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REVIEW

Advances in shrub-willow crops for bioenergy, renewable products, and environmental benefits

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Abstract

Short-rotation coppice systems like shrub willow are projected to be an important source of biomass in the United States for the production of bioenergy, biofuels, and renewable bio-based products, with the potential for auxiliary environmental benefits and multifunctional systems. Almost three decades of research has focused on the development of shrub willow crops for biomass and ecosystem services. The current expansion of willow in New York State (about 500 ha) for the production of renewable power and heat has been possible because of incentive programs offered by the federal government, commitments by end users, the development of reliable harvesting systems, and extension services offered to growers. Improvements in the economics of the system are expected as willow production expands further, which should help lower establishment costs, enhance crop management options and increase efficiencies in harvesting and logistics. Deploying willow in multifunctional value-added systems provides opportunities for both potential producers and end users to learn about the system and the quality of the biomass feedstock, which in turn will help overcome barriers to expansion.

Introduction

There is potential to sustainably produce over 1 billion Mg_{dry} of biomass annually in the United States from a combination of agricultural systems, forestry, and bioenergy crops. Short-rotation coppice (SRC) systems, like shrub willow (*Salix* spp.) and poplar (*Populus* spp.) are projected to supply 20–25% of this potential biomass (U.S. Department of Energy 2011). Shrub willow can be successfully grown on a wide array of agricultural land capabilities and drainage classes to produce bioenergy and bioproducts, with environmental and rural development benefits. Shrub willow has many characteristics that make it an ideal feedstock including high yields, the ability to resprout after coppice and be harvested every 3–4 years, ease of propagation from dormant stem cuttings, ease of breeding, a broad genetic base, and a feedstock composition similar to other sources of woody biomass (Volk et al. 2014). Research on shrub willow for biomass energy and alternative applications (bioremediation, vegetative covers, treatment of organic wastes, riparian buffers, living snow fences) has also been ongoing in the United States since 1986 and has included trials in 15 states across the Northeast and Midwestern United States and several provinces in Canada. Considerable collaborative efforts involving both private and public entities at the local, state and federal level and NGOs have been made to facilitate the commercialization of this system (Volk et al. 2014).

A breeding and selection program for shrub willows has been developed and is producing improved cultivars for both the biomass and agroforestry markets (Volk et al. 2014; Smart et al. 2008) with long-term studies of potential yields across a range of sites (Fabio et al. 2016) over multiple rotations (Sleight et al. 2015). Research has been conducted on various aspects of the production cycle including nutrient amendments and cycling, alternative tillage practices, the use of cover crops for weed and erosion control, plant spacing and density, growth characteristics important for biomass production, harvesting systems, and logistics. Environmental factors have also been studied such as the use of willow plantations by pollinators, birds and small mammals; changes in soil microarthropod communities under willow; changes in soil carbon, greenhouse gas balances; and water quality and quantity. Financial analysis and life cycle assessments have evaluated the overall system through multiple rotations and advanced sustainability studies are now being undertaken to evaluate the entire supply chain using multiple metrics and integrated assessments. Results from these and other initiatives in North America and Europe have provided a base from which to expand and deploy willow biomass crops, and willow projects are being developed as a sustainable cropping system for agricultural and open land (Volk et al. 2006).

Current Willow Biomass Production

Willow is typically planted using 20-cm-long dormant hardwood cuttings at a density of about 13,500 plants ha^{-1}. Competing vegetation is managed using a combination of chemical and mechanical controls over the first few growing seasons. The crop is coppiced (cut back) after the first year to promote the production of multiple stems, followed by the first harvest 3–4 years later using a single-pass cut-and-chip forage harvester. The willow crop resprouts the following spring and is harvested again in another 3–4 years. Seven or more harvests are anticipated to be possible from a single planting. Yields between 8 and 12 Mg$_{dry}$ ha^{-1} year^{-1} across a range of sites have been observed (Volk et al. 2011); or about 42–72 Mg$_{wet}$ ha^{-1} at harvest. Yield increases of 20–40% are anticipated from breeding and selection efforts for new willow varieties (Serapiglia et al. 2013, Volk et al. 2011).

Despite a variety of benefits possible from willow production, deployment has been restricted by high establishment costs, inconsistent markets, and perceptions about willow chip quality and feedstock characteristics. Several of these barriers have been addressed in recent years through the collaborative efforts of numerous organizations and support from federal and state agencies, as well as private companies (e.g., Honeywell International, Case New Holland, Double A Willow, Celtic Energy Farm). Harvesting costs were reduced by about 35% with the development of an effective single-pass cut-and-chip harvesting system based on a New Holland (NH) forage harvester (Eisenbies et al. 2014a). The system is commercially available at NH dealers across North America and Europe and is being used to harvest willow in central and northern New York State and throughout the Northeastern United States. This system also resolved issues with chip size and quality and produces material that is acceptable to the primary end user in New York State, ReEnergy Holdings, and other end users who have tested and utilized the material.

These collaborative efforts among universities and industry partners have contributed to an emerging willow industry in the Northeast, which was catalyzed in New York State by the successful application to the USDA Biomass Crop Assistance Program (BCAP) developed in 2012 by ReEnergy, Cato Analytics and SUNY-ESF. BCAP is designed to improve domestic energy security, reduce the greenhouse gas emissions that cause climate change, and create opportunities for rural development (Volk and Harlow 2014). The rollout of this program has addressed a number of the barriers associated with willow biomass crops. BCAP provides partial cost-share payments for some of the upfront expenses of site preparation and planting willow, as well as annual land rental payments based on soil conservation rates. The site preparation and establishment support in the 2012 program covered up to 75% of the establishment cost, or a maximum of \$1853 ha^{-1}. Subsequent offerings for BCAP in 2015 reduced the cost-share establishment payment to 50% or a maximum of \$1237 ha^{-1}. BCAP also paired producers with an end user for their material.

As part of the 2012 BCAP agreement, ReEnergy signed 11-year contracts with willow producers to purchase harvested biomass, providing producers with a known market for about half of the expected lifespan of these plantings. ReEnergy is mixing willow biomass with other regionally sourced biomass feedstocks such as forest residues to produce biopower at the Black River (60 MW) facility and biopower and industrial process steam for an adjacent paper mill at the Lyonsdale (22 MW) facility. In 2014, ReEnergy signed a 20-year supply agreement with the United States Defense Logistics Agency to provide secure,

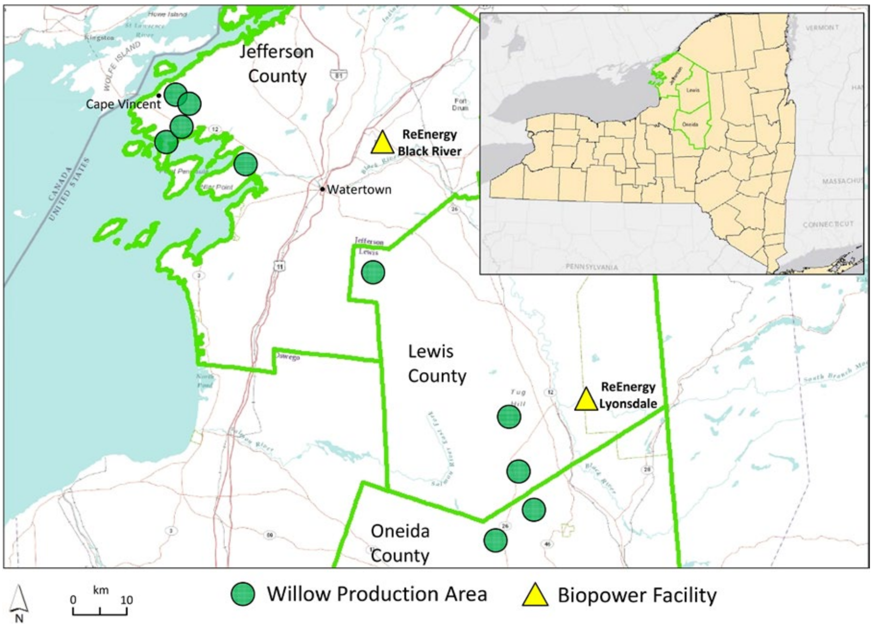

Figure 1. Willow production areas and two ReEnergy end-use facilities in central/northern region of New York State.

renewable electricity to the Fort Drum U.S. Army military base from the Black River facility, creating another level of assurance that this market for willow will remain in place. The window for the first round of BCAP signups in 2012 was limited to a two-month period, and 470 ha of willow biomass crops were enrolled in that time (Fig. 1). A second, one-month signup period was announced in late August 2015 with the potential to increase the area used to grow willow to about 1,000 ha under BCAP, but once again the window for signing up was very limited and this time no additional acreage was enrolled under the deadline, although several parties expressed interest and valuable connections with potential growers were made.

Extension Services

Since the first commercial scale-up of willow crops in 2012, SUNY-ESF (with support from NYSERDA – the New York State Energy Research and Development Authority) and the Northeast Woody/Warm-season Biomass Consortium (NEWBio) are providing a suite of extension services to producers and other stakeholders in New York and the Northeast. Nontechnical barriers to commercialization include a low level of awareness and understanding about the production and management among potential producers and support businesses; lack of understanding about the system among neighbors, policy makers, and broader public; and the lack of a functioning and organized biomass supply chain that meets the needs of the bioenergy system's stakeholders. If initial large-scale deployment of willow is not successful, subsequent deployment in a region can be negatively impacted and delayed by years (Helby et al. 2006; McCormick and Kåberger 2007). To address these barriers and concerns, educational and outreach services are being provided by SUNY-ESF and NEWBio to the nascent willow industry in the Northeast including the development and delivery of educational materials such as brochures and fact sheets; training programs, field tours and webinars for producers and other stakeholders; newsletters, websites, social media, and other forms of information dissemination. Another element of current extension programming focuses on service provision including crop scouting; a willow equipment access program for specialized planting and harvesting machinery; and technical assistance in the field to assist with crop planting, management and harvesting. Analytical services such as soil sampling and interpretation of test results and the development of economic tools and analyses are also being provided. Extension staff are working with producers and end users to develop feedstock confidence and scale-up potential; providing insights from on-the-ground experience to supply chain and other analyses; and coordinating communication and joint efforts among university, public, government, NGO, and industry partners. These type of extension services have been shown to be critical to the adoption and success of novel bioenergy crops such as shrub willow, and were an integral component in each of seven Agriculture and Food Research Initiative (AFRI) Regional Bioenergy Coordinated Agricultural Projects supported by the United States Department of Agriculture National Institute of Food and Agriculture (USDA NIFA).

Economics

Many variables influence the profitability of willow biomass crops and a wide range of possible operating conditions and management strategies exist. Some of the most critical variables influencing profitability are biomass yield, the price received for delivered biomass, the cost of planting stock, efficiency of harvesting operations, the use and cost of fertilizers, and transport distances (Buchholz and Volk 2013). These factors are incorporated into a cash flow model developed by SUNY-ESF, EcoWillow 2.0. The model is a financial analysis tool for willow that encompasses all stages of the crop's life cycle over multiple harvest rotations. Data from research trials and commercial operations has been incorporated into the latest version of the model, along with several new features and a more user, friendly design. Users can download EcoWillow 2.0 and supporting documentation from the SUNY-ESF website (www.esf.edu/willow) for free and change input parameters to reflect the costs and operational realities or assumptions of their willow production systems.

A 2014 assessment of the economics of willow biomass crops in New York State is captured in a base case scenario representing conservative estimates of profitability. In order to assess how the economics of the system would change with improvements in yield and crop management practices (i.e., headlands and unplanted field area reduced from 20% to 10%, chip-collection vehicle capacity increased from 7 to 10 Mg_{wet}) as well as some reduction in input costs (i.e., 50% reduction in fertilizer use/costs, reduction in planting stock costs to \$0.09 $cutting^{-1}$), an improved scenario was created. Each adjustment in this scenario is considered to be a realistic and achievable system improvement or best practice target based on current data, logistics, and management options of the crop.

The model can also assess the impact of incentive programs such as USDA BCAP, and two additional scenarios were created: an incentivized scenario that adds potential BCAP incentive payments to the base case, and an improved-incentivized scenario that adds both potential improvements and BCAP payments to the base case. For each scenario, the model provides outputs of net present value, internal rate of return (IRR), payback time and break-even price of biomass. All scenarios are based on a 22-year life cycle of the planting (including crop tear out). Prices are expressed in terms of Mg_{wet} for clarity from the producers' and end users' perspective. The expected moisture content of the crop is 45% for conversion into dry weight values, but as with other input parameters, this can be changed in the model by users.

The base case scenario indicates that the system is not currently profitable at the 2014 market price of woody feedstocks in the region of about \$30.50 Mg_{wet}^{-1}, which is less than the base case break-even price of 33.00 Mg_{wet}^{-1}(Table 1, Heavey and Volk 2015). The improved scenario provides a positive IRR of 5% over 22 years and has a payback time of 13 years, or at the fourth harvest. The payback time is the same for the incentivized base case, 13 years or four harvests, but the IRR for that scenario is slightly higher at 7%. When the 2015 USDA BCAP incentive rates and the adjustments of the improved scenario are combined in the improved-incentivized scenario, the system has substantially higher 20% IRR and a payback time of 7 years, or just two harvests. The project cost distribution under all these scenarios is about 15% land costs, 20% establishment, 5% fertilizers, 35% harvest, 20% transport, and 5% stock removal. Future work will apply sensitivity analysis to these or similar scenarios and create combined techno-economic and life cycle analyses of willow biomass crops.

Table 1. Internal rate of return (IRR), payback times, and break-even prices for four different production scenarios of willow biomass crops grown in northern New York using EcoWillow 2.0 (Heavey and Volk 2015).

	IRR (%)	Payback	Break-even prices (\$ Mg_{wet}^{-1})
Base case	< 0	None	33.00
Improved	5	13 years	29.75
Incentivized base case	7	13 years	27.50
incentivized improved	20	7 years	22.75

Harvesting Systems and Willow Chip Quality

Harvesting is the single largest cost component of willow biomass production and the single largest source of in-field fossil energy demand and related greenhouse gas emissions (Caputo et al. 2014). Efforts to reduce harvesting costs by improving the performance and reliability of the harvester and chip-collection system are essential to the profitability of willow biomass crops. In addition, having a reliable harvesting system that is commercially available and supported by a major agricultural equipment manufacturer increases the confidence level of potential project developers and producers that willow biomass crops can be grown and harvested effectively and efficiently.

The previous lack of a reliable harvesting system for willow biomass crops in North America had been a barrier to the deployment of the crop because landowners were unsure how their crop would be harvested. Many types of specialized machinery for harvesting SRC exist, including small and large single-pass cut-and-chip systems, whole-stem harvesters, and baling systems (Berhongaray et al. 2013; Ehlert and Pecenka 2013). However, due to the limited scale of willow and other SRC deployment, evolving technology, different operational scales, and management objectives, there has not been a dominant harvesting system in use in the United States. In New York State, several existing or modified harvesting platforms for SRC from Europe and North America were evaluated from 2001 to 2008 in SRC willow. Technical hurdles encountered on various harvesters tested during that time include the durability of equipment, low production rates, irregular feeding of stems into the harvester, limits on maximum stem sizes, and inconsistent size and quality of chips (Volk et al. 2010).

In 2008, Case New Holland and SUNY-ESF began developing and testing a prototype short-rotation coppice header (130FB) for their FR9000 and FR Forage Cruiser series of forage harvesters, specifically designed to cut and chip a range of SRC such as willow, poplar, and eucalyptus (Fig. 2). The header can be attached to a standard New Holland forage harvester in these series, although some modifications to the harvester itself are needed to harvest woody crops such as the use of forestry-grade tyres, an upgraded hydraulic system, and shielding below and across the front of the harvester. The performance objectives of the harvesting platform included the ability to harvest double rows of woody plants containing stems up to 120 mm in diameter at ground level, and to produce chips that are 10–45 mm long. Chipped material should be of a quality that allows it to be transported directly to a variety of end users for conversion to different forms of renewable energy and coproducts without requiring further processing.

Harvests of approximately 60 ha of willow biomass crops during late 2012 and early 2013 in New York State, and 20 ha of poplar biomass in Western Oregon, revealed important patterns in the operation of the New Holland harvesting system (Eisenbies et al. 2014a). The throughput of the harvester is related to the quantity of standing biomass of the crop, but the pattern differs as the amount of standing biomass changes. At low levels of standing biomass, throughput increases in a linear trend until standing biomass reaches approximately 45–50 Mg_{wet} ha^{-1}. In this range of standing biomass, the throughput of the harvester is below its capacity because the speed of the harvester is limited by conditions in the field. If speeds are too high, the harvester becomes more difficult to operate and it begins to pull plants and roots out of the ground before the stems are cut. Beyond 45–50 Mg_{wet} ha^{-1} of standing biomass, the harvester throughput begins to plateau around 70–90 Mg_{wet} ha^{-1} (Eisenbies et al. 2014b). Operator experience, characteristics of the woody crop being harvested (such as stem morphology and size), and ground conditions also appear to be important factors that influence maximum throughput at various levels of standing biomass.

Figure 2. Harvesting willow biomass crops in New York State with a New Holland forage harvester and coppice header.

Over the past few years, the throughput from the single-pass cut-and-chip harvesting system has been improved from less than 20 wet Mg_{wet} h^{-1} with well over 25% downtime due to material jams or mechanical problems, to throughputs of 70–90 Mg_{wet} h^{-1} in willow biomass crops with standing biomass ranging from 20 to 65 Mg_{wet} ha^{-1} (Eisenbies et al. 2014a). The harvester can run consistently in these conditions with less than 10% downtime. Results from these harvesting trials and product development work have successfully led to New Holland making the 130FB short-rotation coppice header commercially available through its network of dealers.

One of the barriers associated with willow biomass in New York State has been the perception that the material is of substantially lower quality than forest residues that are available from the region. End users have expressed concern that willow biomass will have a higher ash and moisture content than forest residues, a lower energy content and a more inconsistent chip size and therefore result in a less desirable feedstock. To address this issue, samples were collected from over 200 truckloads of willow biomass that was harvested in New York State in 2012/2013. The results indicate that the mean ash content of 224 samples was 2.1% (CV 28%) and ranged from 0.8% to 3.5% (Eisenbies et al. 2015). Compared to samples that were hand-harvested from research plots (mean 1.7% CV 28%), the mean ash content of commercial scale samples was almost 0.5% higher but had a similar amount of variation. The ISO 17225-4 (ISO 2015) threshold for short-rotation coppice (B1) chips is < 3% ash content; this cutoff was met by 100% of the samples from one harvest location and 82% of those from a second site. Slight differences were found in the ash content between some willow cultivars that were grown at these sites. Most

Figure 3. Piles of forest residues (left) and a smaller pile of willow biomass crops (right) at the Lyonsdale ReEnergy facility in 2013. After using over 1,000 Mg_{wet} of material in 2013, plant operators were comfortable enough with willow biomass to add it directly to their main wood chip pile in 2014.

notably, the average ash content of the cultivar Fish Creek (*Salix purpurea*) (1.3%) was significantly lower than other cultivars tested, which had mean ash contents up to 2.4%. The moisture and energy content of willow from these large scale harvesting trials is similar to debarked forest wood chips, but ash content of debarked chips was lower (0.6%) (Chandrasekaran et al. 2012).

The mean moisture content of the willow from the commercial harvests was 44% (CV 5%), ranging between 37% and 51% (Eisenbies et al. 2015). Moisture contents for hand-harvested samples from research plots were higher, ranging from 45% to 56%, with a mean moisture content of 46% (CV 6%). The only requirement in ISO standards is that the moisture content is reported for this kind of material.

The higher heating value of the commercial samples was 18.6 MJ kg^{-1} (CV 1%). In comparison, the hand-harvested samples had a higher heating value of 18.8 MJ kg^{-1}(CV 1%). The lower heating value, which accounts for the moisture content in the biomass, was 10.4 MJ kg^{-1} (CV 5%). Because the moisture content of the hand-harvested willow was slightly higher, the lower heating value of the hand-harvested material was slightly lower at 10.1 MJ kg^{-1} (CV 5%) (Eisenbies et al. 2015). Overall, the quality of willow feedstock in commercial trials is very similar to previous results from research trials, and has consistently low variability relative to other bioenergy feedstocks (Eisenbies et al. 2015).

Due to issues with inconsistent chips sizes from previous SRC harvesting systems, a focus of recent development work has been on producing a consistent size chip that meets the quality expectations of end users in the region. With the standard knife and machine configurations, the harvester is typically set to produce chips around 33 mm in size, which is the most fuel efficient mode. In willow crops from recent harvests this has resulted in particle size distributions where 40% of the mass is above 33 mm and 90% of the mass is above 19 mm, and the overall distribution of chips sizes meets the ISO P45S standard for particle size (Eisenbies et al., 2015).

While this data from commercial scale harvesting operations has been informative and helped build confidence in feedstock quality and variability, end users ultimately want to test large amounts of willow biomass in their facilities before they are really comfortable utilizing the feedstock. In 2013, about 1200 Mg_{wet} of willow biomass was delivered to ReEnergy. All of this material was piled separately so plant operators could mix the willow in with other feedstocks in a controlled manner and understand how the material would work in their system (Fig. 3). After processing this material and having no problems in 2013, willow chips were added directly to the main chip piles at ReEnergy's wood yards in 2014, although harvests in 2014 were limited to about 16 ha due to weather and ground conditions which delayed operations at the primary harvest site for the season. In 2015, 36 ha were harvested at this same site, producing about 1,600 Mg_{wet} of willow. Due to wet ground conditions that limited operations the previous season at this site, harvesting operations began in mid-August, prior to the normal harvest window, while leaves still persisted on the willow plants. Due to this fact, ReEnergy again piled willow feedstock separately at the wood yard, but did not encounter any issues mixing the willow with other feedstocks in 2015. Preliminary results from chip samples taken at the field edge and plant gate in 2015 showed that moisture and ash content of leaf-on willow were on the high end, but within the same range as previous commercial-scale trials with leaf-off willow conducted from 2012 to 2014. ReEnergy did not report any problem with the 2015 feedstock and is expected to handle willow in the same manner as other feedstocks in future years. Currently, there is about 80 ha of willow being harvested annually in the northeast using two New Holland FR9000 series harvesters equipped with the 130FB woody crops cutting head. From 2013 to 2015, over 3,500 Mg_{wet} of willow was harvested and delivered to ReEnergy facilities and converted into renewable heat and power. Despite initial uncertainty, experience by operators at ReEnergy has increased overall confidence in the feedstock. Harvests over the next few seasons could reach 160 ha annually or more, as recently planted crops mature, new crops are planted, and the efficiency of harvesting logistics is further improved.

Developing and Deploying Shrub-Willow Systems

The components of a developing willow bioenergy system are now in place in New York State and the Northeast. Efforts are underway to expand willow biomass crop production to meet the demand for woody feedstocks by ReEnergy and other end users in the region and increase the adoption of willow for value-added multifunctional systems. There are several potential pathways to make willow biomass crops more economically feasible so that these systems can be expanded across the region. The first is to work within and improve traditional bioenergy systems. There is a stable long-term market for biomass for heat and power, but the current price being paid (~ \$30 Mg_{wet}^{-1}) does not provide a positive internal rate of return for growers without support from government programs and/or successfully achieving a suite of best practice targets to offset establishment and maintenance costs. The high establishment costs for willow (~ \$2,500 ha^{-1}) is also a barrier to many growers because positive returns are not generated for several years and multiple harvests. Reducing initial costs through programs such as USDA BCAP is one approach to improving economics over the short-term while more innovations are made. ReEnergy's commitment, following the program's initial success, to incorporate more willow into its feedstock supply, positions the region to increase the BCAP area up to 2,500–5,000 ha if future funding should become available. However, this expansion will be impacted by prices ReEnergy receives for electricity, which are currently at the low end of the range of the past few years. If the area planted with willow expands and demand for planting material is more consistent, improvements in the management of nurseries and cutting production can be made that will lower the cost of planting stock. In addition, expanding the area under willow will foster innovation and efficiency improvements in crop management and harvesting, further reducing costs.

Producing a wider array of products and/or higher-value products via a biorefinery pathway would increase the value for biomass feedstock and is another possible method for maximizing returns and expanding production. Trials have been conducted at SUNY-ESF with a biorefinery partner, Applied Biorefinery Sciences, using an incremental deconstruction approach based around a hot-water extraction process to recover hemicellulose and other chemicals from willow and other woody feedstocks (Amidon et al. 2011). Following this process, the remaining biomass can be used for the production of premium quality pellets that have lower ash content, higher energy content and more hydrophobic properties than un-extracted willow. Alternatively, the processed material could be used as a source of cellulose sugars and lignin, although the most effective pathways to recover these products are still being developed. Other pathways are being explored that will generate multiple products from willow and other woody biomass to increase the value of willow feedstock.

A third potential opportunity for the expansion of shrub willow is multifunctional bioremediation/bioenergy systems. SUNY-ESF, Honeywell International and other organizations have worked together since 2004 to develop, deploy, and research an alternative shrub willow evapotranspiration (ET) cap on 50 ha of former industrial land near Syracuse, NY. The primary objective of this system is to address human health and environmental concerns related to chloride salts moving from the site into the watershed. The second objective is to produce biomass for renewable energy. Willows are able to tolerate the salty substrate of the site with minimal remediation efforts of incorporating 15 cm of organic wastes to the top 50 cm of substrate, combined with standard willow site preparation techniques (Mirk and Volk 2010). The willow on this site produce biomass with yields and quality similar to biomass plantings on mineral soils, while also effectively controlling the water budget of the site (Heavey et al. 2013). Life cycle assessments of the system have also shown the willow vegetative cap to be more cost effective than a traditional geomembrane cap, and require about one tenth the energy inputs and greenhouse gas emissions (Patel 2014). Honeywell and SUNY-ESF have engaged with state and local regulatory agencies to demonstrate the effectiveness of this system and the associated benefits, and there is potential to expand it to 250 ha.

A fourth potential avenue for willow expansion is development of multifunctional systems that balance willow establishment and management costs by providing other valuable environmental services. Recent studies of below-ground biomass show that willow crops can store about 31 Mg_{dry} ha^{-1} in roots and stool (stump) material by the time they are 12–14 years old, which is equivalent to about 55 Mg CO_{2eq} ha^{-1} (Pacaldo et al. 2013). If a monetary value were attached to this carbon storage capacity, it would improve the economics of the system. Commercial-scale willow biomass planting can also be combined with wastewater and biosolid treatment systems, and other value-added bioremediation applications. Wastewater treatment is a particularly good option for willow plants, which can benefit from both the additional water and nutrient inputs, likely improving biomass yield, while providing a safe and effective means of processing of waste materials, a valuable environmental service (McCracken et al. 2014). These systems are typically done at smaller scales, but opportunities exist to implement them near larger municipalities and at many rural municipalities that lack waste water treatment infrastructure, and also have nearby sources of organic wastes such as livestock manure. Other potential multifunctional willow systems are being explored to increase the amount of willow being grown in the region, increase producers' experience with the crop, and provide end users opportunities to incorporate the biomass into their systems. Additional environmental benefits and ecosystem services from willow biomass crops include a high life cycle net-energy ratio, low or no pesticide and herbicide use once the crop is established, low potential for soil erosion, improved water quality, an abundant source of early pollen for bees and other pollinators, and the productive use of marginal and idle agricultural land for rural economic development and job creation (Rowe et al. 2009; Volk and Luzadis 2009; Caputo et al. 2014; Tumminello et al. 2015).

Aside from biomass plantings, willow can also be used in smaller scale plantings such as riparian buffers, streambank stabilization, and living fences. Willow living snow fences (LSF) are a promising alternative application that has been researched at SUNY-ESF since 2006. Like willow bioenergy/bioremediation projects or biorefinery pathways, willow LSF can provide a range of benefits including reduced cost of snow and ice control for transportation agencies, improved road safety for drivers, improved travel times, and a suite of environmental benefits (Heavey and Volk 2014). Willow LSF can also be more cost effective than structural snow fences and LSF of other species due to their rapid growth rates, multiple stems and other characteristics.

Conclusion

Research and development on willow biomass crops has been ongoing since 1986 in the United States and considerable progress has been made in understanding and improving the production system. In addition, as the level of understanding about shrub willow has increased, it has been tested and deployed in other applications including living snowfences, bioremediation projects, and other multifunctional systems. While the work over the past three decades has demonstrated a number of shrub willow's valuable attributes in various systems, deployment of the crop for biomass production and other applications is just beginning to develop. One of the largest barriers to deployment is the high establishment costs and the low rate of return in current energy markets. Efforts to improve crop management, harvesting, and logistics will reduce costs and help to improve returns. The development of biorefinery conversion pathways for multiple, higher-value products from each Mg of willow, or the valuation of some of the ecosystem services and environmental benefits provided by shrub willow, may also help to improve revenues for producers and end users and make the economics more attractive. A suite of extension services is bridging the gap between ongoing research and adoption by the commercial industry for a sustainable bioeconomy. These and other methods will be researched and applied over the next few years in continued efforts to expand shrub willow in the United States. Integrative approaches that synergize these various factors and maximize economic, environmental, and social benefits at various scales will further advance the development, deployment, and utilization of shrub willow for multifunctional systems that produce bioenergy, renewable products, and environmental benefits.

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Conflict of Interest

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