.3	0.7	3.2	0.9	1.1	0.4	1.8	0.2
356 DD	100	3.6	0.2	4.0	0.9	2.5	1.1	1.1	0.1	1.8	0.1

Table S-2. Survival and productivity metrics after two years of growth for *P. deltoides x P. deltoides* (140 and 356), *P. trichocarpa x P. deltoides* (185), and *P. deltoides x P. maximowiczii* (230) at a tree density of 5,000 trees ha^{-1}. Metrics are mean values $\pm$ one standard deviation (SD) of aboveground tree volume, height, diameter at breast height (DBH), LAI, and foliar nitrogen (%) Clones are listed in order of high to low tree volume within each treatment at each site.

Williamsdale (fertile soils; 5,000 trees ha^{-1})

Clone	Survival (%)	Volume (dm^3)	SD	Height (m)	SD	DBH (cm)	SD	LAI (m^2m^{-2})	SD	Foliar N (%)	SD
0 kg ha^{-1}											
356 DD	92	17.5	0.5	6.7	0.7	4.9	0.5	1.5	0.7	1.9	0.1
140 DD	92	15.7	0.7	6.2	0.9	4.8	1.1	1.2	0.5	2.0	0.2
230 DM	100	11.8	0.5	5.8	0.6	4.4	1.0	1.7	0.9	1.9	0.2
185 TD	83	4.6	0.3	4.8	1.7	2.7	1.1	1.3	0.6	1.9	0.0
113 kg N ha^{-1}											
356 DD	100	23.6	0.7	6.7	0.6	5.9	0.7	1.4	0.6	2.1	0.1
140 DD	100	19.3	1.0	6.9	0.7	5.1	1.3	1.8	0.8	2.1	0.5
230 DM	100	14.7	0.5	6.1	0.8	4.7	0.8	1.9	1.0	2.1	0.2
185 TD	92	9.6	0.5	5.4	1.1	3.9	1.0	1.5	0.6	1.8	0.2
225 kg N ha^{-1}											
140 DD	100	34.5	1.7	7.4	0.4	6.5	0.9	2.3	0.5	2.1	0.2
356 DD	92	33.5	0.8	7.5	0.5	6.6	0.8	2.1	0.6	2.1	0.1
230 DM	100	14.8	0.4	5.9	0.5	4.9	0.7	2.4	0.4	1.9	0.1
185 TD	75	11.9	0.5	5.5	1.1	4.3	1.3	2.3	0.8	2.1	0.1

Table S-2. Continued

Clinton A (marginal soils; 5,000 trees ha^{-1})

Clone	Survival (%)	Volume (dm^3)	SD	Height (m)	SD	DBH (cm)	SD	LAI (m^2m^{-2})	SD	Foliar N (%)	SD
0 kg N ha^{-1}											
230 DM	100	2.3	0.2	3.4	0.8	2.2	1.1	1.3	0.4	1.8	0.1
140 DD	92	1.7	0.1	3.6	0.7	2.0	0.6	1.8	0.3	1.8	0.1
185 TD	92	1.5	0.1	3.0	1.1	1.6	0.9	1.5	0.5	1.6	0.4
356 DD	92	1.3	0.1	3.3	0.6	1.8	0.5	1.1	0.4	1.7	0.3
113 kg N ha^{-1}											
230 DM	100	9.2	0.6	3.4	0.8	2.2	1.1	1.3	0.4	1.8	0.1
140 DD	92	8.3	0.3	3.6	0.7	2.0	0.6	1.8	0.3	1.8	0.1
185 TD	92	7.4	0.4	3.0	1.1	1.6	0.9	1.5	0.5	1.6	0.4
356 DD	92	5.1	0.4	3.3	0.6	1.8	0.5	1.1	0.4	1.7	0.3
225 kg N ha^{-1}											
140 DD	83	7.0	0.4	4.5	1.3	3.3	1.5	1.5	0.6	1.9	0.2
230 DM	67	5.6	0.4	4.4	1.4	2.9	1.4	2.1	0.2	1.8	0.2
185 TD	100	5.4	0.4	4.2	1.5	2.9	1.4	1.8	0.8	2.0	0.3
356 DD	100	5.2	0.4	4.0	1.6	2.8	1.5	2.1	0.6	1.6	0.2

Table S-2. Continued

Clone	Survival (%)	Volume (dm^3)	SD	Height (m)	SD	DBH (cm)	SD	LAI ($m^2 m^{-2}$)	SD	Foliar N (%)	SD
Clinton B (marginal soils; 5,000 trees ha^{-1})											
0 kg N ha^{-1}											
356 DD	92	5.1	0.3	4.9	0.6	3.1	0.8	1.6	0.6	1.9	0.2
185 TD	92	3.9	0.1	4.5	0.7	2.8	0.7	1.1	0.4	2.2	0.3
140 DD	100	2.4	0.2	3.8	1.2	2.1	1.0	1.3	0.5	1.7	0.4
230 DM	92	2.3	0.3	3.6	1.0	2.0	1.1	1.1	0.5	2.1	0.3
113 kg N ha^{-1}											
140 DD	100	10.4	0.4	5.6	0.6	4.0	0.7	1.8	0.4	1.7	0.1
230 DM	100	9.6	0.2	5.6	0.3	4.0	0.6	1.5	0.2	2.0	0.3
185 TD	92	8.5	0.3	5.5	0.3	3.7	0.8	1.9	0.3	1.6	0.0
356 DD	100	5.5	0.4	4.7	1.1	3.0	1.3	1.4	0.3	1.9	0.2
225 kg N ha^{-1}											
185 TD	83	8.3	0.3	5.0	0.5	3.5	0.6	1.4	0.3	1.9	0.1
140 DD	100	8.1	0.5	4.7	1.5	3.7	1.3	1.3	0.5	1.7	0.2
230 DM	100	6.1	0.5	4.6	1.0	3.2	1.3	1.9	0.3	1.6	0.3
356 DD	67	5.6	0.3	4.7	0.8	3.2	1.0	2.1	0.1	1.4	0.2

Table S-3. ANOVA results of *Populus* aboveground tree volume (volume index) (dm^3) at Clinton A, Clinton B, and Williamsdale after the first growing season ($\alpha = 0.05$).

Effect	DF	Type III SS	Mean Square	F Value	Pr > F [a]
Site	2	1143	571	60.16	<.0001
Planting Density	1	251	83	8.84	<.0001
Site*Planting Density [b]	2	90	15	1.58	0.1493
Clone	3	120	120	12.73	0.0004
Site*Clone	6	116	58	6.15	0.0022
Planting Density*Clone [b]	3	92	30	3.23	0.0218
Site*Planting Density*Clone	6	28	4	0.49	0.8128
Fertilization	2	2321	1160	122.17	<.0001
Site*Fertilization	4	627	156	16.51	<.0001
Planting Density*Fertilization [b]	2	116	19	2.04	0.0586
Site*Planting Density* Fertilization [b]	4	148	12	1.30	0.2121
Clone*Fertilization [b]	6	28	14	1.50	0.2241
Site*Clone*Fertilization	12	112	28	2.95	0.0195
Planting Density*Clone* Fertilization	6	69	11	1.21	0.2985
Site* Planting Density*Clone* Fertilization	12	109	9	0.96	0.4832

[a] Pr > F values lower than $\alpha = 0.05$ are significant; [b] Differ from the second year aboveground tree volume significance; $R^2 = 0.7780$;

Table S-4. ANOVA results of *Populus* survival for Clinton A, Clinton B, and Williamsdale after two growing seasons ($\alpha = 0.05$).

Effect	DF	Type III SS	Mean Square	F Value	Pr > F [a]
Site	2	0.28	0.14	1.98	0.1384
Planting Density	1	0.05	0.05	0.82	0.3664
Site*Planting Density	2	0.16	0.08	1.18	0.3091
Clone [b]	3	5.12	1.70	23.97	<.0001
Site*Clone	6	0.11	0.01	0.27	0.9497
Planting Density*Clone	3	0.30	0.10	1.42	0.2362
Site*Planting Density*Clone	6	0.58	0.09	1.38	0.2197
Fertilization	2	0.20	0.10	1.45	0.2341
Site*Fertilization	4	0.47	0.11	1.66	0.1582
Planting Density*Fertilization	2	0.30	0.15	2.15	0.1176
Site* Planting Density* Fertilization	4	0.26	0.06	0.94	0.4381
Clone*Fertilization	6	0.34	0.05	0.80	0.5668
Site*Clone*Fertilization	12	0.64	0.05	0.75	0.7008
Planting Density*Clone* Fertilization	6	0.52	0.08	1.22	0.2944
Site*Planting Density*Clone* Fertilization	12	0.99	0.08	1.16	0.3063

[a] Pr > F values lower than $\alpha = 0.05$ are significant; [b] Strongest significant effect; $R^2 = 0.1555$;

Table S-5. ANOVA results of *Melampsora* (rust) presence on *Populus* at Clinton A, Clinton B, and Williamsdale ($\alpha = 0.05$).

Effect	DF	Type III SS	Mean Square	F Value	Pr > F [a]
Site	2	66.06	33.03	224.86	<.0001
Planting Density	1	0.02	0.02	0.14	0.7090
Site*Planting Density	2	0.64	0.32	2.19	0.1123
Clone	3	2.00	0.66	4.55	0.0036
Site*Clone	6	0.85	0.14	0.97	0.4468
Planting Density*Clone	3	2.46	0.82	5.59	0.0009
Site*Planting Density*Clone	6	1.54	0.25	1.75	0.1066
Fertilization	2	0.47	0.23	1.62	0.1994
Site*Fertilization	4	0.86	0.21	1.47	0.2091
Planting Density*Fertilization	2	0.71	0.35	2.44	0.0883
Site*Planting Density* Fertilization	4	1.35	0.33	2.31	0.0566
Clone*Fertilization	6	1.26	0.21	1.44	0.1977
Site*Clone*Fertilization	12	3.26	0.27	1.85	0.0372
Planting Density*Clone* Fertilization	6	0.64	0.10	0.74	0.6201
Site*Planting Density*Clone* Fertilization	12	3.06	0.25	1.74	0.0553

[a] Pr > F values lower than $\alpha = 0.05$ are significant; $R^2 = 0.4509$;

Table S-6. ANOVA results *Chrysomela scripta* Fabricius damage presence on *Populus* at Clinton A, Clinton B, and Williamsdale ($\alpha = 0.05$).

Effect	DF	Type III SS	Mean Square	F Value	Pr > F [a]
Site	2	0.42	0.21	0.99	0.3725
Planting Density	1	4.40	4.40	20.60	<.0001
Site*Planting Density	2	2.22	1.11	5.22	0.0056
Clone	3	2.21	0.73	3.45	0.0163
Site*Clone	6	3.76	0.62	2.94	0.0077
Planting Density*Clone	3	2.01	0.67	3.14	0.0248
Site*Planting Density*Clone	6	8.97	1.49	7.00	<.0001
Fertilization	2	3.90	1.95	9.14	0.0001
Site*Fertilization	4	1.72	0.43	2.02	0.0895
Planting Density*Fertilization	2	1.10	0.55	2.59	0.0758
Site*Planting Density* Fertilization	4	1.35	0.33	1.59	0.1761
Clone*Fertilization	6	2.99	0.49	2.33	0.0308
Site*Clone*Fertilization	12	1.96	0.16	0.77	0.6867
Planting Density*Clone* Fertilization	6	1.62	0.27	1.26	0.2719
Site*Planting Density*Clone* Fertilization	12	2.71	0.22	1.06	0.3939

[a] Pr > F values lower than $\alpha = 0.05$ are significant; $R^2 = 0.2120$;

Table S-7. ANOVA results deer damage presence on *Populus* at Clinton A, Clinton B, and Williamsdale ($\alpha = 0.05$).

Effect	**DF**	**Type III SS**	**Mean Square**	**F Value**	**Pr > F [a]**
Site	2	0.01	0.00	0.84	0.4328
Planting Density	1	0.00	0.00	0.00	1.0000
Site*Planting Density	2	0.02	0.01	1.00	0.3690
Clone	3	0.02	0.00	0.67	0.5704
Site*Clone	6	0.06	0.01	1.03	0.4065
Planting Density*Clone	3	0.02	0.00	0.67	0.5711
Site*Planting Density*Clone	6	0.01	0.00	0.30	0.9369
Fertilization	2	0.01	0.00	0.54	0.5837
Site*Fertilization	4	0.02	0.00	0.73	0.5743
Planting Density*Fertilization	2	0.00	0.00	0.00	0.9974
Site*Planting Density* Fertilization	4	0.01	0.00	0.47	0.7607
Clone*Fertilization	6	0.03	0.00	0.60	0.7291
Site*Clone*Fertilization	12	0.09	0.00	0.82	0.6338
Planting Density*Clone* Fertilization	6	0.13	0.02	2.16	0.0450
Site*Planting Density*Clone* Fertilization	12	0.14	0.01	1.20	0.2807

[a] Pr > F values lower than $\alpha = 0.05$ are significant; $R^2 = 0.0800$;

Table S-8. ANOVA results of *Populus* LAI at Clinton A, Clinton B, and Williamsdale (α = 0.05).

Effect	DF	Type III SS	Mean Square	F Value	Pr > F [a]
Site	2	29.50	14.75	65.93	<.0001
Planting Density	1	2.38	2.16	10.65	0.0012
Site*Planting Density	2	7.24	3.62	16.18	<.0001
Clone	3	28.24	9.41	42.07	<.0001
Site*Clone	6	12.99	2.16	9.68	<.0001
Planting Density*Clone	3	2.10	0.70	3.14	0.0248
Site*Planting Density*Clone	6	0.74	0.12	0.55	0.7678
Fertilization	2	38.98	19.49	87.11	<.0001
Site*Fertilization	4	7.26	1.81	8.12	<.0001
Planting Density*Fertilization	2	1.54	0.77	3.44	0.0325
Site* Planting Density* Fertilization	4	20.79	5.19	23.23	<.0001
Clone*Fertilization	6	2.23	0.37	1.67	0.1265
Site*Clone*Fertilization	12	2.05	0.17	0.77	0.6868
Planting Density*Clone* Fertilization	6	0.37	0.06	0.28	0.9461
Site*Planting Density*Clone* Fertilization	12	4.95	0.41	1.85	0.0379

[a] Pr > F values lower than α = 0.05 are significant; R^2 = 0.5040;

Table S-9. ANOVA results for *Populus* on the correlations between LAI, foliar N, *Melampsora spp.* rust, deer damage, and *Chrysomela scripta* Fabricius damage on aboveground tree volume (volume index) (dm^3) for poplar after two growing seasons at Clinton A, Clinton B, and Williamsdale (α = 0.05).

Correlation between LAI and Aboveground Tree Volume (dm^3)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F [a]
Model	1	14,848	14,848	113.36	<.0001
Error	776	101,639	130		
Corrected Total	777	116,486			

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t| [a]
Intercept	1	0.12	1.11	0.11	0.9100
Leaf Area Index	1	6.84	0.64	10.652	<.0001

[a] Pr > F values lower than α = 0.05 are significant; R^2 = 0.1275;

Correlation between Foliar N and Aboveground Tree Volume (dm^3)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F [a]
Model	1	12,095	12,095	89.91	<.0001
Error	776	104,391	134		
Corrected Total	777	116,486			

Table S-9. Continued

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t| [a]
Intercept	1	-15.65	2.86	-5.47	<.0001
Foliar N	1	14.24	1.50	9.48	<.0001

[a] Pr > F values lower than $\alpha = 0.05$ are significant; $R^2 = 0.1038$;

Correlation between *Melampsora spp.* Rust and Aboveground Tree Volume (dm^3)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F [a]
Model	1	10,325	10,325	75.47	<.0001
Error	776	106,161	136		
Corrected Total	777	116,486			

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t| [a]
Intercept	1	8.16	0.54	14.98	<.0001
Melampsora spp. rust	1	7.41	0.85	8.69	<.0001

[a] Pr > F values lower than $\alpha = 0.05$ are significant; $R^2 = 0.0886$;

Correlation between *Chrysomela scripta* Fabricius Damage and Aboveground Tree Volume (dm^3)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F [a]
Model	1	657	657	4.41	0.0361
Error	776	115,829	149		
Corrected Total	777	116,486			

Table S-9. Continued

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t| [a]
Intercept	1	10.37	0.58	17.67	<.0001
Chrysomela scripta Fabricius Damage	1	1.85	0.88	2.10	0.0361

[a] Pr > F values lower than α = 0.05 are significant; R^2 = 0.0056;

Correlation between Deer Damage and Aboveground Tree Volume (dm^3)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F [a]
Model	1	240	240	1.60	0.2056
Error	776	116,246	149		
Corrected Total	777	116,486			

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t| [a]
Intercept	1	11.25	0.44	25.51	<.0001
Deer Damage	1	-5.50	4.34	-1.27	0.2056

[a] Pr > F values lower than α = 0.05 are significant; R^2 = 0.0021;

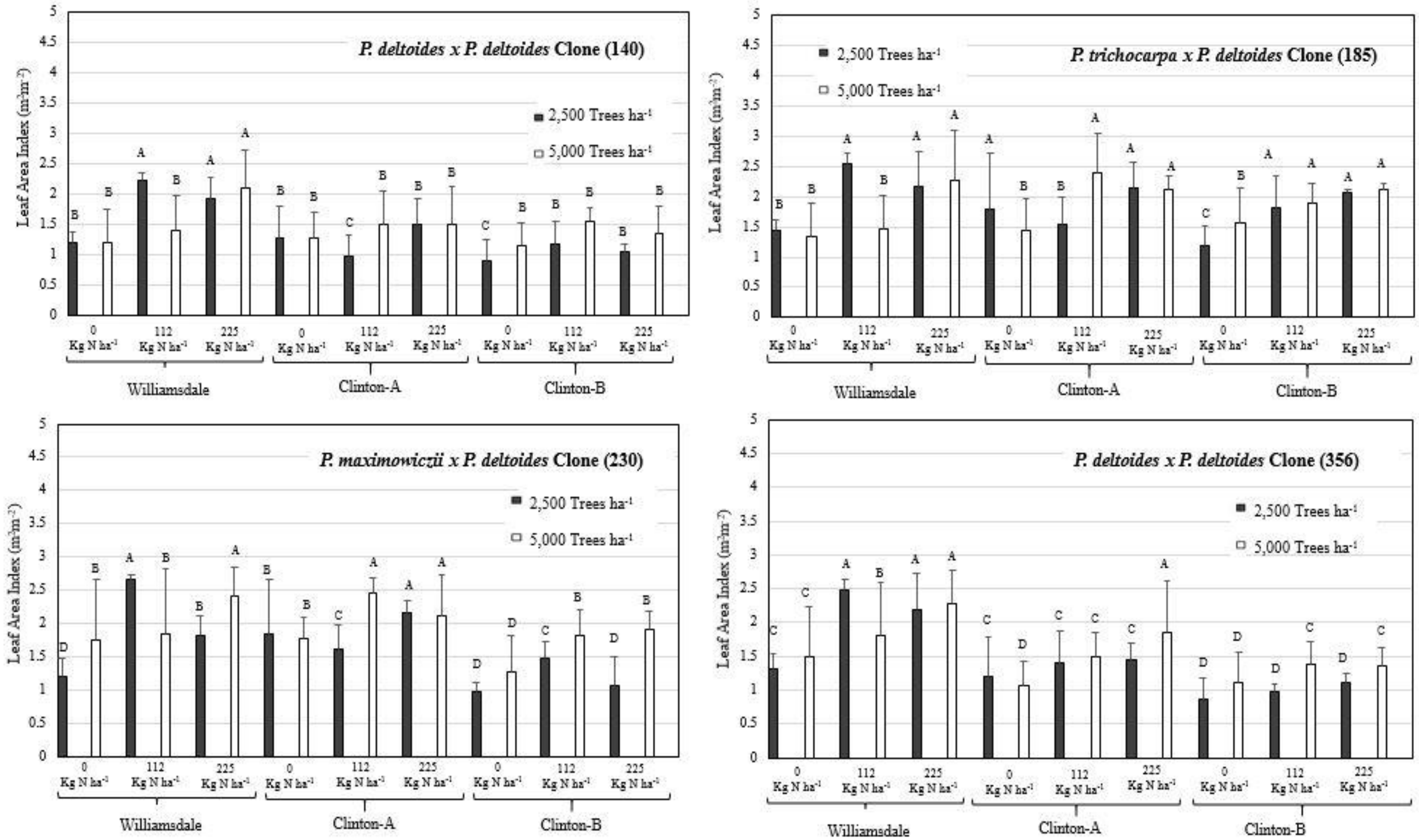

Figure S-3. Leaf area index (m^2 m^{-2}) for each *Populus* clone by site, fertilization treatment, and planting density. Error bars denote one standard deviation of the mean per treatment. Different letters denote significant differences ($\alpha = 0.05$) but do not reflect every significant comparison.

Table S-10. ANOVA results of *Populus* foliar nitrogen (%) at Clinton A, Clinton B, and Williamsdale (α = 0.05).

Effect	DF	Type III SS	Mean Square	F Value	Pr > F [a]
Site	2	9.66	4.83	103.13	<.0001
Planting Density	1	0.02	0.02	0.59	0.4443
Site*Planting Density	2	0.70	0.35	7.55	0.0006
Clone	3	3.13	1.04	22.26	<.0001
Site*Clone	6	1.05	0.17	3.77	0.0011
Planting Density*Clone	3	0.67	0.22	4.77	0.0027
Site*Planting Density*Clone	6	0.60	0.10	2.16	0.0453
Fertilization	2	0.31	0.15	3.38	0.0347
Site*Fertilization	4	1.71	0.42	9.16	<.0001
Planting Density*Fertilization	2	1.67	0.83	17.87	<.0001
Site*Planting Density* Fertilization	4	3.08	0.77	16.46	<.0001
Clone*Fertilization	6	1.09	0.18	3.90	0.0008
Site*Clone*Fertilization Level	12	1.04	0.08	1.86	0.0364
Planting Density*Clone* Fertilization	6	0.69	0.11	2.47	0.0227
Site*Planting Density*Clone* Fertilization	12	1.53	0.12	2.72	0.0013

[a] Pr > F values lower than α = 0.05 are significant; R^2 = 0.4405;

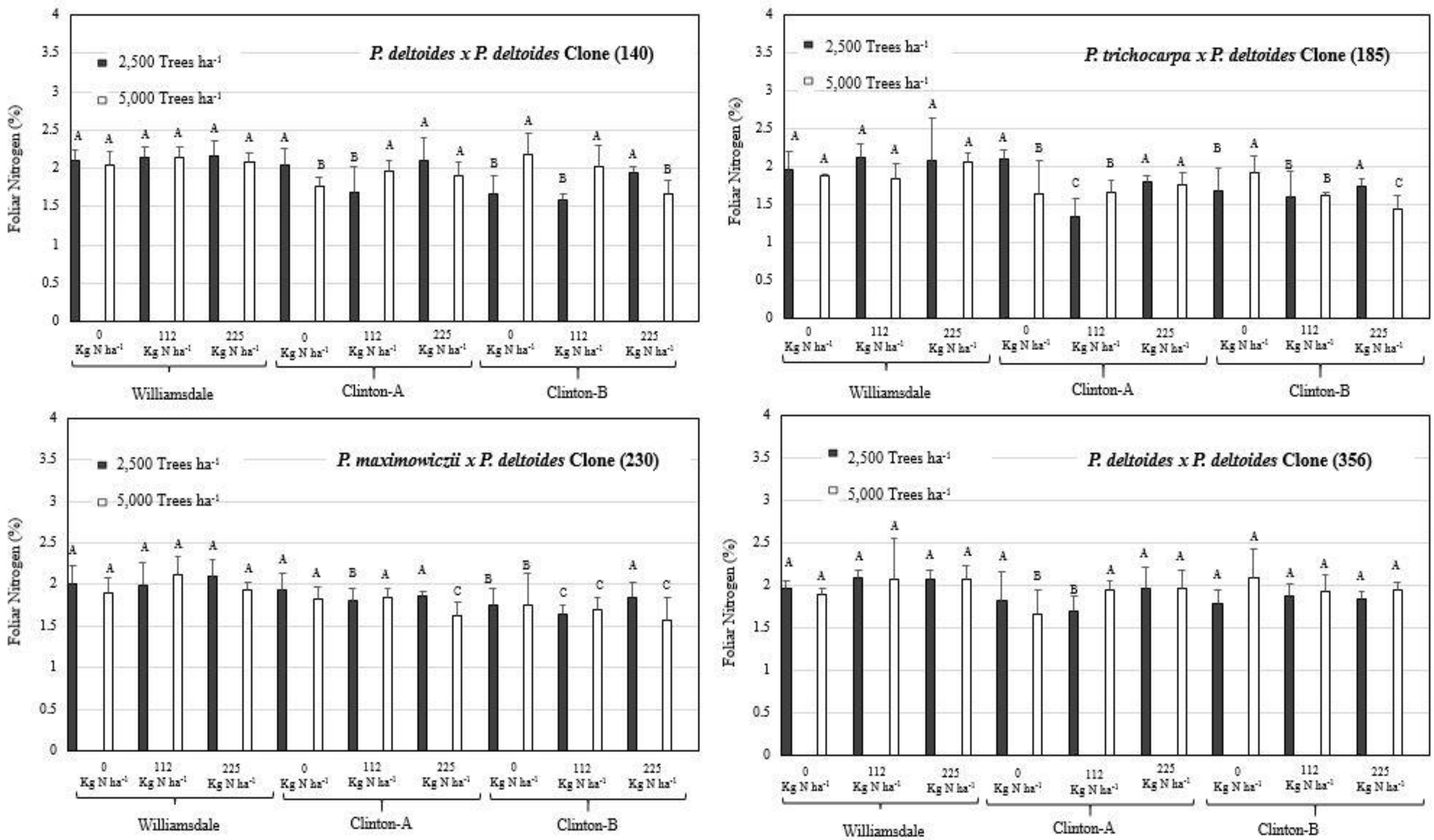

Figure S-4. Foliar nitrogen (%) for each *Populus* clone by site, fertilization treatment, and planting density. Error bars denote one standard deviation of the mean per treatment. Different letters denote significant differences ($\alpha = 0.05$) but do not reflect every significant comparison.

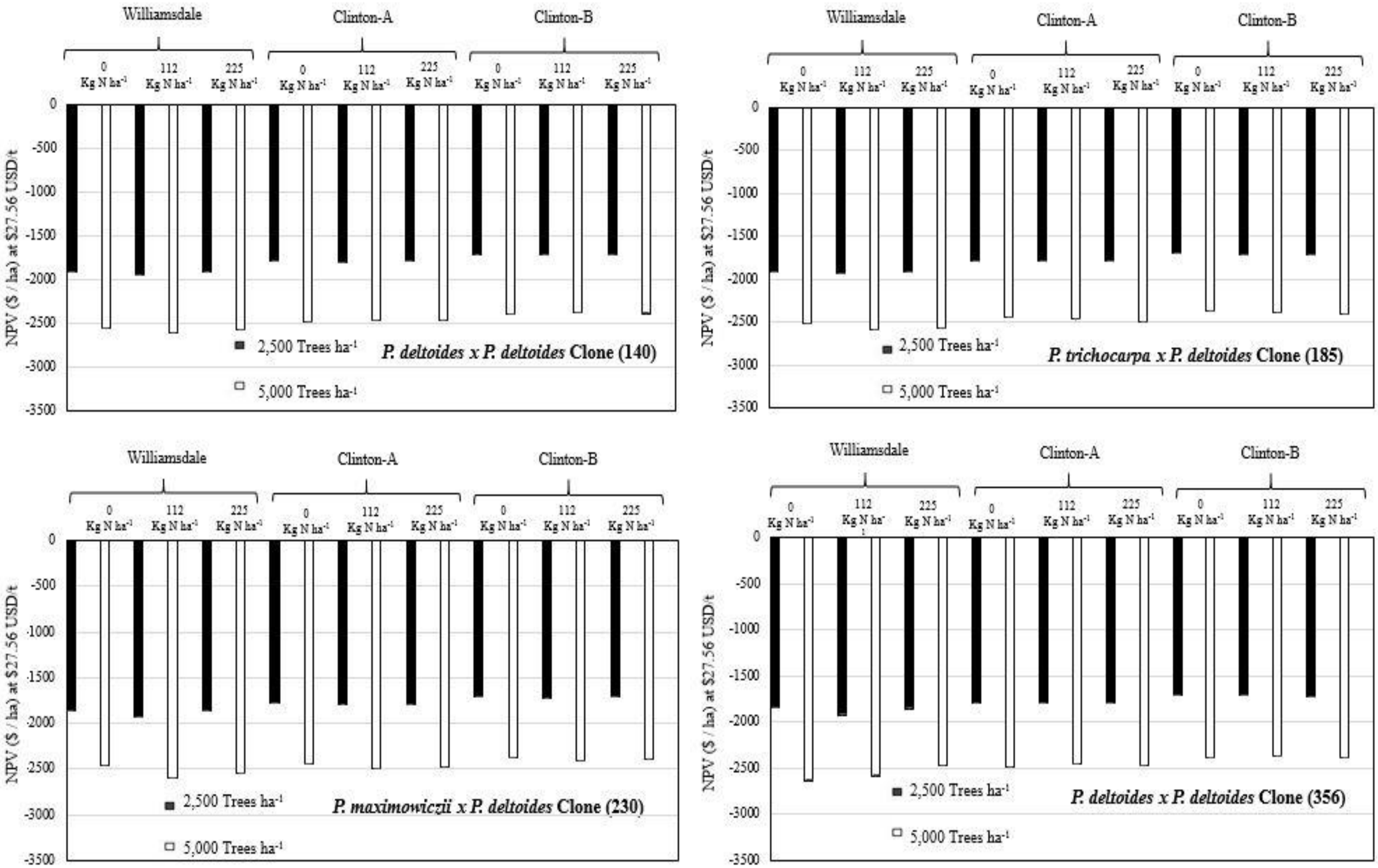

Figure S-5. Mean NPV ($/ha at $27.7/t) for each *Populus* clone by site, fertilization treatment, and planting density after two years of growth.

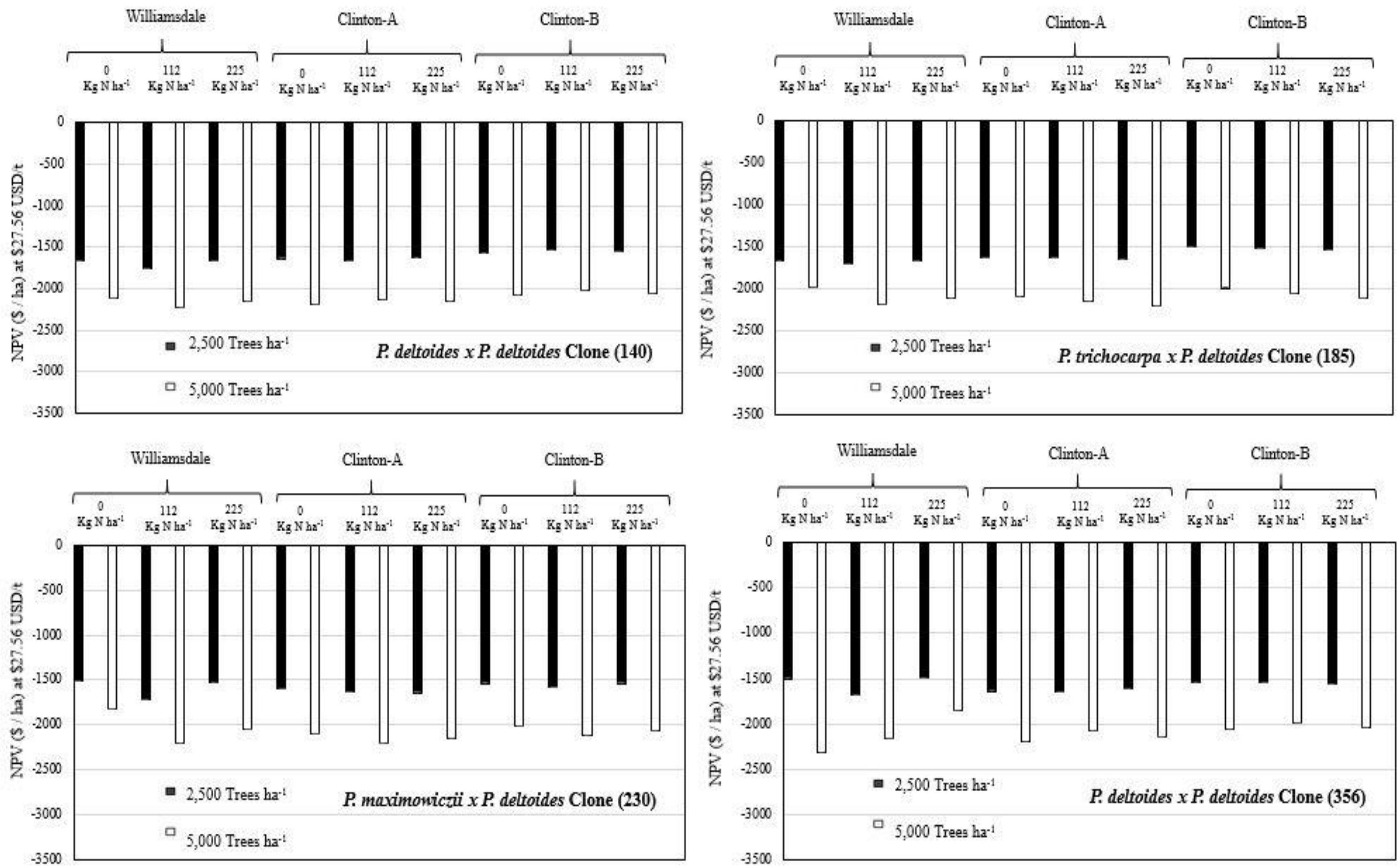

Figure S-6. Projected mean NPV ($/ha at $27.56/t) for each *Populus* clone by site, fertilization treatment, and planting density after six years of growth.

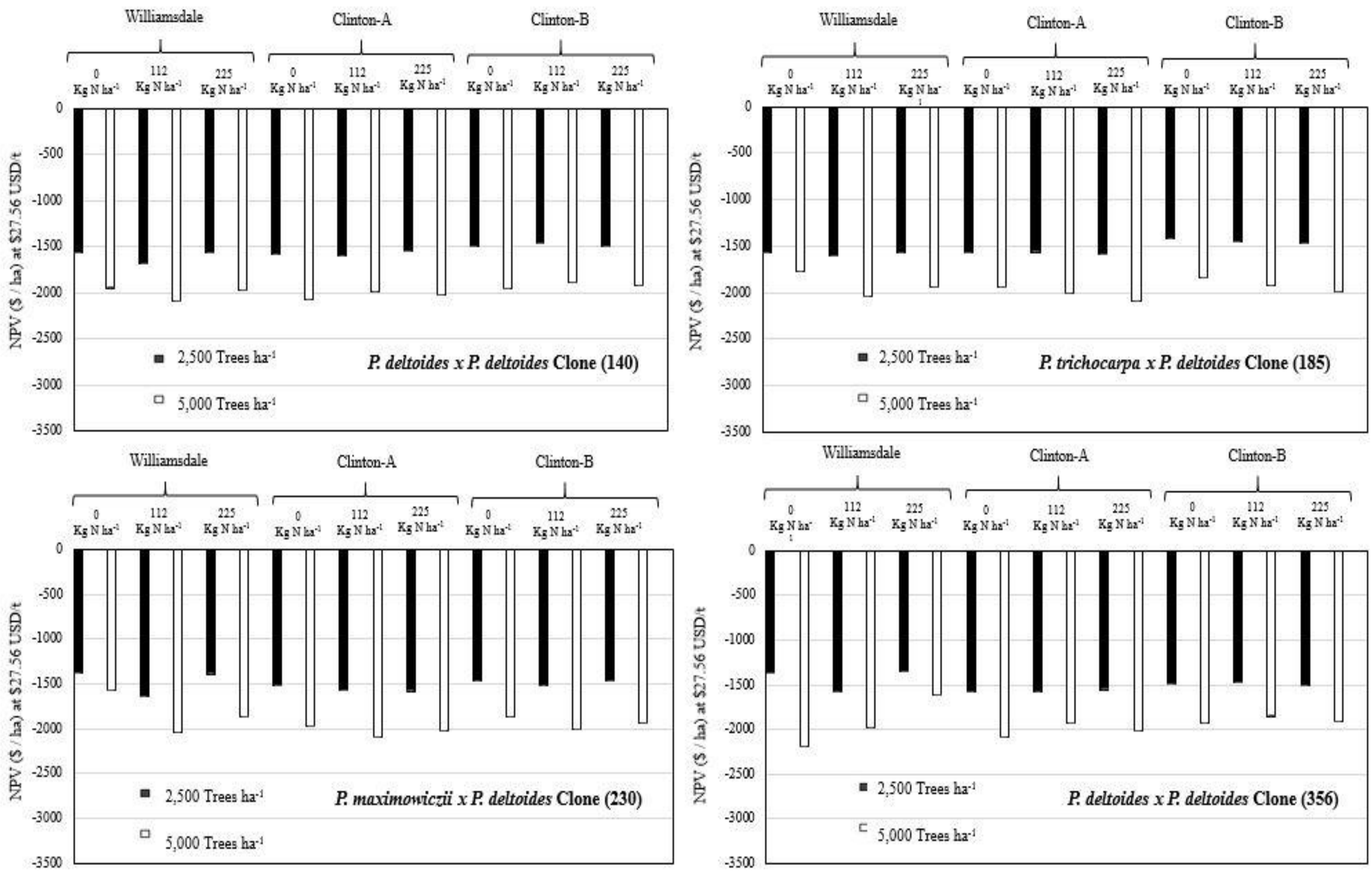

Figure S-7. Projected mean NPV ($/ha at $27.56 USD/t) for each *Populus* clone by site, fertilization treatment, and planting density after eight years of growth.