TWELVE-YEAR PRODUCTIVITY OF WILLOW AND POPLAR CLONES IN A HIGH DENSITY ENERGY PLANTATION IN ESCANABA, MICHIGAN, USA

(A presentation at the 4th International Poplar Symposium, Vancouver, British Columbia, Canada, July 20-23, 2014)

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ABSTRACT

Salix (willow) and *Populus* (poplar) hybrids are adaptable and productive plants for use in short rotation energy cropping systems in northern Europe and in the northeastern portion of North America. Shrub-form willows are planted once at high densities and are repeatedly harvested on 3-year cycles, re-sprouting after each harvest. A long-term test of 12 hybrid willow clones and two hybrid poplar check-clones was established at a density of approximately 18,000 stems per hectare in Escanaba, Michigan, USA in the spring of 2002. This test has now been harvested four times. The most productive of the 12 tested willow clones yielded nearly four times as much biomass as the least productive clone after 12 years. The development and selection of superior hybrids will substantially improve the profitability of energy farming. Total productivity of the top two willow clones averaged 84 dry $Mg \cdot ha^{-1}$ and was comparable to that of the two poplar check-clones, which averaged 89 dry $Mg \cdot ha^{-1}$ over the 12-year life of this test. The growth strategy of the two taxa differed however. Poplar mean annual biomass productivity rates initially averaged 8.3 dry $Mg \cdot ha^{-1} \cdot yr^{-1}$ but declined to 5.2 dry $Mg \cdot ha^{-1} \cdot yr^{-1}$ toward the end of this 12-year period. The mean annual biomass productivity rate of the top two willow clones was initially 3.4 dry $Mg \cdot ha^{-1} \cdot yr^{-1}$ but increased to 9.0 dry $Mg \cdot ha^{-1} \cdot yr^{-1}$ – eventually exceeding that of poplar. Willow has reached a plateau of annual productivity while poplar has declined. This information is critical when determining the number of times a grower can expect vigorous re-sprouting after a harvest before it becomes necessary to remove the old and replant a new energy plantation. Observations of productivity in this test will continue for at least two more rotations.

Key words: *poplar, willow, biomass, productivity, multiple rotations.*

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 $Mg \cdot ha^{-1} \cdot yr^{-1}$ 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.

Hybrids of species in the genus *Populus* (poplars) have also been prime biomass producing candidates throughout the world. Poplars are normally planted at low densities to produce large stems suitable for standard forestry products as well as biomass (Isebrands and Richardson, 2014). Poplars can however be grown under high density silvicultural systems like that previously described for willows. MSU’s early high density trials included poplar hybrids as controls for comparison with willow.

MSU’s first collaborative willow trials were established in 1999 and 2001in East Lansing, Michigan. 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. These two initial studies informed the design of a pair of willow yield trial plantings established in 2002; one in East Lansing and the other in Escanaba, Michigan.

MATERIALS AND METHODS

A set of twelve willow hybrids and two poplar hybrids (Table 1) was assembled in 2002 by the USDA Forest Service North Central Experiment Station for testing in the Lake States Region to evaluate their utility for use in bioenergy production systems. Clonal copies of the 12 willow hybrids were produced by the State University of New York, College of Environmental Science and Forestry in Syracuse and 25cm dormant hardwood cuttings of each were delivered to Michigan State University (MSU) for field planting. 25cm dormant hardwood cuttings of the two hybrid poplar clones were produced at Michigan State University's Tree Research Center in East Lansing, Michigan. Two field trials of these materials were established in the spring of 2002 – one near East Lansing and the other near Escanaba, Michigan. First-rotation results of these willow trials were summarized by Wang and MacFarlane (2012). The East Lansing trial was discontinued after the first rotation but the Escanaba trial has continued for twelve years, been harvested four times, and is the subject of this report.

A site at MSU's Forest Biomass Innovation Center (FBIC) in Escanaba, MI was selected for this planting. The site was essentially flat and had been used for hay production during the previous 30 years at least. Soil at the site was of the Onaway fine sandy loam series and appeared to be fairly uniform throughout the study area. This area received an average of 38cm of rainfall and 1,000 growing Celsius-degree days (base 10°C) during each of the growing seasons since the test was established.

Old hay field vegetation was killed with a broadcast application of 3.4 $kg \cdot ha^{-1}$ glyphosate in the fall of 2001 and 1.7 $kg \cdot ha^{-1}$in the spring of 2002. The site was then rototilled twice and planted on May 17, 2002. Twenty-five cm unrooted cuttings of the 14 taxa were hand planted on a ~91 cm x 61 cm rectangular grid providing a planting density of 18,000 cuttings per hectare. Main taxa plots were composed of 48 cuttings arranged in 6 north-south columns and 8 east-west rows. These plots were arranged in a complete randomized block design with five blocks. Measurements were made of stems on the interior eight stools, leaving the 40 stools that surrounded them as buffers. This was to minimize the edge effect exerted by surrounding plots on measured stools. Thus, each measurement plot occupied 4.46 m^2, or approximately 2,243th of a hectare.

Weed control during the first growing season consisted of spraying the entire site with 1.12 $kg \cdot ha^{-1}$ oxyfuorfen and 2.24 $kg \cdot ha^{-1}$simazine immediately after planting, while the cuttings were dormant. The site was rototilled with a small hand-held unit on several occasions during the middle of the first growing season. Weed control during the second growing season consisted of a directed application (by wick applicator) of glyphosate to weeds between the rows and columns and rototilling as before. No further weed control was conducted.

Willow is normally coppiced at the end of the first growing season to encourage the formation of multiple sprouts. Stems that grew during that first year are not collected but simply cut and left on the ground. They are not counted toward the plantation's yield. The first "harvest" normally takes place after the resulting sprouts grow for three years – at the end of the fourth year.

We deviated slightly from this pattern. Our coppice cut did not occur until the end of the second growing season after planting (2003) and this was followed by a harvest cut at the end of the third growing season after planting (2004). The biomass from these two cuttings was combined and reported as the yield from the "first harvest." So, our first "rotation" comprised the first through third years rather than the second through fourth years, which may partially explain the low yield observed for this rotation. Subsequent harvests were made every three years and so biomass yields were obtained for rotations ending in the falls of 2004, 2007, 2010, and 2013.

The following data were collected at the end of each of these rotations from the eight sample stools in each plot:

1. The **survival** of the 8 stools in the sample plot was recorded.
2. The **number of stems** per stool extending above 1 meter height was recorded.
3. The **stool diameter** at1 meter above the ground was recorded.
4. The **height** of the tallest stem on each stool was recorded.
5. The total **biomass** of the stems was measured. All stems were severed and weighed in the field to determine their "green" weight and then chipped. A sub-sample of these chips was extracted, weighed, oven-dried, and re-weighed to determine moisture content. This moisture content was applied to the green weight of the whole sample plot to determine "oven-dry" biomass weight. This plot weight was expanded to arrive at an areal estimate of biomass production.

RESULTS & DISCUSSION

Cumulative biomass production after 12 years, together with other parameters measured at the end of the 12th growing season is summarized in Table 2. Analysis of variance found significant differences among taxa for all parameters. Six willow clones (SX67, SX61, SX64, PUR12, 94003, and 94001) and both poplar clones grouped together as top biomass producers while the remaining six willow clones grouped together as poor biomass producers.

Hybrids of *S. eriocephala* and *S. interior* parents performed poorly while those of *S. miyabeana* and *S. udensis* performed well. Performance of *S. purpurea* hybrids was mixed.

Carefully selected willow clones can produce biomass equally as well as poplar over 12 years in Upper Michigan. Some willow clones produced nearly four times as much biomass as others; making SRE Plantations of the former clones profitable and of the other clones disastrous failures. The willow clones tested here have been superseded by new hybrids developed by breeding programs in New York. One of the first generation of improved hybrids (variety "Truxton") produced 6% more biomass than the best performing clone in this test (SX67) in the first rotation of a younger, 2008 willow yield trial at FBIC.

Stem heights measured during the course of this experiment were significantly but loosely correlated (r = 0.46 – 0.78) with final 12^{th}-year biomass production. All other stool measurements made throughout the life of this plantation were not correlated with biomass production (Table 3). This is because willow clones follow different growth strategies to produce similar amounts of biomass. For example, PUR12 and SX61 survived and produced biomass equally well but PUR12 did this by growing 25 short stems per stool while SX61 grew 10 tall stems per stool. SX67 had a final survival of 78% while SX64 had a final survival of 98% yet the biomass production of these two hybrids after 12 years was statistically the same (Table 2).

Managers and researchers constantly seek ways to predict final willow system yields from non-destructive measurements made early in the life of a stand. This is confounded by; 1) the wide variation in growth strategies among willow hybrids (Verwijst and Nordh, 1992), 2) age differences and the tendency of clonal ranking and yield to change from one rotation to the next (Volk, *et. al.*, 2011), and 3) strong site differences (Telenius and Verwijst, 1995). Allometric equations that predict individual stem biomass from stem diameters are quite accurate when developed for specific clones at specific ages and sites (Carmela, *et. al.*, 2007) but employing these equations in multi-rotation, mixed clone production plantations scattered throughout a region will be unwieldy at best. Simplified biomass yield prediction methods like those developed for Swedish willow varieties by Telenius and Verwijst (1995) need to be developed for the varieties and sites common in the United States. Even though field technicians love to make tens of thousands of stem diameter measurements, it may be advisable to seek other more easily measured parameters that can yield reasonably precise biomass estimates.

Stool survival changed little after the establishment period. With the exception of three particularly poor performing willow clones whose survival decreased over the life of the trial (S25, S287, and 940012), very few willow stools died after the first rotation. Stool survival was not correlated with 12^{th} year biomass yield but stool survival was negatively correlated with stool diameter (r = -0.414 at Alpha = 0.001). Surviving stools increased in size to occupy the extra growing space made available as their neighbors died. In this way plot yield became independent of survival.

While willow and poplar produced similar amounts of biomass over the 12-year life of this trial, they followed distinctly different growth trajectories (Table 4). Poplar's 3-year Mean Annual Increment (MAI) was high during the first rotation and remained high for two more rotations, but declined precipitously during the fourth rotation. Willow's MAI, on the other hand, was quite low for the first rotation but increased gradually through each subsequent rotation, eventually exceeding that of poplar (Figure 1). Thus, in terms of total biomass accumulation, poplar was well ahead of willow for most of the life of this trial (*e.g.* poplar produced 77% more biomass than willow during the first six years) but willow caught up and appears to be poised to exceed poplar's productivity during the next rotation (Figure 2).

Although willow in New York has shown increased yields from the first to the second and third rotations (Volk, *et. al.* 2011), the increase in willow yield between the first, second, and third rotations seen here (Table 4) is unprecedented. Part of the difference may be that yields reported from New York do not include the establishment year when plants grow slowly. Our reported yields include the slow-growing establishment year which lowered the calculated MAI. Additionally, weed pressure was heavy during the first two years of our test. Willow may have taken longer than poplar to overcome this early competition, causing a lag in early biomass accumulation.

The eventual decline in poplar's vigor (and yield) may have resulted from our repeated tri-annual cutting that forced it to grow as a shrub rather than a single-stemmed tree. This may ultimately have become more than poplar could tolerate. Poplar's decline may have also been due to increased infection by canker-forming diseases like *Septoria musiva* and leaf rusts like *Marssonina brunnea* during the last years of the trial.

Poplar produced significantly more biomass than willow in the early years of this trial and so would be a better choice than willow for a grower seeking early finical returns. It appears however that willow biomass productivity will eventually surpass that of poplar and that poplar may in fact be dying. This argues favorably for the relative long-term superiority of willow to poplar under this production system. We will continue to monitor yields from this trial every three years for at least two more rotations in order to confirm these trends.

CONCLUSIONS

1. Both willow and poplar hybrids can be successfully grown for the production of biomass using high density, short rotation silviculture systems in Upper Michigan, averaging more than 7 dry $Mg \cdot ha^{-1} \cdot yr^{-1}$ from four harvests over a 12-year period.
2. Poplar biomass yield exceeds that of willow for the first three harvests but willow catches up and eventually surpasses willow as the poplar declines in health and productivity.
3. Proper clonal selection is critical to the success of these production systems. The best willow clone produced over four times as much biomass as the poorest willow clone. Clones developed since 2002 by breeding programs in New York will yield more than double the biomass of the best older willow clone tested here.

Partial funding support for this work came from the USDOE Regional Biomass Feedstock Partnership, Michigan State University AgBioResearch, and the USFS North Central Research Station.

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Figure 1. 3-year MAI of Top 2 Willow and Top 2 Poplar Clones in a 12-year-old Yield Trial in Escanaba, Michigan

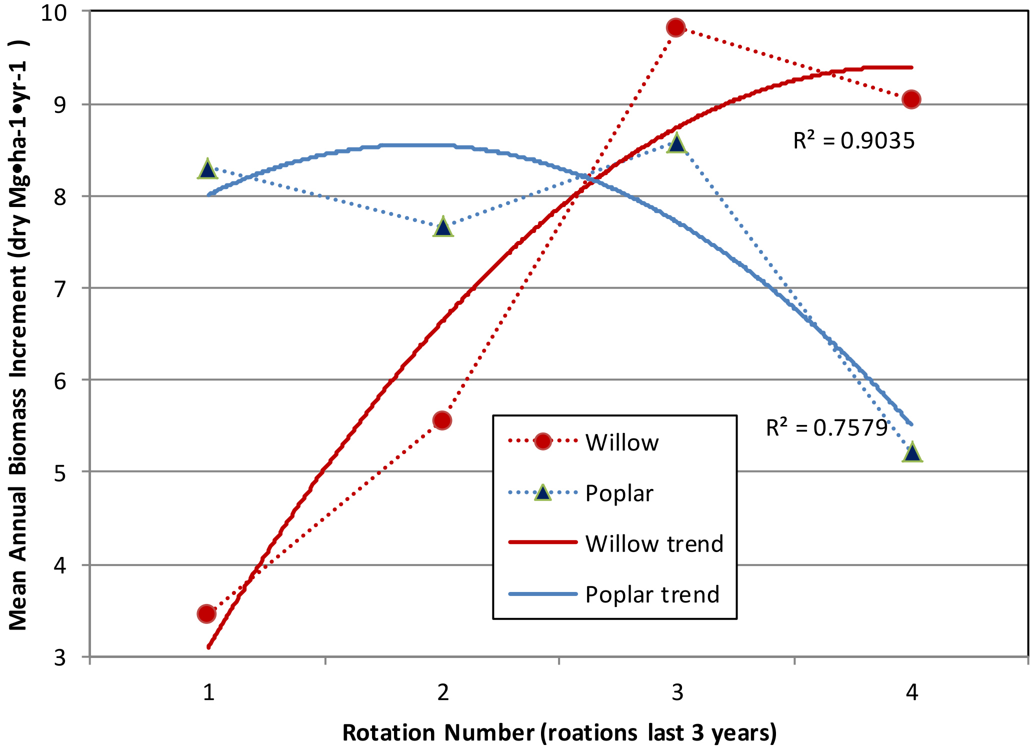

Figure 2. Projected Biomass Accumulation of the Top 2 Willow and Poplar Clones in a 12-year-old Yield Trial in Escanaba, Michigan

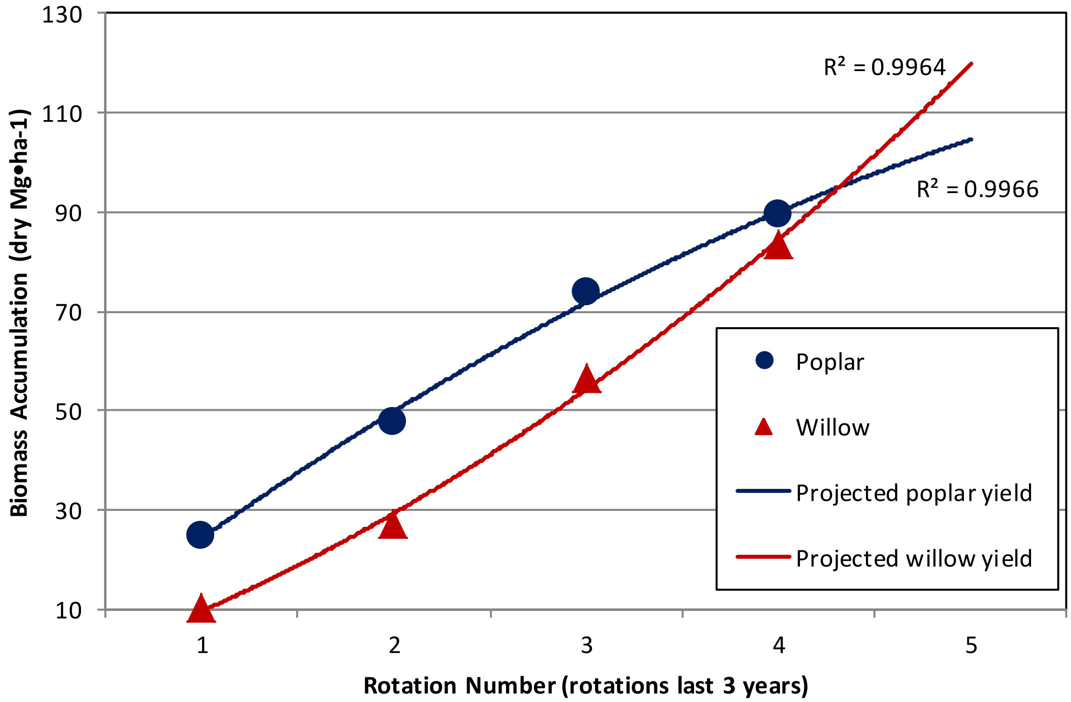

Table 1. Hybrids included in Escanaba, Michigan yield trial

Hybrid Code	Species or inter-species cross	Common name or synonym
Salix		
94001 (AKA FC185)	*S. purpurea*	purple willow
94003 AKA (FC187)	*S. purpurea*	purple willow
94005 (AKA FC189)	*S. purpurea*	purple willow
94012 (AKA B196)	*S. purpurea*	purple willow
PUR12	*S. pupurea*	purple willow
S25	*S. eriocephala X S. eriocephala*	heartleaf willow
S287	*S. eriocephala*	heartleaf willow
S365	*S. eriocephala X S. eriocephala*	heartleaf willow
S301	*S. interior*	sandbar willow
SX61	*S. udensis*	*S. sachalinensis*
SX64	*S. miyabeana*	Miyabe willow
SX67	*S. miyabeana*	Miyabe willow
Populus		
NM5	*P. nigra x P. maximowiczii*	
NM6	*P. nigra x P. maximowiczii*	

Table 2. Average performance of 12 willow and 2 popalr clones in a yield trial in Escanaba, Michigan after twelve growing seasons (and four harvest cycles).

Clone	*Survival (percent)*	*Stems/Stool (count)*	*Stool Diameter (cm)*	*Height (m)*	*Cumulative Biomass (dry Mg/ha)*	*Waller-Duncan subgroups*			
NM5	70%	6	45	5.4	94	a			
SX67	78%	14	55	4.6	89	a	b		
NM6	88%	7	42	4.1	85	a	b		
SX61	83%	10	49	4.3	78	a	b		
SX64	98%	11	49	3.9	76	a	b		
PUR12	83%	25	54	3.8	74	a	b		
94003	93%	21	53	4.1	71	a	b		
94001	90%	21	49	3.8	67		b	c	
S365	93%	19	50	2.0	42			c	d
S301	88%	6	36	2.7	39				d
94005	70%	17	52	3.4	36				d
94012	50%	27	50	3.1	32				d
S25	28%	4	14	1.5	24				d
S287	45%	6	25	1.2	24				d
LSD	**16%**	**3**	**6**	**1.8**	**13**				

** - biomass yields followed by the same letter are statistically similar using the Waller-Duncan test. LSD at Alpha = 0.05 are listed at the bottom of each column. Shaded cells represent the top 2 willow and top 2 poplar clones used in inter-species yield comparisons.*

Table 3. Correlation of various parameters measured every 4 years with 12 years' cumulative biomass production of the six leading willow biomass producers in a yield trial in Escanaba, Michigan.

Trait	*Year*	*Pearson Correlation with 12th-year biomass yield*	*Significance*
Stool Survival	2004	0.157	NS
	2007	0.268	NS
	2010	0.248	NS
	2013	0.294	NS
Stems per Stool	2004	0.367	0.046
	2007	0.254	NS
	2010	0.007	NS
	2013	0.093	NS
Stool Diameter	2007	0.374	0.041
	2010	-0.011	NS
	2013	0.074	NS
Stool Height	2004	0.464	0.010
	2007	0.619	0.000
	2010	0.783	0.000
	2013	0.635	0.000

Table 4. Biomass accumulation of top two willow and two poplar clones in a yield trial in Escanaba, Michigan. Mean Annual Increment during each 3-year rotation and total accumulated biomass during the 12 years of the trial are presented.

3-yr Rotation	*MAI (dry Mg•ha^{-1} •yr^{-1})*		*Accumulating Biomass (dry Mg•ha^{-1})*	
	Willow	*Poplar*	*Willow*	*Poplar*
1	3.45	8.30	10.36	24.89
2	5.56	7.67	27.04	47.89
3	9.82	8.59	56.50	73.65
4	9.04	5.22	83.61	89.33
all 12 years	**6.97**	**7.44**		