# PLANTING DENSITY EFFECTS ON BIOMASS GROWTH OF HYBRID POPLAR VARIETIES IN MICHIGAN

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## ABSTRACT

Hybrid poplars (*Populus* spp.) are commonly used as fiber and biomass producing crops around the world. Varietal performance changes from place to place and stand development changes under different cultural regimes. Consequently, for any particular end product, the optimal choice of variety, planting density, and rotation length varies and will ultimately determine whether a grower will make money or not. For example, choosing the planting density and rotation length for a biomass plantation will have a significant impact on the financial success of the enterprise. Planting too many trees is unnecessarily expensive, harvesting too early compromises yield, and harvesting too late reduces return on investment. Seven hybrid poplar varieties were planted at three densities in Escanaba, Michigan, USA in 2008 in a replicated field trial to determine the interactions of clone, planting density, and rotation length on Short Rotation Energy Plantation productivity. Trees were measured throughout the duration of the test and harvested in the fall of 2014 after seven growing seasons. Significant growth differences were evident among varieties but were independent of the moderate planting densities tested here (777, 907, and 1089 trees per acre). This suggests that planting more than 777 trees per acre in Upper Michigan biomass plantations is an unnecessary expense. The best yielding variety (a *Populus nigra* X *P. maximowiczii* hybrid known as NM6) produced an average of 29.7 dry short tons per acre; a respectable mean annual increment of 4.25 dry tons per acre. Faster growing varieties reached biological rotation age much faster (6-7 years) than slower growing varieties (8-10 years) which makes them even more suitable for commercial biomass plantation production systems.

## INTRODUCTION

Producing poplar (*Populus*) in Short Rotation Energy (SRE) plantations has become a viable method for augmenting the biomass feedstock demand of the emerging renewable energy industry around the world (Perlack and Stokes, 2011; Isebrands and Richardson, 2014). Poplar produced in SRE plantations can be combusted for the production of heat and power or upgraded to liquids or gases for transportation fuels and chemical production (Sannigrahi, *et. al.*, 2010). Biomass like poplar is the only source of *renewable* carbon on the planet and so will be a vital feedstock in replacing the fossil carbon on which we now so heavily depend.

SRE plantations require a different type of forest management (silviculture) than that traditionally employed by foresters. Traditional silviculture is optimized for the production of large trees on long cutting cycles (rotations). Although the underlying fundamentals remain constant, this new SRE plantation silviculture must account for unfamiliar varieties (taxa), short rotations, new landowner expectations, and be optimized for the rapid production of biomass – a low-value forest product. Since the goal is to produce biomass quickly, regardless of individual tree size, SRE Plantation silviculture research focuses on the biology and finances of the first few years of stand development.

Many taxa and management systems have been examined during the past four decades. A "wood grass" system annually harvested plantations with more than 243,000 stools[1] per acre (spa) and relied on sprouts from these stools to re-establish the stand each year (DeBell, 1993). This system was determined to be unworkable both physically and financially. Experience has led us to concentrate on two main systems: (1) "**micro**" rotations of three years duration at "**high**" densities of 5,700 spa and (2) "**short**" rotations of approximately eight years duration at "**medium**" densities of 600 – 1,200 spa. Research seeks to optimize these systems across a range of taxa and planting sites. Work reported here examines the biological development of seven poplar varieties grown under three variations of the "short" rotation "medium" density system on a site in northern Michigan after seven growing seasons.

Annual biomass growth per unit area in woody plant systems, or Periodic Annual Increment (PAI), increases exponentially during the period before individual trees compete with each other for site resources, or reach what is called "crown closure." Site resources prior to crown closure are distributed among crop (trees) and non-crop (weeds) plants. Shortening this time will improve crop productivity and minimize the need for weed control. After crown closure, trees begin to compete with each other and PAI levels-off. As mortality from competition or other causes begins, PAI gradually decreases (Yoda, 1963 ). Maximum PAI is reached earlier in dense plantings because the trees fully occupy the site more quickly than in less dense plantings. However, less dense plantings quickly catch up and maintain high PAI longer than their dense counterparts because inter-tree competition is less severe (Hansen, 1979; DeBell, 1996). Consequently, total biomass production over time is similar for SRE Plantations with initial planting densities that range from 1,200 to 16,000 spa (Johnstone, 2008; Strong, 1993; Ferm, 1989; DeBell, 1996; DeBell, 1993).

Plantations with low densities (450 spa and below) are less expensive to install because fewer trees are purchased and planted. These plantations eventually produce larger individual trees than high density plantations (Fang, 1999; van Oosten, 2006). Low density plantations take much longer to reach maximum PAI than high density plantations, but they maintain maximum PAI

[1] Stems originating from a single planted seedling or cutting form a "stool."

much longer. This is useful for growing traditional forest products that depend on a few big trees but not necessarily for biomass that can just as easily depend on numerous small trees per unit area.

Another way to express biomass growth is Mean Annual Increment (MAI). This is a function of the total standing biomass at any point divided by the age of the stand. MAI can be thought of as similar to a financial interest rate. Rather than earning dollars, poplar stands earn biomass. It is up to the grower, just like an investor, to determine what rate is acceptable. This rate changes with time. Biological (and usually financial) rotation age can be expressed as the point at which MAI equals PAI. MAI begins to decrease after this point in stand development, meaning that annual returns start to decline. Harvesting is usually done at this point and a new more productive stand is established to replace the declining one.

Because initial planting density influences PAI and thereby both biological and economical rotation length, it is critical to understand these dynamics when designing SRE Plantation systems. Admittedly, PAI is influenced by numerous factors including; planting stock genetics, initial planting density, non-crop competition, climate, soil fertility, moisture availability, and pest depredation. We limited our test to the effects of planting density and planting stock genetics at a single site in northern Michigan.

## METHODS

Seven poplar varieties were selected for inclusion based on their positive performance in previous trials in the Great Lakes region of the United States (Netzer, 2002; Isebrands, 2007) and on the commercial availability of sufficient numbers of cuttings for our test. One variety of *Populus deltoides*, four varieties of *P. ×canadensis*, and two varieties of *P. nigra* X *P. maximowiczii* were included (Table 1). Dormant, rooted cuttings of D105 were obtained and hand-planted in holes dug by a 20 cm auger. Unrooted hardwood cuttings of the remaining varieties were obtained and hand-planted by inserting them directly into a well-tilled field at Michigan State University's Forest Biomass Innovation Center (FBIC) (45º 45' 50" N latitude, 87º 11'30" W longitude) in the spring of 2008. Soil in the field was a fine sandy loam from the Onaway soil series. The site received an average of 20" of rainfall and 2,164 growing degree days (base temperature 50º F) during the growing seasons of this trial. Weeds in the plantation were controlled using a combination of herbicides (imazaquin, pendimethalin, and glyphosate) and mechanical rototilling during the first two years after planting. No fertilization or irrigation was applied.

As previously discussed, studies had suggested that for "short" rotation systems there was no yield advantage to planting more than 1,200 spa and that planting fewer than 450 spa produced inferior biomass yields. Consequently we chose to test three densities between these limits;

specifically 777, 907, and 1,089 spa. Cuttings of each taxa were planted in rows separated by 8’. Because Johnstone (2008) had shown that density, rather than the degree of rectangularity of tree spacing, was the factor controlling yield, we varied the distance between cuttings within each row by 5’, 6’, or 7’ to obtain the desired planting density. The test was arranged in a randomized block design with four blocks of approximately tenth-acre plots. Plot size necessarily varied slightly by planting density. Two complete blocks were composed of 21 plots; one for each of the seven poplar taxa planted at each of the three densities. A shortage of NM2 cuttings resulted in two blocks being incomplete, containing only 18 plots.

Measurements were not made during the first two growing seasons because most stems had not reached a height sufficient for stem diameter measurement and meaningful biomass estimation. Measurements were made at the end of the third through seventh growing seasons. Stools in the center of the larger whole plots were measured, leaving a two-stool border to isolate the measurement plot from the edge effects created by adjoining plots. Consequently 24, 28, and 32 stools were measured in the 777, 907, and 1089 spa plots respectively. (1) Stem diameters at 4.5’ above the ground (DBH), (2) stem height, (3) severity of *Septoria musiva* infection, and (4) stool survival was measured and recorded annually. Standing tree biomass was estimated using an allometric equation developed for use in Michigan (Equation 1, Miller, 2016). Biomass per unit area was calculated by summing each stem’s calculated biomass in each measurement plot and multiplying by the appropriate expansion factor for that particular plot’s size.

**Equation 1**:

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

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

All trees were harvested in the fall of the seventh growing season. The total green weight of the chips from all trees within each sample plot was recorded. A 10 pound sub-sample of these chips was retained and placed in a drying oven at 220ºF until their weight stabilized. Moisture content was determined in this way and applied to the whole-plot green weight to obtain whole-plot dry weight. This in turn was converted to a unit area biomass weight for each plot.

An analysis of variance in harvested biomass weights was performed. Correlation analysis was performed to examine the relationship between harvested biomass yield and the various whole-tree measurements made over the course of the trial. PAI and MAI values were calculated using biomass predicted by Equation 1; using basal area derived from the DBH measurements made each year during the course of the trial. The first time standing-tree biomass calculations could be made was in year 3 since trees had to be tall enough to have a diameter at 4.5’. MAI for year 3 was calculated by dividing standing-tree biomass by 3. Since there was no biomass estimate for year 2, it was not possible to calculate PAI for year 3. Consequently, it was assumed that PAI was equal to MAI for year 3 in this analysis. MAI and PAI curves were plotted and biological rotation ages for the varieties was determined by looking for the intersection of these curves – the point at which MAI was projected to begin to decline.

## RESULTS AND DISCUSSION

### Spacing and Variety Impacts on Biomass Yield

Analysis of variance in seventh-year biomass accumulation showed no significant differences among the 3 densities tested here or among the blocks in the trial. There were strong differences among varieties (Tables 2 and 3). NM6 produced about 30 dry tons per acre in seven years, significantly more than any other variety in the study. NM2 and DN5 were the next best biomass yielding clones, producing an average of 21 dry tons per acre. Others like D105, NE222, DN34, and I4551 formed a statistical cluster of the poorer yielding clones that collectively averaged 14 dry tons per acre. Obviously, choice of variety has a dramatic impact on system productivity.

### Density Effects on Diameter Growth & Analysis

Although spacing had no impact on biomass growth, it did effect tree diameters. Individual trees grew larger in diameter when planted at lower densities but, because there were fewer trees per unit area at these lower densities, total biomass production was not increased. More numerous smaller trees can produce an equivalent amount of biomass as fewer larger trees at the densities tested here. This means that over the range of densities tested here, establishment costs can be reduced (by planting fewer trees) without compromising productivity.

### Correlation of Tree Diameter and Height with Biomass Yield

As biomass stands develop, it is useful to non-destructively measure standing tree parameters to estimate and monitor biomass growth. Tree heights and diameters are fairly easy to measure and are fairly well correlated with final rotation biomass yield (Table 4). However, the trait most strongly correlated with final biomass yield was basal area (the cross sectional area of stems at 4.5’ above the ground). Basal area is a function of stem diameter but when many stems are present, combining their individual basal areas together appears to better predict plot biomass than using either height or diameter alone. The biomass algorithm developed for use in Michigan (Equation 1) was constructed with this relationship in mind.

### Survival Analysis

Survival of four of the seven clones (NM6, DN5, D105, and DN34) was initially excellent and remained consistent throughout the test. The two remaining varieties were apparently compromised upon arrival. The cuttings of NE222 and I4551 received from Segal Ranch Nursery were fairly dry when they arrived in Escanaba. In addition to being weakened, they may also have been infected by *Cytospora chrysosperma.* Although we had not previously experienced this disease in Escanaba, it became rampant in plots of these two clones early in the first year of this test. NE222 survived the disease but responded by dying back to the ground and re-sprouting; creating bushes rather than single-stemmed trees. Half of the I4551 stools died completely in the first year. The I4551 stools that survived remained alive for the remainder of the trial but produced the least biomass of any clone in the trial (Table 5).

In well-stocked plots, stool survival was poorly correlated with biomass yield; suggesting that surviving stools occupied and used the extra growing space made available by nearby stools that died. Disease severity was also not correlated with biomass yield but mortality resulting from *Septoria musiva* infection was beginning at the time of harvest and would undoubtedly have caused yield losses for heavily infected clones like NM2 and DN5 if harvesting had been delayed by one or more years.

**Disease Analysis**

Diseases have consistently been the greatest threat to hybrid poplar production in the Lake States and Northeastern Regions of the United States. *Septoria musiva*, in particular, causes stem cankers and is eventually fatal to most of the clones that have been developed and tested in this region. A thorough census of disease severity was conducted in 2013. Severity was scored on a progressive scale that assigned a value of 1 to trees with no infection and progressed to a score of 5 for severe infection. The statistical mean and the statistical mode for each variety was calculated (Table 5). The proportion of trees in each infection class was also tallied and plotted to visualize trends (Figure 1).

Survival of NM2 was initially good but declined precipitously during the last two years of the trial. This can be directly attributed to severe infection by *Septoria musiva*. NM2 was acutely susceptible to this disease; nearly all of the stems showed “severe” or “heavy” infection and breakage at age six. It was doubtful that many stools would remain alive on long rotations. Clones like DN5, DN34, and I4551 were “moderately” to “lightly” infected but had not yet begun to die. Clones like NM6 and NE222 were “lightly” infected or free of disease but were getting worse with each passing year. D105 was hardly infected at all (Figure 1) but unfortunately is one of the slowest growing clones. Combining disease resistance with rapid growth remains the number one goal of poplar breeders in our region.

**PAI & MAI Trends**

Biological rotation age (the point of maximum Mean Annual Increment) can be determined as the point where the Mean Annual Increment (MAI) curve intersects the Periodic Annual Increment (PAI) curve. These curves were plotted for a rapidly growing variety and a slow growing variety (Figures 2 and 3). It is difficult to precisely establish these curves with precision, given the limited number of observations possible in this test. Growth is dependent on more factors than simply plantation age and this test only provides a set of observations at one time and place. For example, PAI in year four was exceptional (about double that of the preceding year) due to highly favorable environmental factors that occurred only once. This data point has a profound influence on the shape of the PAI curves produced here. If that year's growth had been more normal, the intersection of the PAI and MAI curves for both varieties might have been delayed by a year or more. Irrespective of the actual numbers generated here, the trends observed were expected and are instructive. Faster growing varieties not only produce far more biomass but they reach biological rotation sooner than do slower growing varieties. Both of these facts have positive influence on the finances of short rotation energy plantation systems.

It was originally assumed that high density treatments would reach maximum MAI sooner than low density treatments. This has not been the case for the clones and densities tested here. Lower planting densities produce similar biomass yields to higher planting densities under these conditions. So there is no biological or financial case to be made for planting more than 777 stems per acre for rotations of six to eight years duration. However, choosing clones that exhibit rapid early biomass growth (independent of planting density) significantly reduces the time to reach biological rotation age and substantially reduces the break-even cost of the biomass produced.

**Table 1:** Poplar hybrid varieties included in a 2008 density trial in Escanaba, MI, USA

| *Variety* | *Taxa description* | *Nursery providing planting stock* |
|---|---|---|
| D105 | *Populus deltoides* | Iowa State Nursery, Ames IA |
| DN34 | *P. Xcanadensis*<br>*P. deltoides X nigra* | Kathy Haibi, Grand Rapids, MN |
| DN5 | *P. Xcanadensis*<br>*P. deltoides X nigra* | Lincoln Oaks, Bismarck, ND |
| I4551 | *P. Xcanadensis*<br>*P. deltoides X nigra* | Segal Ranch, Grandview, WA |
| NE222 | *P. Xcanadensis*<br>*P. deltoides X nigra* | Segal Ranch, Grandview, WA |
| NM2 | *P. nigra X P. maximowiczii* | Verso Paper, Alexandria, MN |
| NM6 | *P. nigra X P. maximowiczii* | Kathy Haibi, Grand Rapids, MN |

**TABLE 2:** Actual harvested biomass of seven poplar hybrids planted at three densities at Escanaba, MI after seven years.

| **Variety** | **Planted Density (trees/acre)** (differences among planting densities are not statistically 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* | |

**Table 3:** Harvested biomass (in dry tons per acre) of seven poplar varieties planted in 4 replicates of large plots at Escanaba, MI after seven years.

| Variety | **Block** (differences among blocks are not statistically significant) | | | | | Means followed by the same letter are not significantly different from one another α=0.05. |
|---|---|---|---|---|---|---|
| | *oven-dry tons/acre @ age 7* | | | | | |
| | *1* | *2* | *3* | *4* | ***Mean*** | |
| *NM6* | 31.8 | 29.3 | 29.2 | 29.4 | **29.7** | a |
| *NM2* | 21.3 | 22.9 | NA | NA | **22.4** | b |
| *DN5* | 20.3 | 18.8 | 18.8 | 18.2 | **19** | b c |
| *DN34* | 22.4 | 14 | 16.3 | 13.7 | **15.2** | c d |
| *NE222* | 13.3 | 15.6 | 9.9 | 16.8 | **14.1** | c d |
| *D105* | 11.2 | 16.3 | 12.6 | 14.1 | **13.6** | d |
| *I4551* | 7.5 | 8.9 | 6.6 | 6.3 | **7.4** | e |
| ***Mean*** | **17.7** | **17.9** | **15.6** | **16.4** | **17** | |

**TABLE 4:** Correlations between tree parameters from plots measured over time with seventh-year biomass yield of poplar hybrids in a plantation in Escanaba, MI

| *Measured or Calculated Parameter* | *Correlations with Actual Biomass Yield in Year 7* | | | | |
|---|---|---|---|---|---|
| | *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 |
| *Most strongly correlated trait each year is shaded grey.* | | | | | |

**Table 5:** Survival of seven poplar varieties over the life of a density trial in Escanaba, Michigan including severity of *Septoria musiva* infection in year six of the trial.

| *Variety* | ***Survival*** | | | | | | ***Septoria musiva infection score**** | | |
|---|---|---|---|---|---|---|---|---|---|
| | *2009* | *2010* | *2011* | *2012* | *2013* | *2014* | *Statistical Mean* | *Statistical Mode* | *Proportion of trees at the Mode* |
| NM6 | 100% | 100% | 100% | 99% | 99% | 99% | 1.53 | 1 | 63% |
| DN34 | 96% | 96% | 96% | 95% | 95% | 94% | 1.76 | 2 | 50% |
| D105 | 93% | 93% | 93% | 93% | 93% | 93% | 1.10 | 1 | 94% |
| DN5 | 89% | 89% | 89% | 89% | 88% | 87% | 2.36 | 3 | 45% |
| NM2 | 85% | 85% | 85% | 80% | 71% | 70% | 3.92 | 4 | 84% |
| NE222 | 92% | 91% | 88% | 78% | 70% | 68% | 1.39 | 1 | 76% |
| I4551 | 51% | 51% | 51% | 49% | 46% | 45% | 2.05 | 2 | 40% |

*Note: Infection scoring was done in 2013 on a progressive scale: 1=none, 2=light, 3=moderate, 4=heavy, and 5=severe infection.

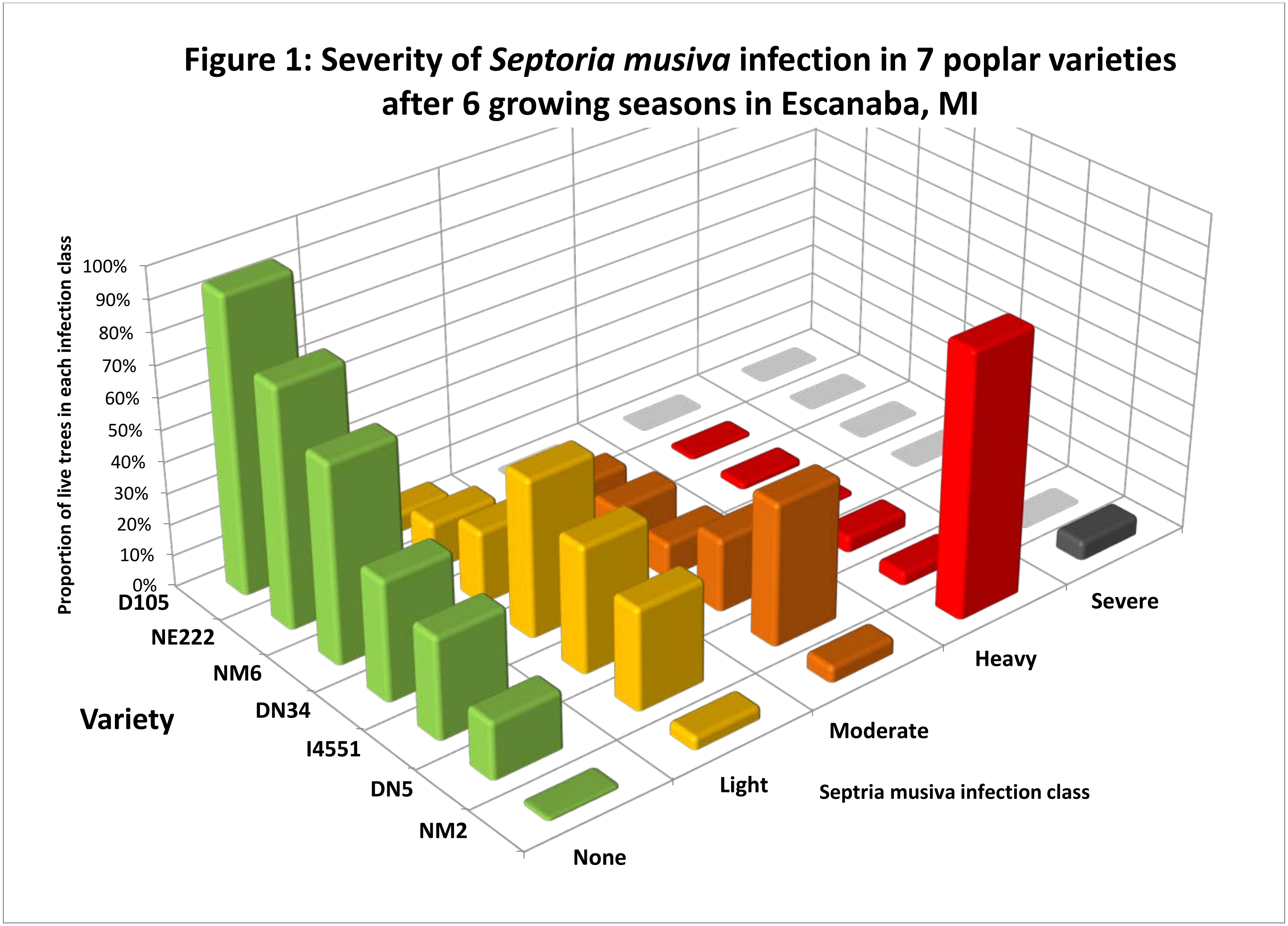
Figure 1: Severity of *Septoria musiva* infection in 7 poplar varieties after 6 growing seasons in Escanaba, MI
Proportion of live trees in each infection class
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Variety
D105
NE222
NM6
DN34
I4551
DN5
NM2
None
Light
Moderate
Heavy
Severe
Septria musiva infection class

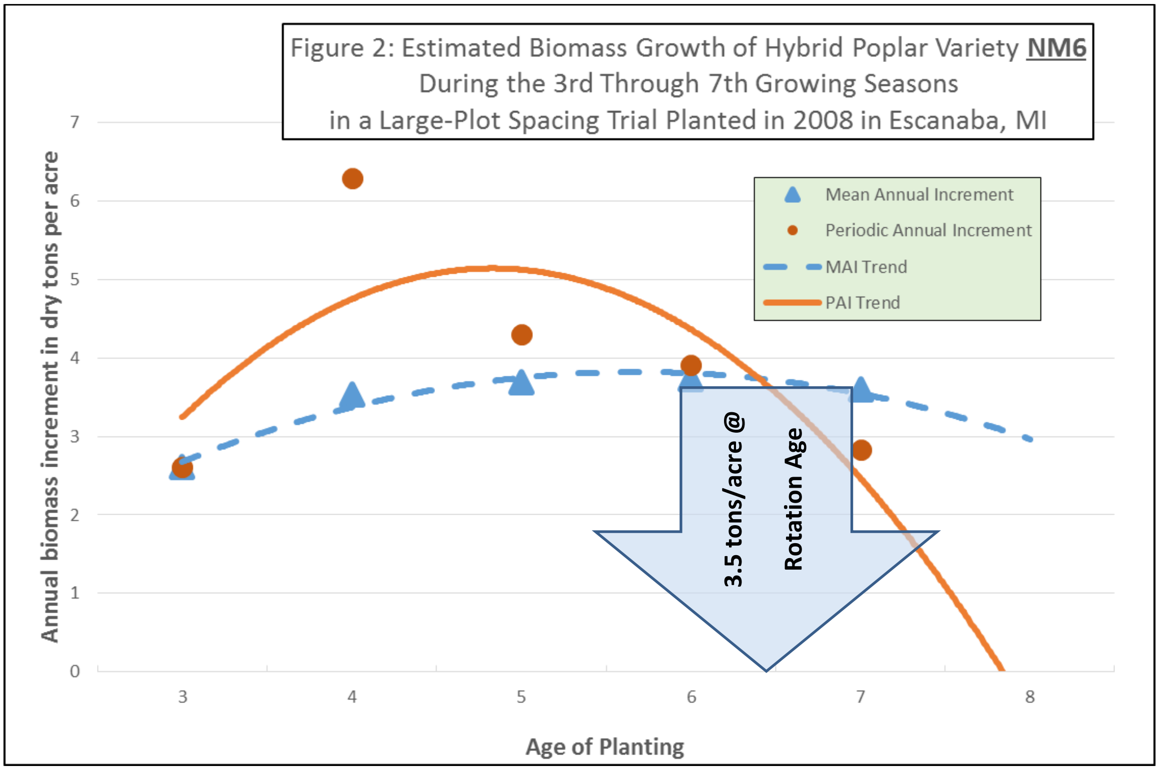
Figure 2: Estimated Biomass Growth of Hybrid Poplar Variety NM6
During the 3rd Through 7th Growing Seasons
in a Large-Plot Spacing Trial Planted in 2008 in Escanaba, MI
Annual biomass increment in dry tons per acre
Age of Planting
Mean Annual Increment
Periodic Annual Increment
MAI Trend
PAI Trend
3.5 tons/acre @
Rotation Age
0
1
2
3
4
5
6
7
3
4
5
6
7
8

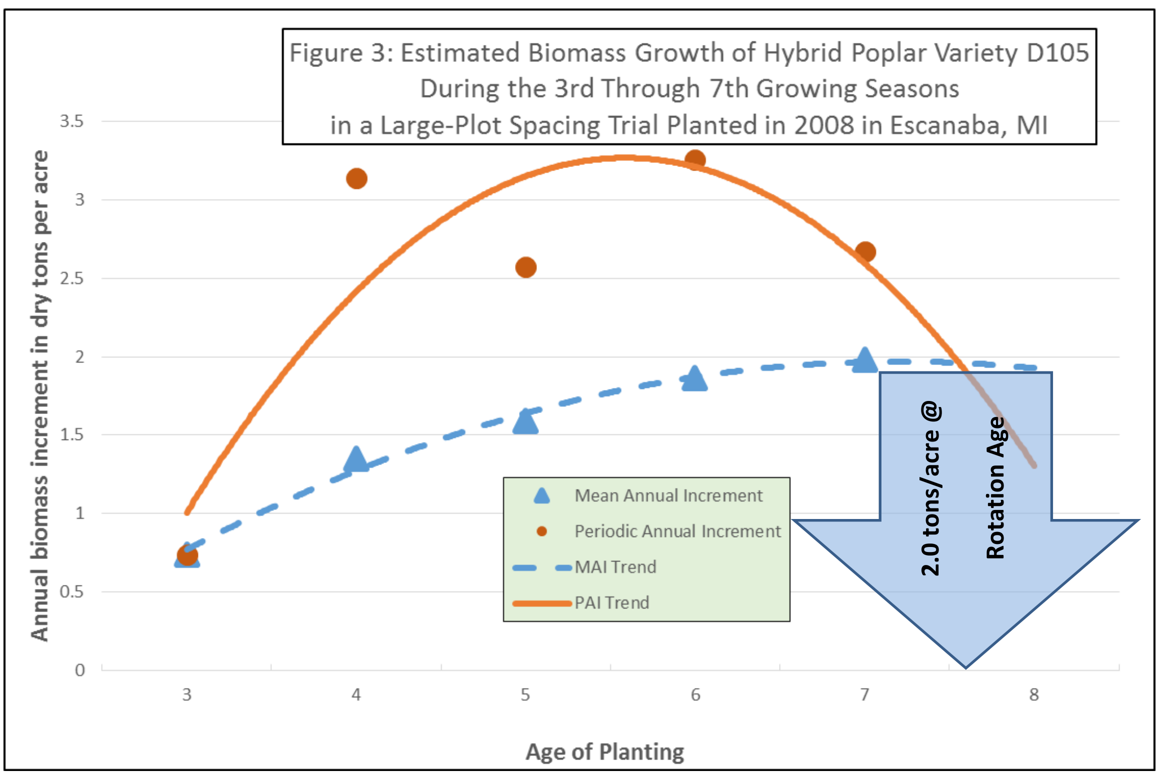
Figure 3: Estimated Biomass Growth of Hybrid Poplar Variety D105
During the 3rd Through 7th Growing Seasons
in a Large-Plot Spacing Trial Planted in 2008 in Escanaba, MI
Annual biomass increment in dry tons per acre
Age of Planting
Mean Annual Increment
Periodic Annual Increment
MAI Trend
PAI Trend
2.0 tons/acre @
Rotation Age
0
0.5
1
1.5
2
2.5
3
3.5
3
4
5
6
7
8

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## ACKNOWLEDGEMENTS

*Funding for this work was provided by Michigan State University’s AgBioResearch and US Department of Energy awards numbered DE-EE-0000280 and DE-FC36-05GO85041. Technical assistance from Kile Zuidema, Paul Irving, Jake Easton, and Jeremy Mason is gratefully acknowledged.*