FINAL REPORT:

REGIONAL FEEDSTOCK PARTNERSHIP – POPLAR IN MICHIGAN

Project Title:

POPLAR

Biomass crop feedstock development plan for 2012 for the Northeast and Midwest U.S.

Project Period:

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The Hybrid Poplar Biomass Trial Network in Michigan

Poplar research trials were located throughout Michigan in a network of six planting sites that span both peninsulas (Table 1 and Figure 1). The East Lansing location mentioned is the site of Michigan State University's main campus. Three trial sites are permanent research centers owned by Michigan State University and the other three were leased from others. Field equipment and staff were located at both the Escanaba and East Lansing locations. Naturally, more attention can be given to test plantations located nearest 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.

Site conditions varied considerably among these test locations. Soil conditions are summarized in Table 2 where for example, pH is reported to range from 5.3 at Brimley to 7.4 at Onaway. Soil texture and drainage also varies considerably among sites. Climatic conditions at each site were monitored by on-site weather stations and also vary among sites. The growing season at Albion averages 38 days longer than at Skandia, for example. Table 3 is constructed to allow a comparison of site temperatures (by way of growing degree days) and moisture availability (by way of rainfall) during three distinct portions of each growing season. At some sites, less than 1/3 of the annual rainfall occurs during the portion of the year when air temperatures are most conducive for poplar growth. This effects 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).

There have been three types of poplar trials established in Michigan (Table 4) including; a) seven "Variety" trials, b) one "Spacing" trial, and c) eight "Yield" trials. All stock used in these trials was derived from clonal copies of poplar hybrids obtained from stem cuttings.

A. **Variety Screening Trials:** Three sets of hybrid varieties developed at the University of Minnesota's Natural Resources Research Institute (NRRI) were tested in these trials. The first set was established at the Escanaba site in 2008. A second set was established in the six-site network during 2009 and 2010. A third set was established in Escanaba in 2012. These trials employ blocks of single-tree plots and consequently can only be used for comparative growth analysis, and not for making areal biomass yield estimates.

B. **Spacing Trial:** A test of seven poplar varieties was installed at the Escanaba site in 2008 and harvested in 2014. Each variety was tested at three planting densities.

C. **Yield Trials:** A set of legacy poplar varieties were established throughout the six-site test network in Michigan between 2009 and 2011. Sets of newer NRRI varieties were also established in 2010 and 2012 at the Escanaba site alone. These trials employ large plots and produce sufficient information to establish reasonable areal biomass yield estimates.

All of these trials were established on old-field sites using a similar protocol. Planting sites[1] were prepared by first mowing and spraying with glyphosate (2 quarts per acre) to kill existing vegetation. Sites were subsequently plowed and cultivated to achieve conditions similar to those needed for the establishment of row crops. Planting stock for all the variety screening trials and for the 2010 yield trial was obtained from NRRI. Planting stock for the 2012 variety screening trial was 10" dormant hardwood cuttings. All other planting stock was rooted, actively growing, containerized "mini-cuttings" (4 inch) and were representatives of recently selected hybrids from the Minnesota poplar improvement program. Planting stock for the 2008 spacing trial and for the yield trials was obtained from a variety of sources (Table 5) based on stock requirements and stock availability. This material was obtained as ten-inch-long dormant hardwood cuttings. Stock was always planted in the early spring into the prepared sites. Planting was immediately followed by the application of post-emergence herbicides (imazaquin at 5.6 oz per acre and pendimethalin at 3 quarts per acre). To avoid injury to sensitive tissue, no herbicides were applied to the actively growing stock used in the variety screening trials. Consequently, weed control was much more difficult in this set of trials (Table 4).

Weed control was maintained in these plantings using a combination of herbicides and mechanical cultivation during the first two or three years – until the trees cast enough shade to control weeds on their own. Deer exclosure fencing was erected around the sites that did not already have some type of protection. A continuously recording weather station was installed at each planting site. All the plantings at the Escanaba site shared a single recording weather station.

Tree survival was monitored at all sites during the first year, annual height measurement began in the second year, and annual DBH measurements began in the third year for each test. Rust and canker scoring was conducted as needed throughout the project on all plantations. Only the interior trees of multiple-tree plots were measured, leaving a 2-row border around the plot to avoid edge-effects. Soil samples were collected from all planting sites in 2012. These samples were analyzed by Agro-One Soil Analysis of Ithaca, NY. Results are summarized in Table 2.

A. Poplar Variety Screening Trials

Varieties formed by hybridizing individuals from within the genus *Populus* have been shown to hold the best promise for high-yielding, adaptable planting stock for short rotation energy plantations. Certain varieties have difficulty adapting to extreme climates and resisting pest pressures, so many must be tested to find the few with the most promise. Poplar varieties also exhibit strong genotype by environment interaction, meaning that a variety that does well in one place may not do well in another. Small-plot variety screening trials are conducted to compare a large number of full-sib families or taxa prior to more intensive testing of individuals selected from these trials in large-plot yield trials.

Variety screening trials at all sites (Table 4) were composed of replicated blocks of single-ramet plots. The 2008 Escanaba variety screening trial contained six blocks of ramets of 56 siblings representing 17 full-sib families planted at 1,089 trees/acre (8'x 5' spacing). The 2009 Skandia

[1] The plantings at the Brimley site were not sprayed with glyphosate because of extreme wet ground conditions, delays in obtaining the lease documents, and operational constraints.

and the 2009 Escanaba variety screening trials formed a pair and contained six blocks of ramets of 70 siblings representing 14 full-sib families planted at 778 trees/acre (8'x 7' spacing). The 2012 Escanaba trial contained six blocks of ramets of 41 siblings representing 17 full-sib families planted at 908 trees/acre (8' x 6' spacing). Trees planted in all these trials were received from NRRI in Minnesota as small, actively growing, containerized stecklings. We had poor experience with this type of stock. They were fragile, sensitive, and could not be treated with the herbicides normally used in other plantations and required extra attention early in the rotation. This meant that trials at sites other than the permanently-staffed site in Escanaba suffered from strong weed competition. The variety screening trials at Brimley, Onaway, and Lake City were abandoned because of excessive mortality. The trial in Skandia had fairly poor survival (64%) but was included here because it provided the only opportunity to estimate variety X site interactions. The 2012 Escanaba trial was still too young to produce meaningful information and is not included in this analysis.

Heights and diameters were measured annually after the third growing season in each of these trials. Broad-sense heritability for height and diameter was calculated annually for the 2008 Escanaba trial and for the 2009 Skandia and Escanaba trial pair (Table 6). In general, these estimates increased steadily as the plantations aged. By age seven, heritability of diameter (which is a good surrogate parameter for tree biomass) was high (48%) in the 2008 Escanaba trial and lower (26% - 28%) in the pair of 2009 trials. This indicates that a significant portion of height and diameter differences observed among varieties are under genetic control and can be passed to subsequent generations. Analysis of variance in seventh-year heights and diameters in the pair of trials established in 2009 revealed that 68% of the total variance was due to the difference between the sites. 4% of the variation was due to family effects and another 4% family by site interactions. The remaining 24% of the variation was due to ramet-within-family differences.

Scoring of diseases (leaf rusts *Melampsora* spp. and *Marssonina brunnea* along with leaf spotting by *Septoria musiv*a) was conducted each year in these variety screening trials. Very little *Melampsora* was observed. Significant negative correlations were observed in the 2008 Escanaba trial between tree height and diameter growth and both *Septoria* and *Marssonina* leaf diseases in the sixth year. Many of the varieties in that trial were susceptible to both diseases (Table 7). This is what might be expected, however the same pattern was much more difficult to observe in the pair of trials established in 2009 at Escanaba and Skandia. Leaf diseases occurred irregularly in time and space and this may have contributed to the difficulty we had discerning patterns in these data. It was not possible to identify individual varieties that consistently resisted these leaf diseases although many varieties performed consistently poorly. Far more work remains to be done to understand and control poplar's susceptibility to this mixture of diseases.

B. Poplar Spacing Trial

Financial returns from short rotation energy plantations are a function of the input and maintenance costs and the yield produced over a fixed rotation. Densely planted stands may produce biomass more quickly than sparsely planted stands, but they are more expensive to establish. The relationship between planting density and rotation length on biomass yield and production costs must be understood in order for growers to make appropriate management decisions. These relationships are established in spacing trials.

A spacing study of seven poplar varieties was established in Escanaba in 2008. Previous work with poplar suggested that short rotation biomass plantings may be most successful when planted at densities between 1,200 and 500 stems per acre. Each of the seven poplar varieties in this trial were established in tenth-acre plots at three, operationally convenient densities within this range: 1,089, 908, and 778 trees per acre. Tree rows were separated by 8' to accommodate equipment and spacing of trees within the rows was varied (5', 6', and 7' respectively) to achieve the desired planting density. The number of trees in each plot varied among the three spacing treatments (96, 88, and 80 trees respectively) and only the interior trees of each plot (32, 28, and 24 trees respectively) were measured to avoid edge effects. Each variety/density combination was replicated four times.

Heights, diameters, and tree conditions were monitored and scored annually throughout the test. All trees were harvested and chipped after the seventh growing season (in the fall of 2014). The green weights of chips produced in each sample plot was recorded. A representative sub-sample of these chips was oven-dried to determine moisture content and this was used to establish the dry biomass weight of each sample plot. These weights were subsequently used to determine biomass yields on an areal basis.

Concurrently with the harvesting of the spacing trial, a set of 72 individual trees from the full range of diameters in the plantation were selected, weighed, moisture content determined, and dry weight calculated. These data were combined with similar data collected from 159 trees in an earlier poplar yield trial in Escanaba. The combined dataset was used to develop regression "Equation 1", to predict individual stool biomass weight. All measured tree parameters were examined as predictor variables. While correlations of standing tree height and diameter decreased with age, plot basal area was consistently and increasingly correlated with final harvest plot weight (Table 8). Basal area was also found to produce the best-fit predictor equation of stool biomass (Equation 1). Note that while the R^2 associated with this regression is high, the root mean square error of this predictor is relatively poor. Although this introduces uncertainty in any prediction made, the error inherent in this equation is less than that observed in other poplar biomass predictor equations reviewed for this project. When actual biomass weights were not available, this predictor equation was used to estimate standing-tree stool biomass throughout all our poplar trials. Biomass of stools with multiple stems was computed by summing the basal areas of those stems and then applying Equation 1 to the resulting total.

Equation 1:

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

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

No statistical difference in harvested biomass was found among the three planting density treatments tested here (Table 9). This suggests that planting more than 778 trees per acre is not necessary to obtain the biomass yields observed here over seven growing seasons. Planting more trees than this will increase establishment costs but not increase yields. Given the time-value of money, this would simply represent a loss to a commercial grower.

Actual harvested biomass of these seven poplar varieties segregated into four statistically distinct growth groups (Table 9). Variety “I4551” was in a group by itself and preformed so poorly, that it is ignored in the following discussion. The remaining three groups included: A fast grower (NM6 produced about 30 dry tons per acre), intermediate growers (NM2, and DN5 averaged about 21 dry tons per acre), and slow growers (DN34, NE222, and D105 averaged about 14 dry tons per acre).

The trajectory of biomass accumulation among these three groups was estimated using tree parameters measured over the course of the trial and Equation 1. Although the predicted biomass differed from actual biomass by up to 15% due to the error inherent in the predictor equation discussed above, the trends identified are instructive. Figures 2, 3, and 4 depict these values for one representative variety of each growth type.

Biological rotation age can be determined by establishing the point at which the Mean Annual Increment of a stand equals its Periodic Annual Increment. The fast growing NM6 achieved this point in the sixth year of growth. If these trees had been harvested at that time, it is estimated that they would have produced approximately 24 dry tons of biomass per acre. The intermediate growing DN5 and the slow growing DN105 did not appear to reach rotation age until after the seventh growing season. Even their actual biomass yields (19 and 13.6 dry tons per acre respectively from Table 9) are less than the predicted yield of NM6 at age 6. Fast growing varieties on short rotations produce more biomass in less time than slower growers on longer rotations. This benefits growers by both shortening the time over which initial investments must be carried and increasing biomass yield.

C. Poplar Yield Trials

Six Site Yield Trial Network: Once poplar varieties have shown early promise, they need to be tested in larger-plot trials to better document their performance over time. This testing needs to be done under conditions that are similar to those that commercial growers will experience. A network of six locations in Michigan, three in the Upper Peninsula and three in the Lower Peninsula was established for variety yield trial testing. These trials were established over a three-year period (Table 4) to accommodate limitations of labor and planting stock availability. Fifteen poplar varieties were selected based on their performance in variety screening trials conducted years ago in the Lake States region and on their availability. These “legacy” varieties were placed in stool beds at Michigan State University’s Tree Improvement Center in East Lansing, MI in order to produce sufficient cuttings for the yield trials. Ten-inch dormant hardwood cuttings were prepared from these stool beds and were planted in replicated yield block trials between 2009 and 2011. All of these yield trials comprised five blocks containing 64-tree plots of these varieties planted at a density of 778 trees/acre (8’x7’). The yield trials in Brimley and Onaway suffered high mortality due to weed competition and draught and were discontinued in 2014. The remaining trials are still active.

Stem diameters at breast height (4.5’ above the ground) were measured within the 16-stool measurement plots each year beginning in the fourth growing season. Biomass accumulation was estimated using Equation 1. It was possible to compare the biomass growth of all six sites after five growing seasons (Table 10). Biomass accumulation of the best poplar variety at each site varied widely (from 3.8 to 17.9 dry tons/acre). The best varieties at only three of the six test sites produced more than 3 dry tons/acre-year of biomass; which is probably the lower limit for commercial viability. In general, poplar appeared to grow poorly when site pH was extreme (5.3 at Brimley or 7.4 at Onaway) and when there were fewer than about 2,000 Growing Degree Days available each year. *Populus nigra* X *maximowiczii* hybrids excelled in productivity at all sites, while P. deltoides X nigra hybrids produced mixed results; sometimes doing well and sometimes doing poorly. Genotype by environment interaction was strongly evident in these tests. “I4551”, for example produced 110% as much biomass as the universal check variety (NM6) at the Albion site, but only 28% as much at the Skandia site.

Mean Annual Biomass Increment (MAI) increased from year 5 onward at all sites. This would suggest that rotation ages in excess of 7 years are advisable for poplar grown under these conditions. The proportional increase in MAI varied widely both among test sites and among varieties but increased an average of 29% across the entire network between years 5 and 6 (Table 11). MAI of NM5 increased only 2% between years 5 and 6 at the Escanaba site but increased 59% during the same interval at the Skandia site. Compared to the meager MAI increase of NM5 at Escanaba, DN164 was able to achieve an increase of 34%. This suggests that the performance of a particular variety cannot be accurately predicted by observing a different variety or by observing that same variety at a remote test site. The variation in poplar varietal performance documented here reinforces the need for variety-specific, long-term, multi-site testing programs to develop the guidelines needed for successful commercialization of these biomass crops.

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

Nine varieties were sufficiently represented at all six test sites (Table 12) to be used in an analysis of varience in fifth-year biomass production (Table 13). The majority (50%) of the variability was due to site effects. This reinforces the need to test varieties at many locations in order to accurately predict yields. Variety differences accounted for 9% of the variation but 14% of the variation was due to genotype by environment interactions. This means that varietal choice is very important but that relative varietal performance will change dramatically among sites. Even though all the trees in this trial were clonally propagated, 27% of the total variation was due to tree-to-tree differences within the sample plots. This variation creates challenges when managing and harvesting these crops, and can reduce feedstock quality.

The Escanaba site was the oldest of the trial sites containing most of the poplar varieties. An analysis of variance in seventh-year biomass production was conducted for all 14 poplar varieties at this site (Table 14). In this case, 23% of the variation was due to varietal effects. Single-site tests routinely overestimate varietal effects because they include variety X site interactions. A small amount (3%) of variation was attributed to block effects but varietal ranking changes within the blocks caused an interaction, accounting for 9% of the total. The largest portion of the total variation (65%) arose from tree-within-plot differences, suggesting once again that understanding and controlling this variation will be of paramount importance in the future.

The analysis of variance points to the importance of choosing appropriate varieties but that the relative performance of these varieties will change from one site to another. Only local tests will produce reliable recommendations for commercial growers. More strikingly, the variation of clonally-propagated trees within individual sample plots is greater than any other source of variance. The reasons that these genetically identical individuals grow so differently are poorly understood. There may be differences in cutting health, nutrient reserves, number of viable buds, or micro-site impacts on tree development at play. In any event, future research should concentrate on understanding and controlling this extreme source of variation. Uniformity of performance will be beneficial to crop managers, simplify harvesting logistics, and improve feedstock quality.

<u>Single-site Yield Trials of Newer Poplar Varieties:</u> New poplar varieties became available from the NRRI breeding program during the course of this project. Yield trials of these materials were added in 2010 and 2012 at the Escanaba location. The 2010 trial comprised four blocks containing 64-tree plots of 10 varieties planted at 778 trees/acre (8’x7’ spacing). The 2012 trial comprised three blocks containing 100-tree plots of 11 varieties planted at 1,556 trees/acre (7’x4’ spacing). Neither of these trials are mature, but an analysis of growth through the fall of 2015 was conducted.

Biomass accumulation of the 10 poplar varieties after six years in the 2010 yield trial in Escanaba are summarized in Table 15. Four “legacy” along with six new NRRI varieties were included in this test. Statistical differences existed among the varieties, but none were producing more biomass than the “NM6” check variety. Two “legacy” varieties and one NRRI variety survived and grew poorly in this test while the rest were not significantly different from one another. The younger, 11 variety yield trial planted in 2012 in Escanaba (Table 16) provides some interesting contrasts with the 2010 trial. Total biomass production after four years in this trial is equivalent to or greater than that produced in the 2010 trial after six years. It should be noted, however, that the planting density of the 2012 plantation was twice that of the 2010 plantation so there were twice as many trees per acre producing biomass. Also, the planting stock used in 2010 were actively growing stecklings (which had been difficult to establish in other trials) while the stock used in the 2012 plantation were standard, reliable dormant hardwood cuttings.

Again there were statistical differences among the varieties. Although the average biomass productivity of three of the newer NRRI varieties exceeded NM6 by 5% to 11%, these differences were not statistically significant. There were three NRRI varieties included in both the 2010 and 2012 trials. The performance of 9732-31 and 99038003, relative to NM6, was similar in both cases. The performance of 9732-19, relative to NM6, was better in the 2010 trial than in the 2012 trial.

Although none of the new NRRI varieties produced significantly more biomass than the NM6 check variety, it is important to note that there were some that were equivalent. NM6 is one of the legacy varieties that routinely outperforms others (Table 10), in terms of early biomass accumulation, throughout the Lake States region. However, it has trouble with the endemic pathogens of the region (*e.g. Septoria*, *Melampsora*, and *Marssonina*), and consequently suffers from damage and premature death in energy plantations. Its performance also tends to be strongly dependent on site quality (Table 10). Identifying varieties that grow at least as well as NM6 but that are more robust is a consequential outcome of these tests.

Reporting

The analysis of these data has been summarized in several presentations, made to professional organizations, and is still underway:

Miller, R.O. and A.L. Doty. 2016. Auxin-producing endophyte inoculation improves early height growth of selected hybrid poplar hardwood cuttings in a Michigan field trial. Forest Biomass Innovation Center Research Report 2016(g). http://agbioresearch.msu.edu/centers/fbic/fbic_reports_and_resources . Also presented as a poster at the 11th Biennial Short Rotation Woody Crops Operations Working Group Conference, Fort Pierce, Florida, USA, October 11-13, 2016.

Miller, R.O., B.A. Bender, P.N. Irving, and K.T. Zuidema. 2016. Common short rotation poplar growth patterns observed in ten trials over 18 years in Michigan, USA. Forest Biomass Innovation Center Research Report 2016(e). http://agbioresearch.msu.edu/centers/fbic/fbic_reports_and_resources . Also presented at the 25th International Poplar Symposium, Berlin, Germany, September 13-16, 2016.

Miller, R.O. and B.A. Bender. 2016. Sources of variation in hybrid poplar biomass production throughout Michigan, USA. Forest Biomass Innovation Center Research Report 2016(d). http://agbioresearch.msu.edu/centers/fbic/fbic_reports_and_resources . Also presented at the 25th International Poplar Symposium, Berlin, Germany, September 13-16, 2016.

Miller, R.O. and B.A. Bender. 2016. Planting density effects on biomass growth of hybrid poplar varieties in Michigan. Forest Biomass Innovation Center Research Report 2016(c). http://agbioresearch.msu.edu/centers/fbic/fbic_reports_and_resources

Miller, R.O. 2016. Financial modeling of short rotation poplar plantations in Michigan, USA. Forest Biomass Innovation Center Research Report 2016(b). http://agbioresearch.msu.edu/centers/fbic/fbic_reports_and_resources

Miller, R.O. 2016. Developing an algorithm to predict single tree biomass weight from stem diameter measurements in young hybrid poplar energy plantations in Michigan. Forest Biomass Innovation Center Research Report 2016(a). http://agbioresearch.msu.edu/centers/fbic/fbic_reports_and_resources

Miller, R.O. and B.A. Bender. 2014. Planting density effects on biomass growth of hybrid poplar clones in Michigan: A sixth-year update. IN Proceedings. 10th Biennial Conference of the Short Rotation Woody Crop Operations Working Group, Seattle, Washington, USA, July 17-19, 2014.

Townsend, P.A., S.P. Kar, and R.O. Miller. 2014. Poplar (Populus spp.) trees for biofuel production. University of Washington Cooperative Extension eXtension Bulletin, May 06, 2014. http://www.extension.org/pages/70456/poplar-populus-spp-trees-for-biofuel-production#.VFOrWGeTdrw

Headlee, W.L., R.S. Zalesny, Jr., R.B. Hall, E.O. Bauer, B.A. Bender, B.A. Birr, R.O. Miller, J.A. Randall, and A.H. Wiese 2013. Specific gravity of hybrid poplars in the North-Central region, USA: Within-tree variability and site X genotype effects. Forests 2013(4) 251-269.

Miller, R.O., D. Keathley, and P. Bloese. 2012. Early Results from Populus and Salix Clonal Yield Trials At Six Locations in Michigan, USA. A poster presented at the 24th session of the International Poplar Commission. October 30 – November 2, 2012, Dehradun, India.

Miller, R.O. and B.A. Bender 2012. Short rotation energy plantation density effects on yield and return on investment in a five-year-old hybrid poplar trial in Michigan. IN PRESS. Presented at the Sun Grant Initiative 2012 National Conference, New Orleans, LA, October 2, 2012.

Berguson, W.E. et. al. 2012. The Sungrant poplar woody crops research program: Accomplishments and implications. IN PRESS. Presented at the Sun Grant Initiative 2012 National Conference, New Orleans, LA, October 2, 2012.

Bloese, P., R. Miller, and D. Keathley. 2012. Identifying superior poplar clones for the production of biofuel in Michigan: 2-year results. IN proceedings of Short Rotation Woody Crops Operations Working Group meeting, Knoxville, TN, November 5, 2012.

Miller, R.O. and B.A. Bender. 2011. Spacing Effects on Stand Development and Tree Growth of Seven Hybrid Poplar Clones After Four Years in a Replicated Trial in Escanaba, Michigan. IN: Poplars & Willows on the Prairies, Joint Conference of the Poplar Council of Canada, the International Poplar Commission, and the Poplar Council of the United States. Edmonton, Alberta, Canada. September 18, 2011.

Miller, R.O., D.W. MacFarlane, D.E. Rothstein, and Z. Wang. 2010. Energy crop plantation system development for Salix and Populus in Michigan, USA. IN: Poplars and willows: from research models to multipurpose trees for a bio-based society. Proceedings of the Fifth International Poplar Symposium, Orvieto, Italy, September 20-25, 2010.

Closing Observations

Growers ask three simple questions: 1) "What should I plant?" 2) "How should I manage it?" and 3) "Will I make money if I do that?" The short answer is; "It depends." That is not very satisfying, but true. In reviewing the plot yield data reported here, it becomes obvious that yield depends on many factors including:

1. Variety selection. Choosing appropriate genotypes for specific sites is critical and can account for six-fold differences in yield. Abundant evidence exists to show strong genotype X environment interaction, meaning that there will never be one best variety or set of varieties for universal use. Observations of varietal resistance to pests has not been presented here but is substantial. As new varieties are produced and commercialized, these yield projections will change substantially, so an expressed yield of 3 dry tons/acre-year of a tired-old variety can easily be surpassed by those being produced today.

2. Site fertility and soil moisture availability. Nearly all of our trials are un-fertilized and un-irrigated but they have been placed on sites with substantially different fertility and moisture regimes. Fertilizer trials of poplar have only recently begun in Michigan. It is expected that fertility and water management can be employed to increase yields, but the impact of these management systems on feedstock production Life Cycle Analysis remains undocumented.

3. Spatial and annual climatic variation. As previously mentioned, the length and conditions within the growing season can account for more than 3-fold difference in growth from one place to another. Annual climatic anomalies can produce equally impressive differences from one growing season to the next. A spectacular growing season during 3rd year (2010) in Escanaba caused trees in the 2008 Poplar Spacing Study to double in size in just one year. However, the adjacent 2009 Poplar Yield Study did not respond in the same way. The latter study trees were a year younger and apparently not physiologically ready to take advantage of the conditions in the 2010 growing season.

   A drought in the 2nd growing season at the Albion site (2012) caused growth to nearly stop that year. That same drought caused the death of young plantations elsewhere in the network. A killing frost on one fall night following a prolonged period of warm weather at the end of the first growing season at the Brimley site caused significant dieback and caused widespread mortality at that site. These seasonal anomalies are unpredictable and uncontrollable. They have serious implications for growth and yield and can be catastrophic for vulnerable young plantations. This emphasizes the need to develop some type of risk sharing with growers that is comparable to the crop insurance program in place for agriculture commodities.

4. Stand development characteristics. Planting density, variety growth habits, and target rotation age are strongly interrelated. One combination might maximize biomass yield in the short term but be financially unfavorable to the grower. Another combination might be inexpensive to establish but never produce significant quantities of biomass. The financial analysis of this new silviculture is incomplete, but it is clear that poor management choices

and consequent loss in yield will be the easiest way for producers to lose money growing biomass.

5. Influence of damaging agents. Diseases, insects, and browsing animals express selective preference for various taxa and varieties. Damage caused by these various agents is constantly monitored in our trials and while it is not summarized in this report, the impact of these agents on yield cannot be overemphasized. There are places in our region where poplar crops are completely impractical as a result. Physical barriers to prevent animal browsing are extremely expensive to build and maintain and can ruin the financials of a production system. The only practical defense against diseases and insects is to plant mixtures of varieties that can co-exist with the pests. While some recent progress has been made, developing resistant varieties (irrespective of yield) should be the main goal of any future breeding program.

6. Weed competition. Among the damaging agents, weeds deserve to be singled-out and belabored (if not eradicated). The most common and non-variety-specific cause of yield loss in energy plantations is weeds. Controlling weeds is expensive and sometimes the most difficult aspect of plantation culture so it is frequently not given the attention it should get – even by seasoned professionals. Adequate site preparation, well in advance of plantation establishment, makes post planting weed control much easier. It is best to begin removing weeds the year prior to planting and continue with multiple chemical and mechanical treatments as needed. Past land use can determine the severity of weed competition after planting. Recently tilled agricultural fields tend to be less weedy than past pastures or meadows. Post-planting weed control during the first two growing seasons is vital to early crop establishment and development. Losses incurred due to early stress in these plantations cannot be overcome with subsequent management treatments. There is absolutely no substitute for a strong start to these plantations. Financial sensitivity analysis has revealed a strongly non-linear and negative impact of reduced yields on short rotation plantation profitability.

7. And Finally. Hybrid Poplar can be successfully grown in nearly all parts of Michigan as a biomass crop. When reasonable sites are selected, appropriate varieties are planted, and proper silviculture methods are followed growers can expect annual yields that average a little more than 4 dry tons per acre. The delivered costs of this material will be equivalent to the pulpwood being used in the region today. Advances in genetics, silviculture, and logistics can easily make improvements assuming there is sustained support for research in these areas.

TABLE 1: Poplar Biomass Trial Plantation Locations in Michigan

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

Figure 1:

Michigan State University's
Network of Poplar and Willow Test Sites

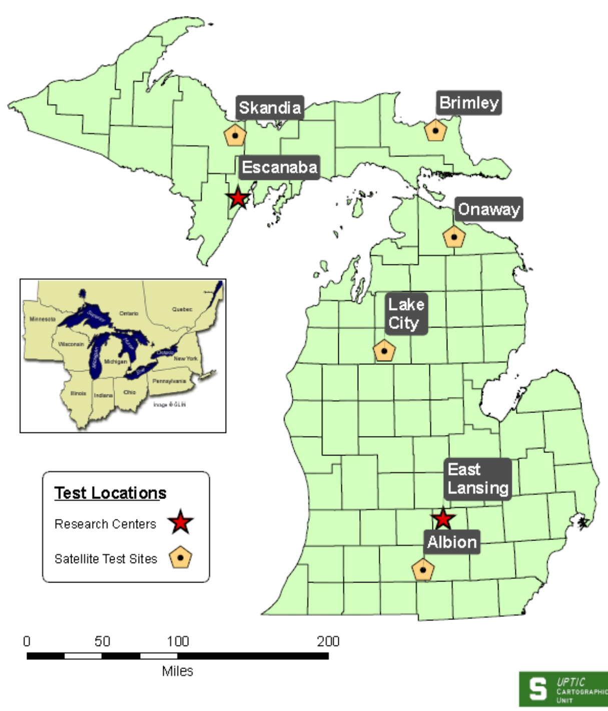

TABLE 2: Soil Conditions at the six trial sites in the Michigan network

Test Plantation	*Soil Analysis from Agro-One @ Cornell*						*NRCS Soil Survey*	
	Organic Matter (%)	*pH*	*P (lbs/ac)*	*K (lbs/ac)*	*Ca (lbs/ac)*	*Past Use*	*Soil Series*	*Drainage Class*
Albion							Hillsdale sandy loam	Well drained
2011 16-variety Poplar Yield Trial	1.8	6.39	10.2	245	1430	Corn		
Brimley							Biscuit very fine sandy loam & Rudyard silt loam	Somewhat poorly drained
2009 10-varietyPoplar Yield Trial	3.7	5.38	2.8	144	2180	Pasture		
Escanaba							Onaway fine sandy loam	Moderately well drained
2009 14-variety Poplar Yield Trial	2.8	6.82	2.0	73	3036	Corn		
2012 11-variety Poplar Yield Trial	2.2	6.70	24.0	130	3907	Potato		
Lake City							Emmet – Montcalm complex (sandy loam)	Well drained
2010 10-variety Poplar Yield Trial	2.0	6.42	3.6	86	1549	Pasture		
Onaway							Bonduel loam	Somewhat poorly drained
2010 15-variety Poplar Yield Trial	4.4	7.50	7.0	123	7937	Hay		
Skandia							Munising fine sandy loam	Moderately well drained
2009 11-variety Poplar Yield Trial	4.5	6.08	2.0	114	2573	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: Summary of biomass feedstock research trials in Michigan related to the National Feedstock Partnership Program

Type of Trial	*Planting Year*	*Location*	*Test Group*	*# varieties*	*Age at last Measurement*	*Establishment weed control*	*Status*	*Planting Density (trees/a)*
NRRI Variety Screening Trials	2008	Escanaba	a	56	8	Moderate	Active in 2016	1089
	2009	Escanaba	b	70	7	Moderate	Active in 2016	778
	2009	Skandia		70	7	Poor	Active in 2016	907
	2009	Brimley		70	4	Poor	Discontinued in 2012	1089
	2010	Onaway		70	2	Poor	Discontinued in 2011	778
	2010	Lake City		70	2	Poor	Discontinued in 2011	907
	2012	Escanaba	c	41	4	Excellent	Active in 2016	778
Legacy Variety Spacing Trial	2008	Escanaba	d	7	7	Excellent	Completed in 2014	various
Legacy Variety Yield Trial Network	2009	Escanaba	e	14	7	Excellent	Active in 2016	778
	2009	Skandia		11	7	Moderate	Active in 2016	778
	2009	Brimley		10	6	Poor	Discontinued in 2014	778
	2010	Onaway		15	5	Moderate	Discontinued in 2014	778
	2010	Lake City		10	6	Moderate	Active in 2016	778
	2011	Albion		16	5	Moderate	Active in 2016	778
NRRI variety yield trial	2010	Escanaba	f	10	6	Moderate	Active in 2016	778
	2012	Escanaba	g	11	4	Excellent	Active in 2016	1556

TABLE 5: Source of poplar cutting planting stock used in Michigan trials.

Poplar Variety Name	*Kathy Halby, MN*	*Iowa State Nursery, IA*	*Segal Ranch, WA*	*Verso Paper Nursery, MN*	*NRRI Belle River Nursery, MN*	*Lincoln Oaks, ND*	*MSU-TRC, MI*	*USFS, WI*	*Isebrands, IA*	*Hramor Nursery, MI*	*Lee's Nursery, MN*
2008 Spacing Trial											
NM2				X							
NM6	X										
D105		X									
DN34	X										
DN5						X					
NE222			X								
I4551			X								
2009 Yield Trials											
NM2							X	X	X		
NM5						X	X				
NM6										X	
DM114							X				
DN154							X	X			
DN164							X	X			
DN17						X	X				
DN182						X	X				
DN2						X	X				
DN34										X	
DN5						X	X				
DN70							X				X
NE222			X				X		X		
I4551			X								
2010 & 2011 Yield Trials											
NM2							X				
NM5							X				
NM6							X				
DM114							X				
DN154							X				
DN164							X				
DN17							X				
DN177							X		X		
DN182							X				
DN2							X				
DN34							X				
DN5							X				
DN70							X				
NE222							X				
99007116					X						
99037049					X						
99038003					X						
83XAA04							X				
9732-19					X						
9732-31					X						
2012 Yield Trial											
NM6							X				
All other varieties					X						

Table 6: Broad-Sense Heritability Estimates From 3 Poplar Variety Trials in Upper Michigan

Parameter	*Years in the Field*				
	3	*4*	*5*	*6*	*7*
2008 56-Variety Trial in Escanaba					
Height	0.19	0.27	0.27	0.27	0.32
Diameter		0.34	0.38	0.42	0.48
2009 70-Variety Trial in Escanaba					
Height	0.10	0.15	0.20	0.24	0.22
Diameter	0.13	0.17	0.23	0.24	0.26
2009 70-Variety Trial in Skandia					
Height	0.31	0.29	0.21	0.29	*
Diameter	0.15	0.21	0.22	0.28	0.28

** - Heights not measured in seventh year*

Table 7: Spearman rank correlations for mean leaf disease scores and stem growth traits after 6 growing seasons in a 2008 full-sib poplar variety trial in Escanaba. 6 clonal copies of 56 siblings from 17 full-sib families are represented.

	Septoria musiva Score	*Marssonina brunnea* Score	Stem Diameter
Marssonina brunnea Score	+0.73**		
Stem Diameter	-0.45**	-0.38**	
Stem Height	-0.34*	-0.33*	+0.88**

Correlation coefficients followed by two asterisks (**) are significant at the 99% or better level, while coefficients followed by a single asterisk (*) are significant at the 95% or better level.

TABLE 8: Correlations between tree parameters and final biomass yield of poplar hybrids after 7 years in a plantation in Escanaba, MI

Measured or Calculated Parameter	*Correlations with Actual Biomass Yield in Year 7 (Pearson Correlation α =0.01)*				
	Growing season when parameter was measured				
	3rd	*4th*	*5th*	*6th*	*7th*
Plot Average Height	0.892	0.902	0.892	0.866	0.743
Plot Maximum Height	0.862	0.888	0.872	0.814	0.742
Plot Average DBH	0.872	0.868	0.870	0.796	0.709
Total Plot BA	0.872	0.909	0.932	0.936	0.938

Note: Yellow-shaded cells indicate which parameter was most strongly correlated with final plot biomass yield. Except in year 3, this was always plot BA.

TABLE 9: Actual harvested biomass of 7 poplar hybrids planted at 3 densities at Escanaba, MI after 7 years.

Variety (MAI/PAI curves are provided for Hybrids marked by *)	**Planted Density (trees/acre)** (differences among dentities are not significant)				Means followed by the same letter are not significantly different from one another α=0.05.
	1089	*907*	*778*	***Mean***	
	oven-dry tons/acre @ age 7				
*NM6**	28.8	29.5	30.9	***29.7***	a
NM2	21.6	22.9	22.7	***22.4***	b
*DN5**	22.1	18.2	16.8	***19.0***	b c
DN34	16.8	13.7	15.0	***15.2***	c d
NE222	11.8	12.7	17.7	***14.1***	c d
*D105**	13.8	12.8	14.1	***13.6***	d
I4551	8.6	7.0	6.8	***7.4***	e
Mean	**17.3**	**16.2**	**17.3**	***17.0***	
Fast Growing Hybrid "a" Average				*30*	
Intermediate Growing Hybrid Group "b" Average				*21*	
Slow Growing Hybrid Group "d" Average				*14*	

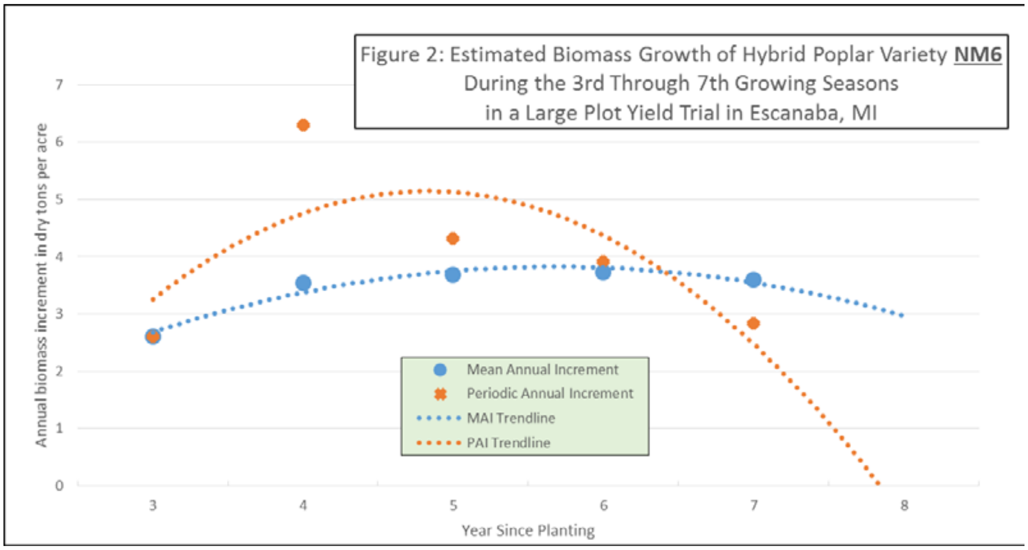
Figure 2: Estimated Biomass Growth of Hybrid Poplar Variety NM6
During the 3rd Through 7th Growing Seasons
in a Large Plot Yield Trial in Escanaba, MI
Annual biomass increment in dry tons per acre
Year Since Planting
Mean Annual Increment
Periodic Annual Increment
MAI Trendline
PAI Trendline
0
1
2
3
4
5
6
7
3
4
5
6
7
8

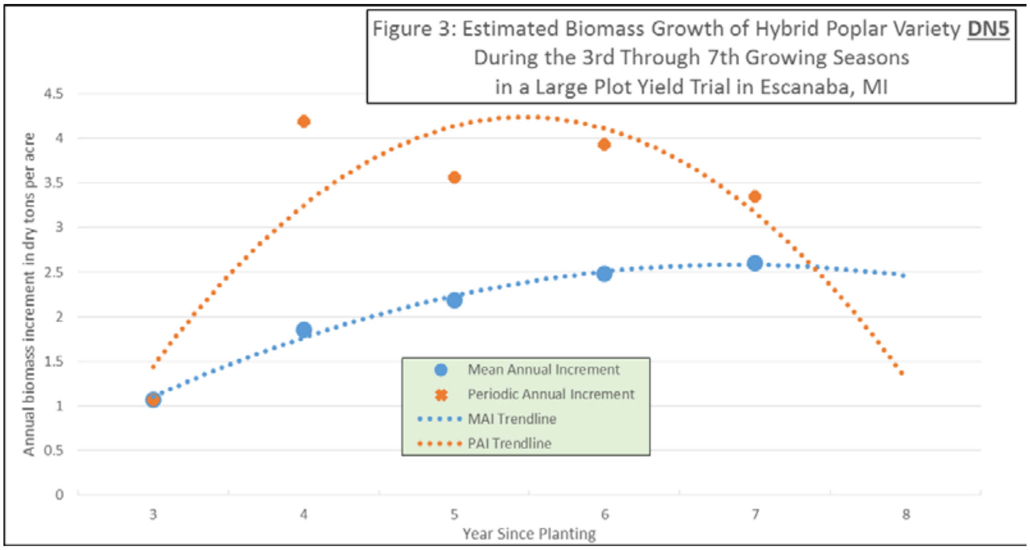
Figure 3: Estimated Biomass Growth of Hybrid Poplar Variety DN5
During the 3rd Through 7th Growing Seasons
in a Large Plot Yield Trial in Escanaba, MI
Annual biomass increment in dry tons per acre
Year Since Planting
Mean Annual Increment
Periodic Annual Increment
MAI Trendline
PAI Trendline
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
3
4
5
6
7
8

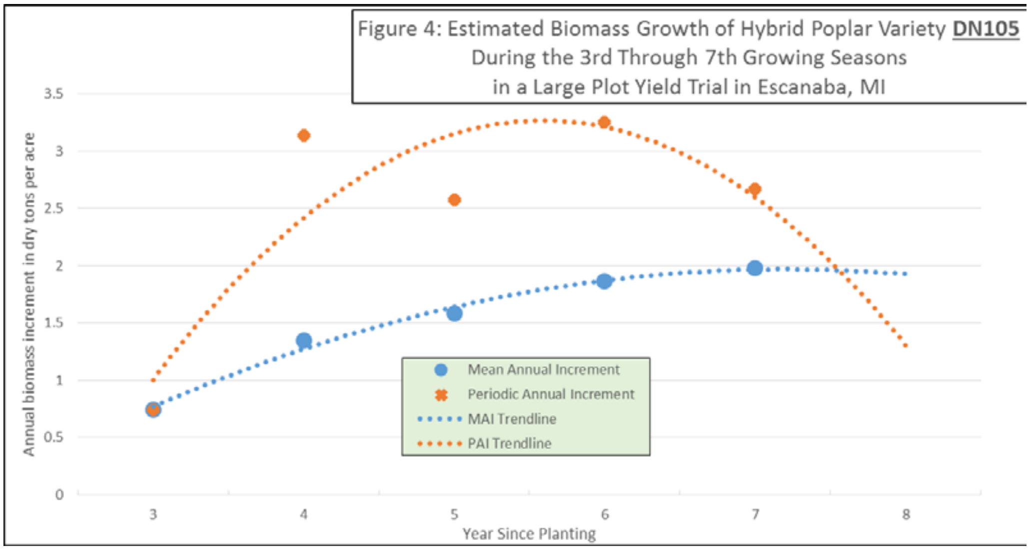
Figure 4: Estimated Biomass Growth of Hybrid Poplar Variety DN105
During the 3rd Through 7th Growing Seasons
in a Large Plot Yield Trial in Escanaba, MI
Annual biomass increment in dry tons per acre
Year Since Planting
Mean Annual Increment
Periodic Annual Increment
MAI Trendline
PAI Trendline
0
0.5
1
1.5
2
2.5
3
3.5
3
4
5
6
7
8

TABLE 10: Yields of poplar varieties at six sites in Michigan, relative to NM6
(Total yield after 5 growing seasons)

Variety	*Brimley*	*Skandia*	*Onaway*	*Lake City*	*Escanaba*	*Albion*	*Average*
Populus nigra X maximowiczii Varieties							
NM5	131%	214%	622%	101%	135%		241%
NM2		166%	256%		134%	123%	169%
DM114			400%	68%	112%	75%	164%
NM6	100%	100%	100%	100%	100%	100%	100%
Populus deltoides X nigra Varieties							
DN2	28%	110%	189%		92%	86%	101%
DN170						95%	95%
DN5	14%	38%	244%	47%	86%	65%	82%
DN154			89%	56%	84%	80%	77%
DN34	10%	79%	133%	43%	106%	59%	72%
DN182	69%	83%	56%		63%	76%	69%
NE222	59%	66%	111%	46%	70%	52%	67%
DN177				30%		98%	64%
DN17	14%	72%	122%		36%	66%	62%
DN70	28%	21%	122%	45%	76%	80%	62%
DN164			67%	36%	60%	91%	64%
I4551		28%			42%	110%	60%
83XAA04						40%	40%
NM6 actual yield (dry tons/acre)	***2.9***	***2.9***	***0.9***	***16.2***	***10.1***	***14.5***	
Best variety (dry tons/acre)	*3.8*	*6.2*	*5.6*	*16.3*	*13.6*	*17.9*	
Conditions at the test site							
5-year total growing degree days (base 50 ° F)	*9,232*	*9,818*	*10,402*	*10,538*	*11,065*	*14,613*	
5-year total precipitation (inches)	*37.8*	*34.6*	*34.0*	*39.7*	*42.4*	*31.7*	
pH	*5.31*	*6.26*	*7.40*	*6.49*	*6.66*	*6.35*	

TABLE 11: Increase in Mean Annual Biomass Increment between the 5th and 6th year in four poplar yield trials across Michigan

Poplar Variety	*Planting Site*				
	Escanaba	***Skandia***	***Brimley***	***Lake city***	***Average***
Populus nigra X maximowiczii varieties					*26%*
NM2	7%	55%			31%
NM5	2%	59%	32%	9%	25%
NM6	11%	98%	41%	4%	38%
DM114	15%			5%	10%
Populus deltoides X nigra varieties					*30%*
DN154	19%			13%	16%
DN164	34%			36%	35%
DN17	23%	63%	25%		37%
DN177				13%	13%
DN182	21%	74%	33%		43%
DN2	11%	64%	46%		40%
DN34	8%	67%	-17%	7%	16%
DN5	15%	112%	-17%	12%	31%
DN70	15%	136%	25%	14%	47%
I4551	29%	25%			27%
NE222	23%	62%	8%	-5%	22%

TABLE 12: Average Survival and Biomass Accumulation of Nine Poplar Varieties After Five Years in Six Hybrid Poplar Yield Trials Throughout Michigan

Variety	*Albion*		*Brimley*		*Escanaba*		*Lake City*		*Onaway*		*Skandia*		***Test-wide***		*Variety*
	Survival	*Biomass (dry tons/a)*	*Survival*	*Biomass (dry tons/a)*	*Survival*	*Biomass (dry tons/a)*	*Survival*	*Biomass (dry tons/a)*	*Survival*	*Biomass (dry tons/a)*	*Survival*	*Biomass (dry tons/a)*	***Survival***	***Biomass (dry***	
NM5			92%	3.8	98%	13.6	94%	16.3	98%	5.6	99%	6.2	**96%**	**9.1**	NM5
NM6	95%	14.5	91%	2.9	99%	10.1	95%	16.3	88%	0.9	100%	2.9	**94%**	**7.9**	NM6
DN2	99%	12.5	81%	0.8	98%	9.3			80%	1.7	95%	3.2	**91%**	**5.5**	DN2
DN5	93%	9.5	73%	0.3	98%	8.7	91%	7.6	71%	1.8	85%	1.1	**85%**	**4.8**	DN5
DN70	91%	11.6	75%	0.8	95%	7.7	91%	7.3	58%	0.7	53%	0.4	**77%**	**4.8**	DN70
DN34	88%	8.5	69%	0.3	96%	10.8	74%	5	68%	0.9	89%	2.3	**80%**	**4.6**	DN34
DN182	96%	11.0	88%	1.6	95%	6.4			60%	0.3	96%	2.4	**87%**	**4.3**	DN182
NE222	90%	7.5	88%	1.7	96%	7.1	71%	4.6	80%	0.8	84%	1.7	**85%**	**3.9**	NE222
DN17	99%	9.6	89%	0.4	93%	3.6			75%	0.7	95%	2.1	**90%**	**3.3**	DN17
Grand Total	**94%**	**10.6**	**86%**	**1.7**	**96%**	**8.6**	**86%**	**9.5**	**75%**	**1.5**	**88%**	**2.5**	**88%**	**5.7**	**Grand Total**

TABLE 13: Analysis of Variance in 5th-year Biomass Production of 9 Poplar Varieties at 6 Sites in Michigan

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

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

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

TABLE 15: Six-year dry biomass production of 10 poplar varieties in a yield trial in Escanaba, MI. Planted in 2010 at a density of 778 trees/acre

Variety	Survival	6th year biomass yield (dry tons/acre)	Yield relative to NM6
NM6	100%	14.9	100%
9732-31	98%	14.3	96%
9732-19	96%	13.5	91%
DN164	95%	13.4	90%
83XAA04	84%	12.2	82%
99038003	100%	11.6	78%
99007116	88%	10.9	73%
DN170	50%	8.5	57%
DN177	58%	7.5	50%
99037049	88%	4.8	32%
LSD (α = 0.05) = 3.9 tons/acre			

TABLE 16: Four-year dry biomass production of 11 poplar varieties in a high-density yield trial in Escanaba, MI. Planted in 2012 at a density of 1,556 trees/acre.

Variety	Survival	4th year biomass yield (dry tons/acre)	Yield relative to NM6
99059016	96%	16.2	111%
9732-31	100%	15.5	106%
9732-24	100%	15.3	105%
NM6	92%	14.6	100%
99038022	92%	13.8	94%
9732-11	100%	12.6	86%
99038003	96%	11.8	81%
9732-19	100%	10.7	73%
99007115	90%	10.3	71%
99038007	96%	8.5	58%
DN5	94%	8.2	56%
LSD (α = 0.05) = 5.9 tons/acre.			