PREMATURE SELECTION AND INADEQUATE TESTING OF WILLOW BIOMASS VARIETIES RESULTS IN SIGNIFICANT LOSSES FOR GROWERS.

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ABSTRACT

Willow (*Salix* spp.) can be a financially sound energy crop when site- appropriate varieties are grown. Because varietal performance changes with time and from place to place, appropriate selections can only be based on long-term and local tests. If choices are made without allowing sufficient time for testing or without adequate local experience, yield and financial returns suffer. Here we examined the yield of numerous willow varieties over a seven-year period at three diverse sites in Upper Michigan. In order to determine the impact of early varietal selection, we compared the total biomass production of a cohort of five top-performing varieties selected based on their growth after four years with a different cohort selected based on their growth after seven years. At one site, the fourth-year cohort yielded 7% less biomass than the seventh-year cohort. This equated to an annual loss to the grower of about $15 per acre. In order to determine the consequence of using varieties selected in distant tests we identified the best five-variety cohort at each test site and then compared the performance distant cohorts with that of the local cohort. At one site the distant cohort produced 15% less biomass than the local cohort. This equated to an annual loss to the grower of about $33 per acre. If a region contained 5,000 acres of willow energy plantations and selections were made prematurely, the financial loss to growers would be $75,000 per year. Selecting varieties based on non-local field testing could represent a financial loss to growers of about $165,000 per year in this same hypothetical region. These investigations place a concrete value on the need to test varieties over long periods and at multiple sites.

INTRODUCTION

Hybrids of various species of the genus Salix (willow) grown under specialized silvicultural systems have demonstrated the potential to routinely produce from 6 to 12 dry Mg·ha-1·yr-1 of biomass in Swedish commercial biomass plantations (Dimitriou and Aronsson, 2005). Research began in the 1990s at the University of Toronto and the Montreal Botanical Garden (Labrecque and Teodorescu, 2005) and the State University of New York (SUNY) (Kiernan, et. al., 2003) to develop hybrids and silvicultural systems appropriate for biomass production in eastern North America. Along with other regional partners, Michigan State University (MSU) joined this effort in 1999. Previously screened or newly developed hybrids were produced either at SUNY or more recently at Cornell University and then distributed to collaborators for testing. Results are pooled to increase our understanding of how these clones perform across the Northeast and Lake States regions of the United States (Volk, et. al. 2011).

The silvicultural system for willow involves planting dormant hardwood cuttings of selected clones into fields prepared as though for an agricultural grain crop. These cuttings are planted at densities as high as 12,000 - 18,000 cuttings per hectare and allowed to grow under weed-free conditions for one year. The plants are cut down ("coppiced") in the fall of the first year. This causes 10 to 20 new stems to sprout from each cut stump (or "stool") the following spring. Stands that develop in this way eventually have more than 200,000 stems per hectare. These stems are allowed to grow for three years (or four years under poor growing conditions) before being harvested by specialized equipment. The stools re-sprout after each harvest to form a new stand (Abrahamson, et. al. 2002). This cycle of harvesting and re-sprouting has been repeated for 20 – 25 years in Sweden (Dimitriou and Aronsson, 2005). Cash flow from this system begins at the first harvest in the fourth year and continues every three (or four) years thereafter.

The objective of these tests was to explore how various clones of willows and poplars would adapt to Michigan's growing conditions and how they would respond over extended periods to this high density, short rotation silviculture system.

METHODS

Trial Locations and Conditions

Willow 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 the other 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 nearest 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 satellite sites.

Soil samples were collected from each of the four blocks at all of the locations during the summer of 2012 and analyzed for organic matter, pH, P, K, and Ca by Agro-One Soil at Cornell University (results in Table 2). Continuously recording weather stations were placed at each site and temperature, precipitation, and relative humidity data was retrieved at regular intervals throughout each growing season. A summary of these data appears in Table 3.

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 varied 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 are 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 occurred during the portion of the year when air temperatures were most conducive for willow 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).

The test at the Onaway site experienced an extreme drought during the summer of 2013 and most of the trees died. Five sites remained in the network. At the time of this report, three of the plantations were old enough to have been harvested twice. The remaining two have been harvested once.

Plantation Establishment
Willow varieties developed in New York (at both SUNY and Cornell) were tested at the six sites in our state-wide network. These trials were established between 2008 and 2011 to accommodate planting stock availability and operational limitations (Table 4). Each replication of this trial included 20 or 26 of 33 total willow varieties. Plots were established using the “Swedish” double-row plantings design which yields a planting density of 5,808 stems per acre. Double rows were separated by 2.5’ with plants spaced 2’ apart within these rows. 5’ gaps were left between double rows. Plots were three double rows wide, containing 78 stools. Only the interior double row, containing 18 stools was measured to obtain yield data.

Sites were prepared by mowing and spraying with glyphosate[1] (2 quarts/acre) to kill existing vegetation. Brimley was not sprayed prior to planting due to logistical complications. When weeds were dead, all sites were then plowed and disked. Sites were finally rototilled (or spaded) immediately before planting. Planting stock was received as 19cm-long dormant hardwood cuttings. These were inserted to their full length vertically into the prepared site. All sites were arranged in a randomized block design with four blocks containing one plot each of the 26 or 20 varieties. Post-emergence herbicides (2 quarts/acre of oxyfluorfen[2] together with 1 quart/acre of simazine[3]) were applied immediately after planting to restrict weed regrowth. Deer fencing was established at all sites using various designs which were modified to improve effectiveness through the course of the study. In year one, each plantation was monitored for herbicide effectiveness and spot-treated when necessary to control weeds. In the second year, sites were all mowed and/or cultivated between the double row pairs to reduce weed growth.

Measurements
All sites were annually scored for leaf rust, insect damage, and survival. At the end of the first growing season all stems were cut (coppiced) to encourage multiple-sprouting on each stool the following year. Stems cut from the inner 18 trees of each 78-tree plot were oven-dried and their mass was recorded.

In year two all plantations were again scored for leaf rust, insect damage, and survival. Diameters of all the stems in these 18-stool sample plots were measured and four of the tallest stem heights in each sample plot were recorded at the end of the second growing season.

Year four was the final year of the first rotation. Plantations were harvested at the end of the fourth growing season using a NyVraa JF192 single-row chipping willow harvester. Measurements at the time of harvest were made of the 18-stool sample plots. Measurements included: plot survival, height of tallest stem on four of the stools in each sample plot, number of stems per stool on the same four stools in each sample plot. The green weight of the chips

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[1] Roundup®
[2] Oust®
[3] Princep®

harvested from each 18-stool sample plot was recorded. A sub-sample was collected for each sample plot, which was oven-dried to obtain dry weight and moisture content for the chips taken from that plot.

The second rotation comprised years five, six, and seven. Insect damage, herbivore damage, and the presence of leaf rust was annually monitored during this time. Data collection and harvesting was conducted in year seven using the same procedure followed in year four. At the time of this report, the Escanaba, Skandia, and Brimley trials had been harvested twice (Table 4).

RESULTS

Pests

Pest pressure in the six willow trials was fairly light during the course of this trial with a few notable exceptions. Leaf rust (*Melampsora epitea*) was observed sporadically at all sites in test. Browsing by white-tailed deer (*Odocoileus virginianus*) occurred sporadically at each of the test sites, despite the fact that fences were erected to deter this. The only insect that appeared to have lasting impact on plant growth and development was the potato leaf hopper (*Empoasca fabae*), and this only occurred at the Escanaba site in 2012. The Escanaba site experienced pest pressure at least as great as any other in the network, so an analysis of pest impacts was performed there and is assumed to be representative of how these willow varieties might respond under equal pressure in other locations. The best biomass producing varieties tended to be effected the least by various pests (Table 5). Varieties containing parents of *Salix dasyclados*, *S. miyabeana*, or *S. purpurea* grew well and were least bothered by pests. *S. eriocephala* varieties were extremely susceptible to all pests and grew extremely poorly. Varieties with *S. viminalis* parents were attractive to both potato leaf hopper and to white-tailed deer, although they did continue to grow fairly well (Table 6). Two of Escanaba's top ranked varieties in the first rotation (Truxton and Tully Champion) ranked poorly after the second harvest (Table 7). This might have been due in part to the fact that both of these varieties were attacked by potato leaf hopper and browsed by deer during the second rotation (Table 5).

Yield

Biomass production varied widely among the sites and varieties. Fourth-year biomass production averaged 10.6 dry tons at the Escanaba site but only 2.8 dry tons at the Lake City site. The pattern of variation among varieties was similar among sites. Using Escanaba as an example (Table 7); varietal productivity ranged from a high of 12.9 to a low of 3.5 dry tons after 4 years. This difference grew even greater after 7 years. Varietal ranking in years 1, 4, and 7 was poorly correlated (Table 8). None of the top 7-year biomass producing varieties in Escanaba were identified after one year of growth (coppice harvest weights) and only 60% of the top five were identified after four years growth (first harvest weights).

Average biomass yield increased by approximately 31% between the first and second full rotations of the older sites. This varied considerably from site to site. Escanaba remained about the same, Brimley increased by 38%, and Skandia increased by 184%. This massive increase at the Skandia site may have been due to some climatic difference between the two rotations but it is difficult to see this in the climatic data we recorded (Table 3). While the Escanaba site average yield remained about the same for both harvests, there were significant differences among the varieties; with some increasing by 30% and others decreasing by a similar amount.

Analysis of Variance

Significant differences were observed in biomass yield (1) among planting sites, (2) among varieties, and (3) within planting sites (both among blocks and within plots). Significant interactions between varieties and planting sites were also observed. All five of the surviving trials in this network had been harvested at least once. The majority of the variance in first rotation biomass yields was due to site effects (66%), but there was sufficient variation among varieties (7%) to accommodate yield improvement through breeding and selection (Table 9). 6% of the variation was attributed to genotype by environment interaction; meaning that there was a great deal of site specificity to varietal performance.

A comparison of variance in first rotation yields with that in the second rotation was performed for the three sites in which those data were available. The partitioning of first-rotation variance components was similar in these three sites to the analysis done for all five sites, but this changed significantly after the second rotation. Variance due to site factors dropped from 73% to 38%. Varietal differences became more pronounced in the second rotation, increasing from 6% to 21% of total variation. Genotype by environment interaction increased as well (Table 9). In general variation among sites decreased and genetic variation increased from the first to the second rotation at these three sites.

DISCUSSION

It is wise to plant cohorts of several varieties in commercial production plantations. Yields may be reduced slightly as a result, but this will be insurance against loss from pests or inclement weather during the multi-year life of the plantation. For willow, it has been suggested that these cohorts contain at least five different varieties. Strong genotype by environment interactions cause certain varieties to perform well everywhere while other varieties only perform well at specific sites. Cohorts can be composed of varieties that perform well across the entire region (good ***general performers***), of varieties that perform well in local tests (good ***local performers***), or of varieties that perform well in remote tests (good ***distant performers***). Cohort performance tends to improve when selections are based on tests done near to the place where they are planted.

The relative performance of all varieties throughout this network was summarized (Table 10). “SX61”, “SX64”, “Millbrook”, “Otisco”, and “Tully Champion” performed in the upper quartile at most of the sites where they were tested. Although they were rarely the most outstanding performers at any of the sites, together they formed the best general performing cohort for Michigan. It was possible to compare the performance of this cohort of ***general performers*** with cohorts composed of good ***local performers*** at each of several sites (Table 11). General performers yielded 2% less biomass (at the Brimley site), 7% less biomass (at the Escanaba site), and 13% less biomass (at the Skandia site) than good local performers after two rotations.

Greater reductions in yield would have resulted if cohorts had been chosen based on their performance in remote test locations. For example, if the best cohort from Brimley had been used at Scandia, there would have been a 27% loss in biomass production. If the Escanaba cohort had been used at Brimley, there would have been a 21% loss in biomass production (Table 11). Choosing the wrong cohort, because of inadequate local testing, produces less biomass than would otherwise be possible and decreases financial returns to growers. The small investment needed to conduct adequate testing is more than offset by the increased productivity of properly chosen cohorts.

It is possible to place a value on the loss in yield that might occur if varieties are selected based on non-local testing. To do this we make two assumptions: 1) a dry ton of willow chips will be worth \$60/ton (as imagined by the DOE's "Billion Ton" report) and 2) a commercial biomass aggregator may manage approximately 5,000 acres of plantations in a region (this would produce the feedstock needed for a small 3.6 Megawatt power station[4] or provide the heating and cooling needs for about 20 medium-size buildings[5]). With these assumptions and the growth data from these trials, the financial calculation that appear in Table 12 are possible. The losses to a modest biomass growing operation if varieties are chosen based on good general performance might range from \$30,000 to \$120,000 per year. If varieties are chosen based on performance at remote sites, these losses can range from \$90,000 to \$240,000 per year. A modest investment in research to help with the selection of appropriate varieties can have large financial implications to growers.

Yield in the three older trials increased between the first and second rotations. The top-five-variety cohort's yield increased modestly at the Escanaba site (10%) intermediately at the Brimley site (34%) and extraordinarily at the Skandia site (193%). Varietal ranking also changed over time so the composition of the top-five-variety cohort changed between the first and second rotations. Early varietal selection after just one rotation would have resulted in potential yield losses between 5% and 7% compared with varieties selected after two rotations (Table 13). Using the same assumptions described above, the financial losses to a 5,000-acre biomass grower caused by selecting varieties too early ranges from about \$21,000 to \$73,000 per year (Table 13). Once again, a modest investment in long-term research can have significant implications to growers.

[4] This assumes that an electrical generator operating at a power supply factor of 0.7 will annually consume approximately 5,600 dry tons of wood per megawatt of rated output. 5,000 acres of energy plantations will produce about 20,000 dry tons annually.
[5] This assumes that a school, apartment, or municipal building will require approximately 1,000 dry tons of wood per year (that is about one vanload of chips per week) to provide heat, hot water, and cooling.

TABLE 1: Willow 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

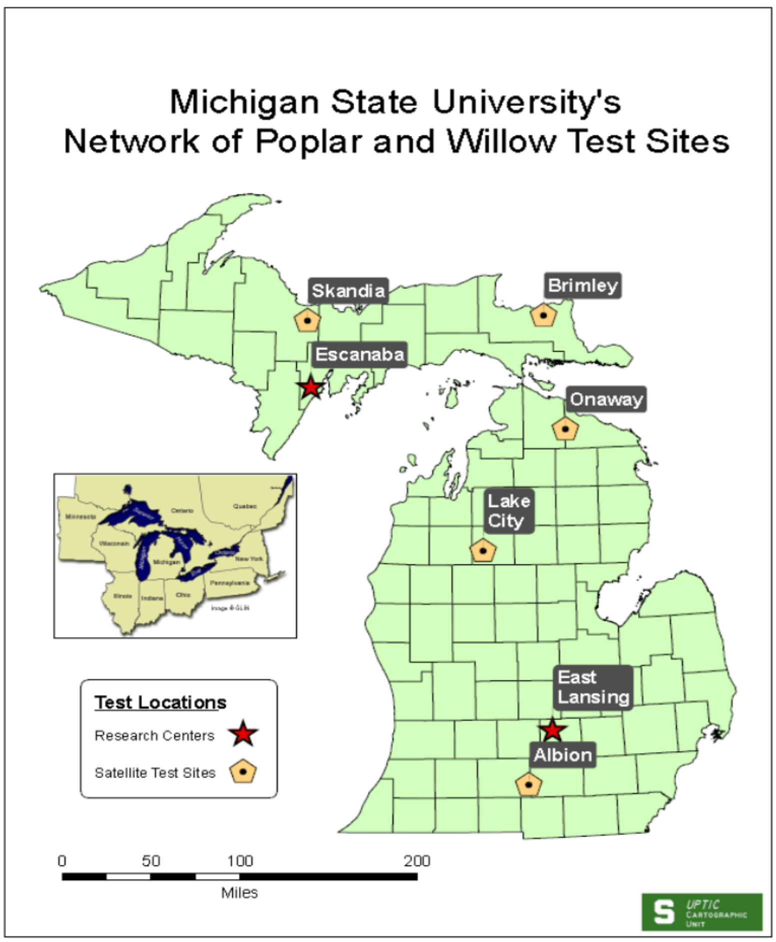

TABLE 2: Soil Conditions at the six willow trial sites in the Michigan network

Test Plantation	*Soil Analysis from Agro-One @ Cornell*						*NRCS Soil Survey*	
	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.

Planting Site	Year	Growing Season Totals			Spring (3/21 - 6/20)			Summer (6/21 - 9/20)			Fall (9/21 - 12/20)		
		Rain (in.)	Growing Degree Days (base 50°F)	Growing Season Length (days)	Rain (in.)	Growing Degree Days (base 50°F)	Days in Season	Rain (in.)	Growing Degree Days (base 50°F)	Days in Season	Rain (in.)	Growing Degree Days (base 50°F)	Days in Season
Albion	2011	28.6	3007	188	*9.2*	*775*	*68*	12.2	1974	90	7.2	258	30
	2012	19.3	3265	178	6.1	963	63	5.8	2098	92	7.4	204	23
	2013	14.4	2802	171	4.8	702	53	3.1	1852	92	6.5	248	26
	2014	22.3	2600	169	9.6	746	52	*8*	*1652*	*92*	4.7	202	25
	2015	11.9	2939	184	4.8	808	57	2.6	1797	92	*4.5*	334	35
	Ave.	***19.3***	***2923***	***178***	***7***	***799***	***59***	***6***	***1875***	***92***	***6***	***249***	***28***
Brimley	2010	23.7	2105	206	6.9	647	73	9.9	1285	92	6.9	173	41
	2011	14.8	1961	186	2.2	459	58	5.1	1268	92	7.5	234	36
	2012	11.5	2098	188	1.9	632	67	2.5	1334	92	7.1	*132*	29
	2013	29.6	1390	131	5.3	227	31	14	1094	86	10.3	*69*	14
	2014	15.7	1134	117	7.0	231	29	0.1	865	81	8.6	*38*	7
	2015	16.2	1381	143	*2.7*	*203*	*29*	6.3	1074	85	7.3	*104*	29
	Ave.	***18.6***	***1678***	***162***	***4***	***400***	***48***	***6***	***1153***	***88***	***8***	***125***	***26***
Escanaba	2009	20.3	1893	192	8.5	445	62	5.1	1292	92	6.7	156	38
	2010	28.1	2476	214	7.6	674	78	12.8	1539	92	7.7	263	44
	2011	23.6	2234	198	9.4	469	59	7.5	1525	92	6.7	240	47
	2012	21.2	2407	204	7.3	692	77	7.0	1545	92	6.9	170	35
	2013	22.9	2055	183	5.4	457	58	10.0	1404	92	7.5	194	33
	2014	31.0	1869	184	8.9	480	59	13.5	1229	92	7.2	156	33
	2015	22.4	2214	206	8.8	496	67	7.6	1448	92	5.4	264	47
	Ave.	***24.2***	***2164***	***197***	***8***	***530***	***66***	***9***	***1426***	***92***	***7***	***206***	***40***
Lake City	2010	24.4	2456	189	*7.6*	*838*	*82*	*12.8*	*1503*	*89*	4.0	115	18
	2011	23.9	2032	142	11.2	433	38	4.9	1453	85	7.8	146	19
	2012	23.3	2249	169	*8.5*	*818*	*74*	*8.2*	*1360*	*85*	6.6	71	*10*
	2013	22.4	1895	151	8.7	444	41	6.7	1343	86	*7.0*	*108*	*24*
	2014	26.3	1906	220	11.5	451	44	*7.1*	*1292*	*92*	*7.8*	*164*	*84*
	2015	17.4	1807	176	*9.1*	*420*	*84*	*8.3*	*1387*	*92*	*NA*	NA	*NA*
	Ave.	***23.0***	***2057***	***175***	***9***	***567***	***61***	***8***	***1390***	***88***	***7***	***121***	***31***
Onaway	2010	24.6	2535	194	*9.8*	*801*	*79*	*9.9*	*1554*	*92*	*4.9*	180	*23*
	2011	31.5	2035	142	11.8	412	37	9.3	1455	86	10.4	168	19
	2012	18.8	2323	146	8.0	561	44	2.7	1542	*90*	8.1	220	*12*
	2013	12.4	1829	142	6.6	376	41	0.2	1344	*82*	5.6	109	*19*
	2014	29.4	1680	135	*8.5*	*316*	*30*	12.0	1232	*86*	*9.0*	*131*	*19*
	Ave.	***23.4***	***2080***	***152***	***9***	***493***	***46***	***7***	***1425***	***87***	***8***	***162***	***18***
Skandia	2009	30.4	1753	175	12.7	*413*	59	7.6	*1224*	*92*	10.1	116	24
	2010	17.4	2295	208	5.9	651	75	5.7	1412	92	5.8	232	41
	2011	20.4	2126	182	7.1	456	55	4.4	1438	92	8.9	232	35
	2012	17.1	2044	186	3.2	*611*	63	7.4	1309	92	6.5	124	31
	2013	18.1	1600	134	4.4	247	25	*9.5*	1185	87	4.2	*168*	22
	2014	16.7	1617	152	5.1	330	35	*2.7*	*1139*	*91*	*8.9*	*148*	*26*
	2015	12.9	1987	121	*NA*	*NA*	*NA*	*3.7*	*1816*	*90*	*9.2*	*171*	*31*
	Ave.	***20.7***	***1964***	***177***	***6***	***451***	***52***	***6***	***1360***	***91***	***8***	***170***	***30***

Table 4: Planting and Harvest Dates of Willow Yield Trials in Michigan			
Test Site	*Planting Date*	*1st Harvest Date*	*2nd Harvest Date*
Escanaba, MI	5/26/2008	11/7/2011	10/16/2014
Skandia, MI	6/18/2009	10/22/2012	10/14/2015
Brimley, MI	6/23/2009	7/8/2013*	9/16/2015
Onaway, MI	5/20/2010	NA	NA
Lake City, MI	5/4/2010	10/23/2013	NA
Albion, MI	4/11/2011	11/4/2014	NA
*Note: This site was too wet to enter at the originally scheduled time for harvesting in the fall of 2012. Harvesting was delayed until the site dried sufficiently.			

Table 5: Observations of pest pressure on 26 willow varieties in a yield trial in Escanaba, MI. Leaf rust (*Melampsora epitea*) severity, Leaf hopper (*Empoasca fabae*) incidence, and browsing by deer (*Odocoileus virginianus)* are recorded along with total 7th-year dry biomass accumulation.

Variety	*7-year Yield (dry t/a)*	*Rust Severity*	*Plots with Leaf Hopper*	*Plots Browsed*	*Hybrid Cross*
SX67	28	Light			Salix miyabeana
Fish Creek	27	None			Salix purpurea
SX64	27	Rare			Salix miyabeana
Millbrook	26	Rare	25%		Salix purpurea x miyabeana
SV1	25	Rare			Salix dasyclados
Oneida	25	Rare			Salix purpurea x miyabeana
Saratoga	25	Rare	25%	25%	Salix purpurea x miyabeana
Fabius	24	Rare	50%	50%	Salix viminalis x miyabeana
FC185	24	Light			Salix purpurea
Otisco	24	Rare	50%	50%	Salix viminalis x miyabeana
Tully Champion	23	Rare	100%	100%	Salix viminalis x miyabeana
Clone_L	23	Rare	100%	100%	Salix viminalis x miyabeana
Wolcott	22	Rare			Salix purpurea
Marcy	22	Light			Salix sachalinensis x miyabeana
Taberg	21	Light	100%	100%	Salix viminalis x miyabeana
Truxton	21	Light	75%	75%	Salix viminalis x miyabeana
Owasco	21	Light	100%	50%	Salix viminalis x miyabeana
Canastota	20	Light	0%	25%	Salix sachalinensis x miyabeana
SX61	20	Rare			Salix miyabeana
Allegany	18	Light			Salix purpurea
Onondaga	17	None			Salix purpurea
Sherburne	17	Light	50%	25%	Salix sachalinensis x miyabeana
Cicero	17	Rare		50%	Salix sachalinensis x miyabeana
Verona	16	None	100%	100%	Salix viminalis x miyabeana
Clone_A	7	Extreme	75%	75%	Salix eriocephala
S25	4	Extreme	50%	100%	Salix eriocephala

Table 6: Observations of pest pressure on various hybrid combinations of willow in a yield trial in Escanaba, MI. Leaf rust (*Melampsora epitea*) severity, Leaf hopper (*Empoasca fabae*) incidence, and browsing by deer (*Odocoileus virginianus)* are recorded along with total 7th-year dry biomass accumulation.

Hybrid Cross	*7-year yield (dry t/a)*	*Rust Severity*	*Plots with Leaf Hopper*	*Plots with Browsing*
Salix dasyclados	25	Rare		
Salix purpurea x miyabeana	25	Rare	25%	25%
Salix miyabeana	25	Rare		
Salix viminalis x miyabeana	22	Rare	84%	78%
Salix purpurea	22	Light		
Salix sachalinensis x miyabeana	19	Light	25%	33%
Salix eriocephala	5	Extreme	63%	88%

Table 7: ESCANABA Willow Trial Cumulative Yields after 1, 4, & 7 Years
Ranked based on lifetime total yield
Units are dry tons/acre & rank number

Variety	Yield Year 1	coppice Rank	Yield Year 4	1st Harvest Rank	Yield Year 7	Cumulative Yield Rank
	dry tons/acre		dry tons/acre		dry tons/acre	
SX67	0.06	7	12.9	3	27.76	1
Fish Creek	0.04	12	12.8	4	27.14	2
SX64	0.05	10	12.4	10	27.05	3
Millbrook	0.03	18	12.8	5	25.73	4
SV1	0.06	8	12.7	7	25.46	5
Oneida	0.04	13	11.1	13	25.34	6
Saratoga	0.03	19	10.7	15	24.63	7
Fabius	0.07	2	11.8	11	24.07	8
FC185	0.03	20	12.5	9	23.73	9
Otisco	0.07	3	12.8	6	23.57	10
Tully Cham	0.07	4	13.6	2	22.87	11
Clone_L	0.06	9	11.6	12	22.56	12
Marcy	0.04	15	10.0	16	21.64	13
Wolcott	0.04	14	9.7	17	21.64	14
Taberg	0.04	16	10.9	14	21.14	15
Truxton	0.07	5	13.8	1	20.97	16
Owasco	0.07	6	12.6	8	20.77	17
Canastota	0.02	23	9.5	18	20.42	18
SX61	0.02	24	9.0	21	19.52	19
Allegany	0.08	1	9.4	19	17.78	20
Onondaga	0.04	17	8.6	23	17.24	21
Sherburne	0.03	21	8.9	22	17.13	22
Cicero	0.02	25	8.0	24	17.02	23
Verona	0.05	11	9.4	20	16.15	24
Clone_A	0.03	22	5.2	25	6.73	25
S25	0.01	26	3.5	26	3.81	26

Selction at age 1 captures 50% and at age 4 captures 70% of top 10 performers.
Selection at age 1 captures none and at age 4 captures 60% of the top 5 performers.

Table 8: Pearson correlations among yield-ranking at various times among 26 willow varieties throughout the 7-year life of a yield trial in Escanaba, MI, USA

	Yield in Year 7	*Yield in Year 4*	*Yield in Year 1*
Yield in Year 7	1		
Yield in Year 4	0.784	1	
Yield in Year 1	0.417	0.655	1
All are significant at α<0.05			

Table 9: Analysis of Variance (and broad sense heritability) Among 24 Willow Varieties Growing in Replicated Yield Trials at Five Sites Across Michigan.
(All sites were harvested at least once, while three sites were harvested twice.)

Comparison of variance in 1st and 2nd rotation biomass yields at three sites for which data was available

Source of Variation	*DF*	*1st Rotation*		*2nd Rotation*	
		% of Total Variance	H^2	*% of Total Variance*	H^2
Variety	23	6%	0.25	21%	0.34
Site	2	73%		38%	
Block-within-site	9	1%		2%	
Site-by-variety	36	5%		18%	
Error	198	15%		21%	

Analysis of variance in first rotation biomass yields at all five sites

Source of Variation	*DF*	*1st Rotation*	
		% of Total Variance	H^2
Variety	23	7%	0.22
Site	4	66%	
Block-within-site	15	2%	
Site-by-variety	65	6%	
Error	249	18%	

Note: all terms in these analyses of variance were significant at the 0.0001 level.

Table 10: Willow Variety Biomass Production Relative to Best Variety at Each Site Throughout a Network of 5 Yield Trials in Michigan

Variety	***Site Ranking After One Rotation***		***2nd Roation Data***			***Average Score***	***Pedigree***	*Average Performance of this Pedigree*
	Albion	***Lake City***	***Escanaba***	***Skandia***	***Brimley***			
SX61	95%	62%	74%	97%	81%	82%	Salix miyabeana	85%
SX64	75%	71%	97%	100%	74%	83%	Salix miyabeana	
SX67		81%	100%			91%	Salix miyabeana	
Millbrook	91%	100%	93%	63%	73%	84%	Salix purpurea x miyabeana	77%
Oneida	74%	37%	91%	98%	70%	74%	Salix purpurea x miyabeana	
Oneonta	100%			91%	58%	83%	Salix purpurea x miyabeana	
Saratoga		42%	89%			66%	Salix purpurea x miyabeana	
Clone_L			81%			81%	Salix viminalis x miyabeana	73%
Fabius	89%	31%	87%	40%	83%	66%	Salix viminalis x miyabeana	
Otisco	80%		85%	74%	81%	80%	Salix viminalis x miyabeana	
Owasco	65%		75%	80%	58%	70%	Salix viminalis x miyabeana	
Taberg			76%			76%	Salix viminalis x miyabeana	
Truxton	75%	77%	76%	83%	52%	73%	Salix viminalis x miyabeana	
Tully Champion		88%	82%	76%	100%	87%	Salix viminalis x miyabeana	
Verona			58%	51%	58%	56%	Salix viminalis x miyabeana	
Canastota	98%		74%	76%	67%	79%	Salix sachalinensis x miyabeana	71%
Cicero	74%		61%			68%	Salix sachalinensis x miyabeana	
Marcy	86%		78%	69%	68%	75%	Salix sachalinensis x miyabeana	
Sherburne	64%	54%	62%	69%	57%	61%	Salix sachalinensis x miyabeana	
SV1	54%	46%	92%	55%	74%	64%	Salix dasyclados	64%
Allegany	61%	37%	64%	62%	58%	56%	Salix purpurea	62%
Boonville	78%	63%				71%	Salix purpurea	
FC185			85%	65%	44%	65%	Salix purpurea	
Fish Creek	80%	25%	98%	67%	41%	62%	Salix purpurea	
Onondaga			62%	69%	59%	63%	Salix purpurea	
Wolcott	55%	23%	78%			52%	Salix purpurea	
Clone_A			24%			24%	Salix eriocephala	26%
Clone_K		19%				19%	Salix eriocephala	
S25		21%	14%		18%	18%	Salix eriocephala	
S365		44%				44%	Salix eriocephala	
Preble	89%					89%	Salix viminalis x (S. sachalinensis x S. miyabeana)	87%
Clone_C	92%	77%				85%	Salix viminalis x (S. sachalinensis x S. miyabeana)	
Sheridan		96%				96%	Salix viminalis x (S. viminalis x S. miyabeana)	96%
Best Hybrid	*2.8 dry t/a-yr*	*1.7 dry t/a-yr*	*4.6 dry t/a-yr*	*3.0 dry t/a-yr*	*2.5 dry t/a-yr*			
Best 5 Hybrids	*2.7 dry t/a-yr*	*1.5 dry t/a-yr*	*4.4 dry t/a-yr*	*2.8 dry t/a-yr*	*2.1 dry t/a-yr*			

Green shaded cells show varieties with yields at least 75% of the best variety at each site.

Red shaded cells show varieties with yields less than 75% of the best variety at each site.

Yellow shaded cells represent good "General Performers" (highest Average score among those tested at 4 of the 5 sites)

Table 11: Yield Comparison among 5-variety cohorts - selected based on performance at different locations. Cohort composition was based on performance at each of 3 test locations as well as general performance across all three locations.

Yield of Cohort when planted in:	Five-Variety Cohort Composition							
	Top **Skandia** Cohort		Top **Brimley** Cohort		Top **Escanaba** Cohort		Top **Test-wide** Cohort	
	Variety	7-year yield (dry t/a)	Variety	7-year yield (dry t/a)	Variety	7-year yield (dry t/a)	Variety	7-year yield (dry t/a)
Skandia	SX64	17.90	Tully Champion	13.60	Fish Creek	12.00	SX61	17.40
	Oneida	17.60	Fabius	7.20	SX64	17.90	SX64	17.90
	SX61	17.40	Otisco	13.20	Millbrook	11.30	Millbrook	11.30
	Oneonta[1]	16.30	SX61	17.40	SV1	9.80	Otisco	13.20
	Truxton	14.80	SV1	9.80	Oneida[2]	17.60	Tully Champion	13.60
	Average	***16.80***	***Average***	***12.24***	***Average***	***13.72***	***Average***	***14.68***
Yield Loss Compared to Skandia Cohort			***27%***		***18%***		***13%***	
Brimley	SX64	11.10	Tully Champion	14.90	Fish Creek	6.10	SX61	12.00
	Oneida	10.40	Fabius	12.40	SX64	11.10	SX64	11.10
	SX61	12.00	Otisco	12.00	Millbrook	10.90	Millbrook	10.90
	Oneonta[1]	8.70	SX61	12.00	SV1	11.10	Otisco	12.00
	Truxton	7.70	SV1	11.10	Oneida[2]	10.40	Tully Champion	14.90
	Average	***9.98***	***Average***	***12.48***	***Average***	***9.92***	***Average***	***12.18***
Yield Loss Compared to Brimley Cohort	***20%***				***21%***		***2%***	
Escanaba	SX64	27.05	Tully Champion	22.87	SX67[2]	27.76	SX61	19.52
	Oneida	25.34	Fabius	24.07	Fish Creek	27.14	SX64	27.05
	SX61	19.52	Otisco	23.57	SX64	27.05	Millbrook	25.73
	Owasco[1]	20.77	SX61	19.52	Millbrook	25.73	Otisco	23.57
	Truxton	20.97	SV1	25.46	SV1	25.46	Tully Champion	22.87
	Average	***22.73***	***Average***	***23.10***	***Average***	***25.46***	***Average***	***23.75***
Yield Loss Compared to Escanaba Cohort	***11%***		***9%***				***7%***	
	1- Oneonta was not planted in Escanaba so Owasco was substituted for comparison.				2- SX67 was not planted at Skandia or Brimley so Oneida was substituted for comparison.			

Table 12: Comparison of yield and revenue in willow biomass plantations when varietal cohorts are chosen based on local test performance versus distant test performance. Yields are based on actual 7-year performance and annual regional losses asssume that 5,000 acres of commercial willow plantations are installed in a region and that willow biomass is worth $60/dry ton.

Planting Site	***Metric***	***Best Skandia Cohort***	***Best Brimley Cohort***	***Best Escanaba Cohort***	***Best Average Cohort***
Skandia	*Annual yield (dry tons/acre)*	2.8	2.0	2.3	2.4
	Annual revenue ($/acre)	$ 168	$ 120	$ 138	$ 144
	Annual regional loss ($)		$ (240,000)	$ (150,000)	$ (120,000)
Brimley	*Annual yield (dry tons/acre)*	1.7	2.1	1.7	2.0
	Annual revenue ($/acre)	$ 102	$ 126	$ 102	$ 120
	Annual regional loss ($)	$ (120,000)		$ (120,000)	$ (30,000)
Escanaba	*Annual yield (dry tons/acre)*	3.8	3.9	4.2	4.0
	Annual revenue ($/acre)	$ 228	$ 234	$ 252	$ 240
	Annual regional loss ($)	$ (120,000)	$ (90,000)		$ (60,000)

Table13: Yield and value comparisons of willow crops grown at 3 sites in Michigan when 5-variety cohorts are selected from local tests after 1, 4, or 7 years. The best yields are achieved when selections are made from local tests after 7 years of observations (2 full rotations).

Trial Location	***5 Variety Cohort chosen after 7 years of testing***		***5 Variety Cohort chosen after 4 years of testing***				***5 Variety Cohort chosen after 1 year of testing***			
	(dry t/a)	***($/acre)***	***(dry t/a)***	***($/acre)***	***Lost Yield***	***Annual Lost Potential***	***(dry t/a)***	***($/acre)***	***Lost Yield***	***Annual Lost Potential***
Escanaba	26.6	$ 1,596	24.9	$ 1,494	-6%	$ (72,857)	21.8	$ 1,308	-18%	$ (205,714)
Skandia	16.8	$ 1,008	15.6	$ 936	-7%	$ (51,429)	14.4	$ 864	-14%	$ (102,857)
Brimley	11.0	$ 660	10.5	$ 630	-5%	$ (21,429)	10.9	$ 654	-1%	$ (4,286)

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