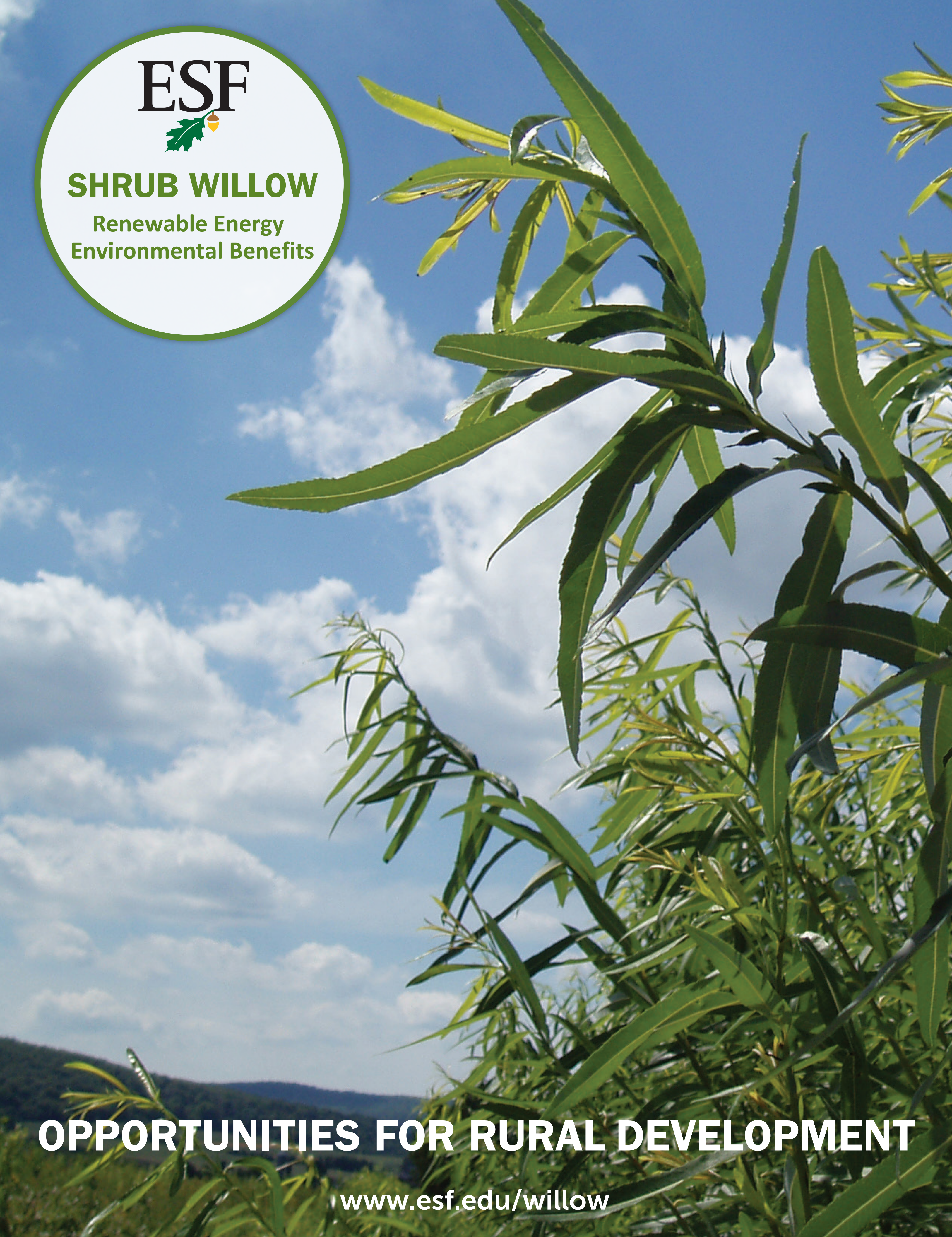
ESF

SHRUB WILLOW

Renewable Energy
Environmental Benefits



OPPORTUNITIES FOR RURAL DEVELOPMENT

www.esf.edu/willow

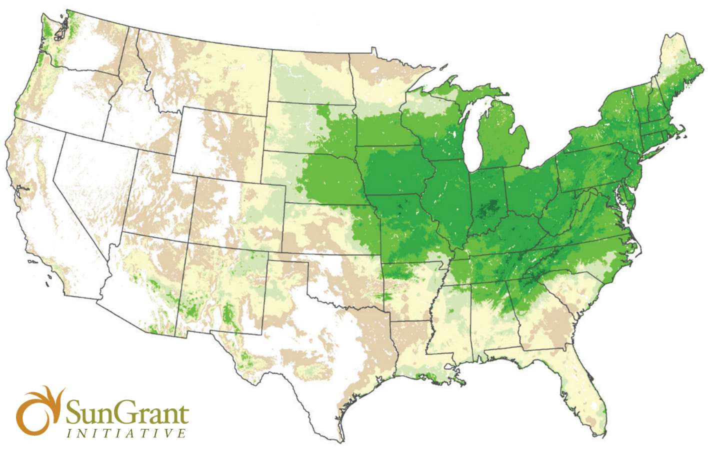
An alternative crop with multiple benefits

Driven by the challenges of rural development, energy independence and environmental sustainability, research on willow biomass crops for renewable energy and environmental applications has been ongoing at SUNY College of Environmental Science and Forestry (ESF) since 1986. SUNY-ESF has teamed up with more than 20 universities, commercial partners and non-profit organizations throughout the U.S. and Canada to conduct research and facilitate the commercialization of willow biomass crops.

- Willow biomass crops are planted once and harvested every three to four years, up to seven times.
- Improvements to the willow production system are increasing potential returns for landowners.
- It is now possible to achieve internal rate of return (IRR) up to 10 percent, with a payback period of three to four harvests (10 to 14 years after planting). If incentive programs such as USDA BCAP are available to establish and grow willow, returns may be 20 percent or greater with a payback as short as one or two harvests (four to eight years).

Willow biomass crops have been tested on a range of sites throughout the Northern U.S. and Southern Canada. The crop consistently yields four to five dry tons of wood chips per acre per year (green areas on map). Continued research and development will further increase these yields in future years.

A FIELD OF ONE-YEAR-OLD WILLOW RESPROUTING IN SPRING



YIELD MAP FOR WILLOW BIOMASS CROPS. DARKER GREEN IS HIGHER POTENTIAL YIELD.

Promoting Rural Development and the Environment

IN SPRING, WILLOW SHRUBS PROVIDE NESTING HABITAT FOR BIRDS LIKE THIS FAMILY OF CEDAR WAX WINGS

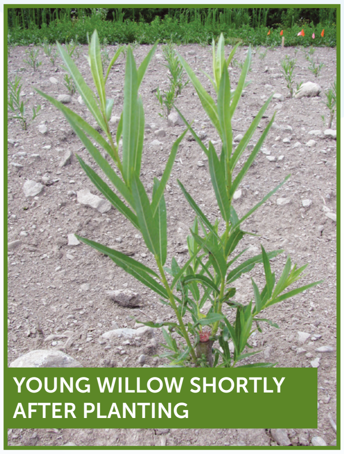
Willow biomass is a low-maintenance crop that stimulates rural economies and enhances the local environment in several ways:

- Shrub willow crops generate income for landowners and create jobs in the local community when converted into renewable energy and products.
- Shrub willow can be grown on marginal farm land so production does not directly compete with food or feed crops.
- Willow is a “carbon neutral” fuel source, meaning no additional CO_2 emissions are created in the production and use of the crop.
- Shrub willows can improve biodiversity, mitigate pollution and provide other environmental benefits to local ecosystems.
- Bird diversity and density in willow biomass crops is similar to natural shrub land and forests.

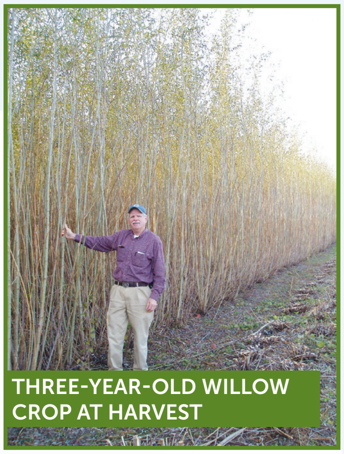
www.esf.edu/willow

Energy, green products and environmental services

Why Grow Shrub Willow?



YOUNG WILLOW SHORTLY AFTER PLANTING



THREE-YEAR-OLD WILLOW CROP AT HARVEST

Shrub willow is easy to establish, grows quickly and provides multiple benefits:

- Adapted to a wide range of site conditions.
- Easily propagated from stem cuttings which grow new roots, shoots and leaves.
- Rapid growth rate, produces hardwood biomass 10-15 times faster than local forests.
- After each harvest, new stems quickly re-grow from the remaining plant.
- Limited maintenance between harvests.
- Willow wood chip properties are similar to forest residue chips and suitable for mixing.
- High ornamental and landscape aesthetic value.

Producing Shrub Willow Crops

PLANTING WILLOW CROPS IN SPRING

Willow biomass crops can be planted on marginal agricultural land. A grower can harvest shrub willow up to seven times from a single planting.

- Land is prepared in fall prior to planting by clearing existing vegetation, plowing and disking.
- Unrooted stems are inserted into prepared ground using a tractor-mounted planter.
- Planting stock is available for purchase from Double A Willow (www.doubleawillow.com).
- Stems are cut back (coppiced) once to encourage more stems and vigorous growth.
- Each plant produces numerous woody stems with diameters approximately 1 - 2 inches at harvest.

MULTIPLE STEMS ON MATURE WILLOW PLANT

Planting and harvesting equipment for shrub willow crops is currently available at reduced costs through the NEWBio program. (www.newbio.psu.edu).

HARVESTING AND CHIPPING A WILLOW CROP

Harvesting and Utilizing Shrub Willow Crops

A WAGON UNLOADS HARVESTED WILLOW CHIPS

SHRUB WILLOW CHIPS HAVE CHARACTERISTICS SIMILAR TO FOREST RESIDUE CHIPS AND CAN BE INTEGRATED INTO EXISTING SUPPLY CHAINS AND UTILIZED AT BIOPOWER FACILITIES SUCH AS REENERGY TO PRODUCE RENEWABLE HEAT AND POWER

Woody biomass from shrub willow can be converted into different forms of renewable energy and environmentally friendly products that offset the use of non-renewable fossil fuels.

- After planting and coppice, the crop can be harvested once every three to four years.
- New Holland Agriculture has developed an effective woody crop header (FB 130) that fits on their FR 9000 series of forage harvesters and is now available.
- The harvester cuts and chips the crop in one pass while chip collection vehicles follow beside it.
- Heat and electricity can be produced from harvested wood chips by direct combustion, co-firing with other fuel sources, or gasification.
- For every one unit of fossil fuel energy used to produce shrub willow crops, about 15 units of renewable electricity are produced, or about 30 units of renewable heat and electricity via co-generation.
- Wood pellets, liquid “biofuels”, biodegradable plastics, and other green products can also be produced from willow.
- All end uses provide local and regional economic benefits.

Other Uses for Shrub Willows

A WILLOW “LIVING SNOW FENCE” TRAPS BLOWING SNOW IN DRIFTS BEFORE IT REACHES THE ROAD

In addition to being a source of renewable energy and green products, the unique characteristics of the shrub willow make it ideal for a wide range of environmental applications:

- **Living Snow Fences** - prevent blowing snow on roadways
- **Vegetated Buffers** - prevent fertilizers and chemicals from entering streams, ponds and waterways
- **Protect Soil Resources** - prevent erosion and stabilize stream banks
- **Environmental Remediation** - clean up and restore former industrial sites
- **Vegetated Cover** - a green alternative for effectively capping landfills

For more info visit www.esf.edu/willow or contact The Willow Project at SUNY-ESF willow@esf.edu or 315-470-6775

Justin P. Heavey and Timothy A. Volk. © 2014 The Research Foundation for the State University of New York College of Environmental Science and Forestry. Syracuse, NY.

Support for shrub willow research and development has been provided by the United States Department of Agriculture (USDA), United States Department of Energy (USDOE), New York State Energy Research and Development Authority (NYSERDA), Empire State Development Division of Science, Technology & Innovation (NYSTAR), and the New York State Department of Transportation (NYSDOT)

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Introduction to Shrub Willow

Welcome

This fact sheet series has been adapted from the Willow Biomass Producers Handbook[1] and the latest research to provide the most up-to-date information in an easily accessible format. This series provides introductory information on producing and utilizing shrub willow biomass for bioenergy, bioproducts, bioremediation and other uses that can create opportunities for sustainable rural development and numerous environmental benefits. This series is for farmers, landowners, project developers, extension professionals, biomass end users and other stakeholders in the Northeast and other areas where shrub willow is being developed. We provide information on each stage of the crop lifecycle, offer cultural and best practice guidelines for optimal returns on investment, and explore the opportunities and challenges of growing willow for multiple uses.

Willow bioenergy crops early in the second growing season

This fact sheet series has been developed by the Willow Project at SUNY-ESF from ongoing research across North America and commercial willow production in New York State. These efforts have been conducted in cooperation with many university, non-profit and industry partners. This first introductory fact sheet in the series will explain willow for bioenergy and other uses, and describe some of the related environmental benefits.

[1]Abrahamson LP, Volk TA, Smart LB and Cameron KD (2010). Willow Biomass Producer's Handbook. State University of New York College of Environmental Science and Forestry, Syracuse, NY.

Willow Bioenergy Crops

The primary use of shrub willow is the production of a bioenergy feedstock (woodchips). Willow is a short rotation woody crop harvested on a three or four year cycle. Willow yields about four to five dry tons of hardwood biomass per acre per year, or about 25 to 35 green tons (45% moisture content) per acre at each harvest. Willow is adapted to grow on a variety of sites including wetter soils and marginal lands. Growing willow on idle land can spur sustainable rural development in the production, transport and use of the crop, providing locally sourced energy and creating jobs. Shrub willow has many characteristics that make it ideal for bioenergy production and other uses. Tolerance of high planting density, rapid growth rates and other traits contribute to willow's ability to produce hardwood biomass ten to fifteen times faster than typical forests in the Northeast.

Willow bioenergy crops three years after planting

New willow plants are easily established from unrooted stem cuttings inserted into properly prepared ground. Plants quickly regrow from the remaining roots and cut stumps after each harvest, a practice called coppicing. One planting can produce seven or more harvests over 20 years with limited maintenance. The quality and variability of woodchip properties important for commercial bioenergy feedstocks such as chip size and moisture, ash, and energy content are similar to forest residues and suitable for current end uses and for mixing these two feedstocks.

Introduction to Shrub Willow

Environmental Benefits

Willow for biomass and other uses can provide many environmental benefits and ecosystem services:

- Willow creates a woodland ecosystem that contributes to wildlife habitat and biodiversity for birds and small mammals.

Willow provides wildlife habitat for many species

- Willow is one of the first species to flower in spring, providing early nectar for pollinators.
- Willow is a carbon-neutral fuel source that does not contribute to climate change as carbon sequestered above and belowground by the crop offsets all greenhouse gas emissions associated with crop production, transport and utilization.
- Willow has a high net energy ratio, an important metric when evaluating renewable energy sources. For every unit of energy invested in the crop, up to 45 units of energy are produced.
- Willow's dense canopy creates heavy shade and natural weed control, eliminating the need for herbicides once the crop is established.
- Willow's natural and cultivated disease and pest resistance also limits the need for pesticides.
- Willow's perennial root system reduces soil erosion and nutrient runoff compared to annual crops.

Other Uses for Shrub Willow

The same unique plant traits that make shrub willow ideal for bioenergy also make it useful for a range of other applications. Willow "living fences" can be used as windbreaks, visual/noise screens, or to trap blowing snow along roadways, which reduces the cost of snow plowing and improves road safety.

A shrub willow living fence keeps blowing snow off the

Willow is naturally adapted to wetter soils and can be used to stabilize stream banks, reducing the risk of flooding and providing a vegetated buffer to prevent pollutants and sediments from entering surface and groundwater. Willow can also be used to remediate former industrial sites and as an alternative landfill cap, adding to the social, economic and environmental benefits that multifunctional willow systems can provide.

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The Northeast Woody/Warm-Season Biomass Consortium
www.newbio.psu.edu

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Willow Bioenergy in New York State

Willow in New York State

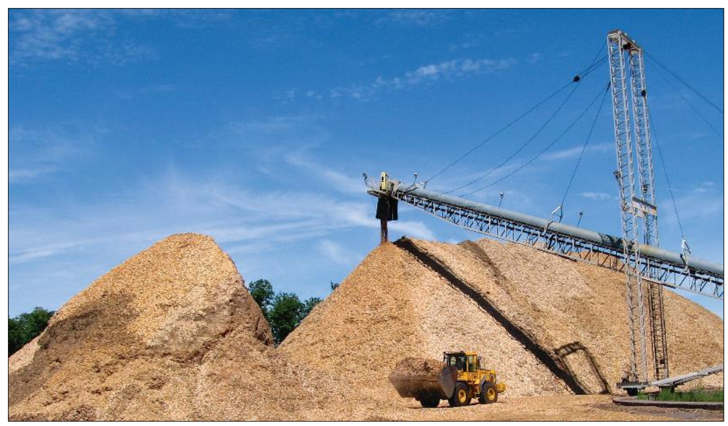
Decades of research on shrub willow by SUNY-ESF and partners has advanced the crop towards a viable, economically sustainable industry. As of 2015, there are 1,200 acres of willow bioenergy crops in New York State. Production is spread across three counties in northern New York, and fields are clustered around two end-use facilities owned by ReEnergy Holdings LLC. ReEnergy has contracted with growers to purchase all willow biomass produced on this land for a period of 11 years under the USDA Biomass Crop Assistance Program (BCAP), and is blending the willow with forest biomass to produce renewable electricity and heat.

A field of one-year-old willow crops in New York State

The first harvest of these crops occurred in 2013 and produced about 2,500 tons of woodchips from 100 acres of land. This biomass feedstock was utilized by ReEnergy to produce about 1,400 Mwh of electricity, enough to power 130 homes for an entire year. Important feedstock properties of the delivered willow (such as ash and moisture content) were similar to forest residues and suitable for blending these two feedstocks, meeting end-user specifications. By 2016, three to four hundred acres of willow will be harvested annually, and this number will increase as more acreages are established. Specialized equipment for planting and harvesting willow is available through the NEWBio equipment access program, and SUNY-ESF is providing outreach and extension services to current and prospective growers and other stakeholders.

USDA BCAP

The willow industry in New York was recently catalyzed by the USDA Biomass Crop Assistance Program (BCAP), which helps growers overcome some of the challenges of growing new bioenergy crops like shrub willow. BCAP is designed to improve domestic energy security, reduce the greenhouse gas emissions that cause climate change, and create opportunities for rural development. BCAP provides partial establishment grants for some of the upfront costs of planting willow, as well as annual incentive payments based on soil conservation rates. BCAP also successfully paired producers with an end user in ReEnergy, ensuring a stable market.



Willow chips are mixed with forest residues at ReEnergy

BCAP is funded through the United States Farm Bill. For the latest information on the availability of BCAP funding to plant willow crops in New York State, please contact The Willow Project at SUNY-ESF by phone or email, or visit our website.

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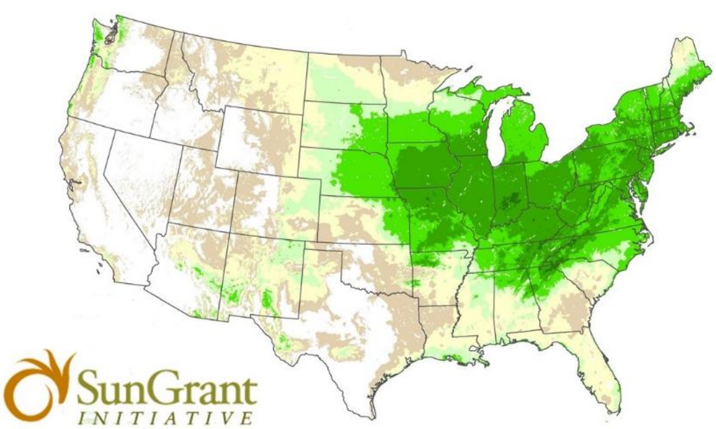
Site Selection for Willow Bioenergy Crops

Site Selection

Shrub willow cultivars developed for bioenergy can produce four to five dry tons (8-10 green tons) of harvestable biomass per acre annually (harvested every three to four years) on a variety of sites. These willow cultivars have a wide geographic range (based primarily on climatic factors of temperature and precipitation) that extends across much of the eastern and central U.S. and into southern Canada. Site conditions within this range can impact willow yield, operations and profitability. Willow can be grown on a wide range of sites including marginal lands, but with potential tradeoffs in plant productivity and the level of operational challenges. Other considerations for willow site selection include the slope of the land, size and layout of the fields, accessibility, and proximity to the biomass end user.



Willow can produce 4-5 dry tons of biomass annually across a wide geographic range (green areas on map)

Soil Characteristics

Soil is an important factor for any crop. Shrub willow can be grown in a variety of soils, but some basic criteria must be met. Soils that do not meet these criteria will inhibit plant survival and growth, and can impact the use of agricultural equipment. Soil characteristics can change within and between fields on a farm, so analysis of the entire land area under consideration for willow is recommended.

Soil drainage classification can be poorly drained to moderately well drained. Soils that are very poorly drained are generally not suitable for willow in most cases, as very wet soil conditions can inhibit plant growth and cause operational difficulties. Excessively well drained soils are also not recommended because willow is vulnerable to drought.

Soil texture classification of sandy clay, silty clay and loams are all generally acceptable. Sands and heavy clays may have associated drainage problems and are therefore not recommended.

Soil pH between 6.5 and 7.0 is optimal for nutrient uptake. Soils outside this range will limit the availability of phosphorous and other nutrients, but willow has been grown successfully on sites with soil pH 5.5-8.0. Soil pH can be adjusted to some degree by the use of amendments such as lime and sulfur.

With proper site selection and site preparation, willow can be grown on a wide variety of sites and soil types.

Soil depth to the root restricting layer (bedrock, hardpan, or seasonal water table) is recommended to be 24 inches or more to provide sufficient rooting volume, available water and nutrients.

Soil fertility should be at least moderate or the soil may require fertilizers or organic amendments during the site preparation phase (see fact sheets on site preparation and nutrient management).

Site Selection for Willow Bioenergy Crops

Marginal Lands

Willow can be grown on marginal lands, but in general, as with most crops, higher quality soils will likely produce higher biomass yields with fewer inputs and fewer operational challenges. Marginal lands, by definition, have one or more biophysical characteristics that limits the productivity and economic viability of traditional annual crops on those lands. Willow is less affected than other crops by some of these limitations, such as wetter soils, but some site limitations may still reduce productivity and operational efficiency in willow plantings.

With the right land and cultural practices, willow can produce 30 green tons of biomass per acre at harvest

The land use history, soil tilth and overall condition of the site should be considered in the decision to plant willow. These baseline conditions dictate the work and investment necessary to properly prepare the soil for planting. Sites that have been idle, compacted, overgrown with brush, etc. will require more work and investment to be made suitable for planting (see fact sheet on site preparation). Some sites may also require rock-picking, removal of hedgerows, new access roads or other site improvements. Despite these challenges, marginal lands may be a feasible option for willow in some cases to make use of idle lands and fields that are generally too wet for other crops, if operational and plant productivity challenges can be overcome.

Other Site Considerations

Transporting feedstock to an end user is often a large percentage of delivered biomass costs, around 20-25%. Fields should generally be located less than 50 miles (one-way) to the biomass end user. The logistics of trucking harvested biomass should be considered, such as site access, load limits, seasonal access roads, height restrictions, etc.

The size and layout of willow fields is also important. The minimum recommended field size is 25 acres, and the preferred project size (group of nearby fields) is 100 acres or more. Larger, rectangular-shaped fields enable longer continuous runs of machinery and higher efficiencies. When renting specialized machinery, fixed costs are reduced in larger projects by spreading the costs of machine transport and use across a larger number of acres. Headlands thirty feet wide or more must be maintained on both ends of the willow rows if using a forage harvester system, but other unplanted areas should be minimized in order to maximize crop production (see fact sheet on headlands and planted area). Slope of the land should be 10% or less.

Each site is unique and should be considered on an individual basis, but following these general guidelines for site assessment and selection can make willow plantings more productive, and make operations more efficient and profitable. Please contact us directly for more information and assistance with individual site assessments.

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Site Preparation for Willow Bioenergy Crops

Overview (Year 1)

Proper site preparation is critical to establishing willow bioenergy crops. Young willow plants require a prepared soil and thorough control of competing vegetation (Figure 1) for willow to achieve optimal growth rates and quickly become the dominant species on a site. The protocols in this fact sheet summarize the tasks required for converting idle fields or pasture to willow. Sites recently used for row crops will require less intensive site preparation. Tasks are identified as 1.1 (year and task number) and so forth, and correspond to the **Willow Calendar** fact sheet (available at www.esf.edu/willow) which provides an overview of all tasks throughout the life cycle of a willow bioenergy crop through multiple harvests. Site preparation should begin at least one full year before planting. Waiting until the spring that planting will occur to start site preparation increases the chances that critical tasks will be skipped, wet conditions will cause delays, planting will occur too late in the season, and thorough control of perennial weeds common on idle land will be difficult or impossible.


Figure 1 (left): A well prepared willow field and headland area ready for sowing of cover crop.
Figure 2 (right): A mature willow planting showing natural control of competing vegetation through shading.

Poor site preparation can lead to low plant density, delays in the first harvest, lower biomass yield, or failure of the crop. Timing and sequence is important in many tasks such as herbicide application. Tasks should not be conducted in compressed time frames or when the weather or other factors are less than optimal. Proper site preparation will make subsequent management of the willow crop easier, and the densely planted willow will form a closed canopy (Figure 2) by the second or third growing season. This closed canopy provides natural control of competing vegetation through shading, and maintenance tasks throughout the remainder of the crop's life cycle (20+ years) are minimal.

1.1 Site Assessment (January-April)

Each field is unique, and site assessment is an important task to inform decision making. The condition of the field will determine the specific site preparation tasks needed, and several factors must be considered. The type, maturity and quantity of existing vegetation on a site will dictate the specific weed control tasks. NRCS soil maps can provide information about the native soil layers, depth, texture and drainage. The plow layer will differ from the native soil after years of various management activities. Soil sampling to assess fertility, organic matter, pH and other factors is recommended (see **Nutrient Management** fact sheet), and local knowledge of fields should be consulted whenever possible. Operational limits of the site such as access, slope, hedgerows, or other divisions between fields may impact tillable acreage, field size and layout. Refer to the **Site Selection** fact sheet for more information on how to decide if a site will support willow and the factors that may limit production, yield and revenues.

1.2 Establishment Plan (January-April)

After site assessment, create a plan and specific timeline for establishing the crop to ensure that the necessary tasks are all conducted, and in the proper sequence. The plan should be detailed and include all the machinery, materials and actions required. Informed planning will reduce delays and unexpected challenges during site preparation, planting and maintenance of the crop. Refer to the Penn State University **Safety and Health Management Planning for Biomass Producers** guidebook for comprehensive safety protocols (http://extension.psu.edu/publications/agrs134) and incorporate the appropriate safety measures into the establishment plan and implementation process.

1.3 Site Improvements (April-July)

Some site improvement steps may need to be taken at the outset, such as improving site access, modifying hedgerows, improving surface drainage, etc. Willow can tolerate wet soils but will not survive or produce substantial biomass in areas with prolonged presence of standing water. Harvesting commercial-scale willow requires a forage harvester and chip collection vehicles (trucks or tractors), so headlands and roads within fields must be able to support these activities during fall, winter and spring. Willow is ideally harvested in the dormant season on frozen ground with little or no snow, but these optimal conditions do not always occur in harvest periods.

1.4 Clear Existing Vegetation (July)

Willow is a pioneer species that will not compete well with other vegetation while the unrooted willow cuttings expend stored resources to grow new roots and stems during the first and second growing seasons. Willow plants must be given the competitive advantage that comes with thorough site preparation and weed control. The first task in this process is to mow vegetation taller than one foot, brush hog old fields, etc. Remove large quantities of biomass by baling so that the remaining vegetation can regrow and be sprayed with herbicide to kill it. Grind or remove woody stumps greater than four inches in diameter from cleared old fields.

Figure 3: Brush hogging is used to clear old fields when woody or large vegetation are too much for simple mowing.
(Image courtesy of Moreland's Lawn and Landscape)

1.5 Contact Herbicide (July)

Once the cut vegetation has resumed vigorous regrowth (one to two weeks, or several inches of new growth) apply a broad-spectrum contact herbicide, or mix of herbicides. Weeds must be actively growing above ground for contact herbicide to be effective. Key factors in assessing vegetation and choosing appropriate herbicides include the prevalence and ratios of specific species, annuals versus perennials, grasses versus broadleaf species, the method of self-propagation, difficulty of control, and time of year.

For example, a field with primarily annual weeds that have not yet gone to seed will be easier to control than a field dominated by a mixture of aggressive perennial weeds that self-propagate from underground rhizomes. Consult an herbicide expert for guidance and follow the manufacturer's instructions on the label. Assess the effectiveness of herbicide treatments about two weeks after application. Effective control is indicated by brown vegetation above ground and dead roots/rhizomes below ground. Reapply the same or a modified herbicide mixture across the whole field, or in spot applications, as necessary. If live rhizomes are found below ground, wait a few weeks until they produce leaves before applying herbicide again. If reapplying herbicides, wait an additional two to three weeks for the herbicides to work before proceeding to the next steps.

1.6 Soil pH Amendments (August)

After vegetation has been cleared and effective herbicide kill is confirmed, add amendments as necessary based on soil tests to adjust soil pH to the 6.0 – 7.0 range. Fertilizers, if needed, are applied in spring of the second growing season after the willow is coppiced (cut back).

1.7 Plow (August)

Willow requires a reasonable soil volume soil for optimal root development and aboveground growth. If a root-restricting hardpan exists 18 inches or less below the surface, break up the hardpan with a tractor-mounted ripper or sub-soiler. Use a moldboard plow to turn soil, break up surface compaction and sod layers, and incorporate pH amendments and organic matter. Zone (conservation) tillage is an alternative site preparation method that may be a viable option in some cases. More information on zone tillage is available from Cornell University Willopedia: (http://willow.cals.cornell.edu).

Figure 4: A moldboard plow turns the soil and breaks up sod and compaction before discing. (Image courtesy of Iowa Dairy Boys)

1.8 Disc (August)

To break down and smooth out the plow furrow, further incorporate organic matter, and improve soil tilth, discing is performed after plowing. This may require multiple passes depending on specific field conditions. The goal is to create a smooth and homogenous planting bed.

1.9 Rock Pick (August)

Fields with a high percentage of rocks four inches in diameter or greater should be combed using a rock-picker tractor attachment (Figure 5) because rocks could damage willow planting and harvesting equipment. Picked rocks should be taken off site if possible. If dumping rocks in a side or corner of the field, make sure the rock piles are in locations that will not interfere with headland mowing and turning of harvesting equipment.

Site Preparation for Willow Bioenergy Crops

1.10 Assess Weed Control (Early September)

Two to three weeks after discing, visually assess regrowth of competing vegetation and the efficacy of weed control across the field. Reapply contact herbicide again if competing vegetation is present on over 25% of the land area. Plowing and discing fields will unearth dormant seed beds that may require further controls. Spot applications and herbicide mixes for specific species may be appropriate. If large amounts of weed regrowth persists (>50% of land area), mechanical and chemical weed control should be continued into the spring before planting. Combinations of discing or cultivators (i.e. spring tooth harrow), and herbicide applications are options at this stage to manage particularly weedy sites.

1.11 Sow Cover Crop (Early September)

If weed control is determined to be adequate by September before planting, a cool-season grass such as winter rye should be planted as a cover crop. The total potential for soil erosion over the life cycle of a willow crop is very low relative to annual crops. Willow is a perennial plant with a fibrous root system, but the potential for erosion is greatest in the first two years when the root system is still being established. In addition to reducing erosion potential, the cover crop will provide additional weed control through the first growing season. The cover crop will inhibit other species establishing on the site and can be easily terminated using a roller crimper or mower before planting willow. The dead vegetation will act as a mulch layer.

Figure 5: Rock picking will help avoid damage to planting and harvesting machinery. (Image courtesy of Highline Manufacturing LTD)

Year 2 (Planting and Maintenance)

Willow is planted in spring of the second year. Completing all the tasks described here the previous year will result in a well-prepared soil and little to no competing vegetation. The effectiveness of each task should be confirmed before moving to the next task. The number of times each task or set of tasks is preformed may be modified based on site conditions (for example, rock picking and discing may be an alternating activity on rocky sites). Proper site preparation and control of competing vegetation sets the stage for successful crop establishment, minimal maintenance in future years, and the first harvest three to four years after coppice. More information is provided in the next fact sheets on **Planting** and **Maintenance.**

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Planting and Maintenance

Overview (Year 2)

Willow is planted in spring of the second year after the site has been thoroughly prepared. Refer to the **Site Preparation** and **Willow Calendar** fact sheets for the tasks required before planting to ensure a proper planting bed and control of competing vegetation. The numerical headings below (2.1 and so forth) refer to the year and task number, and correspond to other fact sheets in this series. Follow standard safety protocols for all tasks and refer to the Penn State University **Safety and Health Management Planning for Biomass Producers** guidebook for more information. These and other resources are available at www.esf.edu/willow.

Figure 1: Terminating a cover crop in spring using a roller-crimper. (Image courtesy of Rodale Institute)

2.1 Terminate Cover Crop (April/May)

Prior to planting willow, terminate any cover crops using a roller-crimper (Figure 1), mower, or contact herbicide. This creates a mat of dead vegetation that acts as a mulch layer to minimize erosion potential and control competing vegetation during the first growing season. A roller-crimper can be mounted on the front of a tractor, with the willow planter on back, to roll the cover crop and plant willow in one pass. Cover crops should be terminated early enough to avoid excessive vegetation which can clump up on willow planters and reduce their effectiveness.

Figure 2: Willow is planted as live stem cuttings that require proper handling until planting.

2.2 Plant (Late April to Early June)

Timing

The recommended planting window for New York State and most of the Northeastern U.S. is late April to early June. Timing will vary with weather and location. Starting too early increases the chance of cold air and soil temperatures that will slow the onset of bud-break, or a hard frost which could damage recently sprouted plants. Fields may also be too wet to operate machinery in early spring. Starting too late in the season runs the risk of soil and plants drying out if weather becomes too hot and dry before a sufficient root system is established by the willow. Waiting longer also gives competing vegetation a head start on the willow and leaves a shorter growing season.

Obtaining and Handling Planting Stock

Planting stock must be ordered several months in advance to allow sufficient time to process and ship the order from the nursery. High-yielding willow cultivars developed for bioenergy plantings by SUNY-ESF and Cornell University are available from Double A Willow (www.doubleawillow.com). Breeding has produced shrub willow cultivars in six diversity groups that represent a range of species and crosses within the *Salix* genus. Plant at least three groups in each field for genetic diversity. Willow planting stock, known as "whips" (about six-feet-long stems), are dormant, one-year-old hardwood cuttings harvested over winter that must be kept cool and moist until the time of planting to maintain viability. A refrigerated truck at 28-30 degrees Fahrenheit is recommended to store whips if planting will take more than five days. If planting

Planting and Maintenance

smaller acreages that can be completed in a few days' time, whips can be stored without refrigeration in a cool, shaded area. Once whips are thawed, they should not be refrozen, if possible. Once thawed, whips can remain dormant up to one week, including transport time, under cool and moist conditions and with proper handling. Cuttings that have sprouted should not be planted because the probability of survival is lower. If whips are exposed to high temperatures and/or allowed to dry out they will lose viability. Never leave boxes of whips out in the open sun, especially with plastic liners sealed, because they will heat up rapidly causing a drop in viability.

Willow Planters

Whips are planted through the terminated cover crop or into bare ground using a mechanized tractor-mounted planter (Figure 3). A minimum 140-horsepower tractor is required to operate a willow planter. Whips are loaded onto the planter in bundles and fed individually into guide belts. The planter cuts each long stem into smaller sections (cuttings) and inserts them into the ground. Studies of commercial willow planting operations have shown this system to be capable of planting about two to three acres per hour. Two to four people — depending on their experience level, planter model, and planting pattern — ride on the planter to load whips. The length of the cutting is generally set at eight inches, but can be varied if necessary for different soil types. Two planter models are available in the Northeast for machinery rental or custom rates from Celtic Energy Farm (http://celticenergyfarm.com/) and Double A Willow (www.doubleawillow.com).

Figure 3: Specialized willow planters plant two rows of willow cuttings from long whips. Two models of planters are available for rental or custom rates.

Planting Pattern

The most common willow planting pattern is an offset double row. This pattern leaves two feet between plants within the row, two-and-a-half feet between rows, and a six-foot alley between double rows (Figure 4). An alternate planting pattern is a single row with one foot between plants and an eight-and-a-half-foot alley between rows. Both of these planting patterns can result in one plant per linear foot down the single or double row. This equates to a density of about 5,500 plants per acre under cultivation (not including headlands). Maintaining at least six-foot alley spacing between rows is important so harvesting equipment can drive down the rows without running over willow stools (stumps) left in the field after harvest. Stool size will expand with repeated harvests and coppice regrowth and the cut stems/stool can puncture tires. The wide alleys ensure that machinery can proceed down the row without running over sharp stools/stems. The planting design for each field should be thought out carefully, because the long life expectancy of willow adds importance to this initial decision. Rows should be as long as possible while maintaining at least thirty-foot headlands. See the research summary on **Maximizing Planted Area** for more information (http://articles.extension.org/pages/73581). GPS guiding planting and automatic steering equipment are recommended.

Planting and Maintenance

2.3 Pre-emergent Herbicide (after initial planting)

Immediately after planting, apply pre-emergent herbicide to control competing vegetation. Choose an herbicide or herbicide mix based on the soil type, the species on the site prior to planting, and species in surrounding fields. Consult an expert and follow the manufacturer's instructions on the label.

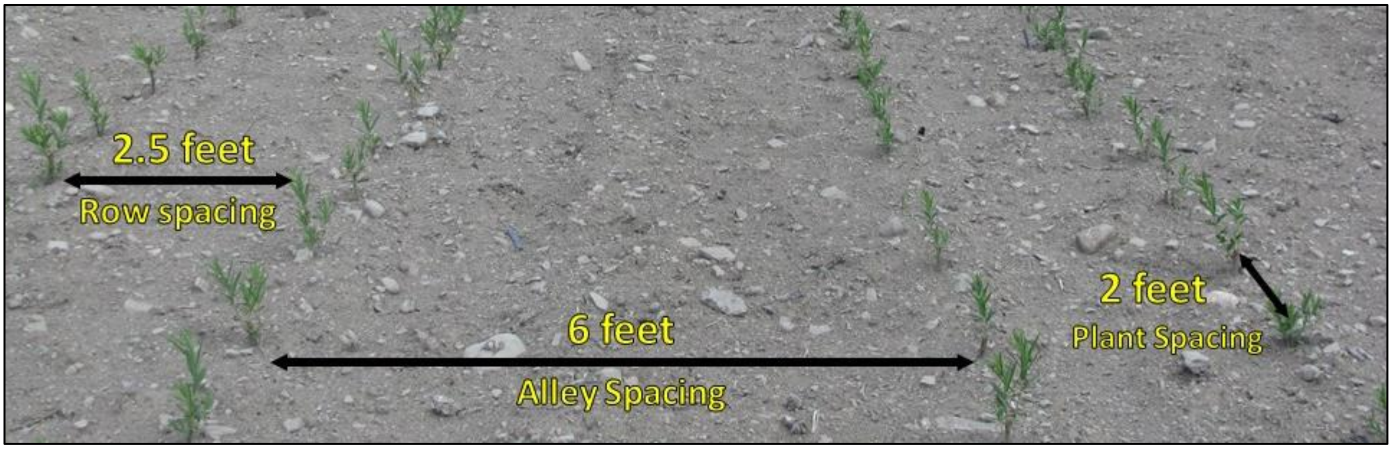

Figure 4: A double-row pattern is the most common for willow bioenergy plantings. This configuration results in about 5,500 plants per acre. The six-foot alley spacing allows machinery access over multiple harvest rotations.

2.4 Inter-planting and Replanting (after initial planting)

It is important to achieve sufficient plant density and distribution for willow to become the dominant vegetation across the entire planted area. One to two weeks after planting, new stems and leaves will begin to emerge from the planted willow cuttings. Fields should be evaluated about two weeks after planting to ensure that no large sections have been left unplanted due to mechanical or human error, and to verify that all cuttings were viable and have become established. Typically, ninety percent of the cuttings will survive. Areas that have less than seventy-five percent plant density should be replanted, either mechanically for large continuous sections, or with six- to eight-inch cuttings by hand for smaller areas. A common method is to survey the field in a utility vehicle and replant six-inch cuttings in areas of low density. Inter-planting after the first growing season is generally not effective, because both weeds and other willow have already begun to occupy the site and will outcompete new willow started from cuttings.

2.5 Crop Monitoring (June-September)

Crops should be monitored periodically throughout the growing season on foot, in a utility vehicle, or with the authorized use of an unmanned aerial vehicle (UAV). Key factors to note while scouting include willow growth and vigor, competing vegetation, pests and diseases. Growth will vary during the first season by cultivar, precipitation, temperature, and soil conditions. Generally, plants should be four to six feet tall by the end of the first growing season, with two to four stems per plant. If weed control is adequate and growth rates are normal, no further action is required until after leaf-fall.

2.6 Weed Control (June-September)

If inadequate weed control is hindering willow growth, take additional measures to control competing vegetation. Cultivators and rototillers can be used for mechanical vegetation control in the alleys. Annual species can often be controlled with one round of mechanical cultivation, whereas perennials may require several rounds. Mowing is another option for mechanical control using a utility vehicle and pull-behind mower. Willows are highly sensitive to most broad-spectrum post-emergent herbicides, so their use is not recommended, even with shielding. Some options exist for treating specific broadleaf weed species with products that do not affect willow. Grasses can be controlled with grass-specific herbicides without effecting the willow. Consult an expert for guidance and follow the manufacturer's instructions on the label.

2.7 Pest and Disease Control (June-September)

Shrub willow cultivars developed by SUNY-ESF and Cornell University are bred and selected for disease and pest resistance, but willow plants are biological systems in nature and the possibility of disturbances to any crop is unavoidable. A variety of insects, rusts, cankers and other pests and diseases can affect willow, so plants should be checked for infestation during crop monitoring and problems addressed using integrated pest management. For more information on common willow pests and diseases, and how to treat them, refer to Cornell Willowpedia (http://willow.cals.cornell.edu).

2.8 Maintain Headlands (June-September)

Headlands (Figure 5) are maintained by mowing once or twice per year for access and to suppress woody vegetation. This maintenance it is important to ensure that equipment can easily access the field during crop scouting and harvests.

Figure 5: Thirty-foot headlands are maintained around willow planting to for equipment access.

2.9 Coppice (November-March)

After the first growing season, coppice (cut back) willow plants using a sickle-bar mower. It is important that the mower has sharp blades, and is driven at the appropriate speed to ensure that the cut is clean and the willow is not pulled out of the ground. Cut the willow stems about two to three inches above ground level. Coppicing promotes more stems per plant and quicker canopy closure in subsequent growing seasons. There is little economic value in biomass cut after one growing season, so stems are left in place on the ground to decompose.

Years 3-25

If fertilizer is being applied, it is generally done so in early spring of the second growing season, and after each harvest when the full site can be accessed. See **Nutrient Management** fact sheet for more info. Harvesting is conducted once every three to four years. Crop monitoring and appropriate follow-up activities for weed and pest control are most important in the two years after coppice, and after harvest. Once the crop has formed a closed canopy, weed control within the planting is generally not needed. At the end of the planting's life cycle, willow can be harvested and the stools removed with herbicide and a forestry mulcher, and soils can be replanted with willow or other crops the following season. See **Stock Removal** fact sheet for more information.

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Northeast Woody/Warm-Season Biomass Consortium
www.newbio.psu.edu

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Harvesting

Timing

Willows should be ready for first harvest three years after coppice (four years after planting). If growth was poor due to weed competition, pests, drought, or other factors, harvesting may be delayed one year or more. Waiting longer than four years of normal growth to harvest is not recommended, as growth rates will begin to decline, and large-diameter stems can damage equipment and make operations less efficient. Harvesting is ideally completed during the dormant season after leaf-fall (Figure 1) and before bud-swell. Optimal conditions for harvesting are frozen ground and little or no snow, but these conditions may not coincide with the planned harvests and equipment availability. Willow can be harvested with leaf-on, but the moisture and ash content of the chips may increase, and nutrients in the leaf will be removed from the site instead of being recycled into the soil. Stem regrowth after harvest that does not harden off before leaf-fall will likely die over winter. This expends some of the plant's stored energy and nutrient reserves, and hinders the plant's ability to compete with weeds the following spring.

Figure 1: Shrub willow is ideally harvested after leaf-fall with frozen ground and little or no snow.

Machinery

The harvesting system that has been used for commercial acreage in the U.S. is a New Holland FR 9000 series or Forage Cruiser series forage harvester, equipped with a FB130 woody-crops cutting header (Figure 2). This machinery was developed by New Holland in partnership with SUNY-ESF and has proven effective in harvesting commercial-scale acreage. The system is most efficient on larger fields and parcels of land in close proximity to one another. This machinery is available from New Holland dealerships, and for rent or custom jobs from Celtic Energy Farm (www.celticenergyfarm.com). A tractor-mounted harvester for smaller willow stems and smaller acreages is available for rental or custom jobs from Double A Willow (www.doubleawillow.com). Tractors and wagons or trucks follow beside the harvester to collect chips. Two or three wagons/trucks are generally needed to maintain efficiencies and avoid harvester downtime, depending on the capacity of the wagons/trucks and the distance to the unloading spot. The type of wagons/trucks used may depend on what is locally available, but silage trucks or large capacity dump wagons, both with heavy-ply tires, are preferred. Silage trucks with flotation tires in the rear have been effective. A skilled operator with experience using the New Holland system to cut woody energy crops should be involved in the process. More information about the specifications of New Holland harvesting equipment is available from the Penn State fact sheet **Willow Harvesting Equipment Considerations** available at www.esf.edu/willow.

Figure 2: Harvesting shrub willow with a New Holland FR Forage harvester and FB130 woody crops cutting header.

Harvesting

Operations

Shrub willow is planted at high density in a double-row pattern and produces numerous woody stems per plant (see **Planting** fact sheet). Plants have a ground-level branching pattern (Figure 3) with an upright or arching stem form. Plants can grow to a height of about 20 to 25 feet or more before harvest. Individual cultivars have different growth forms, stem diameters and numbers of stems per plant, which will affect the ease and logistics of harvester operation. Woody crops are larger and denser than herbaceous crops such as grasses or corn, so care must be taken during willow harvests to avoid damage to machinery. Willow stems should not be allowed to grow beyond three to four years after coppice/harvest to avoid overgrown stems that exceed the mechanical specifications of the harvesting machinery.

Figure 3: Shrub willow has numerous stems per plant that are cut near ground level and re-sprout from the remaining stool in spring.

The New Holland harvesting system cuts and chips willow stems in one pass. An adjustable bar bends the willow stems forward to help feed them into the header. Rotating saw blades at the bottom of the header cut the willow stems near the base of the plant, and two sets of rollers feed cut stems into the forage harvester. Stems are chipped by knives inside the forage harvester and exit through the spout into wagons/trucks. Optimal efficiencies are achieved when harvester downtime is minimized. Factors affecting harvester downtime, material throughput and overall efficiency include the number and capacity of wagons/trucks, field layout, adequate headlands for turning at the end of rows, ground conditions, crop resistance, harvester operator, breakdowns and flat tires. Each site should be assessed to create a harvesting plan based on these factors.

Figure 4: Dumping a load of willow chips onto a large pile for short-term storage before reloading and transport to an end user.

Chip Storage, Loading and Hauling

Harvested chips are typically transported to the edge of the field or nearby landing by wagons/trucks and dumped directly into a large truck for road transport to an end user, or dumped in a short-term storage pile (figure 4). Chips loaded directly into silage trucks can be delivered a short distance to and end user or storage location, but this will increase the number of collection vehicles needed to keep avoid harvester downtime. Short-term storage piles are typically loaded into trucks using a high-dump attachment for a loader or similar machinery. Each acre of mature willow will produce about one semitrailer load of chips at harvest, weighing around 25 tons, so it is important to have a landing area that can accommodate short-term storage.

Harvesting

Safety

There are numerous safety protocols for agricultural operations in general, and additional protocols for dedicated energy crops that are often harvested in winter conditions. Key safety points to consider for willow harvesting are listed below. This is *not* a comprehensive list of safety protocols for biomass harvesting. For complete information, consult the Penn State University **Safety and Health Management Planning for Biomass Producers** guidebook available at www.esf.edu/willow.

- Before harvest season, check that equipment cab heaters and window defrosters are working.
- Allow extra time to harvest. With shorter and cooler day lengths, it takes longer for wet ground to dry if it does not freeze.
- Be certain that reflectors, flashers and lights on equipment are clean and operational. With shorter days it is more likely that equipment will be on roadways when daylight is not optimal.
- Ends of cut willow stools are sharp; be sure of footing near cut stools to avoid falling on them, and take necessary precautions to extend tire life when operating in these fields of willow.
- When operating on frozen ground, remember that snow may be covering patches of ice. This is especially important on slopes.

Figure 5: Aerial photo of a shrub-willow harvest in progress

More Information

More information about willow harvesting equipment, process, costs, and chip quality is available in a series of research summaries and related fact sheets available on the ESF willow publications page (http://www.esf.edu/willow/pubs.htm), or contact us by phone or email using the information below.

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Crop Removal

Shrub Willow Roots and Stools

A common question when considering growing willow bioenergy crops is *what happens after multiple harvests if the landowner wants to remove the willow and plant a different crop?* This is an important consideration in the initial decision to grow willow bioenergy crops and the long-term investment required. It is important to remember that willow bioenergy crops are *shrub* willow (Figure 1), not tree willow. This impacts the type of root system that develops and how the crop can be removed. Shrub willow root systems are typically made up of many smaller roots rather than larger diameter roots more typical of tree. The root system on shrub willow is a diffuse network of roots.

Figure 1: Willow bioenergy crops have a shrub form different from willow trees, and a more fibrous root system belowground. Willow bioenergy crops are also harvested every three to four years, further limiting the size of the root system.

Another factor to consider is that willow bioenergy crops are harvested every three to four years, and the above ground stems are cut and removed in this process. Plants have to maintain a balance between the amount of aboveground stem biomass and root biomass to survive and function, so the size of the root system is limited through regular and repeated harvest of stems causing root dieback and limiting expansion. These factors play a role in the techniques that have been developed and the tools used to remove the root system of willow crops. After harvest, the willow stool, coarse roots and fine roots remain in the field. All of these components can be thoroughly broken down with the proper equipment and techniques, but there is a financial cost of removal.

Timing, Process and Machinery

Willow crops are intended to stay in the ground for seven or more rotations on a three-year harvest cycle, or about 22 years including the first growing season and coppice. After this period of time, it is expected that the size of the stools in the field will begin to restrict harvesting machinery access as stools grow outward from repeated coppice regrowth. There will also likely be improved cultivars with higher yields and other traits to replace the older varieties after two decades. However, it may be possible to let willow grow for additional harvests.

Figure 2: A PTO-driven forestry mulcher is used to chop and grind remaining willow after harvest (photo courtesy of Fecon Inc.).

Crop removal should begin in spring following the final harvest. To remove above ground stems, remaining willow stools are terminated with a forestry mulcher (Figures 2-4) in early spring. The forestry mulcher will grind stools, coarse roots and fine roots so they can decompose and be incorporated back into the soil more

Crop Removal

quickly. After mulching, wait several weeks into the growing season then apply a broad-spectrum contact herbicide to kill any regrowth of willow stems. Follow the manufacturer's instructions on the label.

Ten to fourteen days later, disc the field to mix mulched stools with soil and further break up fine roots. In another ten to fourteen days, evaluate the field to determine if additional discing and/or herbicide treatments are needed. A cleared field can potentially be replanted in the same growing season, but waiting one year to the let the chopped roots and stools decompose can be beneficial. If waiting until the following growing season to replant, cultivate the field and plant a cover crop in fall. Studies have shown little to no re-sprouting of willow once these steps have been taken. The cost to remove willow using these methods is estimated to be about $400 per acre for one round of mulching, spraying and discing.

The above scenario presents one possible method for removing a willow crop, but other techniques and order of steps are possible. If field conditions are too wet in spring, herbicide can be applied to willow after it has sprouted and grown one to two feet high, followed by mulching. Other models of forestry mulchers can be mounted or rented on skid steers and other tracked equipment if working in wet fields. A flail mower has been used to chop stools, but forestry mulchers are more effective. Willow has also been successfully removed by applying herbicide to stools in winter, then mulched and disked in spring after herbicide kill is confirmed. In these and related scenarios, if herbicide, mulching and discing is successful in spring, a new willow planting or summer cover crop can sometimes be established in the same season.

Figure 3: A PTO-driven forestry mulcher grinding cut willow stools and roots so they can decompose back into the soil. The areas around the tractor show previous willow plantings that have already been ground using this method.

Figure 4: Close-up image of a forestry mulcher grinding cut willow stools after harvest. The drum spins at high speeds and the heavy-duty tines chop and grind the woody material and fibrous roots left in the field after harvest.

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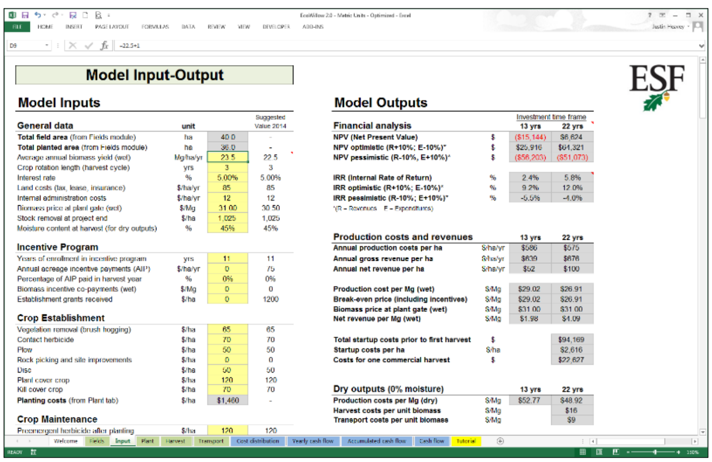
EcoWillow 2.0 – Economic Analysis of Willow Bioenergy Crops

EcoWillow 2.0

Shrub willow is a bioenergy crop being developed as a sustainable commercial enterprise. Willow crops provide a biomass feedstock in the form of hardwood chips that can be converted to renewable heat and power, biofuels and bioproducts. EcoWillow 2.0 is a financial analysis tool for willow that encompasses all stages of the crop's lifecycle over multiple harvest rotations. Data from research trials and commercial operations has been incorporated into EcoWillow 2.0, along with several new features and a more user-friendly design.



The main Input-Output module of EcoWillow 2.0

EcoWillow 2.0 is a versatile analytical tool for landowners, investors, extension professionals and others working with willow bioenergy crops. A default base case scenario is provided with the tool, but users can adjust variables and customize the model scenario to fit their own operating conditions and assumptions. EcoWillow 2.0 allows users to easily model how crop yield, management choices, best practice targets, incentive payments and other factors impact the costs and revenues of growing willow bioenergy crops. The tool is flexible enough to apply to the wide range of sites where willow can be grown. EcoWillow 2.0 is provided as an Excel file containing several linked spreadsheets that correspond to the different stages of the crop lifecycle. The EcoWillow tool, supporting documentation and an instructional video can be downloaded free of charge from our website (www.esf.edu/willow). This fact sheet summarizes each module within EcoWillow 2.0.

Fields Module

The Fields module is a new addition to EcoWillow 2.0 which allows users to combine multiple fields and/or sites into one project analysis. This module also facilitates more precise calculations of transport distances and planted/unplanted areas, important factors in estimating biomass production, costs and revenues.

Input-Output Module

The primary worksheet of EcoWillow 2.0, inputs of this module include biomass yield, price received for the biomass feedstock, incentive payments, and crop maintenance costs. Cost totals from other modules (Fields, Plant, Harvest, Transport) feed into this module to calculate outputs including the financial metrics of net present value (NPV), internal rate of return (IRR), break-even price, and costs/revenues on both a wet and dry weight basis.

Planting Module

The Planting module of EcoWillow 2.0 is based on data from commercial willow operations in New York State. Inputs on this worksheet include the cost of labor, equipment and supplies. An option for refrigerated truck rental is included to account for proper storage of planting stock, as willow cuttings should be kept cool until just prior to planting. Outputs of the planting module include categorized cost totals, total planting costs, and planting costs per unit land area.

Planting a willow crop in New York State

Calendar of Tasks for Willow Bioenergy Crops

	Timeline		Task	Notes
Year 1	Jan-April	1.1	Site assessment	Assess existing vegetation, soil conditions and operational limitations of site.
		1.2	Establishment plan	Create a plan for site improvements, site preparation, weed control, planting and maintenance.
	April-July	1.3	Site improvements	Address challenges to access, operations, drainage, field layout, tillable acreage, etc.
		1.4	Clear existing vegetation	Mow or brush hog perennials and annuals, remove large quantities of biomass.
		1.5	Contact herbicide	Apply contact herbicides to kill existing vegetation. Consult an expert for guidance.
	Aug-Sept	1.6	Soil pH amendments	Add lime or other amendments to adjust soil pH as necessary based on soil test results.
		1.7	Plow	Rip any hardpans, then plow to depth of 10 inches or more using moldboard plow.
		1.8	Disc	Cross disc to create a well-prepared planting bed.
		1.9	Rock pick	Use a rock-picking attachment to clear rocks and avoid planting and harvesting equipment.
		1.10	Assesses weed control	Assess overall weed control and repeat mechanical and/or chemicals controls as necessary.
		1.11	Sow cover crop	Plant winter rye or other cover crop for improved weed and erosion control.

Year 2	April-May	2.1	Terminate cover crop	Kill cover cop using a roller crimper, mower, or contact herbicide.
		2.2	Plant willow crop	Double-row pattern at 2.5-foot row spacing, 2-foot plant spacing and 6-foot alley spacing.
		2.3	Pre-emergent herbicide	Apply pre-emergent herbicide immediately after planting. Consult an expert for guidance.
		2.4	Interplanting and replanting	Interplant by hand and mechanically replant large areas to ensure >4500 plants per acre.
	June-Sept	2.5	Crop monitoring	Monitor crops for growth, weed pressure, pests and diseases, etc.
		2.6	Weed control	Implement mechanical and/or chemical weed control until a closed canopy is achieved.
		2.7	Pest control	Implement integrated pest management as needed.
		2.8	Maintain headlands	Mow in late summer to maintain access and suppress woody vegetation.
	Nov-March	2.9	Coppice	Cut dormant willow plants two inches above ground using sickle bar mower.

Year 3	May-Sept	3.1	Fertilize	Apply fertilizer if necessary based on soil test results. Standard rate for nitrogen is 100 lbs/acre.
		3.2	Crop monitoring	Monitor crops for growth, weed pressure, pests and diseases, animal browse, etc.
		3.3	Weed control	Implement mechanical or chemical weed control for optimal willow growth rates.
		3.4	Pest control	Implement chemical or integrated pest control as needed.
		3.5	Maintain headlands	Mow one to two times per year to maintain access and suppress woody vegetation.

Y 4	May-Sept	4.1	Crop Monitoring	Monitor crops for growth, pests and diseases, manage as needed.
		4.2	Maintain headlands	Mow one to two times per year to maintain access and suppress woody vegetation.

Year 5-23	May-Sept	5.1	Crop Monitoring	Monitor crops for growth, pests and diseases, etc. Repeat annually.
		5.2	Mow headlands	Mow one to two times per year to maintain access. Repeat Annually.
	Nov-March	5.3	Harvest	After leaf-fall, every three to four years.
	April	5.4	Fertilize	Apply fertilizer in the spring following harvest based on soil nutrient management plan.

Year 24	April	24.1	Mulch stools	Grind stools with forestry mulcher after harvest.
	May	24.2	Contact herbicide	Once vigorous regrowth has resumed, spray herbicide to terminate willow.
		24.3	Disc	After confirming effective of herbicide, disc to incorporate stools and smooth the soil.
	May-June	24.4	Replant	Replant with new willow cultivars or other crop, or plant cover crop until next growing season.

Summary

This protocol outlines the tasks generally required for converting idle fields or pasture to willow in the Northeast. Sites recently used for row crops will require less-intensive site prep. Refer to the other fact sheets in this series for more information on each task. Timeframes are approximate Follow standard safety protocols for all tasks and refer to the Penn State University Safety and Health Management Planning for Biomass Producers guidebook or consult and expert for more information. These and other resources, including access to specialized planting and harvesting equipment, are available from The Willow Project at SUNY-ESF and NEWBio.

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EcoWillow 2.0 – Economic Analysis of Willow Bioenergy Crops

Harvest Module

The Harvest module of EcoWillow 2.0 is based on commercial-scale harvesting of willow crops using a New Holland 9000 series forage harvester and 130FB woody crops cutting header. Total harvest time, fuel use, labor, equipment and other variables impacting harvest costs are calculated as a function of standing biomass in the field and the rate of harvest which can be adjusted by the user. Outputs of the harvest module include categorized cost totals, total harvest cost, cost per unit land area, and cost per unit biomass.

Harvesting willow with a New Holland cut-and-chip system

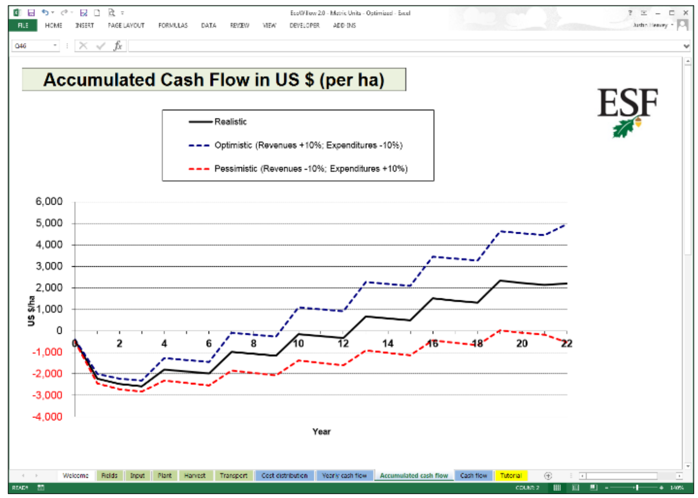
Transport Module

The Transport module of EcoWillow 2.0 is based on logistics and cost estimates from commercial willow operations recently conducted in New York State, with user options for the size of transport vehicles, loading times, and the method of transferring chips (blower, loader or direct) from collection to transport vehicles.

Willow chips are transferred from a collection wagon to a truck for transport

Graphical Outputs

EcoWillow 2.0 provides a series of graphical outputs which display the project cost distribution, the annual cash flow and accumulated cash flow over the project life cycle of 22 years, or seven harvest rotations.



Accumulated Cash Flow Graph in EcoWillow 2.0

Crop Production Scenarios

Four willow crop production scenarios have been developed and tested using EcoWillow 2.0. These include the conservative base case pre-entered into the model upon downloading it, and three alternative scenarios that add potential system improvements and incentive payments to the base case. Outputs and more information on these scenarios is provided in a fact sheet available for download at the address below.

The Willow Project at SUNY-ESF
www.esf.edu/willow (315) 470-6775 willow@esf.edu

The Northeast Woody/Warm-Season Biomass Consortium
www.newbio.psu.edu

Justin P. Heavey and Timothy A. Volk. © 2015 The Research Foundation for the State University of New York College of Environmental Science and Forestry.

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Willow Crop Production Scenarios Using EcoWillow 2.0

Willow Crop Production Scenarios

EcoWillow 2.0 has been comprehensively updated based on the most recent information available from research trials and commercial willow operations. 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 cost of fertilizers, and transport distances.

This fact sheet presents four potential production scenarios for willow biomass crops: (1) a *base case* representing conservative estimates of profitability, (2) an *improved* scenario that modifies the base case with a number of potential system improvements and best practice targets, (3) an *incentivized* scenario that adds potential incentive payments to the base case, and (4) an *improved-incentivized* scenario that adds both potential improvements and incentives to the base case scenario.

For each scenario, the model outputs of internal rate of return (IRR), payback period and break-even price of biomass are summarized in this fact sheet. IRR is the discount rate at which the net present value (NPV) of the project is equal to zero. The payback period is the number of years until the accumulated cash flow becomes positive and stays positive for the remainder of the project lifecycle. The breakeven price is the cost of production per ton of biomass minus any incentives received. All scenarios are based on a 22 year lifecycle of the planting and project analysis period in EcoWillow 2.0. Prices are expressed in terms of wet tons for clarity from the producer's perspective. The expected moisture content of the crop is 45% for conversion into dry tons.

(1) Base Case Scenario

The assumptions of the base case scenario (Table 1) correspond to the suggested values pre-entered into EcoWillow 2.0 upon downloading the model. The inputs of this scenario represent conservative estimates of profitability that should be achievable by most producers in New York and surrounding states based on the current markets, cultural practices, and logistics for willow.

Table 1. Base case for willow biomass production*

- Minimum recommended project size of 25 acres
- Planting rate of 2.5 acres per hour
- Planting density of 5,500 stems per acre
- 10 $tons_{(wet)}$/acre/year biomass production (yield)
- Three year crop rotation (harvest cycle)
- Biomass price received at plant gate of \$27.50/$ton_{(wet)}$
- \$400/acre to remove the willow planting after 22 years

*The complete list of base case assumptions can be reviewed by downloading a copy of EcoWillow 2.0 from: www.esf.edu/willow

The expected IRR for the base case is <0%. The expected payback period is the entire lifecycle of the project, or none. The break-even price is about \$30/$ton_{(wet)}$, slightly more than the assumed price received for biomass of \$27.50/$ton_{(wet)}$.

(2) Improved Scenario

The improved scenario makes changes to the assumptions of the base case across numerous variables of the crop production system. All potential system improvements assumed in this scenario are listed below (Table 2). Each is considered to be a realistic system improvement or best practice target based on current data, logistics and management options of the crop.

Table 2. Improved scenario for willow biomass

- Project size increased to 100 acres, reducing the fixed costs per acre for planting and harvesting operations
- Headlands/unplanted areas reduced from 20% to 10% based on larger field size and other best practice targets
- Expected cost of planting stock reduced from \$0.12 to \$0.09 per cutting
- Planting rate increased from 2.5 to 3.0 acres/hour based on larger field, less turning-time and down-time
- 50% reduction in fertilizer inputs and costs using soil testing and more precise nutrient management
- Biomass yield increase of 0.5 $ton_{(wet)}$ per acre per year assumed with the use of improved cultivars
- Harvest rate increased by 0.25 acres/hour
- Collection vehicle capacity increased from 8 to 12 tons, reducing the number of collection vehicles from 4 to 3
- Transport distance decreased by 5 miles
- Price received for biomass increased by \$0.50/$ton_{(wet)}$

Willow Crop Production Scenarios Using EcoWillow 2.0

The expected IRR for the optimistic scenario is 5%, and the expected payback period is 13 years, or at the fourth harvest. The break-even price is about \$27/ton$_{(wet)}$.

(3) Incentivized Scenario

The incentivized scenario adds a series of subsidy payments (Table 3) to the base case using the framework of the USDA Biomass Crop Assistance Program (BCAP). Nearly 1200 acres of commercial willow crops have been incentivized by BCAP, and more funding may become available. The expected IRR for the incentivized scenario is 10%, and the expected payback period is 13 years, or at the fourth harvest. The break-even price (production cost minus incentives) is about \$25/ton$_{(wet)}$.

Table 3. Incentivized scenario for willow biomass

- All assumptions of the base case scenario (1) plus…
- One-time establishment incentive of \$500/acre
- Acreage incentive of \$40/acre in non-harvest years
- 11-year incentive program enrollment period

(4) Improved-Incentivized Scenario

The improved-incentivized scenario (Table 4) combines the previous scenarios, adding both system improvements and incentives to the base case, representing the most profitable potential outcome of the four example scenarios presented in this fact sheet. The expected IRR for the improved-incentivized scenario is 20%, and the expected payback period is 7 years, or at the second harvest. The break-even price is about \$20/ton$_{(wet)}$.

Table 4. Improved-Incentivized scenario for willow

- All system improvements from improved scenario (2)
- All incentives payments from incentivized scenario (3)

Summary of Outputs

Outputs of the four example scenarios for willow biomass production presented in this fact sheet are summarized in Table 5. For the base case scenario (1), the system is not profitable at \$27.50/ton$_{(wet)}$ received for biomass, with the breakeven price slightly higher at \$30/ton$_{(wet)}$.

The improved scenario (2) increases profitability over the base case with expected IRR around 5%, and a payback of 13 years. The incentivized scenario (3) produces returns similar to the improved scenario, although slightly more profitable. The improved-incentivized scenario (4) offers the best potential returns of these four example scenarios, with expected IRR around 20% and payback seven years (two harvests) after planting. 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, with slight shifts in certain categories between the different scenarios.

Table 5. Summary of four willow production scenarios*

Scenario	IRR	Payback	Break-even Price
(1)Base Case	<0%	none	\$30/ton $_{(wet)}$
(2)Improved	5%	13 yrs	\$27/ton $_{(wet)}$
(3)Incentivized	10%	13 yrs	\$25/ton $_{(wet)}$
(4)Improved-Incentivized	20%	7 yrs	\$20/ton $_{(wet)}$

*IRR values and break-even prices are approximate (rounded)

All of these scenarios are hypothetical situations based on the best information available at this time. The projections are believed to be accurate, but results are not guaranteed. Every project will be unique and users of EcoWillow 2.0 are expected to change all individual variables within the model as appropriate to their specific operating conditions, management decisions and expected outcomes.

The Willow Project at SUNY-ESF
www.esf.edu/willow (315) 470-6775 willow@esf.edu

The Northeast Woody/Warm-Season Biomass Consortium
www.newbio.psu.edu

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This work was supported by the New York State Energy Research and Development Authority (NYSERDA), the US Department of Energy (USDOE) and the US Department of Agriculture National Institute of Food and Agriculture (USDA NIFA).
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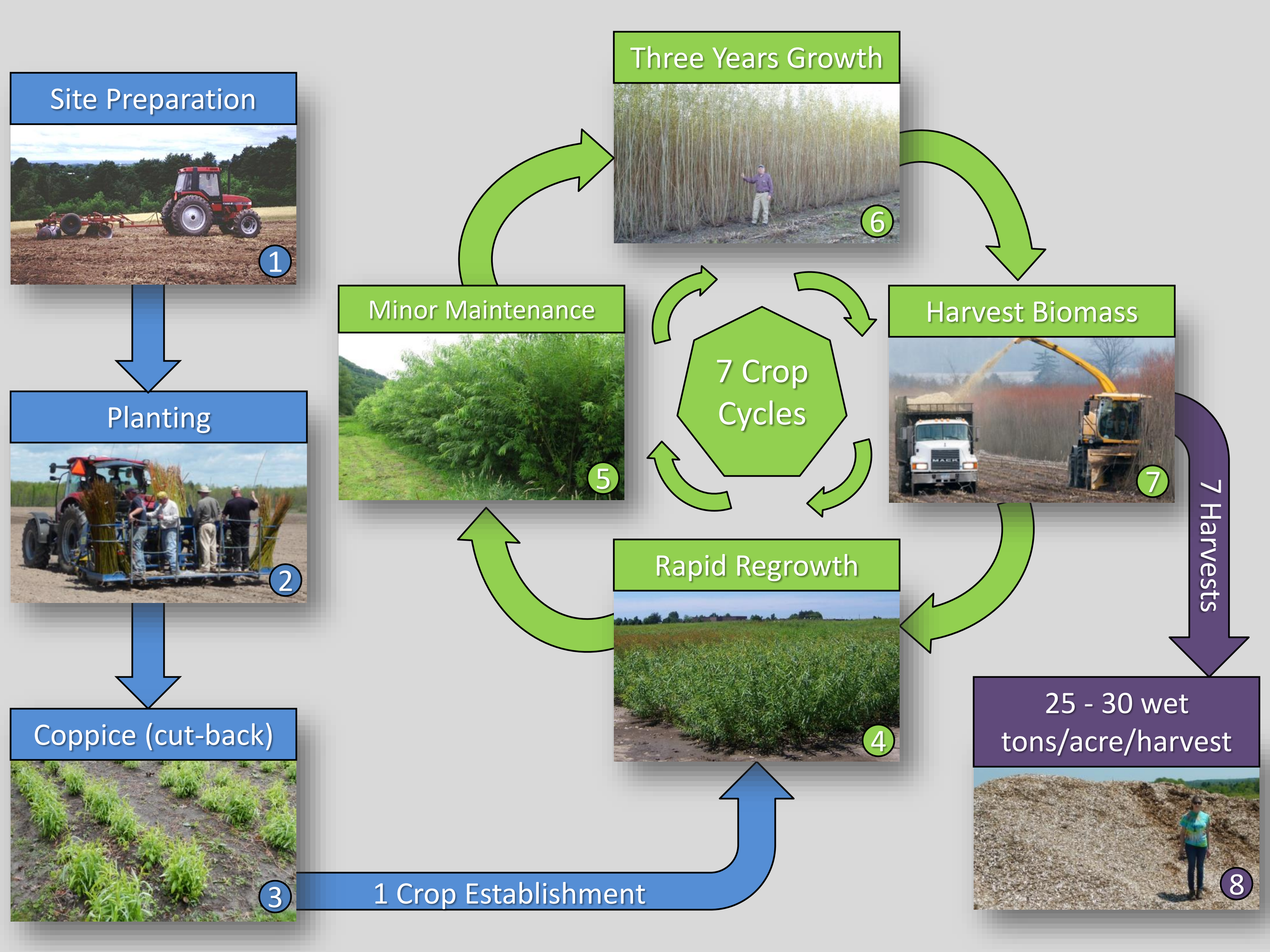
Site Preparation
1
Planting
2
Coppice (cut-back)
3
1 Crop Establishment
Rapid Regrowth
4
Minor Maintenance
5
Three Years Growth
6
Harvest Biomass
7
7 Crop Cycles
7 Harvests
25 - 30 wet tons/acre/harvest
8

Willow Site Preparation

Site preparation is completed once in fall or spring prior to planting.
Typical site preparation includes mowing, herbicide, plow, disc and smooth.
Thorough control of weeds is a critical step in site preparation process.
This photo shows a properly prepared willow field prior to planting.

1

Planting Willow

Planting is completed once in spring using a specialized willow planter.
The willow planter cuts large dormant willow stems to length and plants in one pass.
Willow planters are available through the NEWBio Equipment Access Program.
This photo show a willow planter in operation planting two double rows at a time.

Coppicing Willow Plants

Willow is coppiced (cut back) after the first growing season when plants are dormant.
Coppicing encourages more vigorous growth and more stems per plant.
Cut willow re-grows quickly from the remaining plant after coppice and each harvest.
These photos show willow after first coppice, and a mature plant with multiple stems.

Rapid Growth After Coppice and Harvest

Willow can grow up to ten feet in height in a single growing season.
A well established root system helps the plant grow back quickly from the cut stool.
The large plants and high planting density quickly shade out weed competition.
This photo shows re-growth of a willow field in early summer after the first harvest.

Willow Growth and Harvest Cycle

Willow is grown on a 3 - 4 year cropping cycle, or one harvest every 3 - 4 years.
A mature willow crop is 15 - 25 feet tall with 1 - 2 inch diameter stems.
Each harvest yields about 25 - 30 wet tons per acre, or 4 - 5 dry tons per acre per year.
This photo shows the alley between two double rows of three-year-old willow.

Willow Maintenance

Maintenance is highest in the first two seasons when weed & pest control are critical.
After the crop is established, maintenance is drastically reduced.
Crop monitoring and maintaining headlands between harvests is required.
These photos shows close-ups of shrub willow at various stages of development.

Willow Harvesting Operations

New Holland has developed a woody crops header for its forage harvester series.
This system efficiently cuts and chips one double row of willow in one pass.
The willow chips are blown into collection vehicles such as trucks or dump wagons.
This photo shows a willow harvesting operation in progress.

Multiple Harvests from a Single Planting

Once established, willow can be harvested every 3 - 4 years, up to seven times.
The current market for willow biomass in NY State is for renewable power and heat.
Other uses for willow include cogeneration, pellets, liquid biofuels and green products.
This photo shows forest reside chips mixed with willow at a ReEnergy facility in NY.

ReEnergy Holdings: Offering Markets for Biomass in the Northeast

articles.extension.org/pages/73637/reenergy-holdings:-offering-markets-for-biomass-in-the-northeast

Biomass fuel is loaded into boilers at ReEnergy's green energy facilities. *Photo: ReEnergy*.

ReEnergy Holdings LLC works with willow growers and uses waste and shrub willow wood to generate electricity.

Table of Contents

Introduction

As a vertically integrated renewable energy company, ReEnergy Holdings LLC is an important link in the Northeast's bioenergy supply chain. Since 2008, the company has provided a market for biomass, such as forest residues, shrub willow, and waste wood, while generating renewable electricity in several large facilities. ReEnergy is also a sponsor of the USDA's Biomass Crop Assistance Program (BCAP) for willow in central and northern New York, providing opportunities for growers and other bioenergy entrepreneurs.

The company was formed by affiliates of Riverstone Holdings LLC, a private equity firm focused on energy, and a management and investor team. It now owns eight energy production facilities in three Northeast states, six of which are currently operating. Together these facilities have the capacity to generate approximately 300 megawatts of renewable energy, enough to power 305,000 homes per year . They also own and operate four recycling facilities in Massachusetts, New Hampshire and Maine. They also provide jobs to local economies, many of them rural, employing about 300 people.

Shrub Willow Helps Fire Electric Plants

In northern New York State, ReEnergy owns and operates the ReEnergy Lyonsdale biopower facility in Lyonsdale, New York, and the Black River facility at the U.S. Army's Fort Drum installation near Watertown, New York. In the largest renewable energy project in the history of the U.S. Army, the Black River facility provides 100 percent of the electricity used at Fort Drum, selling additional electricity to the regional grid. ReEnergy has signed a 20-year power supply contract with the Army, ensuring long-term demand for biomass feedstocks in the region (read more here). Approximately 80 percent of the facility's wood fuel is forest residue from logging operations; the remainder is recovered construction and demolition wood, willow, and tire-derived fuel.

Larry Richardson, CEO of ReEnergy, leads a tour at the grand opening of the ReEnergy Black River facility in May 2013. *Photo: ReEnergy.*

About 1,200 acres of shrub willow established in 2013 and before provides fuel to the two facilities. The majority of it is grown by Celtic Energy Farm, another NEWBio collaborator. Shrub willow is a short-rotation woody crop which has been actively researched for bioenergy and other applications by the State University of New York College of Environmental Science and Forestry (SUNY-ESF) since 1986, and more recently by Cornell University.

Over the first two harvest seasons of the BCAP program, the Lyonsdale and Black River facilities have received abut 2,500 and 540 tons of willow chips, respectively. This experience with commercial-scale willow has given facility operators at ReEnergy new confidence with the feedstock, which has performed well as a fuel in their plants and is now seamlessly integrated and directly mixed with other feedstocks coming into the yard. The amount of willow delivered to these facilities will increase over the next few years as plantings established in 2013 reach the end of the first harvest rotation. Supply of willow could increase even further in future years with the potential for additional willow plantings as the industry progresses.

ReEnergy Lyonsdale and Black River also burn green wood chips for forest residues, most of them obtained within 60 miles of the facilities. To ensure that the fuel they burn is sustainably sourced and harvested, ReEnergy became certified to the Sustainable Forestry Initiative® (SFI®) Standard in 2013; it is the first company solely devoted to electricity production to do so. The certification verifies that the company's biomass procurement promotes land stewardship and responsible forestry practices. ReEnergy has also worked with loggers to finance chipping equipment, providing more economic opportunities to local businesses and ensuring a more stable feedstock supply chain.

Working with Willow Growers

Willow Harvest. *Photo: SUNY-ESF.*

As part of the BCAP program in northern New York, ReEnergy contracts with landowners and lessees who grow willow on farmland in Jefferson, Lewis, and Oneida counties. These growers produce, harvest, and deliver the final product to fuel yards at ReEnergy's facilities. ReEnergy pays them a contract price over the 11-year span of the current BCAP project. The BCAP also assists landowners who are early adopters of bioenergy crops by partially subsidising the cost of establishment and providing an acreage incentive payment to landowners in non-harvest years, based on the soil conservation rate of the land on which willow is being grown (visit www.esf.edu/willow for more information).

Over the course of this contract, ReEnergy expects around 75,000 green tons of willow biomass will be produced for use in its facilities. The willow stands have the potential to continue producing biomass for at least another decade after the program is completed (willow bioenergy plantings are typically harvested every three to four years, up to seven times).

The previous BCAP signup period ended in 2013, but ReEnergy plans to sponsor an expansion of the program in this project region if another round of USDA BCAP incentives becomes available under the 2014 U.S. Farm Bill. This would add more growers and willow acreage; meanwhile, more established willow plantings will be ready for harvest soon.

In support of the current BCAP program, SUNY-ESF, in partnership with NEWBio and NYSERDA, provides outreach and extension services to growers and other stakeholders in the project region. SUNY-ESF and NEWBio are also monitoring and researching feedstock quality across the supply chain, willow harvesting and logistics, and the environmental sustainability of willow bioenergy in partnership with the US Department of Energy.

Recycler of Waste Wood

The ReEnergy Black River facility. *Photo: ReEnergy.*

ReEnergy also has a hand in reusing debris left over from the construction and demolition of houses and other buildings. In the last six years, the company's recycling division has purchased and now operates four facilities for this purpose in New England: one in Lewiston, Maine; two in New Hampshire in the towns of Epping and Salem; and one in Roxbury, Massachusetts.

These facilities process a total of 700,000 tons of construction and demolition debris a year — keeping the waste out of the region's burgeoning landfills. Employees recover about 70 percent of that waste as asphalt, brick, and concrete; ferrous and non-ferrous metals, and wood chips to fuel energy-generating facilities owned by ReEnergy and others. They also process construction waste into products used by other industries such as asphalt paving, new cardboard and drywall, and recycled plastic and metal products.

"We believe that waste is not something to be discarded into ever-diminishing landfill space, but rather an opportunity to maximize materials that can be recycled and beneficially reused so we may minimize materials that are landfilled," said Sarah Boggess, director of communications and governmental affairs for ReEnergy.

ReEnergy also operates four electricity-generating plants in Maine that burn biomass from green wood, such as forest residue from the surrounding areas. Two of the plants, in Ashland and Stratton, are located next to sawmills and also burn mill residue. ReEnergy also has two facilities that are idle for the time being: a biomass-fired generating facility in Chateauguay, New York, and one in Sterling, Connecticut, which had burned discarded tires and biomass material until October 2013, when it was closed for economic reasons. These plants may come online again in the near future, depending on possible renewable energy incentives, energy sales agreements, and energy prices.

The Big Picture

Energy prices are volatile, and renewable energy policies and incentives also face an uncertain and changing future. This can have a large impact on the viability of renewable bioenergy. Still, stable, long-term demand for biomass in the region has been secured through ReEnergy's 20-year contract with the U.S. Army through 2024, contributing to the Army's goal of 1 gigawatt of renewable energy by 2025, the Energy Policy Act of 2005, Executive Order 13423, and the Energy Independence and Security Act of 2007.

ReEnergy's New York plants will also play a role in New York's renewable portfolio standard administered by NYSERDA, a program that is tasked with obtaining 30 percent of New York's electricity from renewable sources.

Willow bioenergy, sustainably harvested forest residues, recycled construction debris, and other renewable feedstocks provide a diverse range of fuel sources and economic benefits. ReEnergy is well placed to continue as a leading player in the Northeast's renewable energy industry and contribute to several larger intiatives on the state and national levels.

For More Information

ReEnergy Holdings LLC

New Holland Agriculture Expands Offerings for Biomass Harvest and Handling

Farm Energy June 05, 2015

Renewable energy production options are growing thanks to expanded farm equipment capabilities for harvesting biofuel feedstocks like shrub willow.

Table of Contents

Case New Holland's 130 FB coppice header harvesting shrub willow by cutting and chipping the crop in one pass.

Introduction

Harvesting is the single most expensive operation in the production of shrub willow biomass, accounting for about 30% of costs over the life cycle of the crop (20-plus years). In the past, willow harvesting operations typically encountered problems with equipment durability, chip size, and other technical details.

So when John Posselius, innovation engineering director for New Holland Agriculture, learned that willow grown for bioenergy was being harvested with forage harvesters, he knew that his company could offer a solution. New Holland Agriculture has been building commercial self-propelled harvesters for corn, sugar cane, and other commodity crops since the 1970s.

The company has 120 years of experience developing and manufacturing agricultural equipment. Increasingly, it is focusing that expertise on renewable energy. In 2006, the company established a Clean Energy Leader strategy to promote renewable fuels, emissions reductions, and sustainable agricultural technology.

Posselius and his team helped develop a single-pass cut-and-chip harvesting system for woody bioenergy crops like shrub willow and hybrid poplar for use primarily in the Northeast but which is now sold worldwide. The system was developed in collaboration with NEWBio researchers at the State University of New York College of Environmental Science and Forestry (SUNY-ESF) and others, with support from the U.S. Department of Energy and the New York State Research and Development Authority.

Coppice Header Story

IIn 2004, Posselius contacted Dr. Timothy Volk, senior research associate at SUNY-ESF, who researches the use of short-rotation woody crops for bioenergy. The system they developed is based on the 130 FB woody-crops cutting header, now available through the New Holland's dealerships, which can cut and chip shrub willow or hybrid poplar grown for bioenergy in one pass. The harvesting system has been helpful in the operations of growers enrolled in the USDA's Biomass Crop Assistance Program (BCAP).

Case New Holland's 130 FB coppice header harvesting shrub willow by cutting and chipping the crop in one pass from the back.

The header was designed specifically to harvest willow and poplar more efficiently and to work with New Holland's line of self-propelled forage harvesters with limited modifications to the harvester. Plants are cut at the base and run through the machine; the chips are then blown into an accompanying truck or wagon. The result is a system that can chop 60 to 80 green tons or more per hour of consistently sized chips, doubling the harvester's output while cutting costs by a third.

The header was introduced commercially in 2009, when it won an AE50 award from the American Society of Agricultural and Biological Engineers as one of 50 most innovative products to enter the market that year. Since then, New Holland has sold a number of the harvesting systems, most of them in Europe, where woody crops are more commonly grown for renewable energy. There are about a half-dozen now in the United States; one of them is owned by Celtic Energy Farm in northern New York, where much of the willow is currently being grown for bioenergy.

The new header system gave producers and end users such as biopower facilities more confidence in shrub willow as a feedstock: 500 hectares of the crop were enrolled in the BCAP project in northern New York State in 2012.

The header is a big step forward in the commercial profitability of biomass crops. It opens up opportunities for farmers, especially those who run very expensive harvest equipment, such as a $500,000 forage harvester, for just a short part of the year. Most agricultural base units can harvest several types of crops but that usually requires a specialized head designed for each specific crop.

"With virtually no modification [to the harvester] and by adding a new header like the 130 FB coppice header, we can extend the hours per year a customer can use their harvester. It's a win for everyone," Posselius said.

But the economics are critical to adoption of the harvesting system. Although a producer buying a forage harvester along with several different heads might get a better price from the dealer, the cost of a coppice header still runs between $80,000 and $120,000.

Case New Holland's 130 FB coppice header harvesting shrub willow through the row from the back.

"The 130 FB has to be something that our customers can afford," Posselius said. "What he gets for the chips has to cover his costs and get some profit; the same thing for the customer who buys the chips. So everyone has to make a profit. It's what makes financial sense to all three—New Holland, the customer, and the person who buys the chips or switchgrass bales."

New Holland Looks to a Bioenergy Future

In addition to shrub willow, New Holland participates in studies of other renewable energy crops and the equipment to produce and harvest them. The company's innovation team has been working with biomass crops such as eucalyptus in South Florida and Brazil, and poplar in Europe and in the Northwest, where it is also used for pulp. It has worked with Iowa State University and Penn State University on miscanthus, and with Penn State on corn stover. Both of these crops hold great potential as bioenergy feedstocks in the Northeast.

New Holland is also developing modifications and kits for mower-conditioners so they will function better in heavy biomass crops, and equipment to improve switchgrass baling.

The company has adapted its MegaCutter, a disk mower-conditioner that can also pull a baler, for use with miscanthus. Another piece of equipment, the Cornrower, is an adaptation to the corn chopping header on a combine which handles the stover separately from the grain. The operator chooses the number of rows of stover and stalks to chop and windrow; the remaining stover is left for soil improvement. The harvested stover can be used as feed or for use in a cellulosic energy plant.

Next Steps

Case New Holland's 130 FB coppice header harvesting shrub willow through the row from the front.

A well-functioning supply chain for willow and other short-rotation woody crops includes efficient production, harvest, transport, and delivery to a biorefinery or other end user—and profitably for everyone. The cost of those operations compared to the price received for biomass is one of the challenges facing the development of feedstock supply chains.

With advances like the single-pass system, that supply chain is steadily improving. Commercial production in New York State is creating fertile ground for innovation by growers. The state Department of Energy recently awarded SUNY-ESF another grant to continue working with New Holland to further optimize harvesting and logistics of willow and hybrid poplar.

As companies like New Holland make more useful equipment available to perennial biomass crop producers, they help reduce costs and make bioenergy crops more profitable. Equipment like New Holland's 130 FB coppice header is one step in cutting costs and helping producers harvest faster and more efficiently, while expanding the use of their expensive harvest equipment. This makes it a mutually beneficial arrangement, which will strengthen the supply of renewable energy feedstocks into the future.

For Additional Information

Double A Willow Strengthens Biomass Supply Chain by Providing Willow Plantings to Biofuels Industry

Farm Energy May 29, 2015

As the largest supplier of shrub willow planting stock in the United States, Double A Willow is a critical link between research and the commercial development of renewable energy.

Double A Willow owner, Dennis Rak, with some of his original plantings.

Table of Contents

Introduction

Double A Willow in Fredonia, New York, is the main source of shrub willow planting material for biomass energy and other uses in the United States. Owned by Dennis and Sue Rak, its nursery produces willow planting stock for landowners, institutions, and companies in the bioenergy industry.

The planting stock, in the form of dormant stem cuttings, comes from hybrid cultivars developed through breeding programs and research trials at the State University of New York School of Environment and Forestry (SUNY-ESF) and Cornell University. As such, Double A Willow is an essential link between research and the larger renewable energy industry.

Growing Willow for Others

Double A Willow employees plant nursery blocks with its Egedhal planter, specifically designed to plant willow.

When planted in properly prepared ground, dormant shrub-willow stem cuttings from one-year-old plants produce new roots, stems, and leaves and grow into a new plant. This makes propagation of new willow plants that are genetically identical to the hybrid cultivars from which they were sourced relatively quick and easy compared to planting a rooted shrub. The hybrid cultivars are bred for traits such as fast growth, high biomass yield, and disease and pest resistance.

Double A grows about 150 acres of willow at its Fredonia nursery. In addition to selling the willow stem cuttings, the company helps customers establish willow plantings and does custom planting and harvesting. For the last decade, Double A Willow has been the only commercial nursery licensed to grow and distribute hybrid shrub willow cultivars developed and patented by SUNY-ESF. Growers sign a license agreement with Double A for the right to raise the willow varieties for commercial use.

The majority of Double A's willow cuttings destined for bioenergy are growing on 1,200 acres in northern New York, operated by Celtic Energy. Willow biomass from these plantings is being sold to ReEnergy Holdings LLC, which is using willow and other sources of woody biomass for renewable power and heat in converted coal-fired power plants in the region. With the continued funding under the 2014 Farm Bill of the USDA Biomass Crop Assistance Program (BCAP), Dennis Rak hopes there will soon be the opportunity to plant more willow in New York.

Double A Willow planting willow at Colgate University, Hamilton, New York.

The company has been involved in several other biomass pilot projects, including:

- The East Lycoming, PA school district planted 50 acres of willow for a biomass boiler that replaced an oil-fired heating system and is saving the school money.
- Vernon-Verona-Sherrill High School in Verona, NY, established 2.5 acres of willow to use for fuel in maple syrup production.
- Traxys, a multinational company that deals in metals and mining, planted 30 acres of willow in northern Michigan as part of a project to convert coal-burning plants to biomass.
- Colgate University in Hamilton, NY, planted a seven-acre plot of willow for potential fuel in its campus central-heating facility.

The Long View

Riding out the volatility of the energy business is one requisite for today's producers growing commercial biomass feedstock. With the price of fossil fuels presently so low, Double A Willow's willow-for-bioenergy program is treading water while it concentrates on developing other avenues for its willow-growing operations.

"The real issue is the price of natural gas, which has fallen so much," said Rak. "When we started this ten years ago, one of our first questions was: what am I competing against?" Coal was the cheapest fuel but it had environmental problems. Oil was too volatile to be useful in producing electricity. Natural gas was very expensive. Then came hydraulic fracturing, or fracking, which unleashed shale oil and made natural gas a much more affordable fuel alternative to coal and oil—and renewable energy sources. Today, many coal-burning power plants are converting to natural gas. "With oil at $50 a barrel, the economics are just not there," Rak said. "That road we started down—we're sitting there on it, waiting."

An innovative single-pass cut-and-chip system being used to harvest willow in western New York.

If growing willow for bioenergy is slow at the moment, it's fortunate that Double A Willow's parent company, Double A Vineyards, also owned by Rak and his wife, Sue, produces grapevine cuttings. The Raks don't have to rely on selling willow cuttings to make their business viable. And while they wait for a large-scale biofuel industry to emerge, they are supporting other commercial uses for their shrub willow, such as:

- The New York Department of Transportation is growing living willow snow fences along highways to hold back blowing snow, reducing the cost of highway maintenance and improving road safety.

- Willow is being increasingly used for streambank restoration, such as in a project that helps protect the water quality of Chautauqua Lake in New York State.
- A sub-licensee in Vancouver, Canada, is working with the city of Calgary on wastewater treatment. Called phytoremediation, the operation includes 1,500 acres of willow plants that will filter out pollutants; the willow will then be harvested and burned as fuel.

On a smaller scale, the Raks have sold willow cuttings to be grown for privacy fences, for making baskets and ornamental items, and for sculptures (Patrick Dougherty of Stickwork used Double A’s willow for an installation at the University of Pennsylvania’s Morris Arboretum). Rabbit feed is another potential use: Double A Willow has tested several varieties of willow on rabbits raised for meat. It turns out that the rabbits have a definite preference for certain willow varieties.

Summary

Double A Willow is making the establishment of willow plantings easy and cost-effective for growers, whether they are property owners or producers looking to diversify their land use, or power plants looking to a future of renewable energy.

For Additional Information

Contributors to This Case Study

Research Summary: Development of a Single-Pass Cut-and-Chip Harvesting System for Short Rotation Woody Crops

Woody biomass throughput is tripled using a new single-pass cut-and-chip harvesting system. Operator experience, crop characteristics, ground conditions, and speed all affect throughput.

Funded by AFRI. *Learn More*.

Table of Contents

Introduction

Figure 1. Harvesting willow biomass crops with a single-pass cut-and-chip harvesting system based on a New Holland forage harvester and specially designed cutting head in Upstate New York. (Photo credit: T.A. Volk, SUNY ESF)

Many types of specialized machinery for harvesting short rotation woody crops (SRWC) exist, including small and large single-pass cut-and-chip systems, whole stem harvesters, and baling systems. However, due to the limited scale of SRWC deployment, evolving technology, different operational scales, and management objectives, there is presently no dominant harvesting system in use. In New York State, several existing or modified harvesting platforms for SRWC from Europe and North America have been evaluated since 2001 for use in short rotation willow. Technical hurdles encountered on various harvesters that were 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.

Research Purpose

In 2008, Case New Holland (CNH) began developing a prototype short rotation coppice header (130FB) for their FR9000 series of forage harvesters, specifically designed to cut and chip a range of SRWC such as willow, poplar, and eucalyptus (Figure 1). The header can easily be attached to a standard New Holland forage harvester without modifications. The performance objectives of the harvesting platform include the ability to harvest double rows of woody plants containing stems up to 4.75 in (120 mm) in diameter, and to produce chips that are 0.4 to 1.75 in (10 to 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 co-products without requiring further processing.

Research Activities

Over the course of the project, the New Holland harvesting platform was developed and tested on willow and poplar biomass crops. Time motion data was collected using GPS tracking equipment and then analyzed to assess the harvester's performance and provide insights on how the harvesting system could be improved.

What We Have Learned

Throughput from the single-pass cut-and-chip harvesting system has improved from less than 22 wet tons/hr (20 wet Mg/hr) with well over 25% downtime due to material jams or mechanical problems, to throughputs of 77 to 99 wet tons/hr (70 to 90 wet Mg/hr) in willow biomass crops with standing biomass ranging from 9 to 29 tons/ac (20 to 65 Wet Mg/ha). The harvester can run consistently in these conditions with less than 10% downtime.

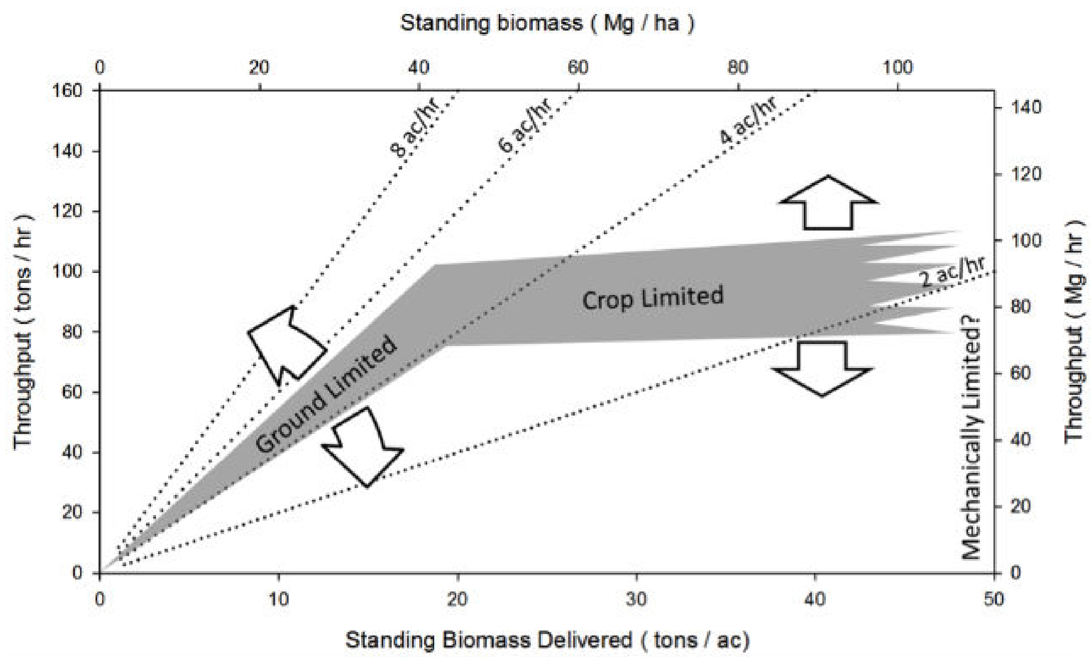

Figure 2: The throughput of the single-pass cut-and-chip harvesting system changes as the quantity of standing biomass of the willow crop changes.

Harvests of approximately 150 acres (60 ha) of willow biomass crops during late 2012 and early 2013 in New York State and 50 acres (20 ha) of poplar biomass in Western Oregon revealed some interesting and important patterns associated with the New Holland harvesting system. 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 (Figure 2). At low levels of standing biomass, throughput increases in a linear trend until standing biomass reaches approximately 20 to 22 wet tons/ac (45 to 50 wet Mg/ha). 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 difficult to handle and it begins to pull plants out of the ground before the stems are cut. Beyond 20 to 22 wet tons/ac (45 to 50 wet Mg/ha) of standing biomass, the harvester throughput begins to plateau around 77 to 99 wet tons/hr (70 to 90 wet Mg/hr). 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.

Why This Is Important

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. Efforts to reduce harvesting costs by improving the performance and reliability of the harvester are essential to the profitability of woody biomass crops. In addition, having a reliable and commercially available harvesting system that is 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.

Harvester throughput relative to speed is often reported as the key parameter when describing harvester performance in coppice systems. Previous studies have suggested that harvester throughput in SRWC can be increased by simply maximizing harvesting speed. However, many of these studies operated in trials with crops with low standing biomass. The results from current research show that overall there is a nonlinear relationship between standing biomass and harvester throughput. This result has important implications for cost modeling SRWC systems, matching equipment to specific SRWC crops, and the optimization of field activities.

Results from these harvesting trials and product development work have successfully led to New Holland making the FB130 short rotation coppice header commercially available through its network of dealers.

For More Information

Timothy Volk (315-470-6774, tavolk@esf.edu)

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Contributors to This Research Summary

This work was supported by the US Department of Energy Biotechnologies Office, New York State Energy Research and Development Authority (NYSERDA), Empire State Development Division of Science, Technology, and Innovation (NYSTAR), and USDA AFRI.

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extension.org
https://www.extension.org/pages/70406/research-summary:-sequestration-of-carbon-by-shrub-willow-offsets-greenhouse-gas-emissions#.VYCA3lL_RvE

Research Summary: Sequestration of Carbon by Shrub Willow Offsets Greenhouse Gas Emissions

Farm Energy January 13, 2015

Grown for biofuel, energy-efficient shrub willow sequesters carbon below-ground, life-cycle assessment shows.

Funded by AFRI. *Learn More*.

Table of Contents

Abstract

Willow biomass harvest, Auburn, NY. Photo: Tim Volk, SUNY ESF

Shrub willow is a short-rotation woody biomass crop that could be an important part of our renewable energy future. By sequestering carbon in below-ground biomass, it can offset any greenhouse gas (GHG) emissions created during its production and transportation to a biorefinery. Research is proving it to be a crop with a high net energy ratio—that is, it provides more energy than is used to produce and process it—and low GHG footprint, even with the variability of the shrub willow's performance under different management practices.

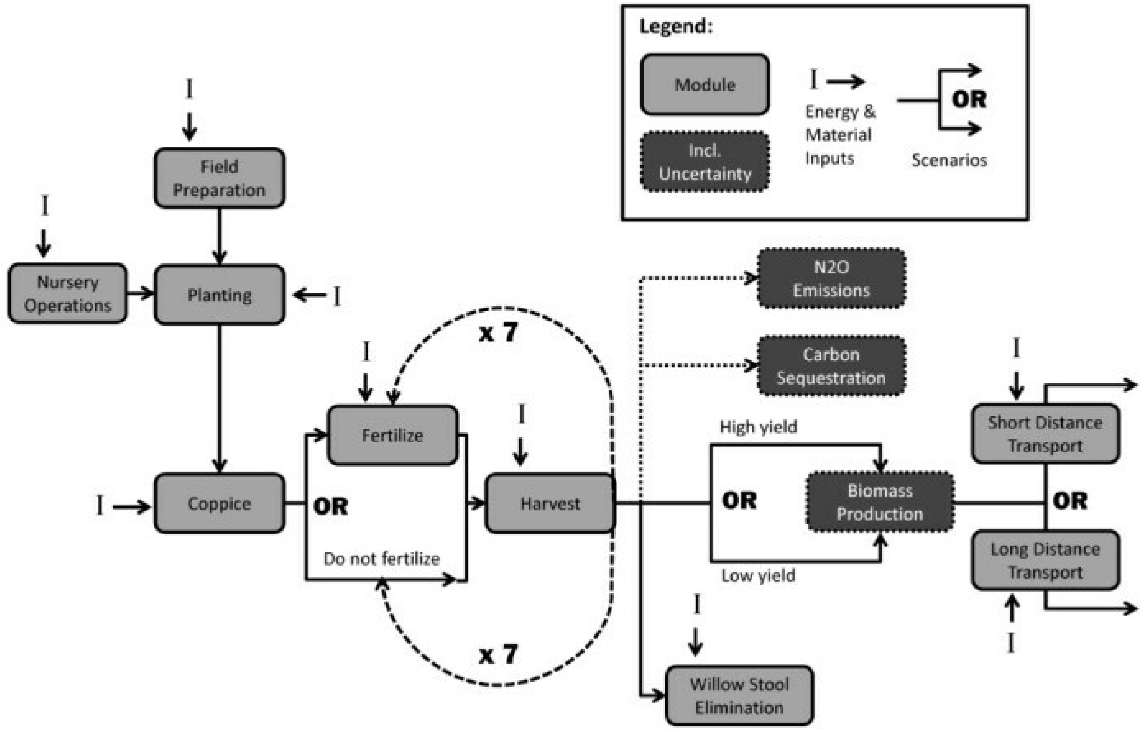
Research Purpose

Short-rotation woody crops such as shrub willow could provide between 126 and 315 million dry tons of biomass for use as biofuels by the year 2030, according to the U.S. Billion-Ton Update report by the U.S. Department of Energy. That would be nearly 30 percent of the biomass estimated to be available from agricultural and forest sources in 2030.

Perennial crops, like the willow, that will contribute to our renewable-energy future must be energy-efficient in their production and processing. They must be low-carbon sources that don't add more GHG emissions into the atmosphere than they replace.

Finding crops that will work as renewable sources for our energy future requires measuring the amount of energy they use up over the crop's entire life cycle, from planting to hauling to a biorefinery for processing into the final product, as well as how much GHG they emit. Crops that emit more GHG and use up more energy than they provide are not sustainable in the long run.

Research by Jesse Caputo of the Department of Forest and Natural Resources Management at the SUNY College of Environmental Science and Forestry and his colleagues used a life-cycle assessment (LCA) model to measure the fossil fuel inputs and GHG balance of shrub willow cropping systems in New York state, incorporating some of the key variables that add uncertainty to LCA models.



Shrub willow Life Cycle Analysis. Flowchart: Stephen B. Balogh, SUNY ESF.

Research Activities

Caputo and colleagues developed an LCA model to measure GHG emissions and carbon sequestration in eight different management scenarios for shrub willow grown for bioenergy in New York. The scenarios varied in crop yield, fertilizer use, and the distance the biomass had to be hauled to biorefinery, where the shrub willow crop would be processed into a biofuel.

They constructed a computer model, using commercial software, to estimate use of fossil fuels and GHG emissions over the crop's life cycle of seven three-year harvest rotations, the practical lifetime of a shrub willow stand grown for biofuels. The cycle stretched from planting and growing the crop, to harvesting the shrub willow as chips, and storing and transporting the shrub willow chips from the field to a biorefinery.

Because crop production is highly variable, there can be a great deal of uncertainty in determining the shrub willow's performance as a bioenergy crop. To incorporate that uncertainty into the research, Caputo documented the variability of three important biological parameters–yield, underground carbon sequestration, and the nitrogen content of decayed leaf litter. Better incorporation of data uncertainty into LCA models should, in the future, provide a clearer picture of how well shrub willow performs as an energy-efficient source of renewable energy.

What We Have Learned

Shrub willow provides a large sink for sequestering carbon below ground. New data on underground biomass, in fact, shifted the shrub willow from a low-carbon bioenergy source to one which sequesters carbon, more than offsetting the GHG emissions in all eight management scenarios studied.

Because of the rapid growth rates for shrub willow and lower energy inputs as a perennial crop, shrub willow had a positive energy balance of between 18.3:1 to 43.4:1, the study found. This means that for every unit of fossil fuel used to grow, harvest, and transport shrub willow biomass crops, between 18 and 43 units of energy are produced in the form of wood chips.

In the production of short-rotation shrub willow grown for biofuels, fossil fuels, especially diesel fuel for operating equipment to plant and harvest the crop, were the greatest source of greenhouse gas emissions, Caputo found. Harvest and delivery of the crop accounted for the majority of fossil fuel use, especially transportation—more than three-quarters of GHG emissions, in some cases, came from delivery of the shrub willow chips to the end user.

Harvesting shrub willow used more energy than other field operations because it was done every three years, or seven times throughout the 21-year lifespan of the crop, as compared with, for example, planting, which was only performed once.

Why This is Important

LCA models which measure energy used throughout a crop's life cycle and the amount of GHG emitted, such as that developed by Caputo and his colleagues, are being improved and refined, and will help determine which crops are the most energy-efficient and useful candidates for bioenergy.

Jesse Caputo, SUNY ESF

For More Information

- Contact: Jesse Caputo, jcaputo@syr.edu
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- Sarah J. Wurzbacher, Extension Educator, NEWBio Consortium, Pennsylvania State University Crawford County Cooperative Extension

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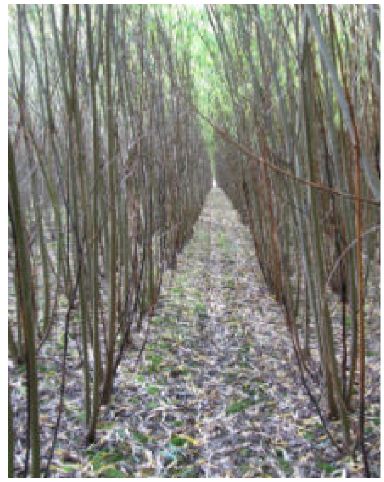
This research is based on data collected as part of the Sun Grant Regional Feedstock Partnership and will contribute to NEWBio, which focuses on three perennial crops: shrub willow, switchgrass, and miscanthus. Additional support for this work was provided by the U.S. Department of Energy Bioenergies Technology Office.

Maximizing Planted Area and Biomass Production in Shrub Willow Bioenergy Fields

articles.extension.org/pages/73581/maximizing-planted-area-and-biomass-production-in-shrub-willow-bioenergy-fields



Willow stand density. *Photo: SUNY-ESF.*

A portion of the land area in commercial willow bioenergy fields must be left unplanted for headlands to facilitate efficient machinery operation. Other unplanted areas, if not functional, should be minimized through best-practice targets in order to maximize biomass production and revenues.

Table of Contents

Introduction

An important consideration for commercial shrub willow crop production for bioenergy is the percentage of land area on which the crop is produced (aka, the planted area) relative to the total land area on which taxes or rent is paid. Land costs can be 15% or more of the total life cycle costs of a willow planting over 20+ years,[1] so maximizing the planted area and resulting biomass production in a field or parcel (group of fields) is an important factor in making willow bioenergy plantings as profitable as possible. However, a certain amount of land must be intentionally kept out of production for headlands (unplanted areas around the edge of a crop field) to accommodate the efficient turning of machinery. Headlands for most willow operations, especially those using a forage harvester system, should be about 30 feet wide on two ends of the willow rows to provide adequate space for turning farm machinery during planting and harvesting. Narrower headlands can reduce the efficiency of operations by increasing the turn time of machinery, causing flat tires on vehicles from driving over cut willow stumps, and creating other safety hazards or damage to machinery when operating in close proximity to standing willow and obstacles near the field edge.

Figure 1. Harvester cane wagon. *Photo: SUNY-ESF.*

(Figure 1. *The willow harvesting system developed by SUNY-ESF, New Holland Agriculture, and others consists of a forage harvester equipped with specialized cutting header. This system cuts and chips the willow stems in one pass and blows them into collection vehicles that follow beside the harvester. Headlands at the end of the willow rows allow these machines to turn efficiently without stopping and backing up, and without driving over cut willow stumps which can cause flat tires that are expensive and time-consuming to repair.*)

In addition to headlands, other areas are likely to be left unplanted in most commercial fields, especially if willow is grown on marginal land or formerly idle fields. Some additional unplanted areas may be functional and necessary to crop-production operations. These include access roads, drainage ditches, and landings for short-term storage and loading of harvested biomass. Other potentially avoidable unplanted areas can result from:

- Hedgerows or other divisions between fields within a parcel
- Trees, shrubs, or other obstructions not cleared during site preparation
- Irregularly shaped field edges or areas that are too small for efficient planting design
- Suboptimal planting design or execution
- Patches of poor soil or other biophysical limitations that prevent crop establishment such as standing water or shallow depth to bedrock

Research Purpose

The summation of all unplanted areas in a field or parcel can equate to substantial acreages on which taxes/rent are paid but biomass is not produced. Thus, best-practice targets for willow bioenergy crops should aim to maximize planted area by minimizing unnecessary and avoidable unplanted areas. However, some area in each field will always be left unplanted for headlands and other uses. It may be possible to find other value-added uses for unplanted areas, such as intercropping, but it is assumed that maximizing willow biomass production is the primary objective. The purpose of this research was to evaluate the level of unplanted area in commercial willow fields and discuss the results in the context of best-practice targets for maximizing planted area, thereby increasing biomass production and profitability.

Research Activities

A 2014 study conducted by SUNY-ESF and NEWBio investigated the percentage of planted and unplanted areas in commercial willow fields in northern New York State. The study sampled 36 individual fields within 11 parcels, totaling 1,113 acres. The potentially tillable acreage under lease/tax of each field was compared to the areas with established willow. Age of the willow ranged from two to eight years after planting, with stems in either the first or second harvest rotation. Tillable acreage boundaries were acquired from a previous study by the United States Department of Agriculture Natural Resources Conservation Service (USDA NRCS, unpublished data) conducted when administering a regional Biomass Crop Assistance Program (BCAP) in 2012. The willow planted area was determined by SUNY-ESF by walking the outer edge of the willow crops within each field and charting the crop boundary with a handheld GPS unit (Trimble GeoXM). The total field area (potentially tillable acreage) was then compared to the planted area, using ArcGIS 10 for this analysis (Figure 2. *Example of a planted-area analysis in a parcel of commercial willow fields in New York State. The total field area or potentially tillable acreage (in black) of this parcel is 41 acres, whereas the total area planted with willow (in red) is 30 acres. This means that, of the potentially tillable acreage on which rent/taxes is being paid, 28% is unplanted, either for headlands, un-cleared obstructions, failed establishment, or other reasons.*).

Figure 2. Example of a planted-area analysis in a parcel of commercial willow fields in New York State. *Photo: SUNY-ESF*.

What We Have Learned

The amount of unplanted area in individual fields ranged from 4% to 43%, with a mean of 21% and standard deviation of 10%. Unplanted area at the parcel level ranged from 14% to 31%, with a mean of 21% and standard deviation of 6%. This percentage of unplanted area is higher than previously anticipated from research-scale willow plantings, which did not fully account for the miscellaneous unplanted areas and other complexities of commercial-scale fields. This level of unplanted area is higher than desirable for commercial willow grown under best-practice targets that aim to maximize biomass production per unit land area.

For an individual field, the amount of unplanted area is a factor of several variables including field size and geometry, headland width, the number of sides of the field with headlands, and the amount of area left unplanted for miscellaneous reasons other than headlands. Larger, rectangular-shaped fields that create longer rows for continuous runs of machinery are more efficient than smaller, square, or irregularly shaped fields. Limiting headlands to 30-foot width (or slightly larger) creates sufficient turning space but not excessive unplanted area. Turning, and therefore 30-foot headlands, is generally only required on two ends of the willow field (assuming all the willow rows planted are in the same direction), so restricting headlands to two sides of the field (with the option for narrower access roads on the other two sides of the field) can also reduce unnecessary unplanted area.

For example, a 25-acre, square-shaped field, approximately 1,000 feet by 1,000 feet, with 30-foot headlands on *four* sides of the field, and four acres left unplanted for miscellaneous reasons, would leave 27% of the total field area unplanted (Figure 3. *Two hypothetical willow plantings show that larger fields, longer rows, and minimizing miscellaneous unplanted areas can help to meet best practice targets of less than 10% of the total field area left unplanted while also maintaining adequate headlands. This increases the biomass production per unit land area on which taxes or lease are paid.*), which is much higher than desirable. If the field in this example is scaled up to a roughly 50-acre rectangle, 2,000 feet by 1000 feet, with 30-foot headlands on only the required two ends of the willow rows, 10-foot-wide access roads on the other two sides of the field (equaling one acre of land area), and the miscellaneous unplanted area limited to two acres, the percentage of unplanted area is reduced to about 9%. Assuming best-practice targets could reduce headlands from approximately 20% to 10% on an average 50-acre field like this example, at modest yield assumptions of 8 green tons per year, the result of these best practices would net the grower an additional 120 green tons of biomass and the associated revenue every three-year harvest cycle. The upfront cost of site improvements and other practices to increase planted area should be considered in the context of the projected life cycle of the planting. The EcoWillow tool for financial analysis of willow bionergy crops can assist in evaluating these scenarios (visit www.esf.edu/willow and follow the link for EcoWillow).

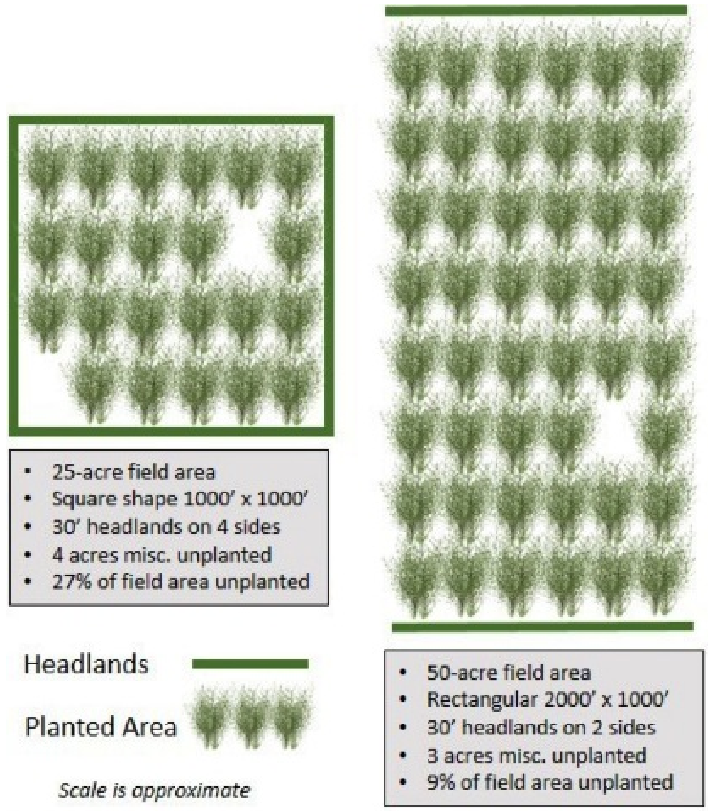


Figure 3. Two hypothetical willow plantings. *Photo: SUNY-ESF.*

Why This Is Important

Numerous, seemingly small areas left unplanted for various reasons across a large field or parcel might appear negligible during site assessment and planting, but these areas can quickly add up and substantially lower planted area, biomass yield, and revenues can result. A suggested best-practice target for commercial willow is to have unplanted area be less than 10% of total field area on which rent or taxes is paid while also maintaining adequate headlands and other functional unplanted areas. Attention to potential problem areas during the site-assessment-and-selection phase can help to reduce the occurrence of unplanted areas later on in the site-preparation-and-planting phases. Site improvements, soil modifications, careful consideration of planting design, GPS-guided planting, interplanting, and replanting can also help to minimize unplanted areas and maximize biomass production over the life cycle of the planting.

For More Information

Additional information on willow site assessment, site preparation, and related topics is available from the Willow Project at SUNY-ESF (www.esf.edu/willow). This work has been supported by the New York State Energy Research and Development Authority (NYSERDA) and the US Department of Agriculture National Institute of Food and Agriculture (USDA NIFA) through the Northeast Woody/Warm-Season Biomass Consortium (NEWBio).

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BCAP Helps Commercialize Shrub Willow for Bioenergy in Northern New York

Three-year old willow biomass crops on a four-year old root system prior to first harvest (Auburn, NY). Photo: T. Volk, SUNY ESF.

Farmers growing shrub willow for bioenergy are helped by a BCAP project in New York State that aims to make the biomass crop more financially viable.

Table of Contents

Introduction

The USDA Biomass Crop Assistance Program (BCAP) was designed to expand bioenergy feedstocks beyond existing cash crops by encouraging both the establishment of new supplies of biomass as well as the collection of existing but underutilized biomass. The program assists landowners with the establishment, maintenance, and harvest of non-food, non-feed biomass dedicated for energy production.

Commercialization of shrub willow grown for as a source of renewable energy has taken several steps forward via a USDA BCAP project in northern New York State. The project is helping to overcome several hurdles faced by growers, including high establishment costs, uneven cash flow for growers, and an uncertain market.

Willow biomass crops resprouting in the spring after being harvested the previous winter. This willow is about a month old above ground on a four year old root system. Photo: T. Volk, SUNY ESF.

The BCAP Project

In 2012, the U.S. Department of Agriculture established the BCAP project area #10 for willow biomass crops in nine counties of northern New York. During summer and early fall of that year, almost 1,200 acres were enrolled in the program. About 70% of the area is new willow crops that were planted in the spring of 2013. The remaining 30% is willow crops that were planted several years earlier and recently made eligible to be enrolled in the BCAP project. Eight landowners are now taking part. All of the willow biomass grown will be used to produce renewable energy at facilities owned by ReEnergy Holdings LLC in northern New York.

Why Shrub Willow?

Willow biomass crops are a carbon-neutral renewable form of energy that can be grown on marginal land. The net energy ratio for willow has been shown to range from 18:1 to 43:1, which means that for every unit of fossil fuel energy invested in the production, harvest, and delivery of willow, about 18 to 43 units of energy are stored in the willow biomass chips that are delivered to a renewable energy facility. The net energy ratio is highest when facilities are closer to the field (about 15 miles) where the willow is grown.

Establishing willow biomass crops by planting one year old stems of selected willow cultivars. The planter cuts 6-8 inch long sections from the stems and inserts them 5-8 inches into the ground. Photo: T. Volk, SUNY ESF.

Although willow biomass is unlikely to be the primary source of woody biomass for renewable energy generation in the region, it has the potential to be an excellent complement to sources such as forest residue and can help to diversity agricultural production. Willow biomass crops can be grown on marginal land in northern NY and across the region. This provides landowners with another option for generating income from this lower quality land.

Obstacles to Commercial Willow

There are several hurdles to the establishment of a viable industry of willow biomass crop production for biofuel. The first is the high cost of crop establishment, which is typically between $800 and $1,000 per acre. The second is cash flow that can be delayed and uneven because the crop is only harvested every three to four years. The third is an uncertain market for the shrub-willow biomass.

Finding Solutions

BCAP directly addresses the first two barriers and indirectly assists in resolving the third barrier. The BCAP provides financial assistance to growers—$1.23 million in direct financial support—to establish and produce biomass crops within the nine-county project area. Landowners participating in the project are eligible to receive cost-share payments for the establishment of willow biomass crops, and annual rental payments for years when there is no crop harvest. The funds from the USDA will be about evenly split between cost-share payments and annual rental payments.

Helping to make the establishment of shrub willow more cost-effective for landowners, Double A Willow, a commercial nursery in Fredonia, New York, grows about 150 acres of willow nursery stock, which is enough to establish thousands of acres of willow each year using genetically improved cultivars.

Four year old willow biomass crops being harvested with a New Holland forage harvester fitted with a New Holland coppice header. This system cuts and chips the willow biomass in a single pass. Photo: D. Angel, SUNY ESF.

The recent acquisition of two different types of European planters designed specifically to plant woody crops from hardwood cuttings should help lower establishment costs and improve planting efficiency. There are currently about 40,000 acres of willow grown for biomass in Europe so the industry here can benefit from those experiences. NEWBio is making an Egedal planter from Denmark (owned by Double A Willow) available to landowners who want to establish willow at a reduced cost. Celtic Energy Farm and the State University of New York's College of Environmental Science and Forestry also own two- and four-row step planters that were manufactured in Europe and are potentially available for use.

To harvest willow biomass more effectively, a single-pass cut-and-chip harvesting system has been developed based on a New Holland forage harvester and a cutting head specially designed for woody crops. The system is currently available through New Holland's dealer network. The U.S. Department of Energy and the New York State Research and Development Authority (NYSERDA) provided essential support for their development.

Celtic Energy Farm, based in Maspeth, New York is managing more than 1,000 acres of shrub willow. It has a single-pass cut-and-chip New Holland harvester, which is available to other growers in the program at a reduced rental cost because NEWBio provided some support for the cutting head.

Building a Market for Willow

A secure market for the project is important for overcoming the uncertainty of commercial production of a perennial crop like willow biomass on a fixed price contract basis. Over the length of the eleven-year project, 100,000 – 120,000 green tons of biomass should be produced. ReEnergy has agreed to purchase all of the willow biomass produced from the acreage in the BCAP program over the next eleven years. ReEnergy recently completed the retrofit of a coal-fired power plant at the Fort Drum, NY army base to use wood chips as its fuel source and also owns other facilities in the region that use woody biomass.

Transferring willow biomass chips produced by a NH harvester at the edge of the field to a truck so the material can be transferred to a short term storage location (Auburn, NY). Photo: T. Volk, SUNY ESF.

How the Region Benefits

The project developers estimate that growing 1,200 acres of willow biomass will create about eight to ten jobs in the region. After the project is completed, the willow crops will still be able to produce biomass for another decade. In addition, the purchase of willow to generate renewable energy will inject about $3 million into the local economy over the course of the project.

Background

SUNY's College of Environmental Science and Forestry has been working since 1986 on research and development of willow as a sustainable crop for bioenergy and bioproducts. It's the longest running and largest such program in North America. The latest focus has been on creating a commercial industry to bring the environmental and economic benefits from this type of industry to people in the region.

Summary

The BCAP project is working to make shrub willow commercially viable as a renewable energy crop and to extend its benefits throughout northern New York. By giving landowners financial and technical support, the project helps them weather the volatile early stages of a nascent industry. BCAP also provides specialized planting and harvesting equipment, and on the other end of the spectrum is helping to develop the markets necessary for commercial success.

For Additional Information

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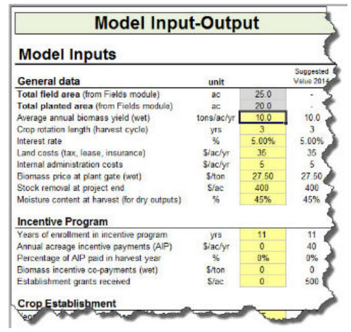
EcoWillow 2.0: An Updated Tool for Financial Analysis of Willow Biomass



Model Input-Output

Model Inputs

General data	unit		Suggested Value 2014
Total field area (from Fields module)	ac	25.0	-
Total planted area (from Fields module)	ac	20.0	-
Average annual biomass yield (wet)	tons/ac/yr	10.0	10.0
Crop rotation length (harvest cycle)	yrs	3	3
Interest rate	%	5.00%	5.00%
Land costs (tax, lease, insurance)	$/ac/yr	35	35
Internal administration costs	$/ac/yr	5	5
Biomass price at plant gate (wet)	$/ton	27.50	27.50
Stock removal at project end	$/ac	400	400
Moisture content at harvest (for dry outputs)	%	45%	45%
Incentive Program			
Years of enrollment in incentive program	yrs	11	11
Annual acreage incentive payments (AIP)	$/ac/yr	0	40
Percentage of AIP paid in harvest year	%	0%	0%
Biomass incentive co-payments (wet)	$/ton	0	0
Establishment grants received	$/ac	0	500

Crop Establishment

EcoWillow is a financial analysis tool developed by SUNY-ESF that allows users to model the costs and revenues of willow biomass production through every stage of the feedstock life cycle from site preparation through planting, harvesting, and transport to an end user for renewable energy

Table of Contents

Figure 1. Planting a willow crop in northern New York State using a specialized double-row willow planter. *Photo: SUNY-ESF*.

Introduction

EcoWillow is a financial analysis tool for willow bioenergy crops developed by the Willow Project Research Group at the State University of New York College of Environmental Science (SUNY-ESF). The tool was first released in 2008 and has been widely used since then, with downloads by over 1,000 users in 70 countries around the world. The original model was based on 20 years of research and development of willow biomass crops at SUNY-ESF. A new version of this tool, EcoWillow 2.0, was released in October 2014. This article summarizes the purpose of the EcoWillow tool, recent updates, willow production scenarios modeled using the tool, and the implications for commercial willow crops.

Research Purpose

Figure 2. Willow in the Northeast is commonly harvested using a newly developed system developed by SUNY-ESF, New Holland Agriculture, and partners. *Photo: SUNY-ESF.*

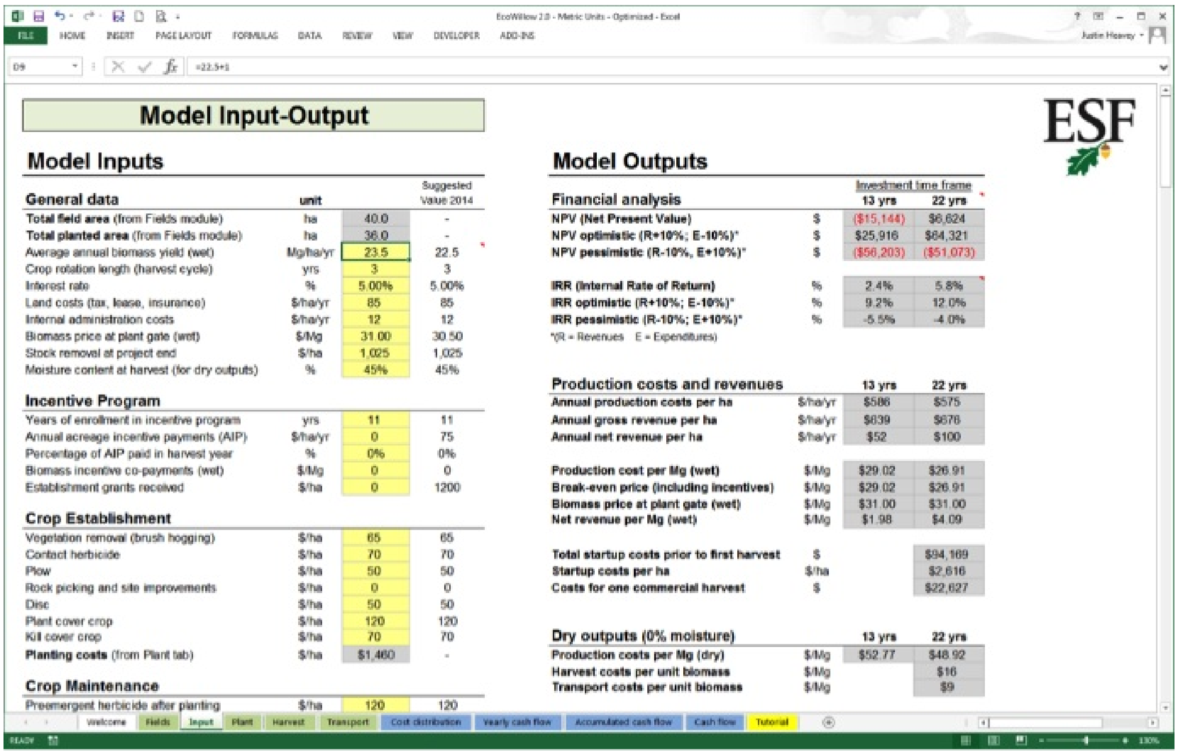
Understanding the factors and conditions that influence returns on investment is critical to the scale-up of shrub willow biomass and the entire bioenergy industry. Producers and investors need to understand the costs, potential returns, and associated time periods in order to make informed decisions about growing perennial energy crops like willow. Willow crops are harvested every three to four years and resprout from the cut stumps after each harvest. The system generally requires multiple harvests to recoup the initial investment in crop establishment, and one planting (Figure 1.) can stay in the ground for 20 years or more. EcoWillow allows users to model the long-term costs and revenues of willow through every stage of the feedstock life cycle from site preparation through planting, maintenance, harvesting (Figure 2. *Willow in the Northeast is commonly harvested using a newly developed system developed by SUNY-ESF, New Holland Agriculture, and partners. This system shown here consists of a forage harvester with a specialized woody-crops cutting header that cuts and chips the willow stems in one pass, and then blows the chips into collection vehicles that follow alongside the forage harvester*), and transport to an end user (Figure 3.). There are many variables associated with each stage of the life cycle, and inputs into EcoWillow can easily be changed to reflect user-specific conditions and demonstrate the interaction between variables in the system.

Research Activities

Figure 3. After harvest, willow chip are transferred into a truck from transport to short-term storage or an end user.*Photo: SUNY-ESF.*

EcoWillow 2.0 has been comprehensively updated based on the latest research studies from trials across North America, data collected from commercial willow operations, and feedback from commercial growers. The harvesting module of EcoWillow 2.0 has been updated based on the development and testing of a single-pass cut-and-chip harvesting system under development since 2008 in collaboration with New Holland Agriculture and other partners. A new module in EcoWillow 2.0 allows users to include multiple fields/locations with different transport distances in one project analysis, and enables more precise calculations of headlands and planted areas. EcoWillow 2.0 also includes a more user-friendly design and other improvements based on feedback from various stakeholders in the willow industry. Four crop-production scenarios have been developed using EcoWillow 2.0: a base case scenario with conservative assumptions of profitability; an improved scenario that adds best-practice targets to the base case; an incentivized scenario that adds possible incentives to the base case; and an improved-incentivized scenario that adds both potential best practices and incentives to the base case. These scenarios demonstrate the impact of key variables on costs and revenues and the potential for willow biomass crops to produce favorable returns on investment.

What We Have Learned



Model Input-Output

Model Inputs

General data	unit		Suggested Value 2014
Total field area (from Fields module)	ha	40.0	-
Total planted area (from Fields module)	ha	36.0	-
Average annual biomass yield (wet)	Mg/ha/yr	23.5	22.5
Crop rotation length (harvest cycle)	yrs	3	3
Interest rate	%	5.00%	5.00%
Land costs (tax, lease, insurance)	$/ha/yr	85	85
Internal administration costs	$/ha/yr	12	12
Biomass price at plant gate (wet)	$/Mg	31.00	30.50
Stock removal at project end	$/ha	1,025	1,025
Moisture content at harvest (for dry outputs)	%	45%	45%
Incentive Program			
Years of enrollment in incentive program	yrs	11	11
Annual acreage incentive payments (AIP)	$/ha/yr	0	75
Percentage of AIP paid in harvest year	%	0%	0%
Biomass incentive co-payments (wet)	$/Mg	0	0
Establishment grants received	$/ha	0	1200
Crop Establishment			
Vegetation removal (brush hogging)	$/ha	65	65
Contact herbicide	$/ha	70	70
Plow	$/ha	50	50
Rock picking and site improvements	$/ha	0	0
Disc	$/ha	50	50
Plant cover crop	$/ha	120	120
Kill cover crop	$/ha	70	70
Planting costs (from Plant tab)	$/ha	$1,460	-
Crop Maintenance			
Preemergent herbicide after planting	$/ha	120	120

Model Outputs

Financial analysis		Investment time frame 13 yrs	22 yrs
NPV (Net Present Value)	$	($15,144)	$6,624
NPV optimistic (R+10%; E-10%)*	$	$25,916	$64,321
NPV pessimistic (R-10%, E+10%)*	$	($56,203)	($51,073)
IRR (Internal Rate of Return)	%	2.4%	5.8%
IRR optimistic (R+10%; E-10%)*	%	9.2%	12.0%
IRR pessimistic (R-10%; E+10%)*	%	-5.5%	-4.0%

*(R = Revenues E = Expenditures)

Production costs and revenues		13 yrs	22 yrs
Annual production costs per ha	$/ha/yr	$586	$575
Annual gross revenue per ha	$/ha/yr	$639	$676
Annual net revenue per ha	$/ha/yr	$52	$100
Production cost per Mg (wet)	$/Mg	$29.02	$26.91
Break-even price (including incentives)	$/Mg	$29.02	$26.91
Biomass price at plant gate (wet)	$/Mg	$31.00	$31.00
Net revenue per Mg (wet)	$/Mg	$1.98	$4.09
Total startup costs prior to first harvest	$		$94,169
Startup costs per ha	$/ha		$2,616
Costs for one commercial harvest	$		$22,627

Dry outputs (0% moisture)		13 yrs	22 yrs
Production costs per Mg (dry)	$/Mg	$52.77	$48.92
Harvest costs per unit biomass	$/Mg		$16
Transport costs per unit biomass	$/Mg		$9

Figure 4. A screenshot showing the main input-output module of EcoWillow 2.0 under the improved base-case scenario. *Photo:* SUNY-ESF*.*

Expected returns on investment are low in the 2014 base-case scenario for shrub willow production, which represents conservative estimates of profitability that should be easily achievable by most growers in the Northeast. When best-practice targets and expected near-term system improvements (such as higher yields from new willow cultivars) are added to this base-case scenario, the model outputs show more favorable returns on investment with an internal rate of return (IRR) around 5%, and a payback period of 13 years (three harvests). The break-even price in this scenario is about $27 per green ton. Adding possible USDA Biomass Crop Assistance Program (BCAP) payments (or similar incentives) to the base case produces returns on investment that are similar to the best-practice scenario. Expected returns on investment are most favorable when both best practice targets and possible BCAP incentive payments are added to the base case. In this scenario, the payback period can be as short as seven years (two harvests) after planting, with an IRR around 20% and a break-even price around $20 per green ton. Details on each of these hypothetical crop production scenarios and the associated inputs and outputs are available in fact sheets on the Willow Project homepage (www.esf.edu/willow).

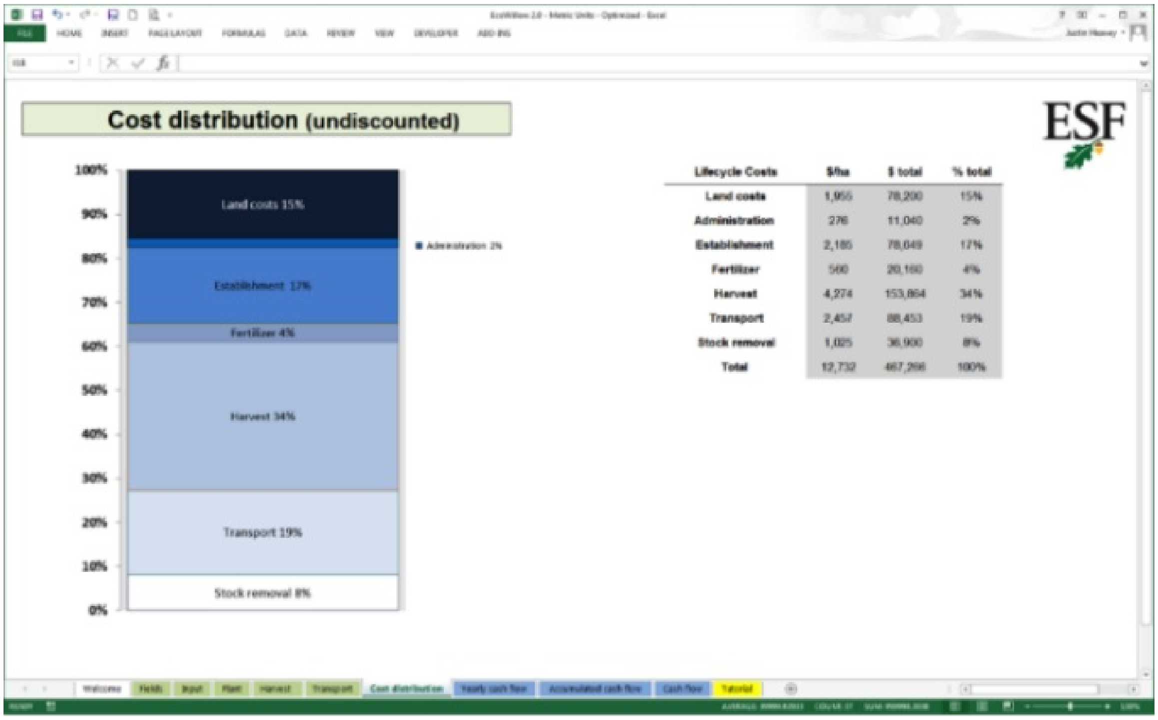


Figure 5. A screenshot showing the cost-distribution graphical output of EcoWillow 2.0 under the improved base-case scenario. *Photo: SUNY-ESF*.

Because of the many variables and range of possible inputs across the life cycle of a willow planting, making small changes to just a few variables at each stage of production can substantially reduce costs and increase revenue. It is important to understand how different variables affect profitability and to make improvements wherever possible to generate favorable returns in commercial bioenergy production. Certain variables can have a large impact on profitability and must be carefully considered and managed such as the percentage of land left unplanted for headlands and other areas, the price paid for planting stock (cuttings), the use of fertilizers, biomass yield, transport distance, and the price received per ton of biomass.

Why This Is Important

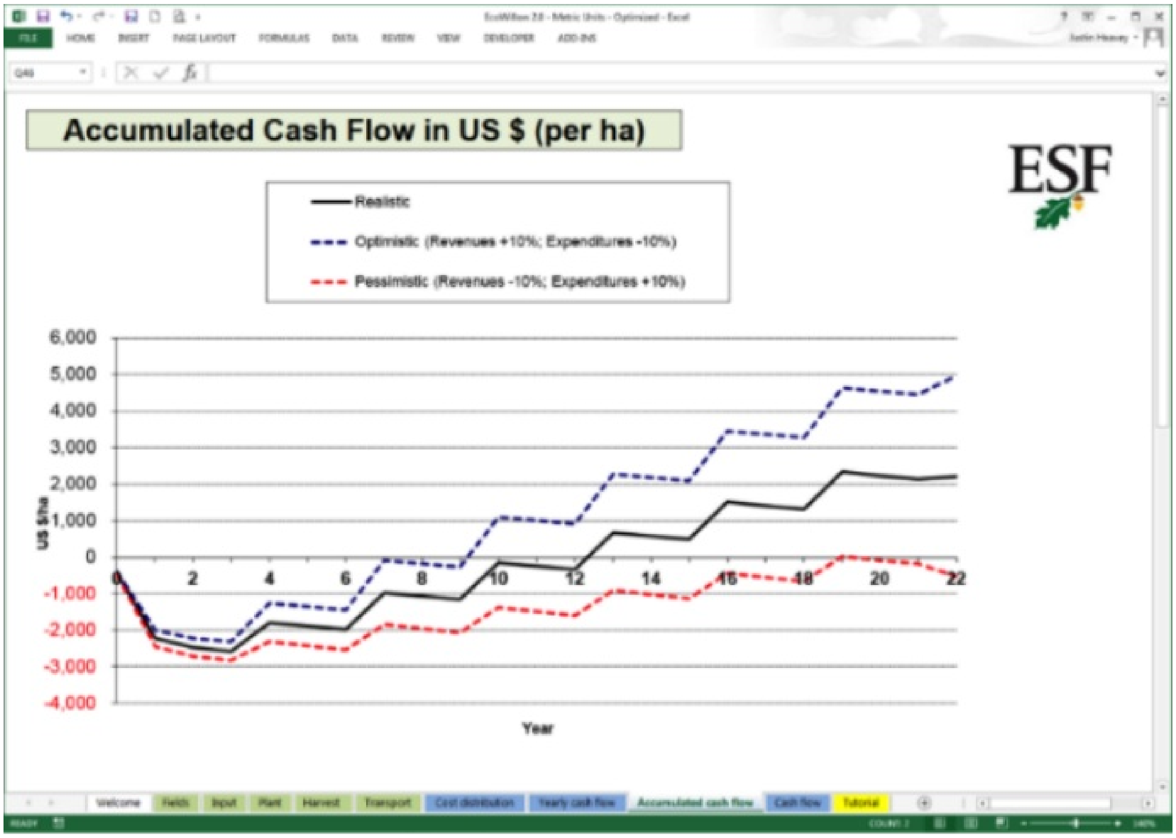


Figure 6. A screenshot showing the accumulated cash flow graphical output of EcoWillow 2.0 under the improved base-case scenario. *Photo: SUNY-ESF.*

Profitability is critical to the survival and growth of any business or industry that includes bioenergy crops. EcoWillow is a user-friendly tool that can assist in the financial analysis of producing, harvesting, and transporting willow biomass. Users can customize the example base-case scenario of crop production to their own specific conditions and best-practice targets and easily see how adjusting different variables affects returns, which can inform decisions about investing in willow and the types of management activities needed. EcoWillow will be updated and improved as collaboration between producers, researchers, and industry partners spurs innovation and advances the system. Future analyses by SUNY-ESF will build on the basic crop production scenarios by incorporating uncertainty and data distributions to determine the probabilities of achieving target biomass prices and net present values.

For More Information

The latest versions of the EcoWillow model and supporting documentation can be downloaded for free from the Willow Project website (go to www.esf.edu/willow and follow the links for EcoWillow). Both English and metric unit versions of the model are available, along with several fact sheets, an instructional video, and contact information for follow-up inquiries. This work has been supported by the New York State Energy Research and Development Authority (NYSERDA), the United States Department of Energy (USDOE), and the US Department of Agriculture National Institute of Food and Agriculture (USDA NIFA) through the Northeast Woody/Warm-season Biomass Consortium (NEWBio).

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Research Summary: Characteristics of Willow Biomass Chips Produced Using a Single-Pass Cut-and-Chip Harvester

Farm Energy January 13, 2015

Harvest method impacts wood chip quality--use a single-pass cut-and-chip method and willow makes the grade.

Sample of willow biomass chips produced from a single pass cut and chip harvester based on a New Holland forage harvester. *Photo: Timothy Volk.*

Table of Contents

Introduction

Biomass for bioenergy and/or bioproducts can be sourced from forests, agricultural crops, various residue streams, and dedicated woody or herbaceous bioenergy crops. Despite this wide spectrum of promising feedstocks, no single biomass source can meet the projected demand, or is clearly superior to alternatives in all aspects of cost, quality, and acceptance.

Shrub willow biomass crops can be grown on a range of agricultural land (including marginal land) using a coppice management system that allows multiple harvests on three- to four-year cycles from a single planting of improved shrub willow cultivars. Despite the benefits of these systems, their expansion and deployment has been constrained by higher production costs and lower market acceptance due to a perception of poor chip quality and inconsistent wood characteristics compared to forest biomass.

View down the alley of a shrub willow biomass energy crop in the third growing season at SUNY-ESF. *Photo: Timothy Volk.*

Most of the available data on the characteristics of willow biomass crops, such as moisture, ash and energy content, comes from material that was hand harvested from small-scale yield trials. However, these hand-harvested samples might not represent the amount of variability in biomass characteristics when material is harvested with large machinery at commercial scales. Significant variation in characteristics creates problems and reduces the efficiency of facilities that convert this biomass into renewable biofuels, heat, or power.

Research Purpose

This research project at the SUNY College of Environmental Science and Forestry (SUNY ESF) studied how commercial-scale harvesting might influence the characteristics of harvested willow chips.

In 2008, CNH Industrial (CNHi) began developing a prototype short-rotation coppice header (130FB) for its New Holland FR9000 series of forage harvesters. This header is specifically designed to cut and chip a range of short rotation woody crops (SRWC) such as willow, poplar, and eucalyptus. A research team from the SUNY ESF evaluated the characteristics willow biomass produced during a commercial-scale harvest using this harvester. They also assessed how the biomass complied with a published biomass standard, and contrasted it with biomass produced from small-scale, hand-harvested field trials. The study evaluated ash, moisture, and energy content; selected elements (N, P, K, Ca, Cu, Mg, Na, S, and Zn); and particle size distribution.

Harvesting willow biomass crops in Auburn, NY with a New Holland single-pass cut-and-chip harvester. *Photo: Timothy Volk.*

Research Activities

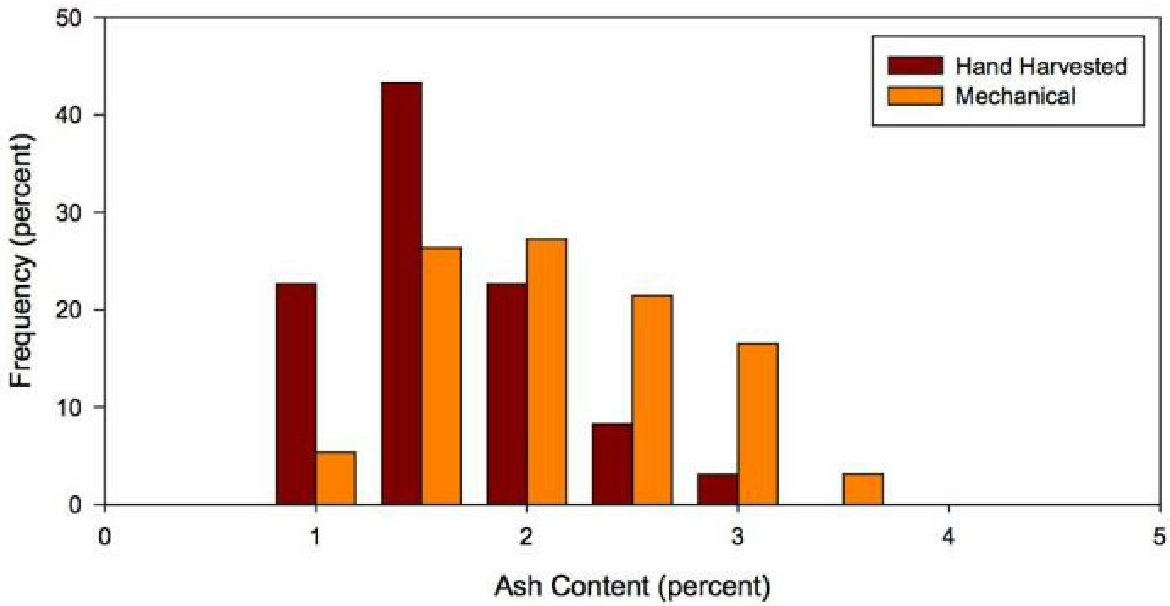
The team harvested approximately 150 acres of shrub willow over 10 days in late 2012 and early 2013 at two sites in Auburn and Groveland, New York. More than 2,500 tons of chipped biomass material were generated and delivered to short-term storage in more than 200 loads. A one- to two- kilogram sample was collected from each load, and laboratory analysis was performed.

Each load was compared for compliance with the recently published standard for graded wood chips (ISO 17725-4:2014), although the requirements of specific end users may vary. Characteristics of the biomass were compared to willow chips that were hand harvested from nearby field trials.

What We Have Learned

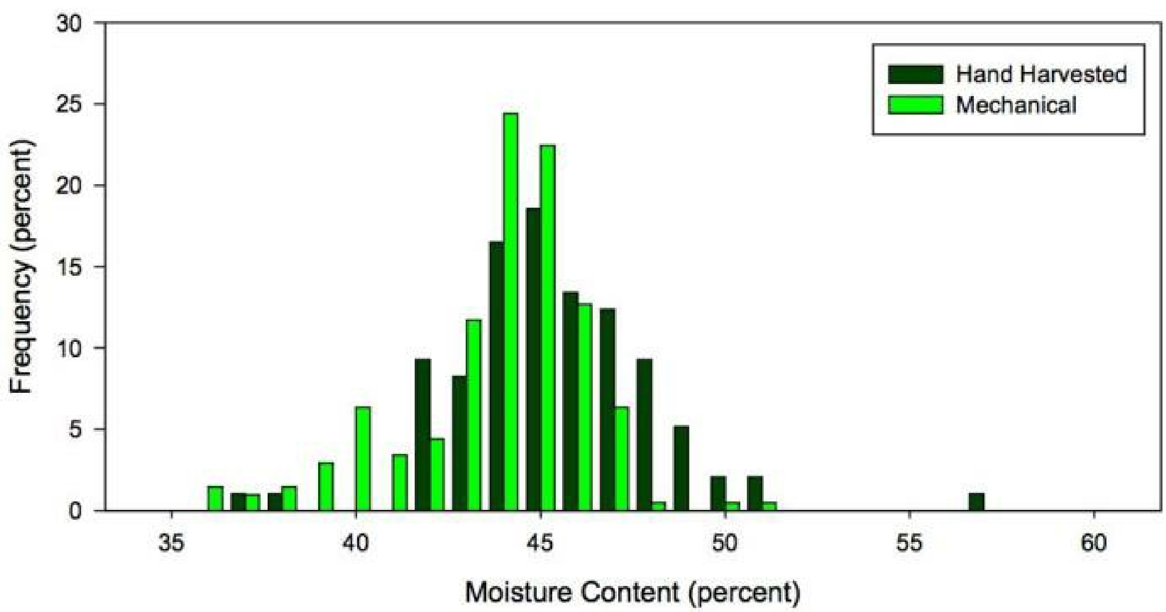
The harvesting system produced consistently-sized biomass chips that met biorefinery and power producing partners' specifications for wood chips.

Ash: Compared to hand-harvested willow biomass, the mean ash content of commercial scale samples was almost 1 percentage point higher and had wider variation. The mean ash content of the 224 commercially harvested samples was 2.1% (SD 0.59) and ranged from 0.8-3.5% on a dry weight basis. The ISO 17225-4 threshold for B1 chips is <3% ash content; this cutoff was met by all of the Auburn site samples, and 82% of those from the Groveland site. Slight differences were also found in the ash content between some willow cultivars that were grown at these sites. Most notably, the average ash content of the cultivar Fish Creek (1.3%) was significantly lower than other cultivars tested, which had ash contents up to 2.4%.



Distribution of ash content (dry basis) of 224 samples of willow biomass chips that were mechanically harvested with a single pass cut and chip harvester compared to 97 hand harvested samples collected from yield trial plots.

Moisture: The mean moisture content of the biomass from the commercial harvests was 44%, ranging between 37 and 51%. Moisture contents for the hand-harvested willow biomass samples used for comparison ranged between 45 and 56%, with a mean moisture content of 46%. The only requirement in ISO standard is that the moisture content is reported for this kind of material.



Distribution of moisture content of 205 samples of willow biomass chips that were mechanically harvested using a single pass cut and chip harvester compared to 97 hand harvested samples collected from yield trial plots.

Energy Content of biomass is typically reported in two ways. Willow is similar to most hardwoods species in the northeast United States.

The *higher heating value* is the energy content of the biomass on a dry basis. For the commercial samples in this study, it was 18.6 MJ kg^{-1} (SD ±1.8). In comparison, the hand-harvested samples had a higher heating value of

18.8 MJ kg^{-1} (SD ±1.8).

The *lower heating value* accounts for the energy that is used to turn the water in the biomass into steam and is impacted by the moisture content of the biomass and some other factors. This is the net amount of energy that will be available to an end user of the biomass. For the commercially harvested willow, the lower heating value was 10.4 MJ kg^{-1}. 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}.

Size: The biomass met the P45S specifications in the ISO 17225-4 standard. This means that less than 1% of the biomass was greater than 45 mm in size and more than 95% of the chips were between 6.35 mm and 45mm. If an end user requires a different chip size, this can be accommodated by adjusting the speed of the feedrolls or the number of knives on the harvester drum.

Unloading willow biomass chips at a temporary storage location in upstate NY after being harvested with a single pass cut and chip system based on a New Holland forage harvester. *Photo: Timothy Volk.*

Why This Is Important

It is important to understand the amount of variation in biomass characteristics in material that is harvested at a commercial scale. Large changes in essential characteristics such as ash or moisture content can cause problems for end users by decreasing the efficiency of the conversion process or damaging boilers or bio-reactors. Being able to produce willow biomass with a consistent set of characteristics will allow end users to adjust their processes to best use it.

Previous perceptions of willow biomass created barriers to its acceptance as a useful source of woody biomass. In particular, it was often assumed that willow biomass was wetter than other hardwood chips and had higher ash content. Willow biomass chips produced with previous harvesting systems tended to create long, stringy pieces that clogged biomass handling systems. This research should help change that perception. Data from willow biomass harvested from a large number of acres has shown that consistently sized material with a small amount of variation in ash and moisture content can be produced using the New Holland single-pass cut and chip harvester. In addition, the essential characteristics of willow biomass (energy, ash, and moisture content) are similar to other hardwoods. Sharing this information with potential end users and others interested in biomass will help people make informed decisions about willow as a biomass source.

Willow biomass chips from a single pass cut and chip operation in temporary storage in upstate NY. *Photo: Timothy Volk.*

The results also suggest that there might be ways to further reduce the variability of willow biomass harvested across large areas. Mixing different cultivars either in the field or during harvesting can mitigate quality problems. For example, cultivars that have been identified in this and other studies as having low ash (e.g., Fish Creek or SV1) could be interplanted, essentially creating mixed or blended feedstocks at the point of production.

Future Plans

This research describes the characteristics of willow biomass just after it is harvested. Changes in some of these characteristics can occur during handling, storage, and transportation of the biomass. Evaluating these changes and developing best management practices is the next important step in understanding the supply chain for willow biomass. It might be possible to improve some characteristics such as moisture content by natural drying of the material or minimizing others such as limiting contamination with dirt from storage locations or in transportation vehicles.

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Food and Energy Security

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REVIEW

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

Timothy A. Volk, Justin P. Heavey & Mark H. Eisenbies

State University of New York College of Environmental Science and Forestry (SUNY-ESF), Syracuse, New York

Keywords
Biomass quality, harvesting, multifunctional systems, *Salix*, short-rotation coppice, extension.

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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

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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,

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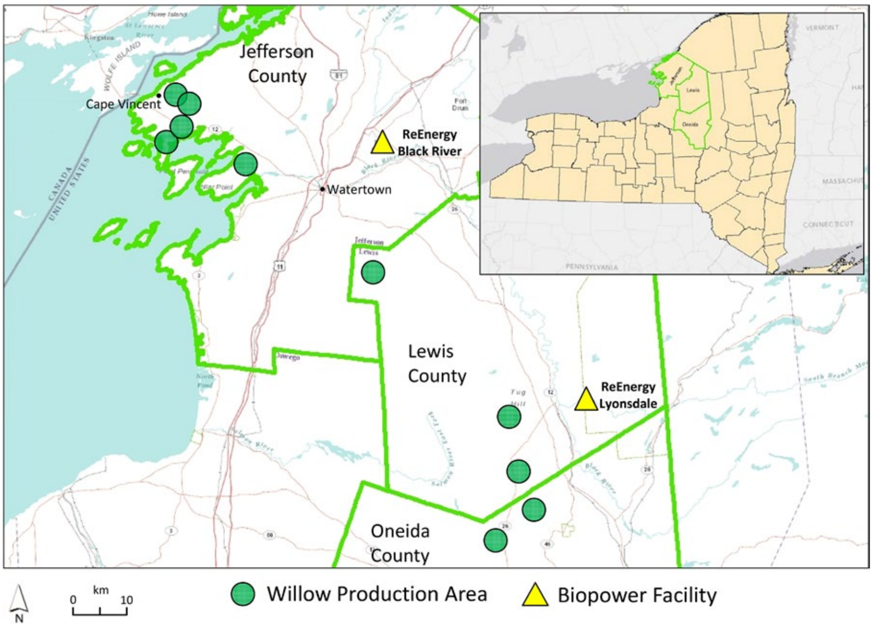

Figure 1. Willow production areas and two ReEnergy end-use facilities in central/northern region of New York State.

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).

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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,

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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

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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.

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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

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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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The economics of growing shrub willow as a bioenergy buffer on agricultural fields: A case study in the Midwest Corn Belt

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Abstract: Landscape design has been embraced as a promising approach to holistically balance multiple goals related to environmental and resource management processes to meet future provisioning and regulating ecosystem services needs. In the agricultural context, growing bioenergy crops in specific landscape positions instead of dedicated fields has the potential to improve their sustainability, provide ecosystem services, and minimize competition with other land uses. However, growing bioenergy crops in sub-productive or environmentally vulnerable parts of a field implies more complex logistics as small amounts of biomass are generated in a distributed way across the landscape. We present a novel assessment of the differences in production and logistic costs between business as usual (BAU, dedicated fields), and distributed landscape production of shrub, or short-rotation willow for bioenergy within a US Midwestern landscape. Our findings show that regardless of the mode of cropping, BAU or landscape design, growing shrub willows is unlikely to provide positive revenues (–\$67 to –\$303 ha^{-1} yr^{-1} at a biomass price of \$46.30 $Mg_{wet}{}^{-1}$) because of high land rental costs in this agricultural region. However, when translated into a practice cost per unit of N removed at the watershed scale (range: \$1.8–37.0 kg N^{-1} yr^{-1}), the net costs are comparable to other conservation practices. The projected opportunity cost of growing willows instead of corn on underproductive areas varied between –\$14 and \$49 $Mg_{wet}{}^{-1}$. This highlights the potential for willows to be a cost effective choice depending on the intra-field grain productivity, biomass price and desirable concurrent ecosystem services. © 2016 The Authors. *Biofuels, Bioproducts, and Biorefining* published by Society of Chemical Industry and John Wiley & Sons, Ltd.

Supporting information may be found in the online version of this article.

Key words: willow; *Salix spp*.; opportunity cost; landscape design; logistics; ecosystem services; biomass

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Introduction

Meeting renewable fuel standards sustainably is an opportunity to challenge the business-as-usual utilization of land, fertilizer, and water resources to minimize externalities, maintain provisioning services of food and other commodities, and reduce the lifecycle carbon intensity and greenhouse gas (GHG) emissions of the goods produced. Landscape design has been embraced by the international environmental and development community as a critical approach to balance multiple environmental and resource management goals.[1] In the agricultural context, through resource allocation,[2] landscape design has been proposed to improve the potential to sustainably support provisioning and regulating ecosystem services to meet future food, feed, energy, and conservation needs.[3–5] Researchers have proposed dedicating marginal agricultural land to the cultivation of perennial bioenergy crops and to obtaining ecosystem services.[6,7] A recent study[8] reported that growing deep rooted perennial bioenergy crops on marginal land, about 20% of a small Midwestern agricultural watershed (207 km^2), has the potential to reduce tile NO_3 export by 25% with total annual biomass output of up to 40 000 Mg. Independent field studies confirm the water quality improvement potential.[9] However, the definition of 'marginal' is broadly debated.[10,11] For the purpose of this paper, we define marginal land as land that is either underproductive, susceptible to environmental degradation, or both.

Landscape placement of bioenergy crops predicates the allocation of specific crops to landscape positions to better match their growth habit and environmental performance to land characteristics. In most cases, these matches imply subfield-scale partitioning of land based on soil properties, elevation, shallow groundwater flow, and other characteristics.[12] Subfield-scale crop allocation can be important in cases where overall field economics are negatively impacted by areas of low productivity in otherwise productive fields.[13,14] In these underproductive lands, bioenergy crops may provide opportunities to reduce economic losses caused by yields not meeting the cost of production.[13] In other cases, targeting perennial bioenergy crops to subfield areas prone to cause environmental damage may prove beneficial in meeting priority conservation targets.[12]

The opportunity for *in situ* recovery of leached nutrients in commodity crop fields is of interest. Nutrient loadings from grain cropping in the Upper Mississippi River Basin have been identified as the dominant source of riverine nutrients reaching the Gulf of Mexico.[15] While the efficiency of nitrogen fertilizer utilization by corn has improved, it still remains generally low (50–65%).[16–18] From a GHG emissions standpoint, lifecycle analyses show that fertilizer production and use contribute 87% of the GHG emissions for corn production, of which N_2O comprises 55%,[19] and represent on average about 39% of the direct input costs to produce corn for example, in Illinois.[20] Therefore, resource recovery is a critical component of energy efficiency and conservation, and is increasingly recognized and regulated as such. For example, the current re-branding of wastewater treatment plants (the second largest source of nutrient externalities) as 'water resource recovery facilities' identifies nutrients, energy, and water as recoverable resources from point source pollution.[21] A similar concept can be applied to the reuse and recycling of nutrients from non-point sources to reduce nutrient export to the Gulf of Mexico.[22] Nitrogen removal strategies such as riparian buffers, treatment wetlands, and more modern bioreactors and saturated buffers are proving relatively effective to mitigate nutrient externalities.[23] However, these methods mostly rely on the process of denitrification to remove nitrate, which fails to recover the valuable nutrients. Conversely, strategies that aim to recover the lost nutrients have not been studied extensively, yet results from some studies indicate significant reduction in nitrate by bioenergy crops, which is largely, but not only, resulting from plant uptake.[9,24]

Growing bioenergy crops in contour strips, buffers, and marginal parts of a field implies more complex logistics as small amounts of biomass are generated in distributed pockets across the landscape. Movement of equipment from field to field, to plant, maintain, and harvest the bioenergy buffer crops may add time and fuel compared to the Business As Usual (BAU) dedicated field cropping. This higher cost, postulated on longer distances between fields and intermittent use of equipment, reflects the additional expense incurred to generate ecosystem services. The major benefits of this land management approach include the avoided fertilizer costs because the leached nutrients conjunctively maintain elevated yields, as well as lower costs in water treatment. The objective of this case study is to compare the economics of growing shrub, or short-rotation willows (referred to as willow(s) in this manuscript) for bioenergy in an agricultural Midwest under different scenarios. These scenarios include BAU- and landscape-based cropping systems in agricultural land. For BAU, willow production is done on either single productive or marginal fields, whereas, landscape based production is done solely on marginal lands in which the same acreage as BAU is grown as a buffer on a single subfield

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(Landscape: single subfield - LSSF) or distributed across multiple subfields (Landscape: multiple subfields - LMSF) at representative inter-field distances in the watershed. We then examine the differences between production costs, net revenues, and opportunity costs, to formulate a value proposition for landscape-produced willow biomass.

Methods and assumptions

Study area

The study area is located in the Indian Creek watershed in central Illinois (USA). The watershed characteristics (climate, major crop rotations, and soils) were described by Hamada *et al.*[25] Briefly, the watershed is a high productivity grains landscape in the heart of the US Corn Belt, with Drummer silty clay loam, Reddick clay loam, and Saybrook silt loam as the most prevalent soils. An alternative future landscape pattern (FLP) was designed for this watershed targeting willow cropping on marginal lands at the subfield scale. Marginal lands were identified as having low crop productivity,[26] and environmental marginalities (e.g. soils susceptible to nitrate leaching, runoff, erosion, flooding, and water ponding) (Fig. 1). Locations were selected using information in the SSURGO database,[27] soil drainage classes,[28] organic matter index, travel time index and depth to the uppermost layer of the aquifer according to Keefer.[29] A description of the subfield areas is provided in Table S1 (Supporting Information) and is further described in Ssegane *et al.*[8] Grain elevators (Fig. 1) near the watershed were chosen as potential depot locations as an adaptive reuse of the current infrastructure or co-location with existing activities, and for their location along the railway transport network. The Grain Elevator N. 1 (located at the watershed boundary: Southeast) was selected because of its proximity to the centroid of the watershed.

Willow production and transport costs

We used EcoWillow 2.0, a publicly available model developed by the State University of New York College of Environmental Science and Forestry (SUNY-ESF)[30] to compute production and transport costs of willow.

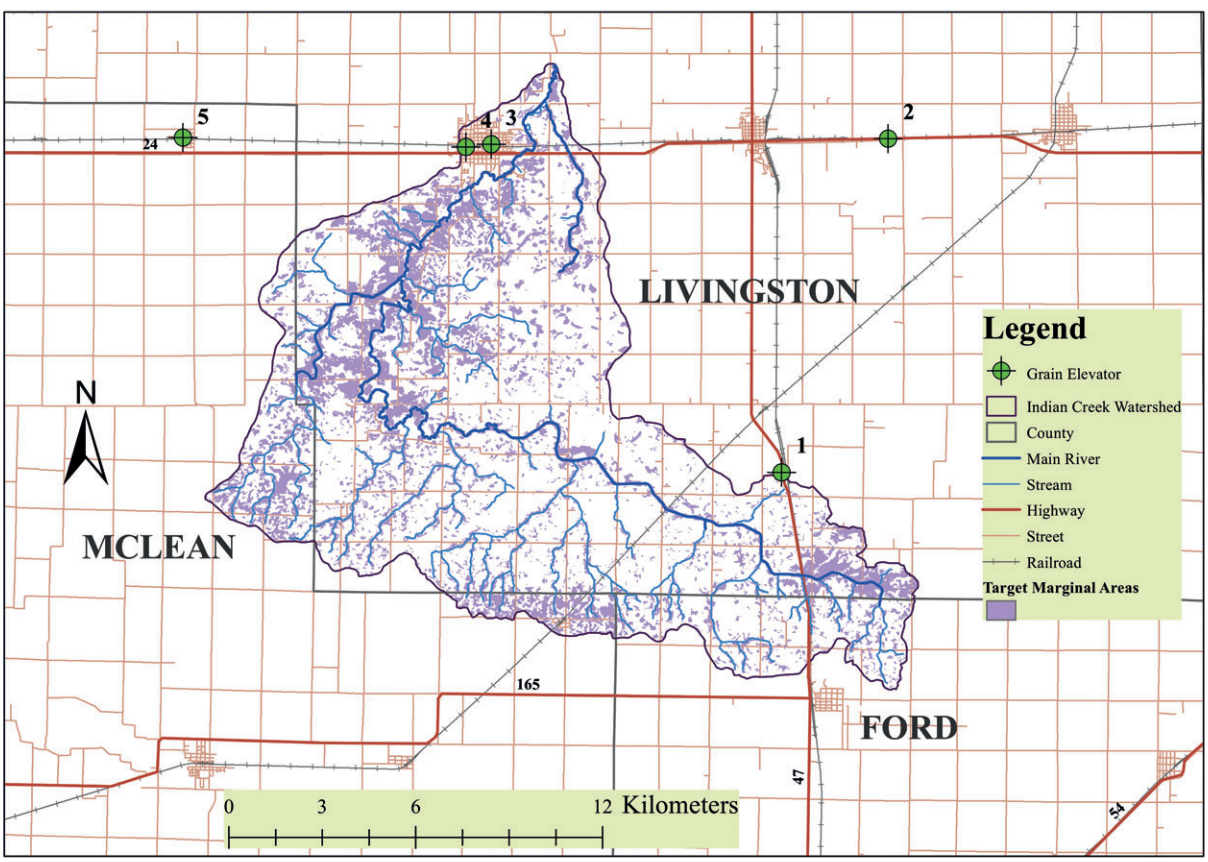

Figure 1. Locations of grain elevators and underproductive or environmentally sensitive soils in the Indian Creek watershed, IL.

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Various inputs for production costs were modified based on Illinois or Midwest-specific statistics (Table S3), recommended management practices,[31] as well as unpublished field data from a research site in Fairbury, Illinois. Several production strategies were modeled to evaluate cost differences based on specific assumptions (Tables 1 and 2). We calculated the costs of growing bioenergy willow on 2.0, 10.1, and 40.5 ha. These values represent the recommended

Table 1. EcoWillow 2.0 Model assumptions used to evaluate cost differences under various production strategies.

Variable	Description
Willow Planting	All fields in the landscape are planted in the same year
Fertilizer Applied	BAU scenario: 112 kg N ha^{-1} applied every 3 years (recommended practice*)
	Landscape scenarios: subfields are buffers alongside a grain crop and require no fertilizer (as they will recover nitrogen from the soil solution)
Headland Required	BAU scenario: 10% for equipment maneuvering
	Landscape scenarios: no headland needed as fieldwork occurs when the remaining grain field is not planted and the grain crop can be planted up to the edge of the buffer
Truck Capacity	30 Mg_{wet} capacity at 45% moisture (equivalent to 19 Mg_{dry} at 15% moisture): For transporting biomass to depot
Land History	Willow production is done on land previously under corn or soybean production

*Volk *et al.* [48]

Table 2. Summary description of parameters for each case and corresponding scenarios where shrub willow is either grown in an entire field (BAU) or in subportions of grain crops fields using a landscape design approach. Harvest downtime and planting time reflect slower operations and inter-field transport losses in efficiency due to the distributed location on the landscape design.

Case	Scenario[a]	Transport distance	Distance (km)	Headland (%)	Fertilizer application ($ ha^{-1})	Harvest downtime (%)	Planting time (ha hr^{-1})
1 (2.0 ha)	BAU	min	2	10	80.3	6	1.21
		max	18	10	80.3	6	1.21
	Landscape: single subfield (LSSF)	min	2	0	0	6	1.21
		max	18	0	0	6	1.21
	Landscape: multiple (4) subfields (LSMF)	most likely	24	0	0	50	0.81
2 (10.1 ha)	BAU	min	2	10	80.3	6	1.21
		max	18	10	80.3	6	1.21
	Landscape: Single subfield (LSSF)	min	2	0	0	6	1.21
		max	18	0	0	6	1.21
	Landscape: multiple (9) subfields (LSMF)	most likely	36	0	0	50	0.81
3 (40.5 ha)	BAU	min	3.5	10	80.3	6	1.21
		max	16.4	10	80.3	6	1.21
	Landscape: single subfield (LSSF)	min	3.5	0	0	6	1.21
		max	16.4	0	0	6	1.21
	Landscape: multiple (43) subfields (LSMF)	most likely	76	0	0	50	0.81

[a] BAU (single field, fertilizer application, & headland), Landscape: single subfield - LSSF (single subfield, no fertilizer & no headland), and Landscape: multiple subfields - LMSF (multiple subfields across the watershed). Total area under all three scenarios is the same.

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minimum (10.1 ha) and recommended optimal (40.5 ha) field sizes for EcoWillow, and a size representative of practical considerations of minimum subfields areas (at least 2.0 ha) in the watershed. For each of the above field or subfield areas, costs corresponding to the three scenarios of BAU, LSSF, LMSF (Fig. 2) were calculated (Table 2).

Differences between the LSSF and LMSF scenarios include Euclidean transport distance, planting time, and harvester downtime to account for differences in travel between subfields. Distances were calculated as Euclidean distances because of a plausible assumption of equal accessibility to all areas in the watershed. The assumption is justified because over 80% of the watershed is under agricultural production and over 60% has a slope of 0–2% terrain. The most likely transport distances under the LMSF scenarios in the Indian Creek FLP were calculated as the mean of at least 300 simulations of optimal Euclidean route between randomly selected subfields (Figs 3(a), 3(b) and 3(c)). The distribution of distances after these simulations was normal. Therefore, the arithmetic mean value is a representative distance under each case, and is referred to here as the most likely transport distance in the watershed based on the spatial distribution of marginal subfields (which assumes every subfield has the same chance of being selected for a combination of subfields) and the location of the depot. For this watershed and size of marginal subfields, on average, the required number of subfields to make up the total 2.0 ha, 10.1 ha or 40.5 ha was 4, 9, and 43 subfields, respectively. The number of subfields for each case was determined by randomly selecting a single field in the watershed, if the field did not meet the total area, that field was kept and another randomly selected field was added until the total area was satisfied. This process was repeated over 10 000 simulations, giving left skewed distributions (e.g. Figs 3(d) and 3(e)). Therefore, the number of fields was determined as the geometric mean of the skewed distribution (e.g. Figs 3(d) and 3(e)).

Net revenue of corn on marginal areas and opportunity costs

Calculation of net revenues at a subfield level adopted an approach used by Bonner *et al.*[13] and adapted it to the watershed scale. Total non-land costs of $427 per acre

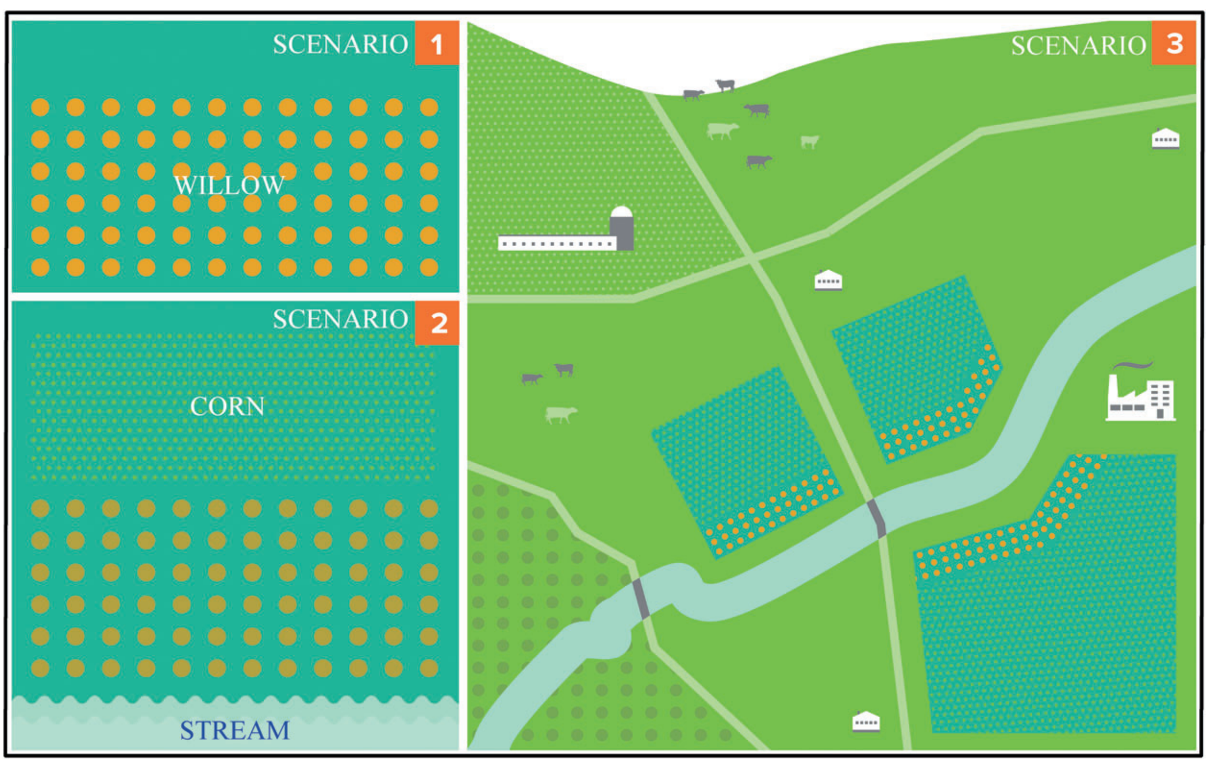

Figure 2. An infographic illustrating the three scenarios. (a) Business as usual, BAU (single field, fertilizer application, & headland); (b) Landscape: single subfield, LSSF (single subfield, no fertilizer & no headland); and (c) Landscape: multiple subfields, LMSF (multiple subfields across the watershed). The illustrations are not on scale. However, the total area under all three scenarios is the same.

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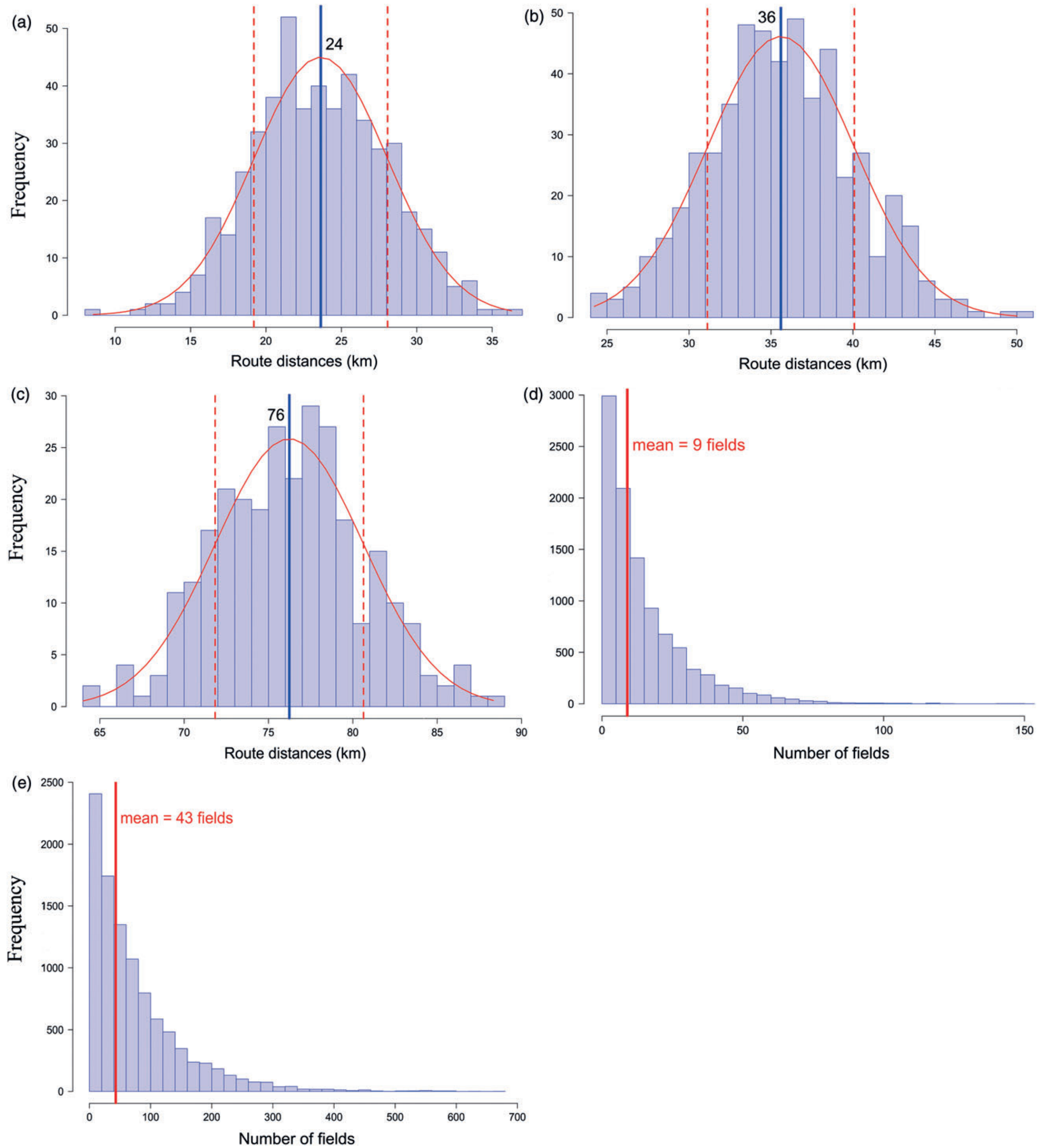

Figure 3. Histograms of simulated most likely transport distances from the subfields to Trainer Grain depot in the Indian Creek Watershed with total subfield area of 2.0 ha (a), 10.1 ha (b), and 40.5 ha (c). The most likely transport distances for Figures 2b and 2c correspond to average number of 9 subfields (d) and 43 subfields (e).

($1055 ha^{-1}) were estimated using a Corn-Soybean rotation tool[13] given a corn after soybean rotation option assuming low productivity land in central Illinois. The non-land costs include direct, power, and overhead costs. Annual corn and farmland cash rent prices for 2008 to 2013 were obtained from Illinois historical corn prices[32] and historical cash rent data.[33] Refer to Table S2 for annual variation of the corn and cash rent prices. Corn yields were estimated using the range of average annual corn yields from three counties that comprise the watershed (Livingston,

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McLean, and Ford). The annual minimum and maximum county level corn yields were reduced by 25% to estimate corn yields grown on marginal lands,[34] hence resulting in corn yield variations of 3.2 to 9.6 Mg_{dry} ha^{-1} (50 to 152 bu ac^{-1}). The corn yield range is due to annual variation in weather conditions and differences in county average yields. Net revenue per hectare at the watershed level for corn was calculated using Eqn (1).

$$revenue\left[\frac{\$}{ha}\right] = yield\left[\frac{Mg}{ha}\right] \times \begin{matrix} corn \\ price \end{matrix}\left[\frac{\$}{Mg}\right] - \begin{matrix} nonland \\ costs \end{matrix}\left[\frac{\$}{ha}\right] - \begin{matrix} cash \\ rent \end{matrix}\left[\frac{\$}{ha}\right] \qquad (1)$$

The average net revenue for corn at the minimum and maximum corn yields was used to calculate the range of opportunity costs for planting willow instead of corn along marginal lands. Net revenue values for willows were based on EcoWillow 2.0 outputs. We assumed an average willow yield of 22.5 Mg_{wet} ha^{-1} yr^{-1} (~45% moisture content at harvest) on marginal areas. Opportunity costs were calculated as the difference in net revenue between willow and corn production on the same subfield soils.

Cost of nitrogen loss reduction

The cost of nitrogen removal by a willow buffer in the watershed was calculated based on the reported range of annual NO_3-N leachate, reported willow nitrate reduction rates, and estimated costs of willow production (net revenue) by this study. Reported annual NO_3–N exports in the watershed vary between 20 and 50 kg N ha^{-1} yr^{-1}.[35–37] Several studies report 40–80% NO_3-N reductions by shrub willows under natural rainfall or under irrigation regimes.[9,24,38] The range of costs of willow production in the watershed was based on calculated annual net revenue under all cases and production scenarios (assuming biomass price of \$46.30 Mg_{wet}^{-1}). Annual cost of nitrogen removal (\$ kg N^{-1}) was computed using Eqn (2). The cost ranges were generated by running 100 000 simulations of combinations of the three variables in Eqn (2). Importantly, nitrate reduction is not equivalent with recovery, as multiple mechanisms for nitrogen removal are concurrently occurring in agricultural lands, including plant uptake, volatilization, leaching, denitrification, surface run-off, and immobilization of N in organic matter. Therefore nitrogen loss reduction should not be equated with nitrogen recovery. Nitrogen recovery compared to other removal mechanisms will be object of a future paper.

$$cost\left[\frac{\$}{kgN}\right] = \frac{revenue\left[\frac{\$}{ha}\right]}{\begin{matrix} NO_3-N \\ leachate \end{matrix}\left[\frac{kgN}{ha}\right] * reduction[\%]} \qquad (2)$$

Results

EcoWillow infield and transport economics

EcoWillow 2.0 estimated production costs and revenues consider both 13- and 22-year investment time frames. The costs reported in this study are for the 22-year time frame because it represents the complete production cycle before willow replanting and includes costs to remove stools after the final harvest at the end of the 22-year period. The annual net revenue under all production scales and scenarios varies between –\$3 and –\$15 Mg^{-1} (–\$67 to –\$304 ha^{-1}) at a biomass price of \$46.30 Mg_{wet}^{-1} (\$71.50 Mg_{dry}^{-1}: Fig. 4). A range of biomass prices (\$23.60 to 46.30 Mg_{wet}^{-1}) was run to account for variability in a potential heating market for wood chips;[41] all yielded negative returns. Therefore, willow biomass production in this watershed is a net loss, with high land cash rents (Table S3) accounting for over 50% of the total cost (Table 3).

The minimum and maximum net losses fall under the LSSF (–\$3 Mg^{-1}) and the LMSF (–\$15 Mg^{-1}) scenarios. Comparison between cases (2.0, 10.1, and 40.5 ha) shows a decrease in revenue losses for the BAU and LSSF scenarios as the total area of production increases (Fig. 4) and thus efficiency in production increases with scale. Net revenues of the LMSF scenario for cases 1 and 2 are comparable due to the limited difference in the most likely transport distance (9 vs. 25 km). However, at the 40.5 ha field size, transport costs are higher because of the increased number of fields and increased transport distance (Fig. 3).

For all cases, the LSSF scenario had the lowest negative return, or better outcome. This was followed by the BAU scenarios, highlighting the impact of the added fertilizer application and headland. The differences in annual net revenue due to differences in transport distance (minimum and maximum) for the BAU and the LSSF were \$1.3 Mg_{wet}^{-1} (\$31 ha^{-1}) and \$2 Mg_{wet}^{-1} (\$29 ha^{-1}), respectively, thus highlighting the impact of transportation. The cost difference of approximately \$5 Mg_{wet}^{-1} between BAU and LSSF is equivalent to the cost of having landscape subfields within a radius of 6 to 21 km. Therefore, the economics of a single dedicated field (BAU) located 2–18 km from the depot are comparable to those of using landscape-placed subfields at distances of 8–39 km from the depot, due to

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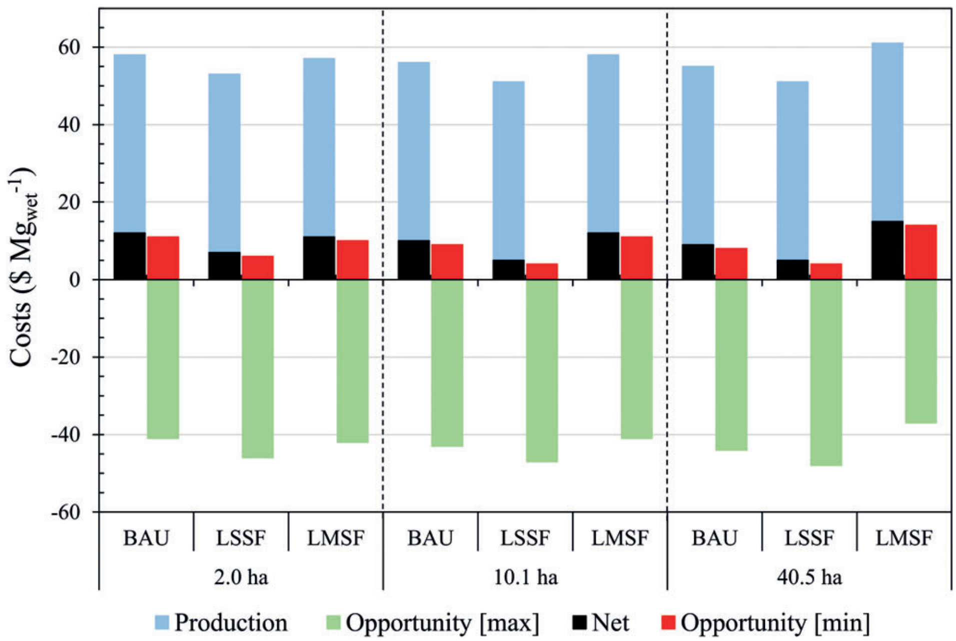

Figure 4. Comparison of production, net, and opportunity costs of willow under business as usual (BAU) and two landscape scenarios (LSSF: single subfield and LMSF: multiple subfields) across three production scales (2.0, 10.1, and 40.5 ha). Net costs are differences between production costs and revenue from sale of biomass. Opportunity costs are costs of growing willow instead of growing corn (willow revenue – corn revenue) on the same marginal land. Maximum and minimum reflect variability in corn yields on marginal land. Corn net revenue on marginal land in the watershed varied between –\$52 Mg^{-1} and –\$0.68 Mg^{-1}. Negative costs reflect a net profit where positive costs reflect a net loss.

savings from fertilizer costs and lack of the need for a headland in the latter.

Opportunity costs

Results of this study show that willow production has negative annual net revenue returns (Fig. 4) under all production scales and scenarios. However, when bioenergy crop production is in landscape design on marginal lands in which corn production profitability may be low, the opportunity costs present a different picture. The opportunity costs shown in Fig. 4 depict the cost of planting willow instead of corn along the marginal land in the watershed. The range of average annual net revenue for growing corn on marginal lands varied between –\$223 ha^{-1} (–\$52 Mg^{-1}) for minimum corn yield of 3.2 Mg ha^{-1} (50 bu ac^{-1}) and \$17 ha^{-1} (–\$0.68 Mg^{-1}) for maximum corn yield of 9.6 Mg ha^{-1} (152 bu ac^{-1}), respectively. The corn yield range is a result of annual variability in soils and weather conditions. Both the variability in corn yield and differences in willow production scales and scenarios resulted in opportunity costs ranging between –\$14 and \$49 Mg^{-1}. This suggests that at low corn yields, willow production can provide a better outcome, but under higher corn yields, a revenue loss is expected.

Cost of nitrogen removal

Under the LSSF and LMSF scenarios, the principal regulating ecosystem service provided by this type of landscape design (or FLP) is nitrogen removal from soil water leachate by deep-rooted willows. Corn would not be able to remove this nitrogen due to its inability to reach deeper soil water. The cost distribution of N reduction by growing willow in landscape design in the Indian Creek watershed is shown in Fig. 5(a). On average, the projected annual cost of removing nitrogen by a willow buffer in the watershed is \$9 kg N^{-1}. This average cost is due to a sample combination of annual nitrate-N leachate of 34 kg N ha^{-1} without the buffer, an average annual nitrate reduction of 64% by the buffer, and annual net revenue loss of \$198 ha^{-1} as cost for establishing and maintaining the buffer. However, this cost varies between \$1.8 and \$37.0 depending on performance of the buffer (NO_3-N reduction rates) and location

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Table 3. Lifecycle cost distribution for willow production under each scenario.

Life Cycle Costs	Case 1					Case 2					Case 3				
	BAU		Landscape: single subfield		Landscape: multiple subfield	BAU		Landscape: single subfield		Landscape: multiple subfield	BAU		Landscape: single subfield		Landscape: multiple subfield
	Min (%)	Max (%)	Min (%)	Max (%)	Most Likely (%)	Min (%)	Max (%)	Min (%)	Max (%)	Most Likely (%)	Min (%)	Max (%)	Min (%)	Max (%)	Most Likely (%)
Land Costs	55	54	57	56	52	57	55	59	57	51	58	56	59	58	48
Administration	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Establishment	11	10	11	10	10	10	10	10	10	9	10	10	10	10	9
Fertilizer	2	2	0	0	0	2	2	0	0	0	2	2	0	0	0
Harvest	21	20	21	21	25	21	20	21	21	25	19	19	20	19	22
Transport	6	9	6	8	8	4	7	5	8	10	5	7	5	7	16
Stock Removal	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
Total	100%														

specific annual NO_3-N leachate loadings. The cost of N removal of \$1.8 kg N^{-1} corresponds to areas in the watershed with annual NO_3-N leachate of about 50 kg N ha^{-1}, willow buffer performance of at least 80% N removal, and cost of willow production of \$67 ha^{-1}. Such subfields are close to the depot (< 5 km) with a buffer area of at least 10.1 ha. The calculated costs of N-removal by willow buffers compared to other conservation practices as estimated by Christianson *et al.*[23] is presented in Fig. 5(b).

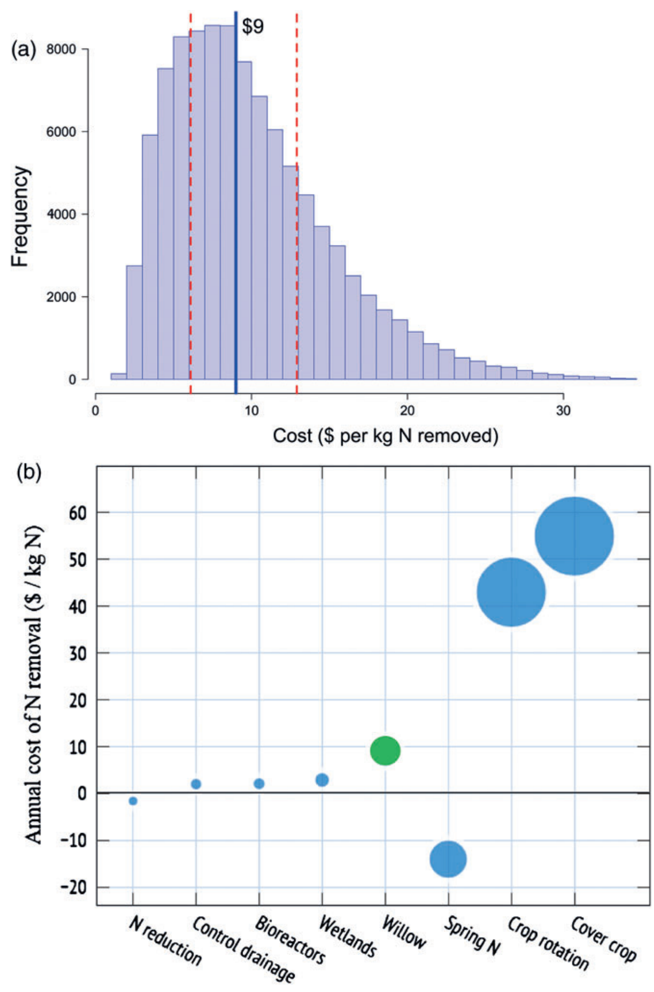

Figure 5. (a) Frequency distribution of nitrogen removal cost by shrub willow buffer in the Indian Creek watershed. Solid line represents the median (\$9) of 100,000 simulations, with the dashed lines representing the 25th (\$6) and 75th (\$13) quartiles. Minimum and maximum values are \$1.8 and \$37, respectively. (b) Comparison of N-removal costs by a willow bioenergy buffer to alternative conservation practices. The size of the bubble corresponds to the cost. Negative costs reflect a net profit where positive costs reflect a net loss. Costs of other conservation practices are taken from Christianson *et al.*[23]

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Discussion

Monetization of ecosystem services

Regardless of the case, scenario, and examined biomass price (\$23.60 to 46.30 Mg_{wet}^{-1}), willow crop production in central Illinois is expected to have negative net revenue returns. Comparing the BAU case at the minimum transport distance to the LMSF on the 40.5 ha production scale, willow production costs ranged from \$54 Mg_{wet}^{-1} (\$1058 ha^{-1} yr^{-1}) for BAU to \$61 Mg_{wet}^{-1} (\$1263 ha^{-1} yr^{-1}) for LMSF; a difference of \$7 Mg_{wet}^{-1} or \$205 ha^{-1} yr^{-1}. This differential reflects the actual incremental costs to obtain the water quality provisioning service enabled by the functional spatial allocation of the buffers on the landscape. Monetization of ecosystem services could bridge, at least the gap of \$7 Mg_{wet}^{-1} between BAU and LMSF or better, the difference to breakeven. Assessment of the impact of biomass price sensitivity suggests that for every \$1 Mg_{wet}^{-1} increase in the depot gate price, the annual net revenue linearly increases by \$1 Mg_{wet}^{-1} or \$23 ha^{-1}. A breakeven biomass price for the 40.5 ha ranged from \$49 Mg_{wet}^{-1} (LSSF: at minimum transport distance) to \$61 Mg_{wet}^{-1} (LMSF). Of the many itemized cost categories, the largest driver for the lower returns for all cropping modalities is land cost, where taxes, lease and insurance are about \$586 ha^{-1}, on average 45–59% of the lifecycle costs. Harvesting (20%: average) and crop establishment (10%: average) follow as the next highest percent costs in all cases and scenarios except case 3 and LMSF scenario. All cases assume no incentive program funding was received. If land cost could be reduced in the landscape scenarios based on its underproductive status, for example through policy incentives, it would be possible to obtain breakeven annual net revenue without increasing the sale price of biomass. However, even without the inclusion of conservation program incentives, the favorable opportunity cost of growing willow (up to \$49 Mg^{-1}) on low corn yielding soils (3.2 Mg ha^{-1}) may provide a sufficient incentive for integration of bioenergy crops into agricultural systems where an end market exists. This opportunity cost assumes an average willow yield of 22.5 Mg_{wet} ha^{-1} yr^{-1} in the watershed based on long-term research data.[42–44] Future work should account for a more granular assessment of the variability of willow yields on marginal areas in the watershed.

Cost comparisons with conservation practices

Importantly, the net revenue losses shown under willow biomass production in landscape-based design are directly related to the extra effort needed to concurrently produce the ecosystem service of improving water quality. A full ecosystem service valuation is beyond the scope of this analysis and will be undertaken in the future. However, here we begin to compare the calculated costs with those of the most common nitrate reduction strategies for the Midwestern agricultural drainage, as provided in Christianson *et al.*[23] Based on the relative efficiency of each in reducing nitrate loadings, the most cost effective practice, deferring nitrogen fertilizer application to the spring provides a saving to farmers of \$90 ha^{-1} yr^{-1}, translating to a mean \$12 kg N^{-1} yr^{-1} not leaving the field. The most expensive best management practices were agronomic practices such as cover crops and crop rotations, with negative balances of \$164 and \$224 ha^{-1} yr^{-1} respectively, or a mean \$55 and \$43 kg N^{-1} removed per year. Practices such as controlled drainage, bioreactors and wetlands seemed to combine good efficiency with affordable costs, quantified between \$9.30 and \$31 ha^{-1} yr^{-1}, or between \$2 and 2.90 kg N^{-1} yr^{-1} removed. The negative net revenues of \$67 to \$304 ha^{-1} yr^{-1} estimated for willow crop production in this study, are comparable to the net revenue ranges estimated by Christianson *et al.*[23] for cover crop and crop rotation. However, in terms of cost of nitrate-nitrogen removed, willow crop production comes out ahead of cover crop and crop rotation with an estimated cost of \$9 kg of N^{-1} yr^{-1} removed (with the 25th and 75th quartiles at \$6 and \$13, respectively). This is possibly due to a higher range of load reduction (40–80%)[9,24,38] by willows compared to cover crops (4.9% to 45.3%) and crop rotation (14.0% to 77.0%).[23] The higher load reduction in willow is probably associated with the perennial nature of the crop, its early growth in the spring, and the root system that develops deeper into the soil and is active for longer time spans compared to short lived cover crops.

Cost comparisons with wastewater treatment

Beyond the field level, system-level nitrogen removal strategies in the form of wastewater and drinking water treatment (although not directly comparable) may be useful in placing a value on ecosystem services. The cost of treating wastewater for nitrogen removal is highly dependent on the size of the waste treatment plant, the target effluent concentration level, and the technology used.[43] For example, Washington DC's Blue Plains advanced wastewater treatment plant, a very large facility treating 1.4 billion L day^{-1} has calculated the cost of removing nitrogen from its effluent as \$1.85 kg N^{-1} removed to reduce N from 14

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to 7.5 mg L^{-1}, then an additional \$8.13 kg N^{-1} to bring the concentration further down to 5 mg L^{-1}, and an additional \$113.52 kg N^{-1} removed to further reduce the concentration to 3.9 mg L^{-1}.[44] Because of economies of scale, smaller plants incur comparatively higher costs, in the vicinity of \$628 kg N^{-1} yr^{-1} for 11.36 million L day^{-1} flows to reach a 5 mg L^{-1} nitrogen effluent concentration.[45] Future research will need to inform system-level planning, encompassing an assessment of the return on investments in both point- and non-point source reductions to achieve State Nutrient Loss Reduction goals in the best interests of taxpayers and all stakeholders. In this context, bioenergy buffers should be examined as a cost-effective tool to be integrated into existing best practices.

Conclusions

The combined interest in nutrient reduction as well as bioenergy crop production comes from the Gulf of Mexico Hypoxia Task force, translated into State goals such as those of the Illinois Nutrient Loss Reduction Strategy, and the Energy Independence and Security Act of 2007 goals of a 45% nutrient reduction of nitrate-nitrogen and phosphorous by 2035 and production of 61 billion liters of biofuel from cellulosic feedstock by 2022.[46, 47] The landscape design in this analysis was developed to provide both biomass production and regulating ecosystem services, limited in this analysis to water quality (nitrogen) improvements. We argue that the revenue gap between BAU and landscape design (\$7 Mg_{wet}^{-1} or \$205 ha^{-1} yr^{-1}), and possibly the entire gap between breakeven price and actual negative revenues (\$3 to \$15 Mg_{wet}^{-1} or \$67 to \$304 ha^{-1} yr^{-1}) could be closed with the value of the ecosystem service provided. This analysis gives us the basis for understanding the costs associated with the ecosystem services. The value of the ecosystem services provided by willow production could cover the costs of willow production where it can provide water quality benefits. For example, the cost of nitrogen removal under all willow production scenarios was found to range between \$6 and \$13 kg N^{-1}, under the assumption that the willows will reduce soil-water nitrate-nitrogen concentrations by 40–80% and the nitrate-nitrogen leachate varies between 20 and 50 kg N ha^{-1} yr^{-1} in the watershed. Therefore, a provisional value of nitrogen removal by willow crop production can indicatively vary between \$6 and \$13 per kg N removed. While this work focused only on the regulating ecosystem service of nitrate removal because of the urgency of achieving better water quality from agricultural land in the Mississippi River basin, it provides a novel framework for a future, more complete evaluation and monetization of stacked ecosystem services. Regulating ecosystem services provided by deep rooted perennial bioenergy crops in landscape designs include for example carbon sequestration, flood management, pollinator habitat improvement, improved biodiversity, and reduction of greenhouse gases. We propose that as the environmental benefits are demonstrated, support or incentives for ecosystem services could provide the additional farmer revenue to compensate for the increased cost of cropping bioenergy together with grains on a landscape design basis.

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