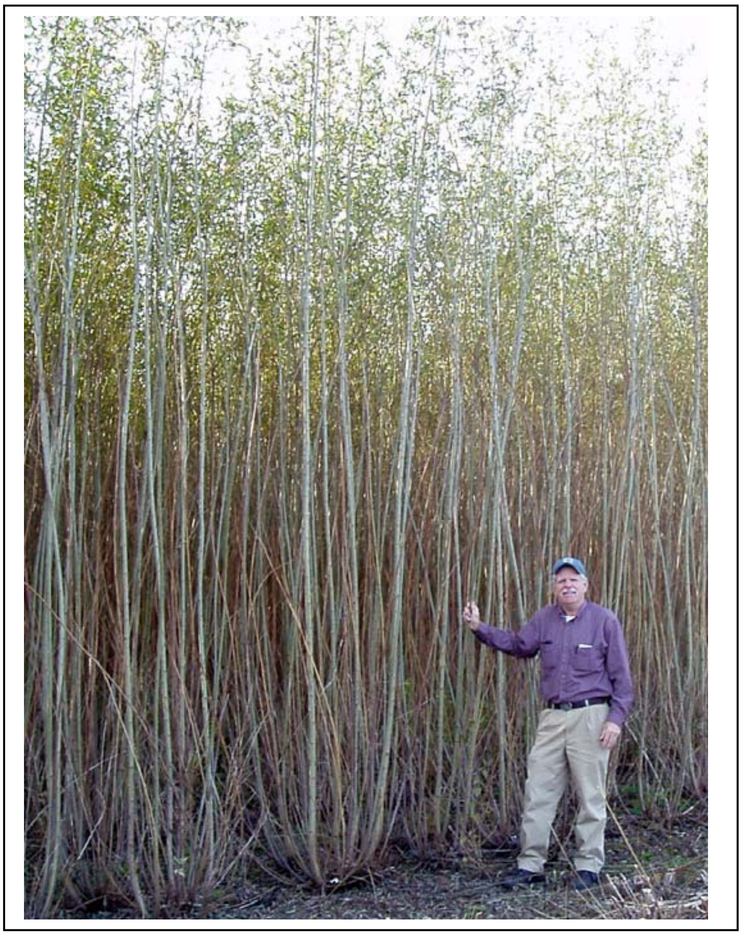
Promising resources and systems for producing bioenergy feedstocks: Shrub willow

Short-Rotation Willow for Bioenergy, Bioproducts, Agroforestry and Phytoremediation in the Northeastern United States

Use of short-rotation willow crops can provide a local woody biomass resource to supplement sustainable harvest of Northeastern hardwood forests, building to a large-scale, reliable supply of woody biomass for bioenergy in the northern U.S.

Short-Rotation shrub willow can also provide other environmental services, such as: nutrient recovery, landscape diversity, living snow fences and phytoremediation.



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SHORT-ROTATION WILLOW FOR BIOENERGY, BIOPRODUCTS, AGROFORESTRY AND PHYTOREMEDIATION IN THE NORTHEASTERN UNITED STATES

Authors

Lawrence P. Abrahamson (SUNY-ESF), Timothy A. Volk (SUNY-ESF), Lawrence B. Smart (Cornell), Edwin H. White (SUNY-ESF)

Summary report

KEY MESSAGES

Decades of research and experience with willow biomass crops in the U.S and Europe has resulted in the development of a system that is currently at a pre-commercial stage as an alternative crop for the production of heat, power, fuels and/or bioproducts. In the future other conversion technologies, including a biorefinery model, will provide other viable bioenergy and bioproduct markets.

Ongoing research will optimize the production system and increase yields, which will further lower costs associated with the system. The current shrub willow biomass crop production system is also being adapted for phytoremediation, living snowfences, and riparian buffers.

Farmers in the U.S. may use willows as an alternative crop – to produce feedstock for fuel and bioproducts applications - and as vegetation filter strips in riparian areas. Land managers, landscape architects, and engineers will incorporate willow into various environmental management systems.

Cover Picture: Three-year-old shrub willow on 16-year-old root stock in Tully, NY (photo by Kimberly Cameron).

EXECUTIVE SUMMARY

Research on willow (*Salix* spp.) as a locally produced, renewable feedstock for bioenergy and bioproducts began in New York in the mid-1980s in response to growing concerns about environmental impacts associated with fossil fuels and declining rural economies.

Simultaneous and integrated activities—including research, large-scale demonstrations, outreach and education, and market development—were initiated in the mid-1990s to facilitate the commercialization of willow biomass crops.

Despite technological viability and associated environmental and local economic benefits, the high cost of producing willow biomass and lack of markets have been barriers to wide-scale deployment of this system. Increases in harvesting efficiency, yield improvements from hybrid breeding efforts and recently improved crop management techniques promise to lower the cost of production and increase returns for growers.

Recent policy changes at the federal level, including the biomass crop assistance program, a provision to harvest bioenergy crops from Conservation Reserve Program land in New York and a closed-loop biomass tax credit; and state-level initiatives such as renewable portfolio standards may help to further reduce the difference and foster markets for willow biomass.

Years of work on research and demonstration projects have increased understanding of the biology, ecophysiology and management of willow biomass crops. This information has led to the deployment of willow for applications such as phytoremediation, living snowfences, and riparian buffers across the northeastern U.S.

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INTRODUCTION

Willow (*Salix* spp.) cultivation and use has a long history in North America. Native Americans understood the biology and benefits associated with willow and used the local species for medicinal purposes and as construction material for a wide array of items including sweat lodges, furniture, baskets, rope, whistles, arrows and nets (Moerman 1998). Coppicing was a common practice among Native Americans, and in some regions willow cuttings were used to stabilize streambanks that were prone to erosion (Shipek 1993). European immigrants began cultivating imported shrub willow in the United States in the 1840's. By the late 1800's willow cultivation for basketry and furniture had spread from the shores of Maryland to the western borders of Wisconsin and Illinois. New York State dominated willow cultivation in the U.S. at this time, with 60% of the total reported area and about 45% of the income generated from willow products (Hubbard 1904). However, at the end of the 1800's, demand for willow was declining due to competition from cheaper and lower quality material and competition from basket production overseas. By the 1930's only isolated pockets of willow cultivation remained.

The cultivation of willow was revitalized in upstate NY in the mid 1980's by Drs. Abrahamson and White at the State University of New York College of Environmental Science and Forestry (SUNY-ESF). The focus was research on cultivation of willow biomass crops as a locally produced, renewable feedstock for bioenergy and bioproducts. This paper summarizes the development of willow biomass crops in the northeastern United States and highlights some of the results from over 25 years of research. The current economic status of willow biomass crops and the impact of recent developments in breeding, harvesting technology and current and future markets for willow biomass will be highlighted. An increased understanding about the biology, ecophysiology and management of willow biomass crops has led to willow being used in applications such as phytoremediation, living snowfences, and riparian buffers. The status of these efforts in the northeastern United States is summarized.

DEVELOPMENT OF WILLOW BIOMASS CROPS IN THE NORTHEASTERN UNITED STATES

As initial research on willow biomass crops in North America, United Kingdom, and Sweden began to yield encouraging results, and concern about environmental issues related to the use of fossil fuels and the declining rural economy in upstate New York grew, interest developed in the concept of a rural based enterprise centered on willow biomass as a renewable source of woody lignocellulosic feedstock for bioenergy and bioproducts. In the mid 1990's, over 20 organizations teamed up to form the Salix Consortium, whose goal was to facilitate the commercialization of willow biomass crops in the northeastern and midwestern regions of the United States (Volk et al, 2006). The Consortium included electric utilities, universities, state and federal government agencies, and private companies with expertise in natural resources management and bioenergy. To reach the Consortium's goals a series of simultaneous activities; including research, regional clone-site trials, a large-scale demonstration program, and outreach and education efforts, were initiated. These activities were aimed at optimizing the production system to produce the highest biomass yields at the lowest cost, educating potential producers and other key target audiences, and expanding markets for bioenergy and bioproducts.

Collaboration among the members of the Salix Consortium resulted in the establishment of over 280 ha of willow biomass crops between 1998 and 2000 in western and central New York. Smaller clone-site/yield trials, ranging in size from 0.5 to 1.0 ha, living snowfence sites, phytoremediation trials, and willow demonstration plantings were established in multiple states and several provinces through 2011(Figure 1). At the biomass trial locations between six and 40 genotypes of willow, and hybrid-poplar in the earlier trials, were screened for suitability to different soils and climate conditions. These trials and the large-scale plantings indicated that shrub willow could be developed across a wide geographical area. Results revealed that several of the clones tested grow well across a range of sites, while other clones were more site-specific (Kiernan et al, 2003). Future trials will be needed to assess this variability, especially as new genotypes are produced from breeding programs and agroforestry and phytoremediation applications for willow are developed.

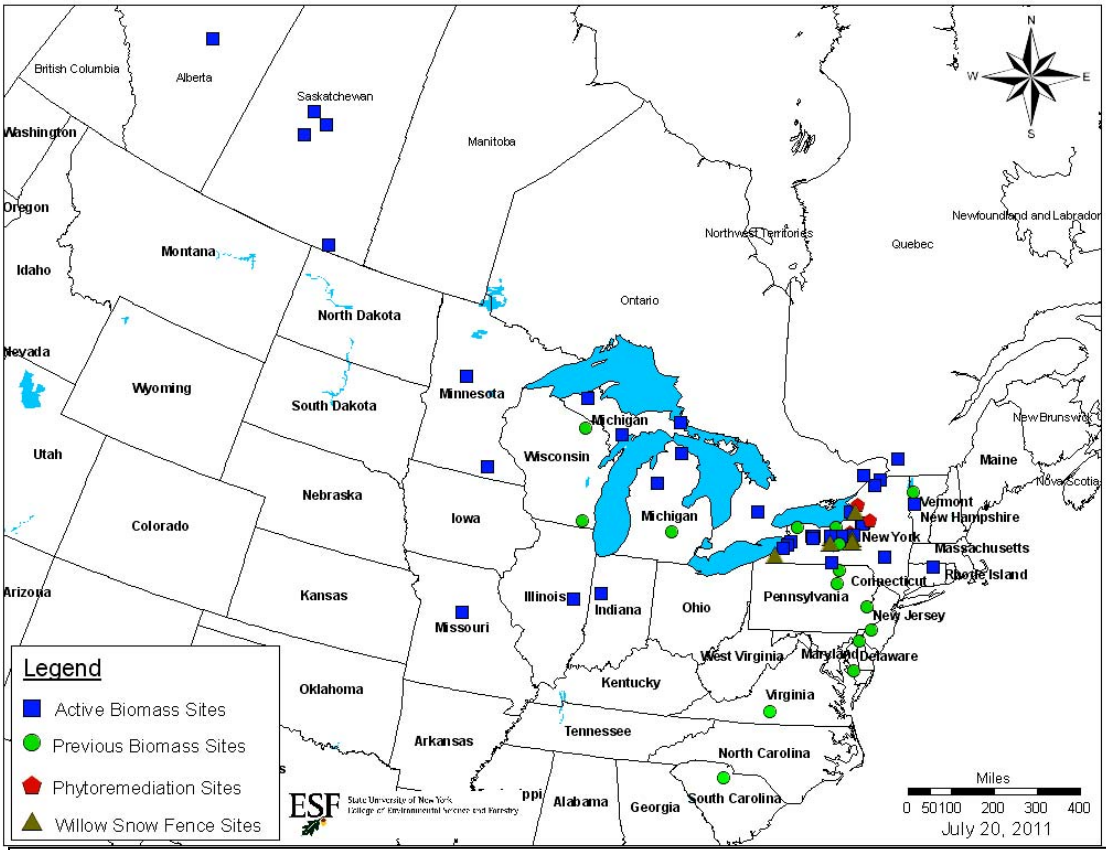

FIGURE 1: WILLOW BIOMASS CROP SITES, CLONE/YIELD-SITE TRIALS, PHYTOREMEDIATION, AND LIVING SNOWFENCE SITES ESTABLISHED WITH PLANT MATERIAL FROM SUNY-ESF IN MULTIPLE STATES AND SEVERAL PROVINCES FROM 1998 TO 2011.

Yields of fertilized and irrigated willow grown in three-year-rotations have exceeded 27 odt ha^{-1} yr $^{-1}$ in North America (Kopp et al, 1997; Adegbidi et al, 2001, 2003) and 30 odt ha^{-1}yr^{-1} in Europe (Christersson et al, 1993). Considering economic limitations, irrigation will probably not be used for most large-scale production operations. However, these yields provide an estimate of the yield potential under ideal conditions and represent a goal in breeding for biotic and abiotic stress tolerance. First-rotation yields of the top three shrub willow clones across 18 willow yield trials have ranged from 7.1 to 14.9 odt ha^{-1} yr^{-1}, with an average of 11.1 odt ha^{-1} yr^{-1} across all the sites (Volk et al, 2011). With an energy content of about 19.4 GJ/dry ton (Volk and Luzadis 2009), current yields can provide about 215 GJ ha^{-1} yr^{-1}.

The first commercial-scale harvests of willow biomass crops in North America began in the winter of 2001/2002 using a Bender harvester, purchased from Sweden, with a cone type chipper. First-rotation commercial scale harvests of the most consistent cultivars resulted in average yields of 7.5 odt ha^{-1} yr^{-1}. Improvements in different parts of the production system, ranging from improved weed control, breeding, matching cultivars to different sites, optimizing planting density and nutrient management, will help reach the production potential of this crop.

Research, demonstration and scale-up efforts have been important in refining the production system for willow biomass crops, improving the knowledge base about the biology and ecology of shrub willows, correcting misconceptions about willow biomass crops among the public, policy makers and non-governmental organizations, and quantifying some of the associated environmental and rural development benefits. Extensive work in Sweden (Verwijst 2001), the United Kingdom (Armstrong 1999), and Canada (Kenny et al, 1990) contributed significantly to efforts to develop willow production systems in North America. The basic characteristics of the willow biomass production system involve genetically improved plant material grown on open or fallow agricultural land. Current production involves intensive site preparation to control weeds, double-row mechanical planting of 15,300 plants ha^{-1}, nitrogen inputs (recent research at SUNY-ESF indicates that fertilizer might not be necessary to maintain good production levels in the northeastern U.S. (Quaye and Volk 2011, Quaye et al, 2011)) at the beginning of each rotation, and multiple 3- or 4-year-rotations (Volk et al, 1999, Abrahamson et al, 2002).

Selected Research Results on the Sustainability of Willow

Quantifying some of the environmental and rural development benefits associated with willow biomass crops has been a focused area of research over the past 15 years. Issues related to soil conservation, biodiversity, greenhouse gas (GHG) and energy balances, and socioeconomic impacts of the system have been studied with different levels of intensity. Results from this research have been important in making the case for the sustainability of willow biomass crops (Volk et al, 2004), which has bolstered public support and encouraged policy decisions at the state and federal level that place value on these benefits.

Concerns expressed by landowners, natural resources and agriculture professionals and other collaborators about erosion on susceptible soils during the establishment phase of willow biomass crops led to research on alternative methods of site preparation. Results indicate that cover crops, like winter rye (*Secale cereale L.*), in the fall and/or common white “Dutch” clover (*Trifolium repens L.*) in the spring, and changes in the timing of tillage practices can effectively be incorporated during the establishment of willow without compromising, and in some cases increasing, aboveground biomass production. The approach to managing cover crops during the establishment of willow and other short-rotation woody crops (SRWC) requires balancing three critical factors, aboveground biomass production, weed control, and residue cover. The most effective management system identified to date that balanced these three critical factors was to establish a rye cover crop in the fall after plowing and disking, kill it with the herbicide glyphosate in the spring, leave the plant residue on the soil surface and control new weed growth with preemergence herbicides (Volk 2002). Recent research at SUNY-ESF indicates that a low growing white clover cover crop planted in the spring followed by a strip application of the herbicide glyphosate in the double-row zone just before planting willow followed by application of preemergence herbicides also worked well if fall site preparation was not done (Adiele and Volk 2011). These results have led to modifications in the establishment of willow biomass crops that allows them to be grown on sloping farmland across the region. The system can be refined further so that the soil conservation benefits are realized and associated expenses are minimized with continued research on both fall and spring cover crops. Zone tillage is another method that can be used to reduce soil disturbance overall, while effectively establishing a rooting zone and breaking existing plough pan layers (Figure 2).

Figure 2: Zone tillage as an alternate site preparation method for willow bioenergy crops (photo by Lawrence Smart).

A common misconception about willow biomass crops is that they are monocultures, which when deployed across the landscape will create “biological deserts”. Mixtures of different species and hybrids of willow are deployed in each field by planting blocks of different varieties across a field or random mixtures of varieties within each row. Years of research on above (Dhondt et al, 2004, 2007) and below ground (Minor et al, 2004) biodiversity in these systems has been essential in correcting misconceptions about diversity in willow crops. Willow crops provide good foraging and nesting habitat for a diverse assemblage of bird species. Seventy-nine bird species were observed in willow plots, 39 of which were seen regularly (Dhondt et al, 2007). Bird diversity in woody crops is greater than in agricultural land and is comparable to natural habitats including shrub land, successional habitats (e.g. abandoned fields, second-growth forest, and regenerating clear-cuts), and intact Eastern deciduous forest. These data, together with other information demonstrating that willow biomass crops enhance landscape diversity, have been important in gaining recognition for the diverse environmental benefits associated with willow biomass crops.

An initial life cycle analysis (Heller et al, 2003) indicated that willow biomass crops have low greenhouse gas emissions (3.7 Mg CO_2eq ha^{-1} rotations) over an entire production cycle of seven three-year-rotations when all greenhouse gases are included in the analysis. These earlier studies were based on a limited amount of data, especially on below ground biomass. A recent study (Pacaldo et al, 2011) indicates that below ground biomass in willow biomass crops increases rapidly in the first few rotations but levels off at a much higher amount than was used in the initial analysis. These new measurements of below ground biomass indicate that the willow biomass crop production system actually sequesters carbon in addition to producing biomass for renewable energy applications.

The net energy ratio for the willow biomass production system is 1:55 over seven three-year-rotations (Heller et al, 2003). This means that for every unit of non-renewable fossil fuel used to produce the willow biomass crops, 55 units of energy are stored in willow biomass chips at the edge of the field after the material is harvested. Replacing commercial N fertilizer with organic amendments can increase the net energy ratio to 1:73 – 80 depending on the type of organic amendments that are used (Heller et al, 2003). Studies have shown that organic amendments are as effective as commercial fertilizer (Adegbidi et al, 2003). In several recent studies in the northeast U.S. neither commercial or organic amendments significantly increased yields, indicating that in many situations nutrient additions may not be required to maintain good yields of willow (Quaye and Volk 2011, Quaye et al, 2011). This would increase the net energy ratio, further reduce GHG emissions, and reduce the cost of production.

Transporting the biomass 96 km and converting it to electricity in a coal-fired power plant with 30% efficiency results in net energy ratio of 1:11 or 1:13 using a gasification conversion system (Heller et al, 2004; Keoleian and Volk 2005). In essence, willow crops are large solar collectors that capture the sun’s energy and store it as woody biomass. Production of willow biomass crops, and other systems with similar positive net energy balances, can be used to address both environmental and energy security concerns now and in the future.

Willow biomass crops have the potential to revitalize rural economies by diversifying farm crops, creating an alternative source of income for landowners, and circulating energy dollars through the local economy. Modeling has indicated that about 75 direct and indirect jobs will be created and over \$520,000 year^{-1} in state and local government revenue would be generated for every 4,000 ha of willow that is planted and managed as a dedicated feedstock for bioenergy (Proakis et al, 1999).

Market Development for Willow Biomass

The development of woody biomass as a feedstock for bioenergy and bioproducts involves the use of multiple sources of material that together create a reliable and consistent year round supply. This is useful for end users because they are not dependant on a single source of material and the fluctuations that can occur within a single source. With multiple sources, there are varying amounts of supplies available depending on locations and time of year. The three main sources of woody biomass are: (1) wood residues from wood manufacturing industries and/or municipal waste streams; (2) low value trees and logging residues in forests that are currently being underutilized; (3) and SRWC like shrub willow biomass crops. Development and deployment of willow biomass crops will occur as one of multiple streams of woody biomass rather than a sole source of material.

The challenge in large-scale deployment of willow biomass crops is to simultaneously optimize production, develop farmer interest, increase crop acreage, and add a new fuel to the power supply and a new feedstock to the developing value-added bioproducts markets. The scenario remains challenging because there is currently not enough willow biomass established to initiate large-scale use of the material, while at the same time there are currently no long-term commitments assuring producers of a stable market in the future. The time frame from planting to first harvest is typically four years, so there is a larger time gap that needs to be bridged compared to new annual crops that are introduced into the market place. Similar challenges have faced the deployment of willow in other countries as well (Hilton 2001).

The utilities initially involved with the Salix Consortium were actively engaged in the process and had begun to discuss setting up supply agreements with producers of willow biomass crops. However, a requirement of restructuring of the energy industry in NY was the sale of power plants by utilities. New owners of the plants have become interested in the concept to a limited degree, but are more sensitive to short-term economic issues since each plant now must operate profitably as a cost center.

There are two coal-fired power plants in NY that have been retrofit to co-fire biomass. The 104 MW Greenidge pulverized coal power plant (originally owned by New York State Electric and Gas, but currently owned by AES) in central NY has been co-firing wood residues at levels up to 10% by heat input for over a decade. Test firing of willow biomass at Greenidge was performed in the late 1990's and valuable lessons were learned about processing and handling the material. Due to cost structures and power prices in New York State, this facility is currently (2011) not operating and is for sale. The second location is one 100 MW boiler at the Dunkirk Steam Station (originally owned by Niagara Mohawk Power Corporation (NMPC), but currently owned by NRG Inc.) in western NY. A week-long test of the co-firing system with woody biomass (including willow chips) at the Dunkirk Steam Station, including intensive monitoring of emissions, was successfully completed years ago. Emissions tests indicated that NO_x, SO_x and particulate matter emissions were reduced when woody biomass was used. These test results provided the data necessary to allow NRG Inc. to obtain regulatory approval to pursue commercial co-firing, which would create a market for willow biomass crops in western NY; however NRG Inc. has not done so to date because of economic conditions.

There are several other facilities across NY where co-firing of coal and woody biomass, including willow could occur. Estimates indicate that woody biomass used in co-firing situations could contribute almost 300 MW of renewable energy (State of New York Public Service Commission 2005). The production of 1 MW of power would require about 300-325 ha of willow biomass crops, if willow were the sole source of woody biomass for co-firing. Even if willow is one of multiple sources of woody biomass, developing co-firing in NY has the potential to provide a significant market for willow.

In addition to co-firing facilities, willow biomass can be used as part of the fuel mix in power plants, heating facilities and combined heat and power (CHP) operations that use woody biomass as fuel. These may range from small systems that are primarily used to generate heat or larger biomass facilities that produce heat and power or just power (Martin et al, 2004). Several end users have expressed interest in using willow biomass because it provides them another source of woody feedstock, making them less vulnerable to price and supply fluctuations associated with other sources of woody biomass, including forest products industry residues and managed forest harvesting. In 2006, the owners of one of the wood chip fired CHP plants in central NY started to grow willow crops with approximately 200 ha in the ground as a source of woody biomass for their operations, but after this facility was sold in 2011, no new willow crop acreage has been planted since 2010.

Alternative technologies that will increase the overall conversion efficiency of these systems and improve their environmental benefits are currently in various stages of research and development, and could help to create markets in the near future. The most promising of these is the development of locally produced, high-efficiency boilers for small-scale heating applications - ranging from 150 to 300 kW - that are capable of using wood chips with up to 30% moisture content. While this equipment has been readily available in Europe, with competition among many high-quality manufacturers, the use of wood chips as heating fuel in the US has untapped potential, especially considering that willow can be grown and harvested on a small scale as a locally-produced heating fuel.

In the near future multiple products will be made from each ton of biomass using the concept of a biorefinery. The biorefinery is based on present day oil refineries, where a barrel of oil is used to simultaneously create multiple products. The model for biomass based biorefineries is evident today in facilities such as corn to ethanol plants, where liquid fuels, animal feed, CO_2 and other products are produced, or pulp and paper mills, where paper products and heat and power are produced. In the future biorefineries will fully utilize a ton of biomass to produce a wider array of products, including biobased fuels, specialized and platform chemicals, biodegradable plastics, materials and heat and power, as alternatives to products currently derived from non-renewable fossil fuels. One location where wood-based biorefineries may develop is in association with wood-fired power plants or pulp mills. At these locations valuable hemicelluloses sugars and chemicals can be extracted before the wood chips are used to produce energy or pulp. Lab-scale tests indicate that an extraction which removes about 23% of the mass from willow and sugar maple (*Acer saccharum*) wood chips can add up to $45 of value to a dry ton of woody biomass (Amidon et al, 2008). The development of these value-added bioproducts will spur demand for woody biomass, including willow, in the future.

Improving the Economics of Willow Biomass Crops

Despite the numerous environmental and rural development benefits associated with willow and other SRWC, and projections of their deployment in the future, their use as a feedstock for bioenergy and bioproducts has not yet been widely adopted in the U.S. The primary reason is their high cost. Current costs to produce and deliver SRWC to an end user are \$50–60 odt^{-1} (\$2.60–3.00 GJ^{-1}) (Walsh et al, 1996; Tharakan et al, 2005a; Buchholz and Volk 2011). On an energy unit basis, these prices are greater than commonly used fossil fuels like coal, which for large-scale power producers in the Northeast have averaged \$1.50–2.00 GJ^{-1} over the last few years, although recent prices have been as high as \$3.40 GJ^{-1}. A commercial SRWC enterprise for power will not be viable unless the biomass price, including incentives and subsidies, is comparable to that of fossil fuels, and parties involved in growing, aggregating and converting the fuel, are able to realize a reasonable rate of return on their investment.

A budget model, EcoWillow *v*1.6, that allows users to analyze the entire production-chain for willow crop systems from the establishment to delivery of wood chips to the end-user was developed at SUNY-ESF and is available to download at http://www.esf.edu/willow/ (Buchholz and Volk 2011). With an average productivity of 12 odt ha^{-1} year^{-1} over seven rotations and a delivered biomass price of \$60 (US dollars) odt^{-1} provides growers with an IRR of 5.5%. Harvesting is the largest cost component for willow production (33%) followed by establishment (23%) and land and insurance costs (16%) (Buchholz and Volk 2011). Increases in willow yield, rotation length, and over road chip truck capacity as well as a reduction in harvester down time, land costs, planting material costs, and planting densities can improve the profitability of the willow crop system. Results indicate that planting speed and fuel and labor costs have a minimal effect on the profitability of willow biomass crops. To improve profitability, efforts should concentrate on (1) optimizing harvesting operations (2) increasing yields (3) reducing planting stock costs, and (4) development of planting designs with new high yielding shrub willow clones to reduce planting density.

In addition to producing value-added bioproducts from SRWC there are two major pathways to make SRWC for power cost competitive with fossil fuels. One is to lower the cost of production by reducing operating costs and increasing yields (as noted above). The other is to value the environmental and rural development benefits associated with the crop. Ongoing research projects at SUNY-ESF and Cornell University are focused on reducing operating costs and increasing yields. The two areas with the greatest potential for immediate impact are improving yields through breeding and reducing costs by improving harvesting efficiency. Recent policy developments in the federal Conservation Reserve Program (CRP), federal renewable energy tax credits, and state Renewable Portfolio Standards (RPS) are mechanisms that begin to value some of the benefits associated with willow biomass crops. Their implementation will have a significant impact on the delivered price of willow biomass and the potential to deploy willow biomass crops in the northeastern U.S.

Increasing Yield through Willow Breeding

There is tremendous potential to increase yields of shrub willows through breeding and hybridization, largely due to the wide range of genetic diversity across the genus, the historical lack of domestication of shrub willow as a crop, and the ability to capture epistatic and heterotic genotypic variance through vegetative propagation. Many species of willow are amenable to hybridization, which can lead to dramatic hybrid vigor and can have the added benefit of reduced fertility of the progeny, limiting the potential for invasiveness. Willow can be quickly and easily propagated vegetatively from stem cuttings, which speeds the analysis of genotype-by-environment interactions and selection of genotypes with superior and stable yield. Once superior genotypes are identified, they can be rapidly propagated for deployment in the production system. A 50% increase in the yield of willow biomass crops more than doubles the internal rate of return from willow biomass crops (Buchholz and Volk 2011).

Major efforts to breed shrub willow as a biomass crop have been progressing for more than 30 years in Sweden (Gullberg 1993) and the United Kingdom (Lindegaard and Barker 1997). Research on the basic genetics of *Salix viminalis* has provided a large body of information on the inheritance of traits important for biomass production (Rönnberg-Wästljung et al, 1994; Rönnberg-Wästljung and Gullberg 1996; Rönnberg-Wästljung 2001) and a genetic map to support breeding for desired traits (Hanley et al, 2002). These long-term breeding programs have produced yield increases of 12–67% in Sweden (Larsson 1998, 2001) and 8-143% in the United Kingdom (Lindegaard et al, 2001). Willow breeding in North America was initiated by Louis Zsuffa at the University of Toronto, and has been carried on in New York with a focused, long-term breeding program that is starting to produce similar increases in yield with novel *Salix* hybrids adapted for growth in the U.S.. Results from nine yield trials that included new cultivars from the first few years of willow breeding in the U.S. indicate the mean yield of the top three new willow clones was 13.9% better than the three reference clones (Volk et al, 2011).

Starting in 1994, researchers at SUNY-ESF were developing the genetic resources and technical expertise to perform controlled pollinations (Kopp et al, 2002a), establish nursery screening trials, and evaluate large numbers of progeny individuals. Significant effort has been dedicated to building a large and diverse collection of individuals of many *Salix* species, both native and exotic. Currently, this collection, planted at the SUNY-ESF Genetics Field Station in Tully, NY and at Cornell University, New York State Agricultural Experiment Station, Geneva, NY, includes more than 750 diverse genotypes of willow collected from natural stands across the northern U.S. or acquired from other breeding programs, including accessions from Europe, Asia, and North America. More than 300 accessions of *S. eriocephala*, *S. purpurea*, *S. nigra*, *S. lucida*, *S. cordata*, *S. dicolor*, and *S. bebbiana*, among others, have been collected since 2000. The breeding strategy, initiated in 1998, involves producing a large number of families, selecting the best individuals from a diverse array of genetic backgrounds by phenotypic analysis, and then propagating those individuals for rigorous, replicated selection trials (Kopp et al, 2001).

Through controlled breeding, several thousand progeny genotypes have been produced. Over the last five years, molecular genetic techniques, including amplified fragment length polymorphism (AFLP), microsatellites, and gene sequencing have been used to determine the genetic diversity within our collection and among natural populations, to develop clone-specific fingerprints, and examine the relationship between the genetic similarities of parents and the vigor of their progeny (Kopp et al, 2002b; Lin et al, 2007, 2009). Application of molecular techniques improves the likelihood of selecting individuals for breeding that will produce improved offspring.

In 1998-2000, progeny from over 100 families of *S. eriocephala*, *S. purpurea*, and involving few other species were produced through controlled breeding, planted in nursery screening trials, genetics trials, and the best individuals chosen for a selection trial planted in 2002. The data from these trials indicated that traits important for biomass yield are readily passed on from superior parents to their progeny and that a majority of progeny perform better than their parents, displaying hybrid vigor (Phillips 2002; Cameron et al, 2008). More than 20 of these new varieties, including *S. purpurea*, *S. viminalis* x *S. miyabeana*, *S. sachalinensis* x *S. miyabeana*, and *S. purpurea* x *S. miyabeana* (7 of which have been patented in the U.S.) are currently being evaluated in regional yield trials, and larger demonstration trials (Smart and Cameron 2008). A commercial nursery, Double A Willow in Fredonia, NY (www.doubleawillow.com) holds an exclusive license to produce and market whips/cuttings of these willow cultivars for deployment in commercial plantings (Table 1).

Table 1: Commercially available shrub willow varieties in the USA

Variety	Species
SV1	*Salix × dasyclados*'SV1'
S365	*Salix caprea* hybrid 'S365'
S25	*Salix eriocephala*'S25'
SX61	*Salix sachalinensis*'SX61'
SX64	*Salix miyabeana*'SX64'
SX67	*Salix miyabeana*'SX67'
Fish Creek	*Salix purpurea*'Fish Creek'
Onondaga	*Salix purpurea*'Onondaga'
Allegany	*Salix purpurea*'Allegany'
Sherburne	*Salix sachalinensisxS. miyabeana*'Sherburne'
Canastota	*Salix sachalinensis×S. miyabeana*'Canastota'
Tully Champion	*Salix viminalis×S. miyabeana*'Tully Champion'
Owasco	*Salix viminalis×S. miyabeana*'Owasco'
Otisco	*Salix viminalis × S. miyabeana*'Otisco'
Oneida	*Salix purpurea×S. miyabeana*'Oneida'
Millbrook	*Salix purpurea×S. miyabeana*'Millbrook'

Willow breeding is now centered at Cornell University, where the emphasis is on the application of next-generation sequencing technology for the development of inexpensive and high-density markers for QTL and association mapping and for genomic selection. In a collaboration between Oak Ridge National Laboratory, J. Craig Venter Institute, Joint Genome Institute, and Cornell University, the *S. purpurea* genome is being sequenced using a whole genome shotgun sequencing approach with next-generation technology (454 and Illumina). Biparental and association mapping populations of *S. purpurea* have been established at the NYS Agricultural Experiment Station and are being phenotyped for many traits. Primary among those is the characterization of variations in woody biomass composition, enabled through the development of high-resolution thermogravimetric analysis. Significant variation in cellulose, hemicelluloses, lignin, stem density, and ash content has been measured among commercial cultivars and in breeding populations (Serapiglia 2008, 2009). New cultivars are being scaled up for regional yield trial testing based on selections made in a recently planted and evaluated selection trial (Figure 3).

Figure 3: Second-year post-coppice growth of a shrub willow selection trial planted at Cornell in Geneva in 2008 (photo by Lawrence Smart).

Improving Harvester Efficiency

Improving the efficiency of harvesting and transportation of willow biomass, which accounts for 32-60% of the cost of willow (Mitchell et al, 1999, Buchholz and Volk 2011), can have a significant impact on delivered price. Increasing harvesting efficiency by 25% could reduce the delivered cost of willow by approximately \$0.50 GJ^{-1}, potentially making it more attractive as a feedstock for bioenergy and bioproducts. Harvesting systems for willow have been developed over the past 15-20 years in Europe, causing harvesting costs to drop considerably. One of these earlier systems, the Bender, was selected for testing in the U.S. (Pellerin et al, 1999), but was unsuccessful due to several factors including higher crop yields and larger diameter material that is being produced in the northeastern U.S..

A review of cut and chip harvesters, which annually harvest about 2,000 ha of willow biomass crop in Europe, indicates that the more successful systems have both higher throughput rates and more power (Hartsough and Spinelli 2000]. The most widely used machine, the Claas Jaguar 695, harvests 60 green tonnes hr^{-1} with 350+ hp (260 kW). However, the Claas cutting head was deemed to be too weak and suffered numerous breakages during the trials with larger willow crops. Large-scale willow demonstration plots in the U.S. have produced yields ranging from 36 to 72 green tonnes ha^{-1} at the end of the first three-year-rotation. Yields in subsequent rotations are expected to increase by 20-30% (Volk et al, 2011). In addition, some of the most productive varieties of willow have specific gravities that are 15% higher than most other varieties (Tharakan et al, 2005b). Based on the experience in Europe, these higher yields, and the higher wood densities; a harvester would require greater than 400 hp (300 kW) (Hartsough and Spinelli 2000) and a cutting head, feeding mechanisms and chipping devices that are robust enough to handle the large volume of material. Starting in 2004-2005 Case New Holland (CNH) began to collaborate on the development of a single pass cut and chip willow harvest system based on their FX forage harvester. The first effective harvesting system made use of a New Holland FX45 forage harvester and a specially designed hydraulically driven willow cutting head from Coppice Resources Ltd in the United Kingdom (Figure 4). The CRL head was then adapted to the New Holland FR 9060 (CNH's new series forage harvester) in 2007/2008. This system worked reasonably well but still had significant feeding problems with the hydraulically driven CRL cutting head, especially in the denser and higher yields of many of the better shrub willow cultivars.

Figure 4: New Holland FX45 forage harvester and a specially designed hydraulically driven willow cutting head (CRL) from Coppice Resources Ltd in the United Kingdom was the first effective willow harvesting system in NY (photo by Lawrence Abrahamson).

Case New Holland designed a new short-rotation coppice cutting head for the FR9000 series New Holland forage harvester based on sugar cane harvester technology. The cutting head was designed and tested in late winter 2008 in Europe and in the U.S. during the 2008/2009 and 2009/2010 willow harvest seasons with excellent results on willow crops harvesting willow up to 15cm in diameter in one or two rows at up to two hectares per hour while providing uniform chips between 1.25 - 4.5cm (Figure 5). The "new willow cutting head", New Holland 130FB coppice header, is now offered for sale for willow crops in both Europe and the U.S. (John Posselius, Innovation Engineering Director and David Wagner, Marketing; CNH America LLC, pers. comm., 2011). CNH, with support from the U.S. Department of Energy and the New York State Energy Research and Development Authority, is currently working with SUNY-ESF, Greenwood Resources LLC, Portland, OR, and others, in the process of tuning/testing the New Holland 130FB coppice header and New Holland FR9000 series forage harvester for use with short-rotation poplar and

Figure 5: New Holland FR9080 and New Holland 130FB coppice header harvesting 3-year old shrub willow in Tully, NY during Spring of 2010 (photo by Lawrence

Recent Policy Changes that Influence the Economics of Willow Biomass Crops

Without any incentives or supports, the delivered cost of willow biomass has not been competitive with the average historical costs of solid fossil fuels like coal and, over the last few years, of natural gas recovered from shale deposits in North America. In addition, the large upfront costs to establish willow biomass crops and inconsistent cash flow because of the three to four year harvest cycles are barriers for landowners who might be interested in growing willow. Two programs have been initiated in the U.S. to incentivize the establishment of willow biomass crops, namely the Conservation Resource Program (CRP) (USDA-FSA 2011a) and more recently the Biomass Crop Assistance Program (BCAP) (USDA-FSA 2011b). The CRP program has been approved for willow biomass crops in NY but has never been implemented because the program is only made available to landowners for short periods of time every few years based on the federal government’s assessment of the program.

The CRP program provides an establishment grant that covers 50% of costs and an annual rental payment of around \$124 -\$136 ha^{-1} yr^{-1} for 10 years and can usually be renewed for a second 10 year period. The profitability of willow biomass crops can be improved under the CRP program, especially for low-productivity sites. An annual rental payment of \$136 ha^{-1} yr^{-1} over 20 years combined with a 50% establishment grant would make a willow biomass crop yielding 6 odt ha^{-1} yr^{-1} profitable with an IRR of 9.3% (Buchholz and Volk 2010). For higher yielding crops (8 –10-16 odt ha^{-1} yr^{-1}) the length and amount of the annual incentive payment (AIP) had little effect on the IRR for medium to high-productivity scenarios. The 50% establishment grant raises the IRR by around 6.5-7.5 percentage points across the range of yields analyzed. Establishment grants are more cost-effective than an annual rental payments in terms of the tons of biomass that are incentivized per dollar, so future programs might want to focus more resources on establishment grants while keeping low and short-term annual incentive payments in place. The exception to this would be areas with low production potential.

The BCAP program's establishment grant is 75% and the annual payment for woody crops can be up to 15 years. A recent analysis of the combination of an 75% establishment grant with the annual rental payment resulted in favorable returns of 14%-33% from willow biomass crops across yields ranging from 8–16 odt ha^{-1} yr^{-1} (Buchholz and Volk 2010). Another part of this program, called the collection, harvest, storage and transportation (CHST) match, matches $1 for each $1 the producer receives per ton of delivered biomass (measured on an oven-dry basis and capped at $49.6 odt^{-1}). Combining all the components of the BCAP program, (establishment grants, annual rental payments and matching payments for delivered biomass) results in high internal rates of return (43%-64%) across all productivity scenarios. If only one component of the program is implemented, only the establishment grant and CHST match provide reasonable returns in the lower productivity scenarios. While both of these incentive approaches have similar results, the CHST match provides higher internal rates of return but comes with a much higher cost per ton than the establishment grant. Presently, there are no BCAP projects involving willow crops that have been approved by the USDA.

Alternative Applications for Willow

Shrub willows have numerous inherent characteristics that make them a good choice as a dedicated biomass crop. They have rapid juvenile growth rates, vigorous coppicing ability that is maintained even after multiple harvests, ease of establishment from unrooted cuttings, tolerance of high planting densities, high degree of genetic diversity, and potential for rapid genetic improvement. The biomass production system that is being developed and formalized (Abrahamson et al, 2002) is based on these characteristics. In addition, willow's perennial nature, long vegetative season, extensive and diffuse root systems, high transpiration rates, and tolerance of waterlogged conditions make them potentially beneficial for a wide range of other applications (Kuzovkina and Volk 2009). Years of research and development on willow biomass production systems in the U.S. and Europe has resulted in an increased level of understanding about willow biology. This information is being used to adapt the current willow production system for other applications in the Northeastern U.S. including phytoremediation (Riddell-Black et al, 1997a), living snowfences (Dickerson and Barber 1999), and riparian buffers (Riddell-Black et al, 1997b). However, site and socioeconomic conditions for willow plantings associated with these new applications are often different from the agricultural-like settings associated with biomass production. New applications use the knowledge developed from existing willow production systems to frame the design, and then custom tailor it to achieve the greatest success rate under the specific conditions using an adaptive management model (Nowak et al, 1999).

Developing Willow Based Phytoremediation Systems

Shrub willows are being used to remediate and contain sites contaminated with various industrial wastes through a process referred to as phytoremediation (Mirck et al, 2005; Licht and Isebrands 2005). Willow have been shown to uptake heavy metals and organics from soils (phytoextraction (Riddell-Black et al, 1997a)), facilitate the breakdown of organics to non-toxic compounds (rhizodegradation (Ebbs et al, 2003)), and control water dynamics, including contaminated groundwater flow and water penetration into soils via evapotranspiration (phytovolatilization and hydraulic control (Corseuil and Moreno 2001; Mirck and Volk 2010a). Willows are useful in phytoremediation because of their perennial nature, fast above- and belowground growth, ability to survive in relatively harsh soil conditions, wet sites, and high capacity to transpire water. A broad gene pool, there are over 450 species of willow across the world (Argus 1997) with many more natural and human-developed species hybrids, provides opportunities to screen and develop willow to grow on a wide range of sites and produce specific phytoremediation effects.

In upstate NY shrub willow is being deployed as an alternative cover on an old industrial site (primarily CaCl & NaCI) that is the remnant of over 100 years of soda ash production in Solvay, NY. The main environmental concern associated with the site is the leaching of chloride into groundwater and nearby surface waters. While a number of mitigation measures have been implanted including several kilometres of French drains to capture leachate so it can be treated, there is a need to manage the precipitation that reaches the site. Over a number of years willows with different mixtures of organic amendments added to the site have been tested to determine if an alternative living cover can be deployed to minimize the amount of water that percolates into the waste beds and ultimately to reduce the amount of leachate generated from the waste beds to decrease the impact on groundwater and nearby surface waters (Mirck and Volk 2010b). During the growing season the willows transpire the incoming precipitation as well as a portion of the water that is stored in the substrate. Precipitation during the dormant season is stored in the zone where organic amendments have been incorporated, which is also in the willow rooting zone. The following growing season a portion of this water is also transpired by the willow and some is evaporated. In addition to managing percolation rates with this system, the willows will be managed as biomass crops and harvested every three to four years as a source of renewable energy. The ability of willows to tolerate harsh site conditions, its rapid growth rates and high transpiration rates (Mirck and Volk 2010b) have been essential characteristics that make the system effective. To date the system has been deployed on about 15 ha of settling basins with plans to implement about 10 ha yr^{-1} over the next several years.

Developing Living Willow Snowfences

In areas where snowfall is prevalent, snow blowing across open fields over highways can create dangerous road conditions for the public, restrict access to emergency services during and after severe winter storms, increase the number of accidents and injuries, and create expensive and challenging situations for road crews to ameliorate. Snow and ice removal costs in the U.S. exceed $2 billion each year, while indirect costs related to corrosion and environmental impacts have been estimated to add another $5 billion year^{-1}. Factoring in costs associated with accidents and injuries would further increase this figure (Taber 2003).

Blowing snow can be controlled using structural or living snowfences, both of which have different benefits and limitations. Installing and maintaining well-designed plastic or wooden snowfences can reduce blowing and drifting snow immediately, but they have limitations, including their capital costs, maintenance and replacements costs, inadequate effectiveness in years of heavy snowfall, and unappealing aesthetics. Living snowfences, which are defined as designed plantings of trees, shrubs and/or grasses (Gullickson et al, 1999), can be used to address some of those problems. A 6 m-tall living snowfence, with the same density as a regular wooden snowfence, can store almost 16 times more snow and will remain functional throughout the winter (Brandle and Nickerson 1996). However, living snowfences are often created using slow-growing species that require 6 to 20 years to become effective (Taber 2003; Gullickson et al, 1999) and occupy two or more widely spaced planting rows for effective control. This requires more land than if structural snowfences are used, which is a significant limitation in the northeastern United States since landowners are less willing to commit strips of land that are several meters wide and roadside rights-of-way are usually narrow. Use of a single or double row of fast-growing willow shrubs, either alone or as part of a mixed planting design, is one way to address some of the limitations of living snowfences, while capturing their multiple benefits.

The most important characteristics for effective living snowfences are high density of stems and branches during the winter, good height growth, relatively uniform density along the length of the plant and upright form. Shrub willows inherently possess several of these characteristics (Kuzovkina and Volk 2009) and others can be manipulated by selecting the right varieties and using different management practices. The density of willow snowfences can be varied by changing the spacing between plants, by coppicing to alter the number of stems on the plants and degree of side branching, and by varying the number of rows of willow planted. Rate of establishment can be modified by changing the size of planting stock, correctly matching varieties to site conditions, and altering site preparation and snowfence management techniques.

From 2000-2006, willow snowfence demonstrations ranging in length from 30 to 300 m were established in five different counties in NY. The siting, design, installation and maintenance of these sites has been a collaborative effort among various agencies including SUNY-ESF, USDA Natural Resources Conservation Service, state and county Departments of Transportation and Soil and Water Conservation Districts. All the demonstrations were single or double rows of willow established at locations where blowing and drifting snow problems were severe. While the establishments of many of the willow snowfences were successful, there have been cases where they were not successful because the wrong cultivar of willow was used or there were problems associated with site preparation and weed control. When a double row of willow is properly established it can begin to function and capture snow at the end of its second growing season. By the third or fourth growing season it can reach an optical density of 60% or greater. Most structural snow fences have an optical density of 50%. The higher density of willow snowfences and greater depth compared to a structural snowfence and the snow and climate conditions in the northeast U.S. has allowed the establishment of willow snowfences much closer to the side of the road (setbacks of 20m have been used) than what is generally recommended based on existing guidelines. The experience from these trials over the past few years has helped to refine the design and installation and increase the effectiveness of these living snowfences and formed the basis of a training and demonstration program with the New York State Department of Transportation (NYSDOT). Since 2009, SUNY-ESF has been working with the NYSDOT and conducted a series of both living snowfence design and installation workshops with NYSDOT personnel in three different regions of the State with the establishment of over 3000 meters of double row willow living snow fences.

Developing Willow Riparian Buffers

Riparian buffers have been identified as an effective barrier to soil and nutrient movement from agricultural fields into watercourses. Buffer strips of perennial vegetation along riparian zones reduces overland flow, decreases the amount of sediment and nutrients entering streams, retains chemicals in their rhizosphere for eventual degradation or uptake, improve soil properties such as infiltration rates and stabilizes stream banks (Schultz et al, 1995). Buffer strips improve stream water quality and productivity, and enhance landscape diversity and wildlife habitat. Riparian buffers that include natural stands of trees have been shown to be more effective than grass strips in reducing nitrate export, especially during months when other vegetation is dormant (Haycock and Pinay 1993).

Several characteristics of willow shrubs make them ideal for use in riparian buffers, especially when they are part of a design that uses multiple types of vegetation. Willow's ability to coppice makes harvesting during the dormant season a potentially viable option. Harvesting on a three- to five-year-rotation may improve the long-term effectiveness of riparian buffers, because nutrients are removed from the site so that the buffer does not become saturated and the plants are maintained in a juvenile growth stage with high nutrient demands. The rapid development of an extensive fine root system at a variety of depths is an important attribute for effective riparian buffers. Fine roots (<2 mm in diameter) make up 70 - 90% of belowground biomass of two-year-old willow biomass crops (Volk 2002). Rapid and extensive fine root development of newly planted willow results in the buffer systems rapidly becoming functional as: (1) nutrient sinks; (2) sources of carbon for microbial process; and (3) soil stabilizers. The abundance and diversity of microorganisms supported in woody crop rhizospheres is an important part of the filtering capacity of riparian buffers. Some of these organisms can degrade herbicides, insecticides, and other toxic compounds. Increasing the amount and distribution of roots in the buffers by planting different sizes of cuttings is one approach to enhancing the population of microorganisms, increasing the environmental benefits of the system.

While the characteristics of willow indicate that they should be effective in riparian buffers, the impact of newly established riparian buffers with willow or other woody species is not well quantified. In 2002 and 2003 six willow-grass and six grass-only buffers were established along two streams in central NY. Soil and shallow groundwater in these buffers and adjacent un-buffered cropland was intensively monitored for NH_4^+, NO_3^-, and P concentrations. Results indicate groundwater concentrations of reactive P, and NO_3^- are significantly lower in both the grass and willow-grass buffers compared to cropland (Young, and Briggs 2005, 2007, 2008). Further monitoring and experiments to understand site and soil factors influencing these results and the role of willow is necessary.

Summary

Research, development and deployment of willow biomass crops over several decades in both Europe and North America has led to the development of a system that has been deployed in Europe and is just beginning to be commercially deployed in North America. Over the years yields of willow biomass crops have been increased through a combination of breeding and improved crop management. These factors have also had an impact on the economic viability of these systems.

1. Current yields of willow cultivars developed in North America and tested across a number of different sites:
    a. First rotation yield of the top three shrub willow cultivars across 18 yield trials is 11.0 odt ha^{-1} yr^{-1}.
    b. With expected yield increases of 23 – 31% that have been reported over multiple rotations with older cultivars would result in yields of 13.2 to 13.5 odt ha^{-1} yr^{-1} over seven three-year-rotations.
    c. With an energy content of about 19.4 GJ/odt (Volk and Luzadis 2009), 256 – 262 GJ ha^{-1} yr^{-1} could be produced.

In determining the economic viability of willow biomass crop systems, yield is an essential factor.

1. At mean yields of 13.2 odt ha^{-1} yr^{-1} and delivered prices of \$60/odt over seven rotations the overall internal rate of return for willow biomass crops is 5.9% (Buchholz & Volk, 2011).
2. Further increasing yields by 50% through a combination of breeding and crop management improvements would raise the IRR from 5.9–13.9% (Buchholz & Volk, 2011).

Another approach to improving the economic viability of willow biomass crops is to reduce the cost of production.

1. Harvesting is the single largest cost of production:
    a. Development of a more efficient single pass cut and chip harvesting system based on a New Holland FR series forage harvester and a New Holland willow cutting head (New Holland 130FB coppice header) should help to reduce these costs.
        i. This harvest system is able to cut and chip stems that are up to 15 cm in diameter, which may allow rotation lengths to be increased from three to four years and further lower the per ton cost of harvesting.

2. Other improvements in the system to reduce costs included:
    a. Weed control and crop management practices.
    b. Reducing planting density with new shrub willow cultivars.
    c. Potential to reduce or eliminate (in the short term) fertilizer inputs on some sites without compromising yields.
    d. Alone none of these factors will make the system economically viable, but in combination they should be effective.

As with any new energy crop production system there are both advantages and disadvantages associated with willow biomass crops.

1. Advantages:
    a. These plants are adapted to marginal conditions, which makes them attractive as an energy crop to minimize competition for food and fiber production.
    b. The development and demonstration of reliable willow planting and harvesting equipment.
    c. The fast growth rate and perennial nature of willow has allowed for the creation of a cropping system that generates multiple benefits, such as:
        i. Improved landscape diversity (biodiversity).
        ii. Improved soil quality.
        iii. The ability to both sequester carbon and produce a source of biomass for renewable energy.
    d. Biomass produced from willow crops can be blended with other sources of woody biomass to produce a range of bioenergy and bioproducts.
        1. In the near term willow biomass crops will probably be used for bioenergy applications in North America, mainly heat and heat and power applications.
    e. The development of conversion technology related to biorefineries where multiple biofuel and chemical bioproducts are produced will create new opportunities and markets for this crop, including;
        i. biobased fuels, specialized and platform chemicals, biodegradable plastics, materials and heat and power, as alternatives to products currently derived from non-renewable fossil fuels.

2. Disadvantages (Barriers):
    a. The perennial nature of the system also means that high, initial establishment costs take a number of years to recover and the profitability of the system is not realized for several rotations.
    b. Uncertainty with a number of factors related to willow biomass crops has delayed deployment of this new system.
        i. The long term nature of the system raises questions about potential problems, such as pests and diseases, which may occur later in the life of the crop and impact its yield.
        ii. The current policy environment in North America related to energy crops is currently not well defined for either growers or end users, which makes individuals at both ends of the production system reluctant to take the risk of investing in this renewable energy crop.
        iii. Since the area planted to this crop is still relatively small in North America, there is limited experience with the system in the farming community, which limits its adoption rate.
    c. As efforts are provided for the expansion of the system and opportunities are provided for individuals and groups to gain experience producing and using willow, some of these barriers should be overcome.

In addition to producing biomass crops for different forms of renewable energy, the unique suite of characteristics associated with shrub willows mean that they will also be deployed to address other issues and challenges.

1. Shrub willow is currently being deployed in a number of former industrial sites in the northeastern U.S. as part of integrated systems to address potential pollution problems.
2. The rapid growth and consistent canopy associated with these plants makes them ideal for living snowfences and windbreaks and these systems are currently being developed and deployed in New York State.
3. The potential that shrub willow has to address nutrient loading concerns is being used to develop riparian buffer and wastewater treatment systems in both North America and Europe.

The adaptability of shrub willows' and their potential to provide multiple benefits has created opportunities to not only develop them as energy crops, but also as key components of other ecological bio-systems that are being used to address various challenges across the landscape.

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IEA Bioenergy

IEA Bioenergy is an international collaboration set up in 1978 by the IEA to improve international co-operation and information exchange between national RD&D bioenergy programmes. IEA Bioenergy's vision is to achieve a substantial bioenergy contribution to future global energy demands by accelerating the production and use of environmentally sound, socially accepted and cost-competitive bioenergy on a sustainable basis, thus providing increased security of supply whilst reducing greenhouse gas emissions from energy use. Currently IEA Bioenergy has 22 Members and is operating on the basis of 13 Tasks covering all aspects of the bioenergy chain, from resource to the supply of energy services to the consumer.

IEA Bioenergy Task 43 – Biomass Feedstock for Energy Markets – seeks to promote sound bioenergy development that is driven by well-informed decisions in business, governments and elsewhere. This will be achieved by providing to relevant actors timely and topical analyses, syntheses and conclusions on all fields related to biomass feedstock, including biomass markets and the socioeconomic and environmental consequences of feedstock production. Task 43 currently (Jan 2011) has 14 participating countries: Australia, Canada, Denmark, European Commission - Joint Research Centre, Finland, Germany, Ireland, Italy, Netherlands, New Zealand, Norway, Sweden, UK, USA.

Further Information

Task 43
Website www.ieabioenergytask43.org
Göran Berndes – Task leader
Email: goran.berndes@chalmers.se
Tat Smith – Associate Task Leader
Email: tat.smith@utoronto.ca

IEA Bioenergy Secretariat
Website: www.ieabioenergy.com
John Tustin – Secretary
Email: jrtustin@xtra.co.nz
Arthur Wellinger – Technical Coordinator
Email: arthur.wellinger@novaenergie.ch

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