SOURCES OF VARIATION IN HYBRID POPLAR BIOMASS PRODUCTION THROUGHOUT MICHIGAN, USA

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ABSTRACT

Performance of sixteen poplar varieties was examined for seven years at six sites throughout Michigan, USA in a large-plot, well replicated yield trial. Sites were established over a three-year period to accommodate limitations of labor and planting stock availability and were allowed to develop without irrigation or fertilization. Performance of the best variety at each site varied widely; from an unacceptable low of 8.5 dry $\mathrm{Mg \cdot ha^{-1}}$ to an impressive high of 40.0 $\mathrm{Mg \cdot ha^{-1}}$ after five years. An analysis of variance in fifth-year biomass growth in the network was performed to understand this variability. The majority (50%) of the variability was due to site effects. This reinforces the need to test varieties at many locations in order to accurately predict yields. Variety differences accounted for 9% of the variation and an additional 14% of the variation was due to genotype by environment interactions. This means that varietal choice is very important but that relative varietal performance will change dramatically among sites. Even though all the trees in this trial were clonally propagated, 27% of the total variation was due to tree-to-tree differences within the sample plots. This variation creates challenges when managing and harvesting these crops, and can reduce feedstock quality. An analysis of variance in seventh-year biomass accumulation at the oldest site in the trial showed similar within-plot variation. Poplar hybrids have the potential to be productive biomass crops in Michigan but will require extensive, variety-specific, localized testing to establish reliable variety recommendations and yield estimates. One of the biggest issues to be addressed in the future will be to understand and then to control within-variety growth variability.

INTRODUCTION

Demand for renewable carbon to produce energy, fuels, and materials is increasing. Biomass is the only renewable source of carbon, and identifying crops that can thrive on idle or retired agricultural land is necessary to avoid competition with already strained food and fiber production. Crops that can be managed successfully with minimal inputs (e.g. water, chemicals, and energy) will be the most desirable. In many parts of the world, hybrids of various members of the genus *Populus* promise to be that crop (Isebrands and Richardson, 2014). But, there are many varieties and most tend to perform best only under specific conditions.

Successful poplar production absolutely depends on long-term field testing of varieties on sites close to where commercial plantings will be established. Testing of hybrid poplar varieties in the Lake State region dates back decades, but recent coordinated testing in Michigan, Wisconsin, Minnesota, and Iowa was organized under the auspices of the North Central *Populus* Research Consortium in the mid-1990s. Coordination was provided by the USDA Forest Service and funding was provided by the US Department of Energy. We assembled and propagated a cohort of poplar varieties from among those that had demonstrated good general adaptability and growth in the field trials conducted by this consortium (Netzer, *et. al.*, 2002). These were established in large-plot, replicated yield trials at six disparate sites throughout Michigan in order to verify their performance and to estimate biomass production potential.

METHODS

Trial Locations and Conditions

Poplar research trials were located throughout Michigan in a network of six planting sites that span both peninsulas (Table 1 and Figure 1). The East Lansing location mentioned is the site of Michigan State University's main campus. Three trial sites are permanent research centers owned by Michigan State University and three were leased from others. Field equipment and staff were located at both the Escanaba and East Lansing locations. Naturally, more attention could be given to test plantations located nearer to these two locations than at the others where the costs of transporting people and equipment limited the frequency of visits and length of time that could be spent. As a result, maintenance of plantations near Escanaba and East Lansing was generally superior to that at the more distant sites.

Site conditions varied considerably among these test locations. Soil conditions are summarized in Table 2 where for example, pH is reported to range from 5.3 at Brimley to 7.4 at Onaway. Soil texture and drainage also varies considerably among sites. Climatic conditions at each site were monitored by on-site weather stations and also varied among sites. For example, the growing season at Escanaba averages 35 days longer than at Brimley, and there were 1,245 more growing degree days at Albion than at Brimley. Table 3 is constructed to allow a comparison of site temperatures (by way of growing degree days) and moisture availability (by way of rainfall) during three distinct portions of each growing season. At some sites, less than 1/3 of the annual rainfall occurs during the portion of the year when air temperatures are most conducive for poplar growth. This effected both plant growth (due to relatively dry summers) and field staff's ability to enter the sites to conduct cultural operations (due to excessively wet ground conditions in spring and fall).

Plantation Establishment

All of these trials were established on old-field sites using a similar protocol. Planting sites were prepared by first mowing and spraying with glyphosate[1] to kill existing vegetation. The Brimley site was not sprayed with glyphosate because of extreme wet ground conditions resulting from delays in obtaining the lease documents and other logistical constraints. Sites were subsequently plowed and cultivated to achieve conditions similar to those needed for the establishment of row crops. Planting stock for the trials was obtained from a variety of sources (Table 4) based on stock requirements and stock availability. This material was obtained as 25.4 cm-long dormant hardwood cuttings. Stock was always planted in the early spring by vertically inserting these cuttings to their full length into the prepared sites. Planting was immediately followed by the application of post-emergence herbicides (imazaquin[2] and pendimethalin[3]). All of these yield trials comprised five blocks containing 64-tree plots of these varieties planted at a density of 1,922 trees/ha (2.4m x 2.1m).

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[1] Roundup® applied at a rate of 2.2 kg/ha active ingredient.
[2] Scepter® applied at a rate of 274 gm/ha active ingredient
[3] Pendulum® applied at a rate of 3.2 kg/ha active ingredient

Weed control was maintained in these plantings using a combination of herbicides and mechanical cultivation during the first two or three years – until the trees cast enough shade to control weeds on their own. Deer exclosure fencing was erected around the sites that did not already have some type of protection. A continuously recording weather station was installed at each planting site. The yield trials in Brimley and Onaway suffered high mortality due to weed competition and drought and were discontinued in 2014.

Measurements

Only the interior 16 trees of the larger 64-tree plots were measured, leaving a 2-row border around the plot to avoid edge-effects. Tree survival was monitored at all sites during the first year, annual height measurement began in the second year. Stem diameters at breast height (1.4m above the ground) were measured within the 16-stool measurement plots each year beginning at the end of the third growing season. Individual stool biomass accumulation was calculated by converting all the stem diameters in a stool to basal area, summing these basal areas (when multiple stems issued from a particular stool), and applying Equation 1 (Miller, 2016a). Areal biomass production was calculated by summing the individual tree biomass estimates of the trees in each sample plot and multiplying by an area expansion factor. Rust and canker scoring was conducted as needed throughout the project on all plantations. Soil samples were collected from all planting sites in 2012. These samples were analyzed by Agro-One Soil Analysis of Ithaca, NY. Results are summarized in Table 2.

Equation 1:

$$Stool\ Biomass\ \frac{OD\ lbs}{stool} = Sq.Ft.Basal\ area\ X\ 562.089$$

R^2= 0.968, Root Mean Square Error = 21%

RESULTS

Plantation ages allowed the comparison of biomass growth of all six sites after five growing seasons (Table 5). Biomass accumulation of the best poplar variety at each site varied widely (from 8.5 to 40.1 dry Mg/ha). The best varieties at only three of the six test sites produced more than 6.7 dry Mg/ha-year of biomass; which is probably the lower limit for commercial viability. In general, poplar appeared to grow poorly when site pH was extreme (5.3 at Brimley or 7.4 at Onaway) and when there were fewer than about 2,000 Growing Degree Days[4] available each year. *Populus nigra* X *maximowiczii* hybrids excelled in productivity at all sites, while the yields of *P. deltoides* X *nigra* hybrids were mixed; some did well and others did poorly. Genotype by environment interaction was strongly evident in these tests. “I4551”, for example produced 110% as much biomass as the universal check variety (NM6) at the Albion site, but only 28% as much at the Skandia site (Table 5).

Mean Annual Biomass Increment (MAI) increased 29% between the fifth and sixth years at the older sites (Table 6). This would suggest that rotation ages longer than 5 years are advisable for poplar grown under these conditions. Growth increase was not uniform among varieties or

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[4] Growing degree days are computed here using Fahrenheit degrees and a base temperature of 50ºF.

among sites however. MAI of NM5 increase averaged 25% across all sites but ranged from 2% at Escanaba and 59% at Skandia. The average increase across all varieties at Skandia was 74% but only 11% at Lake City.

This suggests that the performance of a particular variety at a specific site cannot be accurately predicted by (1) observing a different variety, (2) observing early growth, or by (3) observing that same variety at a remote test site. The variation in poplar varietal performance documented here reinforces the need for variety-specific, long-term, multi-site testing programs to develop the guidelines needed for successful commercialization of these biomass crops.

Analysis of Variance

This trial encompassed sixteen poplar varieties on six sites throughout Michigan. A great deal of variation was observed among varieties, sites, blocks-within-sites, and among trees-within-plots. Variation was also attributable to genotype by environment interactions. An analysis was conducted to understand the contribution of each of these sources to the total variation.

Nine varieties were sufficiently represented at all six test sites (Table 7) to be used in an analysis of varience in fifth-year biomass production (Table 8). 50% of total variability was due to site effects and 2% was due to block effects. This reinforces the need to test varieties numerous times at many locations in order to accurately predict yields. Genetic variation components accounted for 23% of the total (9% attributable to variety differences and 14% to genotype by environment interactions). This means that varietal choice is very important but that relative varietal performance will change dramatically from site to site. Even though all the trees in this trial were clonally propagated, 25% of the total variation was due to unexplained tree-to-tree differences within the sample plots. This within-plot variation creates challenges when managing and harvesting these crops, and can reduce feedstock quality.

An analysis of variance in seventh-year biomass production was conducted for all 14 poplar varieties at the Escanaba site (Table 9). In this single-site analysis, 23% of the variation was due to varietal effects compared to 9% in the 6-site analysis. Single-site tests routinely overestimate varietal effects because they include variety X site interactions. Genotype by environment interactions (performance differences from block to block) accounted for 9% of total variation. This was only slightly less that the 14% observed in the 6-site analysis. A small amount of variation was attributed to block effects (3%). The largest portion of the total variation (65%) arose from unexplained tree-to-tree differences, suggesting once again that understanding and controlling this within-plot variation will be of paramount importance to developing uniform crops in the future.

DISCUSSION

Environmental Effects (52% of total)

It comes as no surprise that the different conditions at our planting sites caused the greatest variation (50%) in biomass growth. A small amount of variation also occurred within the planting sites (block effects accounted for 2% of total variation). These differences arise from climatic, edaphic, temporal, and cultural circumstances that can be unique to each test site and to each rotation of the crop. Even though cultural conditions were kept as uniform as possible by following the same project protocol as closely as possible at each site, there were still differences. Field trials do not take place in growth chambers. The three-year span between establishment of the first and the last test sites unavoidably contributed to temporal variability – some growing seasons were simply better than others.

Certain climatic and edaphic factors were monitored at each planting site (Tables 2 and 3) and correlation analysis was conducted to look for relationships between poplar growth and environmental factors (Table 10). The length of the frost-free growing season and the number of growing degree days was positively correlated with growth. This was expected and consistent with previous observations made in Michigan willow and poplar plantations by both Miller and Bloese (2002) and Wang and MacFarlane (2012). The amount of organic matter in the soil was the only edaphic factor measured here that correlated with biomass growth. This correlation was strong, highly significant, and *negative*. Oddly, as organic matter content increased, biomass yield declined. One normally associates low organic matter with poor productivity but that was not the case here. It may be that soil drainage class is the actual culprit here. Our sites with higher soil organic matter were also less well drained and this might have been the causal agent responsible for lower productivity – not organic matter itself. It may also be that sites with lower inherent productivity had been left fallow much longer than the others and consequently had a more extensive sod layer that was incorporated by plowing and tilling when the sites were prepared for planting. This might have increased their organic matter without necessarily changing the factors that made these sites less productive in the first place.

Environmental conditions vary by planting site and also vary over time. Some of these factors are uncontrollable (*e.g.* growing season length or soil type), others can be controlled through cultural treatments (*e.g.* weed control, fencing, fertilization, or irrigation), while still others may be completely random (*e.g.* damaging frosts or droughts). Annual crops are exposed to the same volatility in conditions as perennial woody biomass crops, but only for one year at a time. A grower who experiences a good year reaps a bonanza while in loss years they can simply collect insurance and try again the following year. Perennial crops are exposed to these volatile conditions over many years; compounding the risk. This means that good growing seasons are averaged with poor growing seasons over time; evening-out the highs and lows of annual yield of other crops. It also means that a calamity can negate many years of crop development leaving the grower with nothing. It is important to recognize this, and to be prepared to offer insurance or other adequate compensation to growers for assuming these risks. This is how we assure adequate food production in the United States. It will undoubtedly be necessary to achieve the promise of abundant biomass carbon production.

Genetic Effects (23% of total)

Certain varieties grew relatively well across the entire test network. 9% of the genetic variation was due to this. Growers that choose from among these good “general performers” will certainly do better than if they use untested varieties. However, 14% of the genetic variation here was attributed to poplar’s strong genotype by environment interaction. This means that it is possible for growers to obtain even better yields from good “specific performers” that are uniquely suited to their site. The only way to find these “specific performers” is to conduct local yield trials like those done here. As breeding programs create new better adapted or higher yielding varieties, new tests like these will be necessary. Only timely, local tests will produce reliable recommendations for commercial growers.

Within-plot Effects (25% of total)

Strikingly, the variation within individual sample plots was substantial and marginally greater than the variation caused by genetic factors. It is important to remember that trees in these plots are genetically identical – having been clonally propagated from stem segments. The variation in tree size will undoubtedly become more pronounced in time (as inter-tree competition effects increase) and will have an influence on harvesting efficiency and on feedstock quality. There is a long list of possible causes for the within-plot variation observed here and elsewhere:

- Planting stock irregularities due to improper handling, unequal nutrient reserves, differences in viable buds, or inherent rooting propensity.
- Uneven site preparation or weed control from place to place.
- Microsite variability in fertility, moisture, or micro-biome composition.
- Inter-tree competition effects.
- Unequal pest pressure from insects, diseases, or browsing animals.
- Phenological difference between stools with single versus multiple stems.
- Stem characteristics that cause measurement errors (*e.g.* bulges or interfering branching).

Increased uniformity of performance will be beneficial to crop managers. It will simplify harvesting logistics and improve feedstock quality. We saw extreme variation even under fairly controlled experimental protocols. Commercial production systems will be less uniform and so will certainly experience even greater variability. Understanding the factors that are causing this to happen and developing methods to control and reduce this tree-to-tree variation should be a priority for future research.

When conditions are favorable, varieties are properly selected, and best management practices are followed, short rotation poplar plantations in Michigan can produce biomass for break-even farm gate prices of approximately 54 €/dry Mg ($54/oven-dry short ton) (Miller, 2016b). This price is slightly less than the 60 €/ dry Mg ($60/dry short ton) target set as the base case by the US Department of Energy in the 2016 Billion-ton Report (2016), and it is comparable to delivered pulpwood prices in the Upper Great Lakes States area. So, short rotation poplar biomass production in Michigan teeters on the cusp of profitability under average conditions. The variability described here can easily tip the balance in either direction. Controlling these sources of variation is absolutely critical and represents a major challenge for the future.

TABLE 1: Poplar Biomass Trial Plantation Locations in Michigan

Site Name	***Location in Michigan***	***Latitude***	***Longitude***	***Site Owner***
Albion	Albion, MI, Calhoun Co.	42º 11’ 32.64” N	84º 44’ 4.20” W	Michigan State University
Brimley	Brimley, MI Chippewa Co.	46º 24’ 2.25”N	84º 28’ 4.30”W	Chippewa – E. Mackinac Conserv. Dist.
Escanaba	Escanaba, MI Delta Co.	45º 46’ 10.65”N	87º 12’ 2.44”W	Michigan State University
Lake City	Lake City, MI Missaukee Co.	44º 17’ 54.39”N	85º 12’ 23.49”W	Michigan State University
Lansing	East Lansing, MI Ingham Co.	42º 40' 12.37" N	84º 27' 50.20" W	Michigan State University
Onaway	Onaway, MI Presque Isle Co.	45º 22’ 53.36”N	84º 14’ 31.01”W	Mark McMurray
Skandia	Skandia, MI Marquette Co.	46º 21’ 42.77”N	87º 14’ 39.21”W	Barry Bahrman

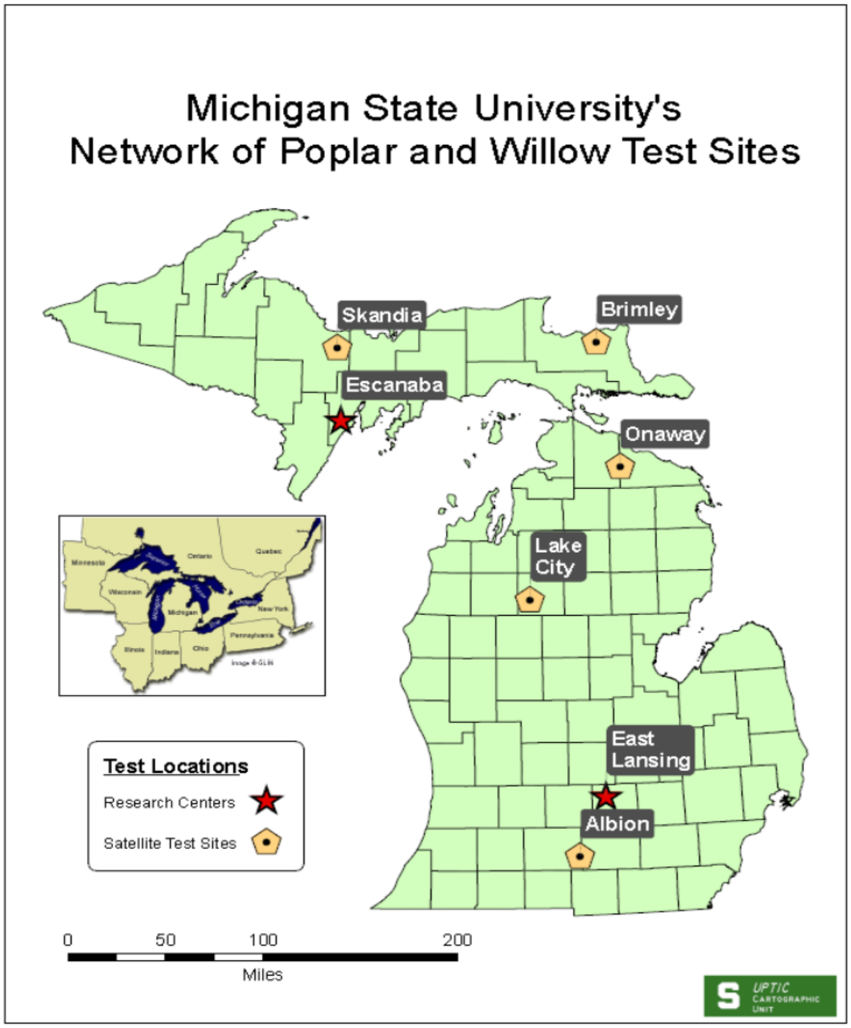

TABLE 2: Soil Conditions at the six poplar variety trial sites in the Michigan network

	Soil Analysis from Agro-One @ Cornell						*NRCS Soil Survey*	
Test Plantation	*Organic Matter (%)*	*pH*	*P (kg/ha)*	*K (kg/ha)*	*Ca (kg/ha)*	*Past Use*	*Soil Series*	*Drainage Class*
Albion							Hillsdale sandy loam	Well drained
2011 16-variety Poplar Yield Trial	1.8	6.39	11.4	275	1603	Corn		
Brimley							Biscuit very fine sandy loam & Rudyard silt loam	Somewhat poorly drained
2009 10-varietyPoplar Yield Trial	3.7	5.38	3.1	161	2444	Pasture		
Escanaba							Onaway fine sandy loam	Moderately well drained
2009 14-variety Poplar Yield Trial	2.8	6.82	2.2	82	3403	Corn		
Lake City							Emmet – Montcalm complex (sandy loam)	Well drained
2010 10-variety Poplar Yield Trial	2.0	6.42	4.0	96	1736	Pasture		
Onaway							Bonduel loam	Somewhat poorly drained
2010 15-variety Poplar Yield Trial	4.4	7.50	7.8	138	8897	Hay		
Skandia							Munising fine sandy loam	Moderately well drained
2009 11-variety Poplar Yield Trial	4.5	6.08	2.2	128	2884	Hay		

TABLE 3: Precipitation, growing degree days, and growing season length at each of six field test sites.

Data for certain years at particular sites are missing because weather stations had not yet been installed or malfunctioned.

Data in *"italics"* were obtained from a nearby automated weather station.

(Growing degree days are calculated using Fahernheit degrees and a base temperature of 50°F.)

Planting Site	Year	Growing Season Totals			Spring (3/21 - 6/20)			Summer (6/21 - 9/20)			Fall (9/21 - 12/20)		
		Rain (cm)	Growing Degree Days (base 50°F)	Growing Season Length (days)	Rain (cm)	Growing Degree Days (base 50°F)	Days in Season	Rain (cm)	Growing Degree Days (base 50°F)	Days in Season	Rain (cm)	Growing Degree Days (base 50°F)	Days in Season
Albion	2011	72.7	3007	188	*23.4*	*775*	*68*	31.0	1974	90	18.3	258	30
	2012	49.0	3265	178	15.5	963	63	14.7	2098	92	18.8	204	23
	2013	36.6	2802	171	12.2	702	53	7.9	1852	92	16.5	248	26
	2014	56.6	2600	169	24.4	746	52	*20.3*	*1652*	*92*	11.9	202	25
	2015	30.2	2939	184	12.2	808	57	6.6	1797	92	*11.4*	334	35
	Ave.	***49.0***	***2923***	***178***	***17.5***	***799***	***59***	***16.1***	***1875***	***92***	***15.4***	***249***	***28***
Brimley	2010	60.1	2105	206	17.5	647	73	25.1	1285	92	17.5	173	41
	2011	37.7	1961	186	5.6	459	58	13.0	1268	92	19.1	234	36
	2012	29.2	2098	188	4.8	632	67	6.4	1334	92	18.0	*132*	29
	2013	75.3	1390	131	13.5	227	31	35.6	1094	86	26.2	*69*	14
	2014	39.9	1134	117	17.7	231	29	0.4	865	81	21.8	*38*	7
	2015	41.2	1381	143	*6.8*	*203*	*29*	15.9	1074	85	18.5	*104*	29
	Ave.	***47.2***	***1678***	***162***	***11.0***	***400***	***48***	***16.0***	***1153***	***88***	***20.2***	***125***	***26***
Escanaba	2009	51.6	1893	192	21.6	445	62	13.0	1292	92	17.0	156	38
	2010	71.4	2476	214	19.3	674	78	32.5	1539	92	19.6	263	44
	2011	60.0	2234	198	23.9	469	59	19.1	1525	92	17.0	240	47
	2012	53.8	2407	204	18.5	692	77	17.8	1545	92	17.5	170	35
	2013	58.2	2055	183	13.7	457	58	25.4	1404	92	19.1	194	33
	2014	31.0	1869	184	22.6	480	59	34.2	1229	92	18.2	156	33
	2015	22.4	2214	206	22.3	496	67	19.3	1448	92	13.8	264	47
	Ave.	***49.8***	***2164***	***197***	***20.3***	***530***	***66***	***23.0***	***1426***	***92***	***17.5***	***206***	***40***
Lake City	2010	61.9	2456	189	*19.3*	*838*	*82*	*32.5*	*1503*	*89*	10.1	115	18
	2011	60.6	2032	142	28.4	433	38	12.4	1453	85	19.8	146	19
	2012	59.1	2249	169	*21.6*	*818*	*74*	*20.8*	*1360*	85	16.7	71	*10*
	2013	56.9	1895	151	22.1	444	41	17.0	1343	86	*17.8*	*108*	*24*
	2014	66.9	1906	220	29.1	451	44	*18.0*	*1292*	*92*	*19.8*	*164*	*84*
	2015	44.3	1807	176	*23.2*	*420*	*84*	*21.1*	*1387*	*92*	*NA*	NA	*NA*
	Ave.	***58.3***	***2057***	***175***	***24.0***	***567***	***61***	***20.3***	***1390***	***88***	***16.8***	***121***	***31***
Onaway	2010	62.4	2535	194	*24.9*	*801*	*79*	*25.1*	*1554*	*92*	*12.4*	180	*23*
	2011	80.1	2035	142	30.0	412	37	23.6	1455	86	26.5	168	19
	2012	47.7	2323	146	20.3	561	44	6.9	1542	*90*	20.5	220	*12*
	2013	31.6	1829	142	16.9	376	41	0.5	1344	*82*	14.2	109	*19*
	2014	74.7	1680	135	*21.5*	*316*	*30*	30.4	1232	*86*	*22.8*	*131*	*19*
	Ave.	***59.3***	***2080***	***152***	***22.7***	***493***	***46***	***17.3***	***1425***	***87***	***19.3***	***162***	***18***
Skandia	2009	77.3	1753	175	32.3	*413*	*59*	19.3	*1224*	*92*	25.7	116	24
	2010	44.2	2295	208	15.0	651	75	14.5	1412	92	14.7	232	41
	2011	51.8	2126	182	18.0	456	55	11.2	1438	92	22.6	232	35
	2012	43.4	2044	186	8.1	*611*	63	18.8	1309	92	16.5	124	31
	2013	46.0	1600	134	11.2	247	25	*24.1*	1185	87	10.7	*168*	22
	2014	42.5	1617	152	13.0	330	35	*6.9*	*1139*	*91*	*22.6*	*148*	*26*
	2015	32.8	1987	121	*NA*	*NA*	*NA*	*9.4*	*1816*	*90*	*23.4*	*171*	*31*
	Ave.	***52.5***	***1964***	***177***	***16.3***	***451***	***52***	***14.9***	***1360***	***91***	***19.4***	***170***	***30***

TABLE 4: Source of poplar cutting planting stock used in Michigan trials.

Poplar Variety Name	*Segal Ranch, WA*	*Lincoln Oaks, ND*	*MSU-TRC, MI*	*USFS, WI*	*Isebrands, IA*	*Hramor Nursery, MI*	*Lee's Nursery, MN*
2009 Yield Trials							
NM2			X	X	X		
NM5		X	X				
NM6						X	
DM114			X				
DN154			X	X			
DN164			X	X			
DN17		X	X				
DN182		X	X				
DN2		X	X				
DN34						X	
DN5		X	X				
DN70			X				X
NE222	X		X		X		
I4551	X						
2010 & 2011 Yield Trials							
NM2			X				
NM5			X				
NM6			X				
DM114			X				
DN154			X				
DN164			X				
DN17			X				
DN177			X		X		
DN182			X				
DN2			X				
DN34			X				
DN5			X				
DN70			X				
NE222			X				
83XAA04			X				

TABLE 5: Yields of poplar varieties at six sites in Michigan, relative to NM6
(Total yield after 5 growing seasons)

Variety	*Brimley*	*Skandia*	*Onaway*	*Lake City*	*Escanaba*	*Albion*	*Average*
			Populus nigra X maximowiczii Varieties				
NM5	131%	214%	622%	101%	135%		241%
NM2		166%	256%		134%	123%	169%
DM114			400%	68%	112%	75%	164%
NM6	100%	100%	100%	100%	100%	100%	100%
			Populus deltoides X nigra Varieties				
DN2	28%	110%	189%		92%	86%	101%
DN170						95%	95%
DN5	14%	38%	244%	47%	86%	65%	82%
DN154			89%	56%	84%	80%	77%
DN34	10%	79%	133%	43%	106%	59%	72%
DN182	69%	83%	56%		63%	76%	69%
NE222	59%	66%	111%	46%	70%	52%	67%
DN177				30%		98%	64%
DN17	14%	72%	122%		36%	66%	62%
DN70	28%	21%	122%	45%	76%	80%	62%
DN164			67%	36%	60%	91%	64%
I4551		28%			42%	110%	60%
83XAA04						40%	40%
NM6 actual yield (dry Mg/ha)	***6.5***	***6.5***	***2***	***36.3***	***22.6***	***32.5***	
Best variety (dry Mg/ha)	*8.5*	*13.9*	*12.6*	*36.5*	*30.5*	*40.1*	
			Conditions at the test site				
5-year total growing degree days (base 50 ° F)	*9,232*	*9,818*	*10,402*	*10,538*	*11,065*	*14,613*	
5-year total precipitation (cm)	*96.0*	*87.9*	*86.4*	*100.8*	*107.7*	*80.5*	
pH	*5.31*	*6.26*	*7.40*	*6.49*	*6.66*	*6.35*	

TABLE 6: Increase in Mean Annual Biomass Increment between the 5th and 6th year in four poplar yield trials across Michigan

Poplar Variety	***Planting Site***				
	Escanaba	***Skandia***	***Brimley***	***Lake City***	***Variety Average***
NM2	7%	55%			**31%**
NM5	2%	59%	32%	9%	**25%**
NM6	11%	98%	41%	4%	**38%**
DM114	15%			5%	**10%**
DN154	19%			13%	**16%**
DN164	34%			36%	**35%**
DN17	23%	63%	25%		**37%**
DN177				13%	**13%**
DN182	21%	74%	33%		**43%**
DN2	11%	64%	46%		**40%**
DN34	8%	67%	-17%	7%	**16%**
DN5	15%	112%	-17%	12%	**31%**
DN70	15%	136%	25%	14%	**47%**
I4551	29%	25%			**27%**
NE222	23%	62%	8%	-5%	**22%**
Site Average	**17%**	**74%**	**20%**	**11%**	**29%**

TABLE 7: Average Survival and Biomass Accumulation of Nine Poplar Varieties After Five Years in Six Hybrid Poplar Yield Trials Throughout Michigan

Variety	*Albion*		*Brimley*		*Escanaba*		*Lake City*		*Onaway*		*Skandia*		***Test-wide***		*Variety*
	Survival	*Biomass (dry Mg/ha)*	*Survival*	*Biomass (dry Mg/ha)*	*Survival*	*Biomass (dry Mg/ha)*	*Survival*	*Biomass (dry Mg/ha)*	*Survival*	*Biomass (dry Mg/ha)*	*Survival*	*Biomass (dry Mg/ha)*	***Survival***	***Biomass (dry Mg/ha)***	
NM5			92%	8.5	98%	30.5	94%	36.5	98%	12.6	99%	13.9	**96%**	**20.4**	NM5
NM6	95%	32.5	91%	6.5	99%	22.6	95%	36.5	88%	2.0	100%	6.5	**94%**	**17.8**	NM6
DN2	99%	28	81%	1.8	98%	20.9			80%	3.8	95%	7.2	**91%**	**12.3**	DN2
DN5	93%	21.3	73%	0.7	98%	19.5	91%	17.0	71%	4.0	85%	2.5	**85%**	**10.8**	DN5
DN70	91%	26	75%	1.8	95%	17.3	91%	16.4	58%	1.6	53%	0.9	**77%**	**10.7**	DN70
DN34	88%	19.1	69%	0.7	96%	24.2	74%	11.2	68%	2.0	89%	5.2	**80%**	**10.4**	DN34
DN182	96%	24.7	88%	3.6	95%	14.3			60%	0.7	96%	5.4	**87%**	**9.7**	DN182
NE222	90%	16.8	88%	3.8	96%	15.9	71%	10.3	80%	1.8	84%	3.8	**85%**	**8.7**	NE222
DN17	99%	21.5	89%	0.9	93%	8.1			75%	1.6	95%	4.7	**90%**	**7.4**	DN17
Grand Total	**94%**	**23.8**	**86%**	**3.8**	**96%**	**19.3**	**86%**	**21.3**	**75%**	**3.4**	**88%**	**5.6**	**88%**	**12.9**	**Grand Total**

TABLE 8: Analysis of Variance in 5th-year Biomass Production of 9 Poplar Varieties at 6 Sites in Michigan

NOTE: AOV performed on measurements prior to conversion to metric units, SS, MS, & V² are effected. Proportions are not.

Source of Variance	*Degrees of Freedom*		*Type III SS*	*MS*	*F*	*Expected Mean Squares*	*Variance Component Analysis*		
Clone (c=9)	c-1	8	81,725	10,216	7.009	$V^2_e + tV^2_{cb} + tbV^2_{cs} + tbsV^2_c$	V^2_c =	24	9%
Site (s=6)	s-1	5	328,355	65,671	33.796	$V^2_e + tV^2_{cb} + tbV^2_{cs} + tcV^2_b + tcbV^2_s$	V^2_s =	137	50%
Block(Site) (b=5)	s(b-1)	23	19,771	860	2.299	$V^2_e + tV^2_{cb} + tcV^2_b$	V^2_b =	5	2%
Clone X Site	(c-1)(s-1)	36	52,467	1,457	3.898	$V^2_e + tV^2_{cb} + tbV^2_{cs}$	V^2_{cs} =	17	6%
Clone X Block(Site)	s(c-1)(b-1)	157	58,693	374	5.226	$V^2_e + tV^2_{cb}$	V^2_{cb} =	21	8%
Tree-within-Plot (t=16)	csb(t-1)	3009	215,264	72		V^2_e	V^2_e =	72	26%
Note: Actual degrees of freedom vary from theoretical as a result of the incomplete nature of the design (missing data).								276	

TABLE 9: Analysis of Variance in 7th-year Biomass Production of 14 Poplar Varieties at a Single Site in Escanaba, MI

NOTE: AOV performed on measurements prior to conversion to metric units, SS, MS, & V² are effected. Proportions are not.

Source of Variation	*Degrees of Freedom*		*Type III SS*	*M.S.*	*F*	*E.M.S.*	*Variance Component Analysis*		
Clone (c=14)	(c-1)	13	96,837	7,449	10.245	$V^2_e + tV^2_{cb} + btV^2_c$	V^2_c =	84	23%
Block (b=5)	(b-1)	4	11,723	2,931	4.031	$V^2_e + tV^2_{cb} + vtV^2_b$	V^2_b =	10	3%
Clone X Block	(c-1)(b-1)	52	37,809	727	3.085	$V^2_e + tV^2_{cb}$	V^2_{cb} =	31	9%
Tree-within-Plot (t=16)	cb(t-1)	974	229,536	236		V^2_e	V^2_e =	236	65%
Note: Actual degrees of freedom vary from theoretical as a result of the incomplete nature of the design.								361	

Table 10: Correlation Matrix: Poplar variety 5th-year growth as influenced by local Edaphic and Climatic factors at six field test sites in Michigan.

Site Factors	***Best Variety @ Each Site***	***NM6 Standard***	***9 Variety Mixture***
	Pearson Correlation Cooeficient		
	2-tailed Significance		
EDAPHIC FACTORS (from Table 2)			
Organic Matter (%)	-0.930*	-0.967*	-0.947*
	α = .007	*α = -.002*	*α = .004*
pH	0.194	0.000	0.116
	α = .713	*α = 1.000*	*α = .828*
P (kg/ha)	0.388	0.260	0.308
	α = .447	*α = .619*	*α = .553*
K (kg/ha)	0.229	0.162	0.196
	α = .663	*α = .759*	*α = .709*
Ca (kg/ha)	-0.495	-0.632	-0.561
	α = .318	*α = .178*	*α = .247*
CLIMATIC FACTORS (from Table 3)			
Yearly Rainfall	0.010	-0.012	-0.096
	α = .984	*α = .982*	*α = .857*
Summer Rainfall	0.478	0.470	0.527
	α = .338	*α = .347*	*α = .282*
Total Growing Degree Days	0.752	0.594	0.706
	α = .085	*α = .214*	*α = .117*
Summer Growing Degree Days	0.725	0.560	0.668
	α = .103	*α = .248*	*α = .147*
Length of Growing Season	0.603	0.562	0.674
	α = .205	*α = .246*	*α = .142*

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