# FIFTEEN-YEAR PRODUCTIVITY OF WILLOW AND POPLAR VARIETIES IN A HIGH DENSITY ENERGY PLANTATION IN ESCANABA, MICHIGAN, USA

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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 varieties and two hybrid poplar varieties was established at a density of approximately 18,000 stems per hectare in Escanaba, Michigan, USA in the spring of 2002. This test underwent five three-year rotations. The most productive willow varieties in this test yielded nearly four times as much biomass as the least productive variety after 15 years. The development and selection of superior hybrids will substantially improve the profitability of energy farming. Cumulative yield of the top two willow varieties averaged 98 dry $Mg \cdot ha^{-1}$ and was comparable to that of the two poplar varieties, which averaged 99 dry $Mg \cdot ha^{-1}$ over the 15-year life of this test. Poplar mean annual biomass productivity rates averaged 8.3 dry $Mg \cdot ha^{-1} \cdot yr^{-1}$ during the first rotation but by the fifth rotation had declined to 3.0 dry $Mg \cdot ha^{-1} \cdot yr^{-1}$. Willow mean annual biomass productivity of the top two willow varieties averaged 2.8 dry $Mg \cdot ha^{-1} \cdot yr^{-1}$ during the first rotation but reached a maximum of 9.8 dry $Mg \cdot ha^{-1} \cdot yr^{-1}$ during the third rotation. Despite these different growth strategies, the top performing varieties of both genera had produced an equal amount of biomass over the 15-year life of the trial. Information about yield over multiple rotations is critical when determining the number of rotations over which a grower can expect adequate growth before it becomes necessary to remove the old and replant a new energy plantation.

Escanaba, MI willow and poplar trial during the 2nd rotation (left) and the 3rd rotation (right).

## 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 varieties were produced either at SUNY and more recently at Cornell University and then distributed to collaborators for testing. Results are pooled to increase our understanding of how these varieties 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 varieties 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.* 2010). 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 2001 in East Lansing, Michigan. The objective of these tests was to explore how various varieties 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 varieties 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 varieties 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 fifteen years, been harvested five 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 varieties were hand planted on a ~91 cm x 61 cm rectangular grid providing a planting density of 18,000 cuttings per hectare. Main variety 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 2,243$^{th}$ 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 complete datasets were obtained for 3-year rotations ending in the falls of 2004, 2007, 2010, 2013, and 2016.

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

1. The total **biomass** of the sample plot 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 at 93°C, and re-weighed to determine the moisture content of the green sample. The green weight of the plot was reduced using the calculated moisture content to arrive at the "oven-dry" biomass weight of the plot. This plot weight was expanded based on the size of the plot to arrive at an areal estimate of biomass production.
2. The **survival** of the stools in the sample plot was recorded.
3. The **number of stems** in each sample stool extending above 1 meter height was recorded.
4. The **height** of the tallest stem on each sample stool was recorded.
5. The **stool diameter** (representing the area occupied by all the stems emanating from that stool) at one meter above the ground was recorded.

## RESULTS & DISCUSSION

### Cumulative Growth and Survival

A summary of cumulative biomass production after 15 years, together with other parameters measured at the end of the 15$^{th}$ growing season is presented in Table 2. Analysis of variance found significant differences among varieties for all parameters. Six of the willow varieties formed a cohort of significantly inferior producers. Information about these varieties is presented in *italics* in this document's tables. This cohort included all three *S. eriocephala* varieties (S365, S25, and S287), the *S. interior* variety (S301), and one of the *S. purpurea* varieties (94005). Interestingly, three other *S. purpurea* varieties produced significantly more biomass than 94005 which suggests that while this species has the potential to excel, there is variability to be overcome. The best yielding variety in this test was the *P. nigra x maximowiczii* variety, “NM5.” There were three other varieties that produced a statistically similar amount of biomass over 15 years (*P. nigra x maximowiczii* “NM6”, *S. miyabeana* “SX67”, and *S. purpurea* “PUR12”). Information about this cohort of “Top” biomass producers is presented in green-shaded cells in this document’s tables.

Carefully selected willow varieties can produce biomass equally as well as poplar over 15 years in high density plantations in Upper Michigan. The top two willow varieties here produced an average of 98 dry Mg/ha over 15 years; a mean annual increment of 6.5 dry Mg/ha-yr. This yield was statistically the same as for the two poplar varieties (99 dry Mg/ha). Yields here were below the national target established for biomass crops in the “U.S. Billion Ton Update” (U.S Department of Energy, 2011) of 11 to 18 dry Mg/ha-yr. Yield in Upper Michigan could be improved by using new, better yielding varieties that have been developed during the 15 years since this test began. Additional gains could be achieved by omitting the latter, lower yielding rotations. Yield of the top willow varieties in the third and fourth rotations was 10 Mg/ha-yr. This comes quite close to the national goals despite the short growing seasons of this region.

Some willow varieties produced roughly four times as much biomass as others (Table 2); suggesting that plantations of the former varieties will be successful while those of the latter varieties will be disastrous failures. The older willow varieties tested here have been superseded by new varieties developed by breeding programs in New York. One of the first generation of improved varieties (“Tully Champion”) produced 9% more biomass than the best performing variety in this test (“SX67”) during the first 3-year rotation of a younger willow yield trial in Escanaba (Miller, 2016). Continued breeding promises to improve the yield potential of willow in production systems like this.

<u>Incremental Growth and Survival</u>

Measurements made at the end of each 3-year rotation were summarized by variety. Three-year biomass yield (Table 3) varied by variety and rotation but in general willow and poplar followed distinctly different strategies (Figure 1). Poplar yields were significantly greater than willow during the first two rotations and began to decline by the fourth rotation. Willow yields were much less than poplar during the first two rotations, but they equaled poplar in rotation 3 and exceeded poplar in rotations four and five. So even though poplar and willow plots developed differently over time, similar amounts of biomass were produced over the course of five rotations (Figure 2).

Willow and poplar varieties are noted for exhibiting strong genotype by environment interaction that leads to yield ranking changes among varieties from place to place (Fabio, et. al., 2017). Similar changes in varietal yield ranking have been observed from one rotation to the next (Miller, 2016). One of the top four biomass producers in this trial (“PUR12”) was among the worst producers in the first rotation and did not appear as one of the top four producers until third rotation (Table 3). In fact, two of the top eight biomass producing varieties would have been missed if selections had been made after only one rotation. Inadequate testing of biomass varieties (either in time or in space) leads to mistaken selections and yield losses for growers.

The 40% increase in yield observed here between the first and second rotations and the 60% increase between the second and third rotations are striking (Table 3). Volk, *et. al.* (2011) noticed that yield in New York willow plantations increased by about 23% between the first and second rotations and then by another 13% over the next two rotations. Part of the difference between New York and Michigan may be that the first 3-year rotation here included the slow growing plantation establishment year while the first 3-year rotation in New York did not. Additionally, weed pressure was heavy during the first two years of our test. The 60% increase in this trial's yield between the second and third rotations is not so easily explained unless it is simply the result of a spectacular series of growing seasons. Yield in this trial began to decrease in the fourth rotation as mortality and deer predation became severe for certain varieties. Five rotations may be too many, under these conditions, for many of the varieties tested here.

The precipitous 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 latter 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 financial returns. Willow biomass productivity eventually equaled that of poplar by the end of the trial. This argues favorably for the relative long-term superiority of willow to poplar under this production system.

Biomass yield of all three *S. eriocephala* varieties and of *S. interior* was essentially zero during the fifth rotation (Table 3). This was because those varieties had been preferentially browsed by white-tailed deer. In fact two of these varieties were killed as a result of this depredation. With these exceptions, stool survival in general was initially excellent and either remained consistent or declined only slightly over the course of the trial (Table 4).

<u>Correlation Among Growth Traits</u>
Stool characteristics like number of stems (Table 5), stool height (Table 6), and stool diameter (Table 7) remained fairly constant from rotation to rotation but varied among varieties. Relationships between stool characteristics and biomass productivity are difficult to find. For example, 94012 was an exceptionally poor biomass producer, yet it had stool diameters as great as SX67 which was the best producer. The two top producing willow varieties (SX67 and

PUR12) has similar biomass yields, stool survivals, stool diameters, and stool heights yet SX67 had 11 stems per stool while PUR12 had 19. This suggests that individual stems of SX67 must have been more massive. Perhaps SX67 stems had greater diameters or higher specific gravities – but this was not determined here.

A correlation analysis of traits measured at the end of each of the five rotations with cumulative biomass yield across all 14 varieties in this trial was conducted (Table 8). With the exception of stool height, none of the stool parameters measured were correlated with total biomass productivity. Overall stool survival appeared correlated with biomass production during the fourth and fifth rotations, but this was due entirely to the high mortality among the four varieties that succumbed to deer browsing.

A second correlation analysis was conducted for the top six willow varieties alone in order to explore relationships among willow stool characteristics (Table 9). Again, stool height correlated positively with the biomass yield of each rotation as well as with total cumulative biomass yield. And again, none of the other stool parameters were consistently correlated with biomass productivity. However, stool survival was consistently and significantly correlated (albeit weakly) with stool diameter. With the exception of the first rotation, when differences in survival among varieties had not yet emerged, plots with lower survival tended to have larger diameter stools at the end of each rotation. This can be explained if surviving stools expanded into the extra growing space provided by their departed neighbors. Stools with larger diameters also tended to consistently have more stems per stool at the end of each rotation; independent of stool survival. This suggests that larger stools have higher stem density than smaller stools. This may have engineering implications for harvesting equipment.

Stool heights at each rotation were consistently correlated with total biomass productivity. So taller stemmed varieties produce more biomass. However, trying to predict that biomass precisely using stool height was problematic. A regression to predict the biomass yield of the top six willow varieties during the fifth rotation using the average plot heights of the tallest stems was developed (Figure 3). A strong positive relationship between height and biomass is evident but the average prediction error for this allometric equation is 35%. This degree of accuracy is of little use to a researcher or grower.

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 task 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 stool and stem parameters can be quite accurate when developed for specific varieties at specific ages and sites (Arevalo, *et. al.*, 2007;

Nordh and Verwijst, 2004) but employing these equations in multi-rotation, mixed variety production plantations scattered throughout a region will be unwieldy at best. Although field technicians love to make tens of thousands of stem diameter measurements, it may be advisable to seek other easily measured parameters that can yield reasonably precise biomass estimates. Simplified biomass yield prediction methods like those developed for Swedish willow varieties by Telenius and Verwijst (1995) might yet be developed for the varieties and sites common in the United States.

## 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 6.5 dry $Mg \cdot ha^{-1} \cdot yr^{-1}$ from five harvests over a 15-year period.
2. Incremental poplar biomass yield exceeds that of willow for the first three rotations but willow catches up and eventually surpasses poplar as poplar health and productivity declines.
3. Proper varietal selection is critical to the success of these production systems. The best willow variety produced over four times as much biomass as the poorest willow variety. Varieties developed since 2002 by breeding programs in New York will produce substantially more biomass that the older willow variety tested here.
4. Stool and stem parameters were either not correlated or were exceptionally poor predictors of biomass yield. However, stools tended to expand in diameter as their neighbors died and larger diameter stools tended to have more stems than their smaller couterparts.

*The help of Bradford Bender, Kile Zuidema, Paul Irving, and several interns in this test's establishment, maintenance, and data collection is gratefully acknowledged. 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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**Table 1. Willow and poplar varieties included in an Escanaba, Michigan yield trial.**

| Variety Code | Species or inter-species cross | Common name or synomym | |
|---|---|---|---|
| NM5 | *Populus nigra x P. maximowiczii* | hybrid poplar | Top biomass producers |
| SX67 | *Salix miyabeana* | Miyabe willow | |
| NM6 | *Populus nigra x P. maximowiczii* | hybrid poplar | |
| PUR12 | *Salix purpurea* | purple willow | |
| SX61 | *Salix udensis* | Salix sachalinensis | Good biomass producers |
| SX64 | *Salix miyabeana* | Miyabe willow | |
| 94003 | *Salix purpurea* | purple willow | |
| 94001 | *Salix purpurea* | purple willow | |
| 94005 | *Salix purpurea* | purple willow | Inferior biomass producers |
| S365 | *Salix eriocephala* | heartleaf willow | |
| 94012 | *Salix purpurea* | purple willow | |
| S301 | *Salix interior* | sandbar willow | |
| S25 | *Salix eriocephala* | heartleaf willow | |
| S287 | *Salix eriocephala* | heartleaf willow | |

**Table 2. Average performance of 12 willow and 2 poplar varieties in a yield trial in Escanaba, Michigan after 15 years (5 harvest cycles).**

| | ***15th-year parameters*** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| *Variety* | *Stool Survival (%)* | *Stems/Stool (count)* | *Stool Diameter (cm)* | *Height (m)* | *Cumulative Biomass (dry Mg/ha)* | *Biomass means followed by similar letters are statistically the same.* | | | |
| NM5 | 60% | 4 | 41 | 5.1 | 105.6 | a | b | | |
| SX67 | 78% | 11 | 68 | 4.1 | 103.5 | a | b | | |
| NM6 | 75% | 5 | 42 | 3.8 | 91.5 | a | b | c | |
| PUR12 | 80% | 19 | 60 | 4.3 | 89.6 | a | b | c | |
| SX61 | 78% | 6 | 48 | 3.6 | 88.1 | | b | c | |
| SX64 | 98% | 7 | 50 | 3.5 | 87.4 | | b | c | |
| 94003 | 93% | 19 | 55 | 4.1 | 83.6 | | | c | |
| 94001 | 90% | 16 | 52 | 3.8 | 78.7 | | | c | |
| *94005* | *75%* | *17* | *55* | *3.3* | *43.9* | *Significantly inferior group* | | | |
| *S365* | *93%* | *0* | *0* | *0.7* | *41.9* | | | | |
| *94012* | *50%* | *27* | *68* | *3.0* | *40.3* | | | | |
| *S301* | *55%* | *4* | *32* | *0.8* | *39.1* | | | | |
| *S25* | *0%* | *0* | *0* | *0.0* | *24.2* | | | | |
| *S287* | *0%* | *0* | *0* | *0.0* | *23.8* | | | | |
| **LSD α=0.05** | **15%** | **3** | **7** | **0.3** | **17.1** | | | | |

**Table 3. Incremental and total biomass accumulation during each of five 3-year rotations in a yield trial of 12 willow and 2 poplar varieties in Escanaba, Michigan.**

| Variety | Rotation 1 | | Rotation 2 | | Rotation 3 | | Rotation 4 | | Rotation 5 | | 15 year Total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | (dry Mg/ha) | Rank | (dry Mg/ha) | Rank | (dry Mg/ha) | Rank | (dry Mg/ha) | Rank | (dry Mg/ha) | Rank | (dry Mg/ha) |
| NM5 | 24.6 | 2 | 23.3 | 1 | 25.6 | 6 | 20.1 | 7 | 11.9 | 4 | 105.6 |
| SX67 | 11.8 | 3 | 16.6 | 4 | 30.2 | 1 | 30.1 | 1 | 14.7 | 2 | 103.5 |
| NM6 | 25.4 | 1 | 22.7 | 2 | 25.8 | 5 | 11.2 | 10 | 6.4 | 10 | 91.5 |
| PUR12 | 4.9 | 12 | 13.9 | 6 | 28.7 | 2 | 26.3 | 3 | 15.9 | 1 | 89.6 |
| SX61 | 8.8 | 5 | 16.8 | 3 | 28.7 | 3 | 24.1 | 5 | 9.6 | 8 | 88.1 |
| SX64 | 7.7 | 6 | 15.4 | 5 | 28.2 | 4 | 24.8 | 4 | 11.3 | 6 | 87.4 |
| 94003 | 5.3 | 10 | 13.3 | 7 | 25.1 | 7 | 27.4 | 2 | 12.5 | 3 | 83.6 |
| 94001 | 7.2 | 7 | 13.3 | 8 | 22.6 | 8 | 23.8 | 6 | 11.9 | 5 | 78.7 |
| *94005* | *3.6* | *14* | *6.2* | *14* | *12.5* | *12* | *14.2* | *8* | *7.5* | *9* | *43.9* |
| *S365* | *6.0* | *9* | *8.7* | *10* | *18.1* | *9* | *9.1* | *11* | *0.0* | *11* | *41.9* |
| *94012* | *3.9* | *13* | *8.3* | *11* | *13.3* | *11* | *13.8* | *9* | *10.1* | *7* | *49.4* |
| *S301* | *8.9* | *4* | *9.5* | *9* | *13.4* | *10* | *7.4* | *12* | *0.0* | *12* | *39.1* |
| *S25* | *7.0* | *8* | *7.8* | *12* | *8.6* | *14* | *1.9* | *14* | *0.0* | *13* | *25.3* |
| *S287* | *5.2* | *11* | *6.6* | *13* | *10.2* | *13* | *2.9* | *13* | *0.0* | *14* | *25.0* |
| **LSD α=0.05** | **2.3** | | **3.5** | | **6.0** | | **4.8** | | **5.0** | | **17.1** |
| **Test Average** | 9.3 | | 13.0 | | 20.8 | | 16.9 | | 8.0 | | |
| **Change from previous rotation:** | | | 40% | | 60% | | -19% | | -53% | | |

**Table 4. Average survival of stools at the end of each of five 3-year rotations in a yield trial of 12 willow and 2 poplar varieties in Escanaba, Michigan.**

| Variety | Rotation 1 | Rotation 2 | Rotation 3 | Rotation 4 | Rotation 5 |
|---|---|---|---|---|---|
| | (percent survival) | | | | |
| NM5 | 92% | 90% | 80% | 70% | 60% |
| SX67 | 83% | 78% | 78% | 78% | 78% |
| NM6 | 96% | 95% | 93% | 88% | 75% |
| PUR12 | 85% | 85% | 85% | 83% | 80% |
| SX61 | 85% | 85% | 85% | 83% | 78% |
| SX64 | 92% | 100% | 98% | 98% | 98% |
| 94003 | 90% | 93% | 93% | 93% | 93% |
| 94001 | 91% | 90% | 90% | 90% | 90% |
| *94005* | *85%* | *70%* | *78%* | *70%* | *75%* |
| *S365* | *98%* | *95%* | *95%* | *93%* | *93%* |
| *94012* | *62%* | *58%* | *53%* | *50%* | *50%* |
| *S301* | *95%* | *95%* | *98%* | *88%* | *55%* |
| *S25* | *83%* | *85%* | *75%* | *28%* | *0%* |
| *S287* | *89%* | *70%* | *88%* | *45%* | *0%* |
| **LSD α=0.05** | 9% | 16% | 14% | 18% | 15% |

**Table 5. Average number of stems per stool at the end of each of five 3-year rotations in a yield trial of 12 willow and 2 poplar varieties in Escanaba, Michigan**

| *Variety* | *Rotation 1* | *Rotation 2* | *Rotation 3* | *Rotation 4* | *Rotation 5* |
|---|---|---|---|---|---|
| | *(number of stems)* | | | | |
| NM5 | 9 | 5 | 6 | 6 | 4 |
| SX67 | 16 | 11 | 14 | 14 | 11 |
| NM6 | 8 | 7 | 6 | 7 | 5 |
| PUR12 | 12 | 13 | 19 | 25 | 19 |
| SX61 | 10 | 9 | 9 | 10 | 6 |
| SX64 | 12 | 10 | 10 | 11 | 7 |
| 94003 | 10 | 10 | 16 | 21 | 19 |
| 94001 | 14 | 12 | 18 | 21 | 16 |
| *94005* | *9* | *8* | *14* | *17* | *17* |
| *S365* | *12* | *9* | *9* | *19* | *0* |
| *94012* | *14* | *15* | *23* | *27* | *27* |
| *S301* | *9* | *8* | *9* | *6* | *4* |
| *S25* | *13* | *7* | *8* | *4* | *0* |
| *S287* | *13* | *12* | *15* | *6* | *0* |
| **LSD α=0.05** | **3** | **2** | **3** | **4** | **3** |

**Table 6. Average height of the tallest stem in each stool at the end of each of five 3-year rotations in a yield trial of 12 willow and 2 poplar varieties in Escanaba, Michigan**

| *Variety* | *Rotation 1* | *Rotation 2* | *Rotation 3* | *Rotation 4* | *Rotation 5* |
|---|---|---|---|---|---|
| | *(meters)* | | | | |
| NM5 | 3.2 | 4.1 | 6.1 | 5.4 | 5.1 |
| SX67 | 2.7 | 4.0 | 5.0 | 4.6 | 4.1 |
| NM6 | 3.1 | 4.4 | 5.7 | 4.1 | 3.8 |
| PUR12 | 1.9 | 3.2 | 4.5 | 3.8 | 4.3 |
| SX61 | 2.9 | 3.7 | 4.9 | 4.3 | 3.6 |
| SX64 | 2.2 | 3.8 | 4.6 | 3.9 | 3.5 |
| 94003 | 2.0 | 3.4 | 4.5 | 4.1 | 4.1 |
| 94001 | 2.1 | 3.5 | 4.1 | 3.8 | 3.8 |
| *94005* | *1.5* | *3.1* | *3.7* | *3.4* | *3.3* |
| *S365* | *1.5* | *4.0* | *3.2* | *2.0* | *0.7* |
| *94012* | *1.7* | *2.8* | *3.4* | *3.1* | *3.0* |
| *S301* | *2.2* | *3.3* | *3.5* | *2.7* | *0.7* |
| *S25* | *1.9* | *2.4* | *2.3* | *1.5* | *0.0* |
| *S287* | *1.1* | *2.5* | *2.4* | *1.2* | *0.0* |
| **LSD α=0.05** | **0.2** | **0.8** | **0.3** | **0.3** | **0.3** |

| Table 7. Average stool diameter (1 m above the ground) at the end of each of five 3-year rotations in a yield trial of 12 willow and 2 poplar varieties in Escanaba, Michigan. | | | | | |
|---|---|---|---|---|---|
| ***Variety*** | ***Rotation 1*** | ***Rotation 2*** | ***Rotation 3*** | ***Rotation 4*** | ***Rotation 5*** |
| | | *(centimeters)* | | | |
| NM5 | Not Measured in First Rotation | 48 | 46 | 45 | 41 |
| SX67 | | 60 | 55 | 55 | 68 |
| NM6 | | 54 | 40 | 42 | 42 |
| PUR12 | | 55 | 58 | 54 | 60 |
| SX61 | | 52 | 46 | 49 | 48 |
| SX64 | | 55 | 51 | 49 | 50 |
| 94003 | | 51 | 53 | 53 | 55 |
| 94001 | | 50 | 50 | 49 | 52 |
| *94005* | | *49* | *45* | *52* | *55* |
| *S365* | | *57* | *42* | *50* | *0* |
| *94012* | | *61* | *58* | *62* | *68* |
| *S301* | | *58* | *41* | *36* | *32* |
| *S25* | | *58* | *49* | *34* | *0* |
| *S287* | | *73* | *73* | *42* | *0* |
| **LSD α=0.05** | | **8** | **8** | **6** | **7** |

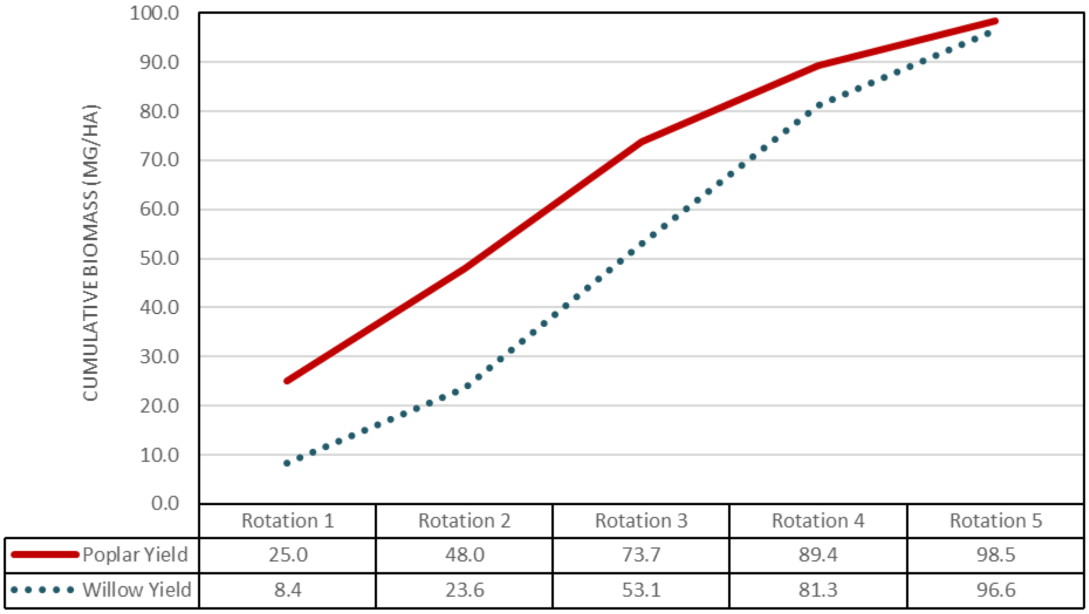
| Table 8. Correlations among stool traits of all 12 willow and 2 poplar varieties measured throughout the life of the trial and cumulative biomass yield at age 15. | | | | |
|---|---|---|---|---|
| ***Stool Trait*** | ***Rotation*** | ***Pearson Correlation [r]*** | ***Significance (2 tailed)*** | ***Comments*** |
| Stool survival | 1 | 0.113 | NS | |
| | 2 | 0.348 | NS | |
| | 3 | 0.137 | NS | |
| | 4 | 0.57 | 0.033 | Mortality increased dramatically for S301, S25, and S287 leading to dramatic loss of yield. |
| | 5 | 0.642 | 0.013 | |
| Stems per Stool | 1 | -0.087 | NS | |
| | 2 | -0.074 | NS | |
| | 3 | -0.083 | NS | |
| | 4 | 0.128 | NS | |
| | 5 | -0.339 | NS | |
| Stool Diameter | 1 | --- | --- | Not measured at the end of Rotation 1. |
| | 2 | -0.161 | NS | |
| | 3 | -0.169 | NS | |
| | 4 | 0.365 | NS | |
| | 5 | 0.092 | NS | |
| Stool Height | 1 | 0.775 | 0.001 | Height is routinely and strongly correlated with cumulative biomass production. |
| | 2 | 0.739 | 0.003 | |
| | 3 | 0.938 | 0.000 | |
| | 4 | 0.935 | 0.000 | |
| | 5 | 0.836 | 0.001 | |

**Table 9. Pearson Correlations among measured traits of the top 6 willow varieties over 15 years (5, 3-year rotations).**

***(Highlighted correlations are significant at $\alpha$ > 0.05)***

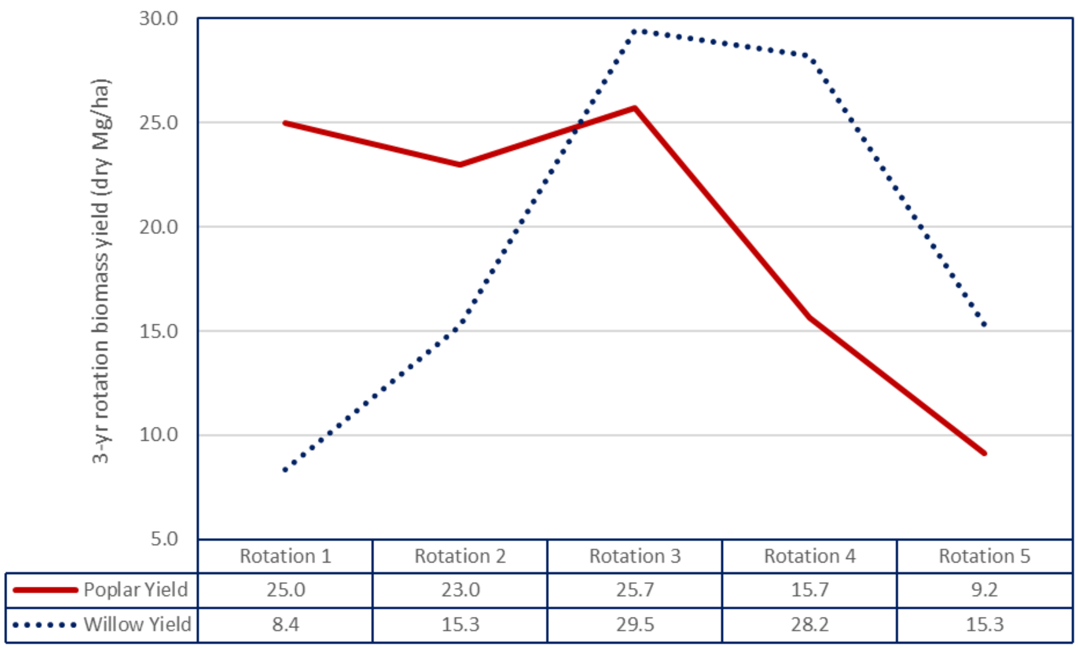
| Factor | Rotation | Stool Survival | | | | | Stems per Stool | | | | | Stool Diameter | | | | Stool Height | | | | | Plot Biomass | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 1 | 2 | 3 | 4 | 5 | 2 | 3 | 4 | 5 | 1 | 2 | 3 | 4 | 5 | 1 | 2 | 3 | 4 | 5 | Total Biomass |
| Stool Survival | 1 | 1 | .627** | .521** | .434* | .545** | -0.185 | -0.022 | -0.009 | -0.112 | -0.093 | -0.263 | -0.335 | -.383* | -.521** | -0.120 | -0.120 | -0.213 | -0.276 | -0.351 | -0.019 | -0.209 | -0.247 | -0.223 | -0.275 | -0.270 |
| | 2 | .627** | 1 | .892** | .863** | .895** | -0.134 | -0.170 | -0.119 | -0.122 | -0.083 | -0.341 | -.502** | -.495** | -.532** | -0.021 | 0.217 | 0.101 | -0.040 | -0.052 | 0.210 | 0.309 | 0.162 | 0.177 | 0.087 | 0.238 |
| | 3 | .521** | .892** | 1 | .965** | .927** | -0.105 | -0.012 | -0.082 | -0.100 | -0.035 | -0.199 | -.521** | -.543** | -.451* | -0.051 | 0.027 | 0.034 | -0.140 | 0.104 | 0.179 | 0.346 | 0.229 | 0.098 | 0.127 | 0.251 |
| | 4 | .434* | .863** | .965** | 1 | .953** | -0.014 | -0.044 | -0.051 | -0.077 | 0.002 | -0.182 | -.449* | -.475** | -.375* | -0.088 | 0.097 | 0.038 | -0.090 | 0.163 | 0.188 | .364* | 0.265 | 0.176 | 0.204 | 0.311 |
| | 5 | .545** | .895** | .927** | .953** | 1 | -0.056 | -0.017 | 0.018 | -0.069 | 0.013 | -0.143 | -.373* | -.417* | -.402* | -0.145 | 0.097 | -0.014 | -0.129 | 0.082 | 0.173 | 0.296 | 0.156 | 0.137 | 0.210 | 0.245 |
| Stems per Stool | 1 | -0.185 | -0.134 | -0.105 | -0.014 | -0.056 | 1 | 0.121 | 0.053 | 0.115 | 0.067 | 0.192 | 0.026 | 0.114 | .458* | 0.200 | 0.172 | 0.234 | 0.251 | 0.267 | .367* | 0.206 | 0.316 | 0.343 | 0.157 | .362* |
| | 2 | -0.022 | -0.170 | -0.012 | -0.044 | -0.017 | 0.121 | 1 | .596** | 0.206 | 0.188 | .662** | 0.332 | 0.107 | 0.174 | -0.100 | -0.004 | 0.090 | -0.151 | 0.332 | 0.162 | 0.232 | 0.314 | 0.115 | 0.065 | 0.240 |
| | 3 | -0.009 | -0.119 | -0.082 | -0.051 | 0.018 | 0.053 | .596** | 1 | .735** | .702** | 0.090 | .415* | 0.209 | 0.313 | -.503** | -0.018 | -0.191 | -0.193 | .426* | -0.123 | -0.059 | -0.018 | 0.169 | 0.304 | 0.083 |
| | 4 | -0.112 | -0.122 | -0.100 | -0.077 | -0.069 | 0.115 | 0.206 | .735** | 1 | .876** | -0.149 | .416* | .389* | 0.330 | -.692** | -0.237 | -.387* | -0.337 | .530** | -.417* | -0.206 | -0.062 | 0.220 | 0.334 | 0.002 |
| | 5 | -0.093 | -0.083 | -0.035 | 0.002 | 0.013 | 0.067 | 0.188 | .702** | .876** | 1 | -0.132 | .381* | 0.292 | .374* | -.638** | -0.220 | -.380* | -0.252 | .581** | -.384* | -0.266 | -0.095 | 0.124 | 0.347 | -0.041 |
| Stool Diameter | 2 | -0.263 | -0.341 | -0.199 | -0.182 | -0.143 | 0.192 | .662** | 0.090 | -0.149 | -0.132 | 1 | .518** | 0.358 | 0.293 | 0.138 | 0.064 | 0.247 | 0.136 | 0.263 | 0.152 | 0.348 | .464** | 0.218 | 0.059 | 0.345 |
| | 3 | -0.335 | -.502** | -.521** | -.449* | -.373* | 0.026 | 0.332 | .415* | .416* | .381* | .518** | 1 | .820** | .473** | -.420* | 0.082 | -0.215 | -0.117 | 0.251 | -.378* | -0.171 | 0.099 | 0.228 | 0.222 | 0.047 |
| | 4 | -.383* | -.495** | -.543** | -.475** | -.417* | 0.114 | 0.107 | 0.209 | .389* | 0.292 | 0.358 | .820** | 1 | .496** | -0.218 | 0.050 | -0.031 | 0.031 | 0.257 | -0.270 | -0.105 | 0.100 | .363* | 0.262 | 0.131 |
| | 5 | -.521** | -.532** | -.451* | -.375* | -.402* | .458* | 0.174 | 0.313 | 0.330 | .374* | 0.293 | .473** | .496** | 1 | -0.021 | 0.066 | 0.223 | 0.342 | .518** | 0.150 | 0.035 | 0.275 | .376* | .502** | .366* |
| Stool Height | 1 | -0.120 | -0.021 | -0.051 | -0.088 | -0.145 | 0.200 | -0.100 | -.503** | -.692** | -.638** | 0.138 | -.420* | -0.218 | -0.021 | 1 | 0.295 | .732** | .659** | -0.141 | .763** | .530** | 0.292 | 0.160 | -0.044 | .398* |
| | 2 | -0.120 | 0.217 | 0.027 | 0.097 | 0.097 | 0.172 | -0.004 | -0.018 | -0.237 | -0.220 | 0.064 | 0.082 | 0.050 | 0.066 | 0.295 | 1 | .494** | .597** | -0.084 | .432* | .453* | .562** | .587** | 0.052 | .559** |
| | 3 | -0.213 | 0.101 | 0.034 | 0.038 | -0.014 | 0.234 | 0.090 | -0.191 | -.387* | -.380* | 0.247 | -0.215 | -0.031 | 0.223 | .732** | .494** | 1 | .764** | 0.201 | .798** | .761** | .584** | .583** | 0.152 | .728** |
| | 4 | -0.276 | -0.040 | -0.140 | -0.090 | -0.129 | 0.251 | -0.151 | -0.193 | -0.337 | -0.252 | 0.136 | -0.117 | 0.031 | 0.342 | .659** | .597** | .764** | 1 | 0.143 | .647** | .608** | .429* | .534** | 0.098 | .585** |
| | 5 | -0.351 | -0.052 | 0.104 | 0.163 | 0.082 | 0.267 | 0.332 | .426* | .530** | .581** | 0.263 | 0.251 | 0.257 | .518** | -0.141 | -0.084 | 0.201 | 0.143 | 1 | 0.113 | .365* | .453* | .510** | .547** | .545** |
| Plot Biomass | 1 | -0.019 | 0.210 | 0.179 | 0.188 | 0.173 | .367* | 0.162 | -0.123 | -.417* | -.384* | 0.152 | -.378* | -0.270 | 0.150 | .763** | .432* | .798** | .647** | 0.113 | 1 | .689** | .416* | .388* | 0.215 | .652** |
| | 2 | -0.209 | 0.309 | 0.346 | .364* | 0.296 | 0.206 | 0.232 | -0.059 | -0.206 | -0.266 | 0.348 | -0.171 | -0.105 | 0.035 | .530** | .453* | .761** | .608** | .365* | .689** | 1 | .689** | .635** | 0.229 | .832** |
| | 3 | -0.247 | 0.162 | 0.229 | 0.265 | 0.156 | 0.316 | 0.314 | -0.018 | -0.062 | -0.095 | .464** | 0.099 | 0.100 | 0.275 | 0.292 | .562** | .584** | .429* | .453* | .416* | .689** | 1 | .734** | 0.343 | .876** |
| | 4 | -0.223 | 0.177 | 0.098 | 0.176 | 0.137 | 0.343 | 0.115 | 0.169 | 0.220 | 0.124 | 0.218 | 0.228 | .363* | .376* | 0.160 | .587** | .583** | .534** | .510** | .388* | .635** | .734** | 1 | .366* | .849** |
| | 5 | -0.275 | 0.087 | 0.127 | 0.204 | 0.210 | 0.157 | 0.065 | 0.304 | 0.334 | 0.347 | 0.059 | 0.222 | 0.262 | .502** | -0.044 | 0.052 | 0.152 | 0.098 | .547** | 0.215 | 0.229 | 0.343 | .366* | 1 | .569** |
| Total Biomass | | -0.270 | 0.238 | 0.251 | 0.311 | 0.245 | .362* | 0.240 | 0.083 | 0.002 | -0.041 | 0.345 | 0.047 | 0.131 | .366* | .398* | .559** | .728** | .585** | .545** | .652** | .832** | .876** | .849** | .569** | 1 |
| Factor | Rotation | 1 | 2 | 3 | 4 | 5 | 1 | 2 | 3 | 4 | 5 | 2 | 3 | 4 | 5 | 1 | 2 | 3 | 4 | 5 | 1 | 2 | 3 | 4 | 5 | Total Biomass |
| | | Stool Survival | | | | | Stems per Stool | | | | | Stool Diameter | | | | Stool Height | | | | | Plot Biomass | | | | | |

**Figure 1. Cumulative biomass production of top 2 poplar and top 2 willow varieties over five 3-year rotations.**




| | Rotation 1 | Rotation 2 | Rotation 3 | Rotation 4 | Rotation 5 |
|---|---|---|---|---|---|
| Poplar Yield | 25.0 | 48.0 | 73.7 | 89.4 | 98.5 |
| Willow Yield | 8.4 | 23.6 | 53.1 | 81.3 | 96.6 |

Figure 2. Incremental biomass production during each of five 3-year rotations of the top 2 poplar and top 2 willow varieties.




| | Rotation 1 | Rotation 2 | Rotation 3 | Rotation 4 | Rotation 5 |
|---|---|---|---|---|---|
| Poplar Yield | 25.0 | 23.0 | 25.7 | 15.7 | 9.2 |
| Willow Yield | 8.4 | 15.3 | 29.5 | 28.2 | 15.3 |

**Figure 3.** Scatter plot of fifth rotation biomass vs. stem height of the six best willow varieties
(with Regression Line and Predictor Equation)