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Yields of willow biomass crops across a range of sites in North America

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Summary

Yield is an important factor in determining the economic feasibility of willow biomass crops. Over the past 18 years a series of yield trials have been established across North America with older clones from the Ontario Ministry of Natural Resources and the University of Toronto and new genotypes from the SUNY-ESF breeding programme. One trial that has been harvested four times showed that the yield of four commercial clones increased by 23.0% from the first to second rotation and by 30.8% from the first to fourth rotation. Quantifying these changes is important when modeling production and cash flow of these perennial systems. Across all yield trials, those with new willow clones have produced 38% more biomass than trials with the older clones. The top three new clones in each of the nine trials that have been harvested produced a mean yield of 11.5 odt ha^{-1} yr^{-1}, which was 13.9% better than the three older reference clones in these trials.

Key words: Breeding, *Salix*, short rotation woody crops, yield

Introduction

Interest in short-rotation woody crops (SRWCs) for the production of biomass has developed in Europe and North America over the past few decades because of the multiple environmental and rural development benefits associated with their production and use (Volk *et al*., 2004; Rowe *et al*., 2009). SRWC development in the United Sates (U.S.) has concentrated on willow shrubs (*Salix* spp.) and hybrid poplar (*Populus* spp.), but other species including southern pine and eucalyptus are currently being rapidly developed in the U.S. (Volk *et al*., 2011). Willow shrubs have several characteristics that make them an ideal feedstock for biofuels, bioproducts and bioenergy: high yields that can be obtained in 3–4 years, ease of propagation from dormant hardwood cuttings, a broad underutilized genetic base, ease of breeding for several characteristics, ability to resprout after multiple harvests, and chemical composition and energy content similar to other northern hardwood species.

Initial trials with shrub willows as a biomass crop were conducted in the mid-1970s in Sweden and in the U.S. starting in 1986 (Volk *et al*., 2006). The original research in the U.S. made use of shrub willows from the Ontario Ministry of Natural Resources (OMNR) and the University of Toronto (UofT). A broad selection of this plant material was shared with SUNY-ESF in the late 1980s and became the basis for the development of the willow biomass crop system in the U.S. Both the OMNR and The UofT programmes, however, ended in the mid-1990s. This material was used in a series of yield trials in the U.S. and Canada from the late 1990s until 2001. To broaden and improve the plant material being used, a selection of some of the best plant material was imported from the Svalöf Weibull breeding programme in Sweden in the late 1990s. However, it soon became clear that most of this material was not going to be effective because it was susceptible to damage from the potato leaf hopper (*Empoasca fabae* Harris). A breeding programme was initiated in the mid-1990s in New York state starting with the collection of a wide range of plant material from the Northeast and Midwest U.S. The first crosses were completed in 1998 and over 800 crosses have been attempted since that time. New willow clones along with some older genotypes included for reference have been used in a network of yield trials that have been planted since 2005.After a series of selection and yield trials, the best producing new clones were selected for scale up, which has been done by a nursery in western NY, Double A Willow.

Rapid growth rate is one of the attributes that make shrub willows an appealing biomass crop. Yields in research plots of fertilized (Labrecque & Teodorescu, 2003) and fertilized and irrigated (Adegbidi *et al*., 2001) unimproved clones of willow grown for 3 yrs have exceeded 27 odt ha^{-1} yr^{-1}. Due to the costs associated with irrigation and the relatively low value for biomass, irrigation will not be used for most large-scale production operations, with the exception of situations where willow crops could be irrigated with wastewater as part of a nutrient management plan. However, these studies set a benchmark for the potential of unimproved willow shrubs grown in this type of system, and higher yields will be possible with improved genetic material from breeding programmes.

Despite the numerous environmental and rural development benefits associated with willow biomass crops, their use as a feedstock for bioproducts and bioenergy has not yet been widely adopted primarily due to the current high cost to produce and deliver the biomass to an end user and the low value of the product on the market. At current energy market prices for wood chips, willow biomass crops can provide an internal rate of return of 5.5% over a 22-year production period (Buchholz & Volk, 2011) with the breakeven point occurring at year 12. Improving yield is an important factor in improving determining the economic feasibility of willow biomass crops. Other areas that need to be addressed to make this system economical are reducing production costs and increasing the amount or value of the biomass being produced.

This paper presents results from multiple harvests of one yield trial in the U.S., as well as first rotation data from the network of yield trials in both the U.S. and Canada that have been established with both older clones from the OMNR and UofT programmes and newer clones from the SUNY-ESF programme.

Materials and Methods

Production over multiple rotations

The study was established in Tully, NY in 1997 at the SUNY-ESF Genetics Field Station (42º47’30”N, 76º07’30”W). The soil was a well-drained Palmyra gravelly silt loam (Glossoboric

Hapludalf). The trial originally included 32 willow and eight hybrid poplar clones, but data analysis was limited to 30 willow clones due to poor survival and growth of two of the willows. Hybrid poplar data is not presented in this paper. Most of the plant material in this trial originated from the OMNR and UofT programmes but 10 genotypes of *S. purpurea* that were collected from the natural stands in 1994 from NY were included as part of the initial efforts to build a willow population for a breeding programme in New York. Only four clones (SX61, SX64, SX67 and SV1) from this trial are still being recommended for commercial biomass production. The trial was planted in late April 1997 as a randomized complete block design with four replications. Plots were planted with 25-cm-long cuttings of each clone in an eight by six array at 0.6 m × 0.9 m spacing for an initial density of about 18,400 plants ha^{-1}. At the end of the first growing season, the shrubs were cutback (coppiced) at 2–4 cm above the ground. The plots were harvested four times on a 3-year rotation. Production measurements were taken on the central four stools in every plot.

First rotation data from a network of yield trials

A series of yield trials with 6–30 different willow clones from the SUNY-ESF collection have been established across the U.S. and Canada since 1993. Trials established before 2005 made use of plant material that originated from the OMNR and UofT willow programmes and some material that was collected from the natural stands at the start of the breeding programme in NY. Trials planted after 2005 focused on testing new willow clones that were developed and selected as part of the SUNY-ESF programme. All the trials use a similar experimental design and plot layout. Trials are completely randomized designs with three to four replications and planted with 25 cm long dormant cuttings. Plots are comprised of three double rows (6.9 m wide) with 1.5 m between double-rows, 0.76 m between rows and 0.61 m between plants within the rows providing an initial density of about 15,400 plants ha^{-1}. The number of willows planted within the row varied from 25 to 13 so the length of plots varied from 7.3 to 14.6 m. All measurements were taken on plants in the inner double row. All trials were coppiced after their first growing season, fertilized with 100 kg N ha^{-1} at the start of the second growing season (except 1999 Arlington, WI and the three 2007 trials in Saskatchewan) and harvested for the first time 3 years after coppice. Biomass from the measurement plot was measured in the field and a subsample was collected and weighed for moisture content analysis. Wet weights were adjusted using moisture content data and results were scaled up based on the area of the measurement plot to oven dry tons per hectare (odt ha^{-1}).

Results

Production over multiple rotations

First 3-year rotation production ranged from 5.3–27.8 odt ha^{-1}, with four of the clones producing more than 24 odt ha^{-1} (Fig. 1). Production of individual clones in the second rotation ranged from a decrease of 30% to an increase of 55%. Production increased for 25 of the clones and decreased for five of the clones. Production increased by 19.4% across all the clones and 23.0% for the commercial clones (SX61, SX64, SX67 and SV1).

Production by the fourth rotation ranged from 5.4–40.2 odt ha^{-1}. Production of 17 of the clones had increased while 13 had decreased. Changes in production of individual clones ranged from a decrease of 65% to an increase of 99% with a mean increase of 13.6% across all the clones. The largest change in production was for one of the natural collections of *S. purpurea* (clone ID 94006), for which production increased from 20.9–40.3 odt ha^{-1}. Production of the commercial clones in the fourth rotation ranged from 23.4–32.4 odt ha^{-1}, an increase of 30.8% across all four clones. Six other clones, all *S. purpurea*, produced yields in the fourth rotation that were comparable to or above those of the commercial clones.

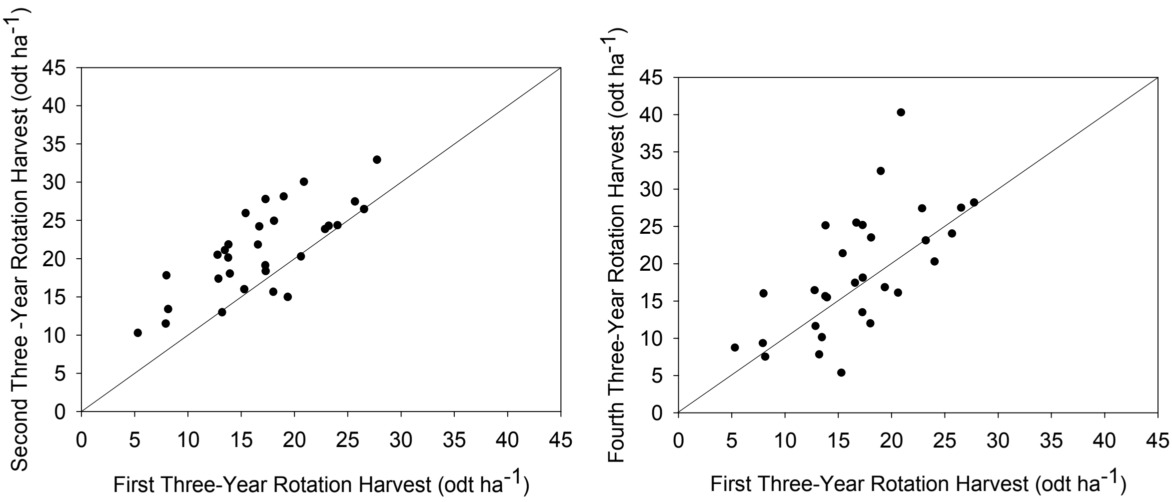

Fig. 1. Three-year production from the first and second 3-year harvest (left) and the first- and fourth-year harvest (right) for 30 willow clones planted in Tully, NY in 1997.

First rotation data from a network of yield trials

Average yield across all clones during the first rotation was 8.0 odt ha^{-1} yr^{-1} and ranged from 4.1–12.9 odt ha^{-1} yr^{-1} (Table 1). Trials planted after 2005 with newer willow clones produced 2.3 odt ha^{-1} yr^{-1} more biomass than the trials planted with older clones, which is an increase of 33.3% (Table 2). The introduction of these new willow clones as well as the effect of site conditions and improved management had a positive impact on yield.

A direct comparison of old and new genotypes planted on the same site is possible by considering the 1993 trial and the 2005 trial planted in Tully, NY. The mean yield of the first harvest from the 2005 Tully trial was 69% greater than the mean yield of the 1993 trial. The mean yield of SV1, the only reference clone in both trials, was 8.9 odt ha^{-1} yr^{-1} in the 1993 trial and 8.4 odt ha^{-1} yr^{-1} in the 2005 trial, suggesting that site conditions and management were comparable. The mean yield of the top five clones in the 2005 Tully trial was 49% greater than the top five clones in the 1993 trial, reflecting a dramatic improvement in the yield potential of the new genotypes in the 2005 trial.

These yield trials include between six and 30 different willow clones in any single trial. The mean yield of the top producing clone in each of the old trials (11.7 odt ha^{-1} yr^{-1}) was only slightly lower than the mean of the top clone for the new trials (12.3 odt ha^{-1} yr^{-1}). The greatest yield by any one clone in the old trials was 15.6 odt ha^{-1} yr^{-1} in Arlington, WI and 17.2 odt ha^{-1} yr^{-1} at Boisbriand, QC among the new trials. Current recommendations are to plant a mixture of several clones in any large planting to maintain diversity in fields and minimize production risks. Therefore, we averaged yield data for the top three or five clones at each site as a way to evaluate potential productivity at a larger scale. First rotation yield for the top three clones across all the trials was 11.1 odt ha^{-1} yr^{-1}. Mean yield of the top three clones in the newer trials was 13.5% greater (11.8 odt ha^{-1} yr^{-1}) than in the older trials (10.4 odt ha^{-1} yr^{-1}). If the top five clones in each trial are included then the increase in yield was 21.7%.

Three of the better producing clones (SX61, SX64 and SV1) from the older trials were included in each of the new trials as reference clones. The production of the reference clones was 7.5% higher in the new trials than in the old trials. Clone SV1 failed at the two mid Atlantic sites included in the older trials, 1998 Peter Tract, DE site and 2001 Queenstown, MD. If the SV1 data is excluded from these sites then the mean yield of the reference clones in the older sites is 10.4 odt ha^{-1} yr^{-1}, which is slightly greater than the yield of the reference clones in the new trials.

Comparing the yield of the reference clones with the top three new clones provides an indication of the changes that can be largely attributed to genetic improvement. In seven of the nine new trials, the mean yield of the top three new clones was greater than the mean of the reference clones, but the increase varied from 3.9% in the 2005 Tully trial to 28.8% in the 2007 Birch Hills, SK trial.

In two of the trials in Saskatchewan, the reference clones had slightly higher yields than the new clones but one of these lacked SV1, which was the poorest yielding of the reference clones. Across the nine new trials that have reached the end of their first rotation, the mean yield of the top three new willow clones was 13.9% better than the three reference clones.

Table 1. *First rotation yield (odt ha^{-1} yr^{-1}) for a series of willow biomass crop yield trials established between 1993 and 2001*

	1993 Massena, NY	1993 Tully, NY	1997 Burlington, VT	1998 Canastota, NY	1998 Peter's Tract, DE	1998 Sheridan, NY	1998 Wolcott, NY	1999 Arlington, WI	2001 Queenstown, MD	Average	SE
No. clones	14	19	7	14	14	12	12	10	6	12.0	
Top clone	12.3	8.9	12.3	11.2	11.6	8.0	11.7	15.6	14.0	11.7	0.77
Top 3 clones	11.4	7.7	9.7	10.6	9.8	7.1	9.6	14.9	12.5	10.4	0.79
Top 5 clones	10.4	7.0	9.0	10.0	8.3	6.2	8.6	12.1	11.2	9.2	0.64
Site mean	6.8	5.2	8.6	7.7	4.1	4.9	6.7	8.7	9.3	6.9	0.62
Reference clones											
SV1	12.3	8.9	8.5	9.9	0.6	6.3	8.5	7.3	0.0	6.9	1.37
SX61			12.3	10.8	8.8	6.9	11.7	15.6		11.0	1.22
SX64				11.2	11.6	8.0		13.7	11.5	11.2	0.91
Mean	12.3	8.9	10.4	10.6	7.0	7.1	10.1	12.2	5.7	9.4	0.78

Willow genotypes in these trials were from the OMNR and UofT programmes and natural collections in NY. Site labels include the year of planting and location. Data for 1993–1998 trials from Kiernan *et al.* (2003).

The reference clone SV1 was planted at all but two of the smaller trials in Saskatchewan. The yield of this clone varied widely from complete failure at the trial in Queenstown, MD to 14.7 odt ha^{-1} yr^{-1} in the trial in Boisbriand, QC, which reflects the wide range of site and weather conditions across these trials and this specific clone's G×E interactions. The yield of SV1 was 37.7% higher in the new trials compared to the old trials but SV1 failed in the Queenstown, MD and Peter's Tract, DE trials. If these two trials are dropped then the mean yield of SV1 in the new trials (9.5 odt ha^{-1} yr^{-1}) is only 7.9% higher than in the old trials (8.9 odt ha^{-1} yr^{-1}).

Yield and ranking among the new clones varied across the in the range of trials reported here. Eleven different clones were in the top five yielding clones across the sites. One clone (clone ID 9970-036 – *S. sachalinensis* × *S. miyabeana* 'Canastota') was among the top five clones in five of the new trials. Only two clones (clone ID 99202-004 – *S. viminalis* × *S. miyabeana* 'Fabius' and clone ID 9882-34 - *S. purpurea* 'Fish Creek') were among the top five clones in more than three trials. All of the other top five clones only appeared once or twice.

Discussion

Increases in yield of perennial crops over multiple rotations has been recognized previously, but not well quantified for woody crops managed in a coppice system. It is likely that once shrub willow crops establish an extensive root system, over time less photosynthate and nutrients need to be allocated for belowground growth and more can be dedicated to aboveground biomass production.

Table 2. *First rotation yield (odt ha⁻¹ yr⁻¹) for a series of willow biomass crop yield trials established with new willow genotypes between 2005 and 2007*

	2005 Belleville, NY	2005 Tully, NY	2006 Constableville, NY	2006 Waseca, MN	2007 Middlebury, VT	2007 Boisbriand, QC	2007 Birch Hills, SK	2007 Prince Albert, SK	2007 Saskatoon, SK	Average	SE
No. clones planted	18	18	30	26	30	27	6	6	30	21.6	
Top clone	13.6	10.8	10.1	10.1	14.6	17.2	11.8	12.1	10.8	12.3	0.79
Top 3 clones	12.8	10.6	9.6	10.0	14.3	16.9	11.3	11.1	9.2	11.8	0.84
Top 5 clones	12.2	10.4	9.4	9.8	14.1	15.6	10.5	10.0	8.7	11.2	0.77
New clone top 3*	12.3	10.2	9.6	9.8	14.3	16.7	11.3	9.8	9.2	11.5	0.85
Site mean	9.9	8.8	6.1	8.4	11.0	12.9	10.0	9.5	6.1	9.2	0.73
Reference clones											
SV1	12.7	8.4	9.0	4.7	10.9	14.7			6.1	9.5	1.18
SX61	10.5	10.8	7.5	9.6	12.0	13.4	7.8	11.8	5.1	9.8	0.87
SX64	7.7	10.3	5.9	10.1	11.1	17.2	9.8	9.1	6.2	9.7	1.11
Mean	10.3	9.9	7.5	8.1	11.3	15.1	8.8	10.5	9.6	10.1	0.74

Clones in these trials were bred at SUNY-ESF with the exception of the three reference clones (SV1, SX61, SX64) and some other select clones (SX67, S365, and S25) that were originally from the OMNR and the UofT programmes. Site labels include the year of planting and location.

The amount of belowground biomass in these systems appears to increase rapidly during the first few years of the crop, eventually reaching a maximum biomass threshold during the fourth 3-year harvest rotation (Pacaldo *et al.*, 2011). This allows the crop to increase aboveground biomass production over time, as was the case in the multiple rotation data in this study, and also has important implications for the greenhouse gas (GHG) balance of these systems.

The increase in yield over multiple rotations is important for modeling the production and economics of willow biomass systems. If the yield increases measured for the reference clones over multiple harvest rotations are applied to the first rotation data from the new yield trials, then yields over multiple rotations can be extrapolated. Multiplying the mean first-rotation yield of the top five clones in the new yield trials (11.0 odt ha^{-1} yr^{-1}) by the 23.0% increase expected for the second through seventh harvest rotations results in a mean yield over seven rotations of 13.2 odt ha^{-1} yr^{-1}. If the factor applied to the fourth through seventh rotations is instead a 30.8% increase over the first-rotation yields, then the mean yield over seven rotations is expected to be 13.5 odt ha^{-1} yr^{-1}. At mean yields of 13.2 odt ha^{-1} yr^{-1} over seven rotations the overall internal rate of return for willow biomass crops is 5.9% (Buchholz & Volk, 2011). Further increasing yields by 50% though a combination of breeding and crop management improvements would raise the IRR from 5.9–13.9% (Buchholz & Volk, 2011).

The difference in the mean yields of the reference clones and the new clones provides some indication of the impact of improved plant material on overall yield. Across all sites the top three new clones had a 13.9% greater mean yield than the reference clones. At individual sites this difference ranged from a high of just over 28% at both the Constableville, NY and the Birch Hills, SK sites to a low of -6.7% at the Prince Albert, SK site. The new genotypes in these trials were predominantly from the first generation of breeding efforts in NY, and the gains being made provide an early indication of the potential yields gains that can be achieved with shrub willow. Furthermore, a large base of genetic material combined with a greater understanding of breeding and genomics has improved our ability to increase yields even further (Smart & Cameron, 2008).

At all the sites in eastern North America and one of the sites in western Canada the top three new willow clones produced greater mean yields than the reference clones, but at two locations in Saskatchewan the reference clones produced greater mean yields. The lack of a consistent set of top producing clones across this range of sites is not surprising considering that these genotypes were selected in a single environment in NY and emphasizes the need to better understand the G×E interaction for this system so that, ideally, clones with a wide range of site plasticity can be selected to optimize the yield potential. This will require improved and more extensive breeding selection trials across a wider range of environments. Alternatively, selections made in each particular growing environment can be made, resulting in a set of clones selected for optimum performance in that region that may not outperform the best suite of clones selected in other regions.

The data presented here are from the first rotation of all these trials and unfortunately many of them were removed after the end of their first rotation. Assessing one trial over four rotations indicated that only 60% of the top 10 producing clones in the trial were still among the top ten at the end of the fourth rotation (Volk *et al*., 2010). Because of the perennial nature of this system it is important to monitor trials over more than one rotation to capture the responses of different clones to the range of conditions in a region and select the best genotypes for sustained long-term productivity.

In addition to plant genetics there are a number of other factors that influence the yields of willow biomass crops including soil properties, weather conditions, pests and diseases, and crop management - especially site preparation and weed control (Aylott *et al*., 2008). The top five clones in the new trials had 21.7% greater yield than the older trials. Some of this increase can be attributed to the improved genotypes (new clones had 13.9% greater yield than reference clones in the new trials), but a portion of it is also due to site factors and crop management. Previous analysis of soil physical and chemical properties for a subset of the older trials did not reveal any strong relationships between these characteristics and willow yield (Kiernan *et al*., 2003). Preliminary analysis of weather factors for a subset of these trials in the Northeast and Mid Atlantic region suggested that July temperatures and precipitation were important factors driving yield, but further analysis of the available data is necessary. Weed competition during the establishment of willow biomass crops is an important factor that influences survival and production during the first rotation. This is a factor that has previously not been well quantified in these trials, but adds a degree of variability that makes identification of relationships between yield, soil properties, and weather conditions more difficult. The impact of pests and diseases, winter dieback in some regions and deer browse on willow yield are important factors that need to be better understood. Based on a limited amount of sampling done on a subset of these trials, rust incidence was significantly correlated with yield (L B Smart, M J Serapiglia and K D Cameron, unpublished), but further work needs to be done to address the impact of these factors as well, especially because of the perennial nature of this system and the genetic variability of insect and disease pests on clonal material.

Willow biomass cropping systems are in their infancy and there is potential for large gains in yield by improving production practices and through breeding. This work in combination with other research and development to reduce production costs and add value to each tonne of biomass produced will help to make the system more economical. As the knowledge base about the biology, genetics, and management of shrub willow expands and the environmental functions it can provide as it is integrated across the landscape are better understood, it will be deployed more effectively so that other benefits derived from this system, in addition to biomass, can be optimized.

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