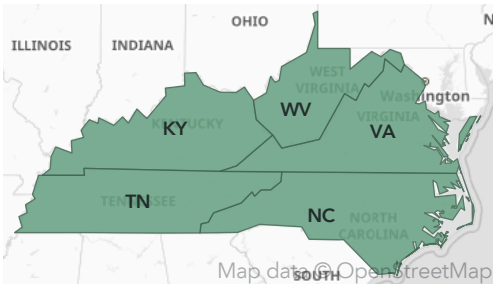
QUICK START GUIDE

Willow in Appalachia

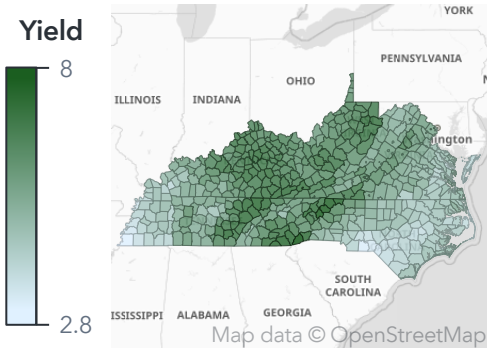
Willow is a low-input bioenergy crop with net energy ratios of 10-16:1, harvested every 3-4 years using a cut-and-chip system. It requires minimal inputs such as fertilizer, irrigation, and pest control, and regrows from stumps, reducing replanting costs. It offsets about 1 ton CO_2/dry ton when displacing fossil fuels and provides co-benefits like soil carbon storage, erosion control, and land rehabilitation. Its resilience and high energy return make it a viable option for biomass strategies, depending on site conditions.

USDA Region Appalachia



Yield

County yields (dry tons/ acre) in map below are estimates derived from regional field trials and do not account for competition with other crops.



Field trials for KY, TN, and NC indicate moderate yield potential in the Appalachia region, with a narrow range of 4.6-5.5 tons/acre. Field trial gaps remain for WV and VA, where no trials were found.

Equipment and Harvest

Harvesting is challenged by terrain in places like WV but feasible with adapted small-scale forestry equipment or custom harvesters. KY and NC could leverage existing agricultural/forestry infrastructure with modifications. Winter harvest is preferred across the region to minimize leaf content and utilize frozen ground.

Fertilizer

Between 50-100 lb N/acre after each 3- to 4-year harvest cycle maintains productivity. Organic sources (manure, biosolids) are effective alternatives, especially on reclaimed land. P and K applications follow soil tests, and leaf litter contributes to nutrient cycling.

Pest and Weed Control

Common issues include deer browsing, fungal rusts, and leaf beetles. Genetic resistance and early weed control (herbicides, mulching) are key. Diverse planting and site-specific integrated pest management can reduce chemical needs. NC may face higher pest pressure due to longer growing seasons.

Market Opportunities

Markets may include co-firing with coal and district heating in WV, KY, and TN. Humid areas could support pellet production with proper storage. Willow fits well in restoration projects such as mine reclamation or water buffers, where biomass is a byproduct adding value.

Costs

Establishment costs of $500-1,500/acre (e.g. $540/acre for cuttings), annual maintenance costs of around $10-15/acre, and harvest costs of about $30/ton, with terrain and equipment access driving variability.

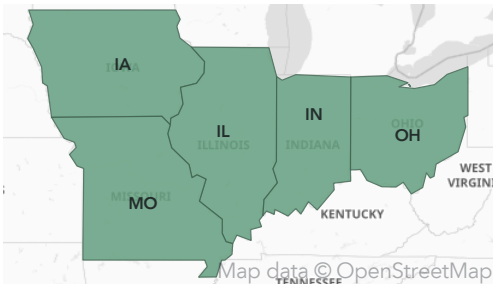
Authors: Daniela Jones, North Carolina State University; Tasmin Hossain, Idaho National Laboratory; Haley Casper, North Carolina State University. **Acknowledgement**: Supported by the U.S. Department of Energy (DOE), Office of Energy Efficiency and Renewable Energy (EERE), Bioenergy Technologies Office (BETO), the Feedstock-Conversion Interface Consortium (FCIC), under DOE Idaho Operations Office with Contract No. DE-AC07-05ID14517.

QUICK START GUIDE

Willow in Corn Belt

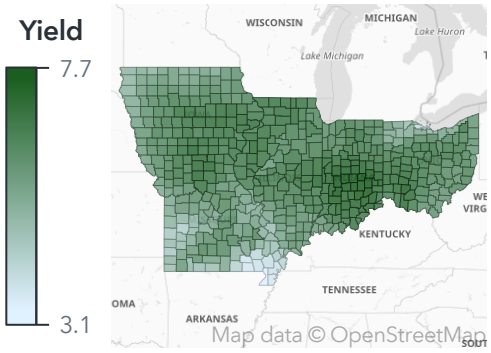
Willow is a low-input bioenergy crop with net energy ratios of 10-16:1, harvested every 3-4 years using a cut-and-chip system. It requires minimal inputs such as fertilizer, irrigation, and pest control, and regrows from stumps, reducing replanting costs. It offsets about 1 ton CO_2/dry ton when displacing fossil fuels and provides co-benefits like soil carbon storage, erosion control, and land rehabilitation. Its resilience and high energy return make it a viable option for biomass strategies, depending on site conditions.

USDA Region Corn Belt



Yield

County yields (dry tons/ acre) in map below are estimates derived from regional field trials and do not account for competition with other crops.



Field trials for IL, MO, and OH indicate variable willow yield potential in the Central Midwest, ranging from less than 1.1 tons/acre in OH to 6.8 tons/acre in IL. Field trial gaps remain for IA and IN, where no trials were found.

Equipment and Harvest

Willow in the Corn Belt is planted at high densities (5,800 - 6,200 stems/acre), coppiced after the first year, and managed on short harvest cycles. Harvest typically requires modified or manual equipment such as mechanical harvester, forestry mower or modified forage harvester.

Fertilizer

Moderate fertilization (about 100 lb N/acre post-coppice) is used when soils are low in fertility. P and K as per soil test; otherwise, residual nutrients from nearby cropland often suffice. In IL, willow was grown without fertilization due to passive nutrient uptake from nitrate leaching out of adjacent cornfields.

Pest and Weed Control

Weed control in Corn Belt willow trials was minimal. Mowing was often used instead of herbicides, and protection from competition and wildlife (deer and rodents) is critical during establishment. Any plantings would need weed management similar to other woody crops (pre-emergent herbicides and possibly glyphosate between rows).

Market Opportunities

Opportunities are limited due to modest yields, but short-haul pellet markets, riparian buffers, and bioproducts (e.g., natural fiber composites) may provide niche uses.

Costs

While no costs were found from trials in this region, Willows in IL significantly reduced nitrate leachate (by 70-88% in 2015-2016), demonstrating environmental benefits of integration into row-crop landscapes.

Authors: Daniela Jones, North Carolina State University; Tasmin Hossain, Idaho National Laboratory; Haley Casper, North Carolina State University. **Acknowledgement**: Supported by the U.S. Department of Energy (DOE), Office of Energy Efficiency and Renewable Energy (EERE), Bioenergy Technologies Office (BETO), the Feedstock-Conversion Interface Consortium (FCIC), under DOE Idaho Operations Office with Contract No. DE-AC07-05ID14517.

QUICK START GUIDE

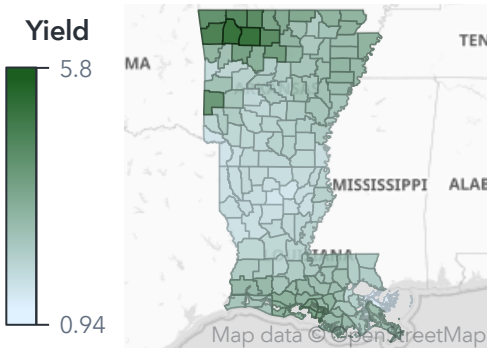
Willow in Delta States

Willow is a low-input bioenergy crop with net energy ratios of 10-16:1, harvested every 3-4 years using a cut-and-chip system. It requires minimal inputs such as fertilizer, irrigation, and pest control, and regrows from stumps, reducing replanting costs. It offsets about 1 ton CO_2/dry ton when displacing fossil fuels and provides co-benefits like soil carbon storage, erosion control, and land rehabilitation. Its resilience and high energy return make it a viable option for biomass strategies, depending on site conditions.

USDA Region Delta States

Yield

County yields (dry tons/ acre) in map below are estimates derived from regional field trials and do not account for competition with other crops.



LA and AR field trials yielded 2-6 tons/acre, with top sites over 10 tons/acre. Data gaps remain for other southern states with no reported trials.

Equipment and Harvest

Initial harvests use adapted forestry gear like feller-bunchers with chippers. European-style willow harvesters improve efficiency but need investment or shared use. Winter harvests use low-pressure equipment for wet soils. Both states have chipping and transport infrastructure.

Fertilizer

Between 50-100 lb N/acre applied after each harvest cycle. Additional P and K may be required based on soil testing. Organic amendments (biosolids, manure, effluent) are often recommended and cost-effective.

Pest and Weed Control

Pest and disease risks are moderate. Beetles, borers, deer, nutria, and rabbits can affect growth. Rust, scab, and canker occur in humid areas like eastern AR and southern LA. Resistant clones, weed control, pre-emergent herbicides, and mulching or cultivation are recommended.

Market Opportunities

Primary opportunities include co-firing with coal, pellet production for domestic or export markets or use in wood-fired boilers for industrial heat. Willow could integrate with poultry litter energy systems in AR or bioenergy combined heat and power (CHP) linked to agriculture/forestry residues in LA. Moist alluvial soils favor riparian biomass markets.

Costs

Establishment costs of $300-600/acre largely for cuttings and planting. Annual maintenance costs of $10-20/acre, and harvest and transport costs of $20-35/ton.

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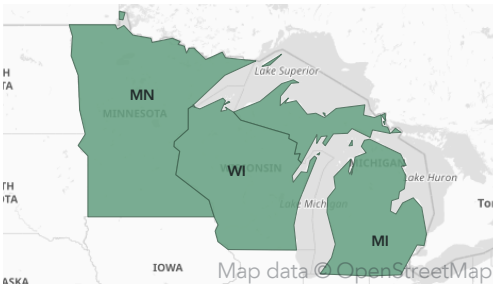
QUICK START GUIDE

Willow in Lake States

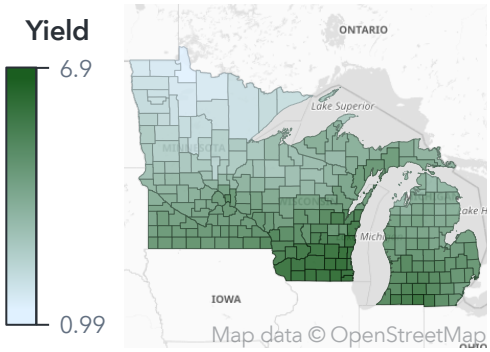
Willow is a low-input bioenergy crop with net energy ratios of 10-16:1, harvested every 3-4 years using a cut-and-chip system. It requires minimal inputs such as fertilizer, irrigation, and pest control, and regrows from stumps, reducing replanting costs. It offsets about 1 ton CO_2/dry ton when displacing fossil fuels and provides co-benefits like soil carbon storage, erosion control, and land rehabilitation. Its resilience and high energy return make it a viable option for biomass strategies, depending on site conditions.

USDA Region Lake States



Yield

County yields (dry tons/ acre) in map below are estimates derived from regional field trials and do not account for competition with other crops.



Field trials for MI and MN indicate moderate willow yield potential in the Upper Midwest, with reported yields ranging from 1.2 to 5.0 tons/acre. Field trial gaps remain for WI, where no trials were found.

Equipment and Harvest

MI trials (Escanaba, Skandia, Brimley) planted 14,400 stems/ha with 25 cm cuttings, coppiced after year 1, and harvested 3-3.5 years later using mechanical harvesters. MN trials (Waseca) used the same protocol with cut-and-chip harvesters for final harvest.

Fertilizer

Between 50-90 lb N/acre after coppice is typical. Fertilization is skipped in establishment year. Many sites rely on residual fertility or recycled nutrients (biosolids, manure) rather than synthetic fertilizers to provide low-cost fertilization and added environmental benefits.

Pest and Weed Control

In MI and MN trials, pre-emergence oxyfluorfen and simazine were applied before budbreak, and mechanical or spot chemical control was used as needed. Potential issues include willow beetles, sawflies, rust, and rodent browse (especially under snow).

Market Opportunities

Strong fit for district heating, pellets, and bioproducts (especially fiber for pulp/paper). These states have agricultural and industrial infrastructure (ethanol plants, pulp mills, biomass facilities) that could adapt to include willow as a feedstock. Ties to existing bioenergy research at MI and MN institutions support scaling.

Costs

Establishment costs in woody biomass systems often reach $500-1,000/acre in well-managed cases, and harvest costs of $30/ton are commonly reported in budgets using mechanized harvesters.

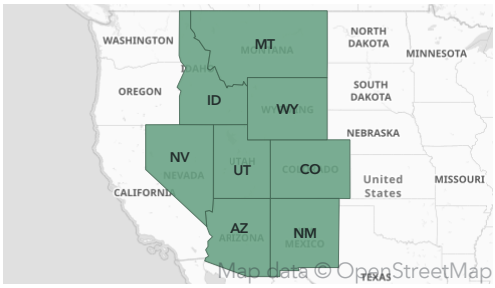
Authors: Daniela Jones, North Carolina State University; Tasmin Hossain, Idaho National Laboratory; Haley Casper, North Carolina State University. **Acknowledgement**: Supported by the U.S. Department of Energy (DOE), Office of Energy Efficiency and Renewable Energy (EERE), Bioenergy Technologies Office (BETO), the Feedstock-Conversion Interface Consortium (FCIC), under DOE Idaho Operations Office with Contract No. DE-AC07-05ID14517.

QUICK START GUIDE

Willow in Mountain States

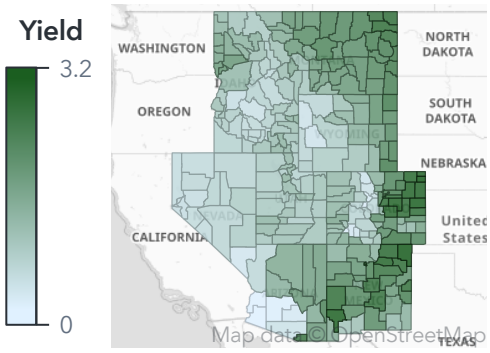
Willow is a low-input bioenergy crop with net energy ratios of 10-16:1, harvested every 3-4 years using a cut-and-chip system. It requires minimal inputs such as fertilizer, irrigation, and pest control, and regrows from stumps, reducing replanting costs. It offsets about 1 ton CO_2/dry ton when displacing fossil fuels and provides co-benefits like soil carbon storage, erosion control, and land rehabilitation. Its resilience and high energy return make it a viable option for biomass strategies, depending on site conditions.

USDA Region Mountain States



Yield

County yields (dry tons/ acre) in map below are estimates derived from regional field trials and do not account for competition with other crops.



Not cultivated regionally due to arid conditions. With irrigation, yields reach 2-4 dry tons/acre in ID, WY, and CO. Wetter MT sites yield 4-6 dry tons/acre. AZ and NM show riparian potential using native willow with limited data.

Equipment and Harvest

Harvesting requires specialized coppice harvesters (e.g., New Holland forage harvester with a willow header), which are not common in the region. Custom harvesters may be needed. In riparian restoration contexts (e.g., AZ and NM), manual pole harvesting is more common. Mechanized commercial-scale harvest is largely theoretical due to lack of local infrastructure.

Fertilizer

Fertilization after each 3-year harvest cycle is typical (100 lb N/acre), often supplemented with phosphorus and potassium based on soil tests. Organic amendments (e.g., manure, biosolids) may significantly boost yields, particularly on marginal or reclaimed land. Practices remain experimental due to lack of regional trials. Spring application timing is key to ensure nutrient uptake.

Pest and Weed Control

Deer, rodents, and possibly elk are common browsing threats. Weed control is critical in the first two years and typically involves pre-emergent herbicides (e.g., oxyfluorfen, pendimethalin) and manual or mechanical cultivation. Pest pressure is expected to be lower in the region's drier conditions, but vigilance is needed, especially in wetter areas where fungal pathogens or insects like leafhoppers may appear.

Market Opportunities

There is no established willow biomass market in the Mountain States. Markets would rely on irrigated niches or riparian buffers, with limited scale. Biomass could feed small-scale pellet or conservation projects, but large markets are unlikely. Might be used for erosion control, nutrient uptake, streambank stabilization, and phyto-remediation.

Costs

Establishment costs of $1,000-1,200/acre, with minimal maintenance between harvests. Harvest and transport add $30-40/ton, making scale and incentives critical for cost-competitiveness.

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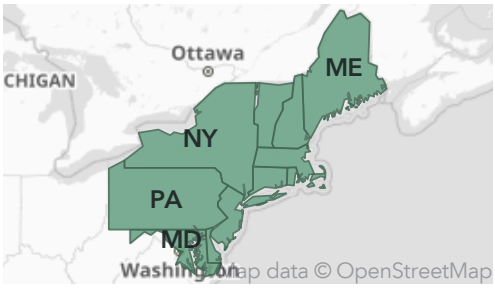
QUICK START GUIDE

Willow in Northeast

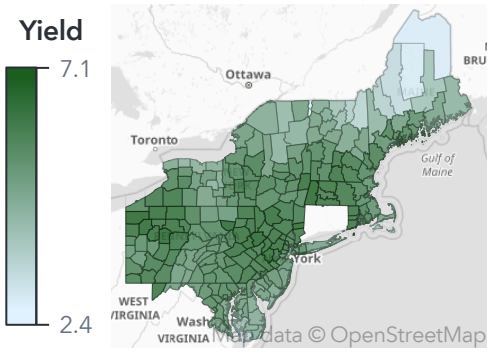
Willow is a low-input bioenergy crop with net energy ratios of 10-16:1, harvested every 3-4 years using a cut-and-chip system. It requires minimal inputs such as fertilizer, irrigation, and pest control, and regrows from stumps, reducing replanting costs. It offsets about 1 ton CO_2/dry ton when displacing fossil fuels and provides co-benefits like soil carbon storage, erosion control, and land rehabilitation. Its resilience and high energy return make it a viable option for biomass strategies, depending on site conditions.

USDA Region Northeast



Yield

County yields (dry tons/ acre) in map below are estimates derived from regional field trials and do not account for competition with other crops.



Northeast willow field trials yielded 4-9 tons/acre. NY reports 5-8 tons/acre, similar to VT and CT. Data gaps remain for other states in the region.

Equipment and Harvest

Mechanized cut-and-chip systems (e.g., New Holland forage harvesters) from SUNY-ESF are common in NY and nearby states. CT, NY, and VT trials planted 5,800 stems/acre, coppiced after year 1, and harvested 3-4 years later using cut-and-chip harvesters.

Fertilizer

No N during establishment. After the first coppice, 50-100 lb N/acre every 3-4 years. P/K added per soil test or harvest removal. Nutrient removal is low, and nutrient cycling (e.g., leaving leaf litter) helps conserve soil fertility. Wastewater or sludge irrigation can increase yields by 40-60%.

Pest and Weed Control

Key issues include deer, voles, beetles, and rust, managed with IPM and resistant cultivars. CT, NY, and VT trials used oxyfluorfen or simazine before budbreak plus mechanical or spot control. Fertilization is delayed under heavy weed pressure to aid young roots.

Market Opportunities

Most states in the Northeast and Mid-Atlantic lack large-scale commercial willow markets. They are exploring regionally integrated, policy-supported, and niche applications for pellets, district heating, bioproducts, and co-firing trials with NY leading the way. NY already has commercial willow plantings linked to bioenergy facilities.

Costs

Establishment costs of $500-1,000/acre ($540/acre for cuttings in typical budgets), with delivered costs of $50-70/ton and up to $80/ton under less favorable conditions.

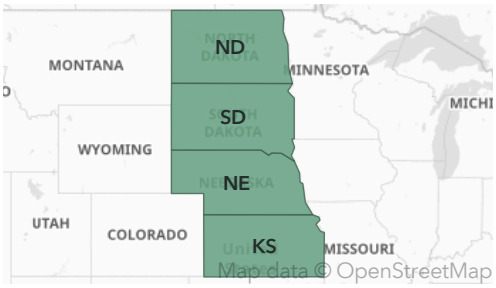
Authors: Daniela Jones, North Carolina State University; Tasmin Hossain, Idaho National Laboratory; Haley Casper, North Carolina State University. **Acknowledgement**: Supported by the U.S. Department of Energy (DOE), Office of Energy Efficiency and Renewable Energy (EERE), Bioenergy Technologies Office (BETO), the Feedstock-Conversion Interface Consortium (FCIC), under DOE Idaho Operations Office with Contract No. DE-AC07-05ID14517.

QUICK START GUIDE

Willow in Northern Plains

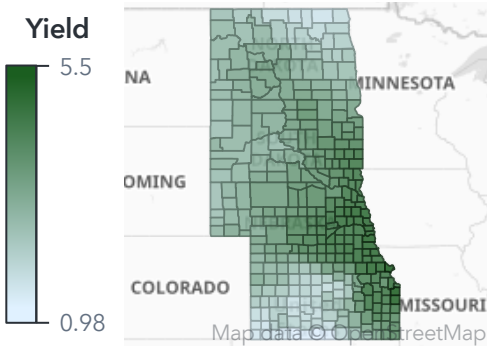
Willow is a low-input bioenergy crop with net energy ratios of 10-16:1, harvested every 3-4 years using a cut-and-chip system. It requires minimal inputs such as fertilizer, irrigation, and pest control, and regrows from stumps, reducing replanting costs. It offsets about 1 ton CO_2/dry ton when displacing fossil fuels and provides co-benefits like soil carbon storage, erosion control, and land rehabilitation. Its resilience and high energy return make it a viable option for biomass strategies, depending on site conditions.

USDA Region Northern Plains



Yield

County yields (dry tons/ acre) in map below are estimates derived from regional field trials and do not account for competition with other crops.



Great Plains willow field trial yielded 2-4 tons/acre yearly. Irrigated or fertile NE sites may reach 5 tons/acre, while ND and SD average about 3. Moisture availability remains the main limiting factor.

Equipment and Harvest

All states lack willow harvest infrastructure. Specialized cut-and-chip machines are needed, often imported or custom-built. Winter harvests in ND, SD, and NE benefit from frozen ground reducing compaction. Storage and transport are feasible but need new operational models.

Fertilizer

Between 50-100 lb N/acre after harvest is adequate. P/K applied based on soil testing, often adequate on bottomlands. Organic options like manure or biosolids are suitable for the region. Early fertilization is avoided to minimize weed growth.

Pest and Weed Control

Pest pressure is moderate to low in cold, dry climates. Beetles, sawflies, leafhoppers, deer, rabbits, and voles pose risks to young shoots. Weed control is vital early, using pre-emergent herbicides, mulch, or cultivation. By year 2-3, canopy closure suppresses most weeds.

Market Opportunities

Low yields limit markets, but biochar or bioenergy in ethanol refineries, shelterbelts, conservation programs, and small-scale heating could provide value. Co-firing only feasible with irrigation-supported stands. Policy or corporate demand (carbon credits, renewable mandates) is the key enabler for willow adoption.

Costs

Establishment costs of $500-900/acre, largely for cuttings and planting labor. Harvest costs around $40-$60/ton per cycle depending on scale and equipment access.

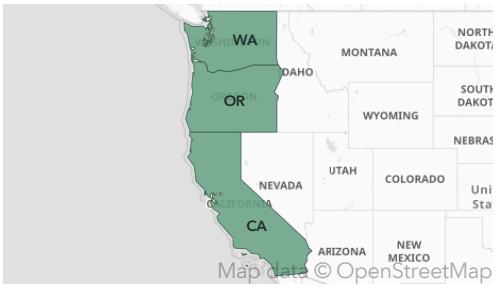
Authors: Daniela Jones, North Carolina State University; Tasmin Hossain, Idaho National Laboratory; Haley Casper, North Carolina State University. **Acknowledgement**: Supported by the U.S. Department of Energy (DOE), Office of Energy Efficiency and Renewable Energy (EERE), Bioenergy Technologies Office (BETO), the Feedstock-Conversion Interface Consortium (FCIC), under DOE Idaho Operations Office with Contract No. DE-AC07-05ID14517.

QUICK START GUIDE

Willow in Pacific

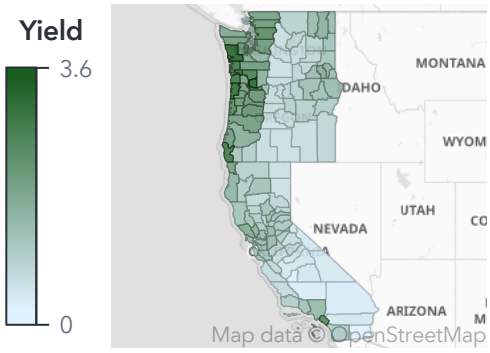
Willow is a low-input bioenergy crop with net energy ratios of 10-16:1, harvested every 3-4 years using a cut-and-chip system. It requires minimal inputs such as fertilizer, irrigation, and pest control, and regrows from stumps, reducing replanting costs. It offsets about 1 ton CO_2/dry ton when displacing fossil fuels and provides co-benefits like soil carbon storage, erosion control, and land rehabilitation. Its resilience and high energy return make it a viable option for biomass strategies, depending on site conditions.

USDA Region Pacific



Yield

County yields (dry tons/ acre) in map below are estimates derived from regional field trials and do not account for competition with other crops.



Willow is not grown at scale in the Pacific region. WA field trials yielded 4.2 tons/acre. No trials found in OR or CA. Moist valleys in OR and WA offer the best prospects where rainfall or irrigation supports growth.

Equipment and Harvest

No dedicated willow harvesting infrastructure exists in the region, but forestry equipment used for poplar and eucalyptus (e.g., feller-bunchers, hydraulic shears, chippers) could be adapted. If willow gains traction, European-style cut-and-chip harvesters may be imported.

Fertilizer

Fertilizer needs are modest. On irrigated or low-fertility sites, applications of 50-75 lb N/acre after coppice may be needed, with P/K as per soil test. Willow systems integrated with effluent reuse or bioswales could eliminate synthetic inputs. Rain-fed systems in western WA/OR may require little to no fertilizer.

Pest and Weed Control

Willow faces potential threats from fungal rusts (Melampsora spp.), browsing animals (deer, beavers), and insects in riparian zones. Weed pressure is significant during establishment. Given the stringent pesticide regulations in CA and OR, resistant cultivars and integrated pest management (IPM) strategies are preferred.

Market Opportunities

Potential for pellet exports through Pacific Northwest (PNW) ports and biomass power tied to pulp mills or aviation fuels. Willow could enter niche roles such as supplemental feedstock for dairy digesters and biogas (especially in CA), riparian buffers or phytoremediation with biomass recovery (OR/CA nitrate pollution zones).

Costs

No region-specific cost estimates for willow establishment or production were found for OR, CA, or WA. Cost is expected to be higher due to high land, labor, and irrigation costs, especially in CA. Establishment would require policy support, cost-sharing, or co-product strategies. Without subsidies or premium markets, willow remains economically uncompetitive in the Pacific.

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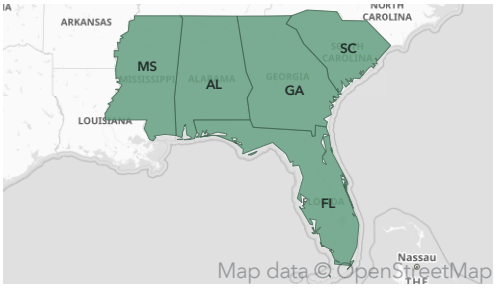
QUICK START GUIDE

Willow in Southeast

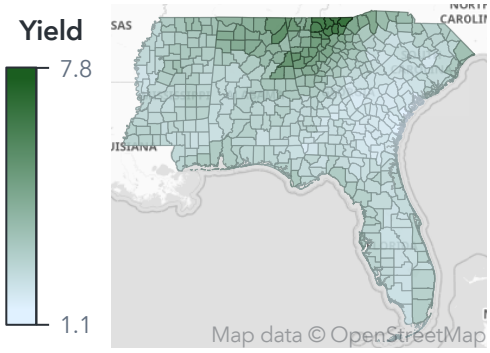
Willow is a low-input bioenergy crop with net energy ratios of 10-16:1, harvested every 3-4 years using a cut-and-chip system. It requires minimal inputs such as fertilizer, irrigation, and pest control, and regrows from stumps, reducing replanting costs. It offsets about 1 ton CO_2/dry ton when displacing fossil fuels and provides co-benefits like soil carbon storage, erosion control, and land rehabilitation. Its resilience and high energy return make it a viable option for biomass strategies, depending on site conditions.

USDA Region Southeast



Yield

County yields (dry tons/ acre) in map below are estimates derived from regional field trials and do not account for competition with other crops.



GA and SC field trials yielded 5.6-6.0 tons/acre, above the typical 2-4 range. MS may reach 7 tons/acre under ideal conditions, while native black willow yields 3-5 tons/acre in moist lowlands. Data gaps remain for other southern states.

Equipment and Harvest

Harvesting can be adapted using forestry or silage equipment (e.g., feller-bunchers, chippers, or possibly sugarcane harvesters), but efficiency is lower than in purpose-designed systems. Planting requires importing cuttings and using modified or custom equipment for insertion into soil. Transport and storage of chips are feasible due to the region's existing wood product infrastructure.

Fertilizer

Between 50-100 lb N/acre applied after each harvest, with moderate P/K based on soil tests. Organic fertilizers (e.g., poultry litter or wastewater sludge) are suitable substitutes. Lowland sites or nutrient-rich runoff areas may require little or no fertilizer.

Pest and Weed Control

High insect and disease pressure across all states due to warm, humid conditions. Pests like cottonwood leaf beetles, sawflies, and fungal diseases (e.g., rust, scab) are prevalent. Weed management is critical in early years, especially to control invasive vines (e.g., kudzu, morning glory). Success depends on resistant clones, diverse plantings, and integrated pest management (IPM).

Market Opportunities

Markets could tie to pellet exports, poultry litter blending, and erosion control. Black willow's adaptation to heat and wetlands may support local feedstock systems. Currently, abundant pine resources and existing forestry infrastructure outcompete willow in cost and availability.

Costs

Establishment costs of $500-1,000/acre mainly due to cost of cuttings and specialized planting. Annual maintenance of $50-100/acre, and harvest costs around $40/ton.

Authors: Daniela Jones, North Carolina State University; Tasmin Hossain, Idaho National Laboratory; Haley Casper, North Carolina State University. **Acknowledgement**: Supported by the U.S. Department of Energy (DOE), Office of Energy Efficiency and Renewable Energy (EERE), Bioenergy Technologies Office (BETO), the Feedstock-Conversion Interface Consortium (FCIC), under DOE Idaho Operations Office with Contract No. DE-AC07-05ID14517.

QUICK START GUIDE

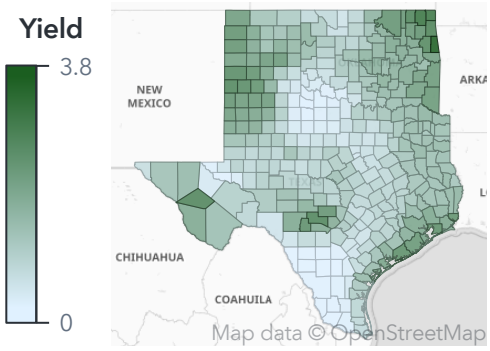
Willow in Southern Plains

Willow is a low-input bioenergy crop with net energy ratios of 10-16:1, harvested every 3-4 years using a cut-and-chip system. It requires minimal inputs such as fertilizer, irrigation, and pest control, and regrows from stumps, reducing replanting costs. It offsets about 1 ton CO_2/dry ton when displacing fossil fuels and provides co-benefits like soil carbon storage, erosion control, and land rehabilitation. Its resilience and high energy return make it a viable option for biomass strategies, depending on site conditions.

USDA Region Southern Plains

Yield

County yields (dry tons/ acre) in map below are estimates derived from regional field trials and do not account for competition with other crops.



TX and OK trials yielded 3-7 tons/acre in humid or irrigated areas, with lower yields elsewhere. Moisture, clone choice, and site conditions are key, while heat and drought limit productivity.

Equipment and Harvest

Potential options include adapted forestry equipment (feller-bunchers, portable chippers) and custom harvesters imported from willow-growing regions. Local tree service or logging crews could contract for harvests. Harvest cycle likely every 2-3 years, possibly adjusted for growing conditions or machinery limits. Winter harvests preferred to reduce foliage, though wet soil may require low ground pressure equipment.

Fertilizer

About 50 lb N/acre after harvest maintains growth on moist or irrigated sites. P/K added only when soil tests indicate deficiency. Willow could self-fertilize on runoff-rich sites (e.g., effluent fields, pastures). Organic amendments (e.g., poultry litter in OK or municipal wastewater in TX) or effluent irrigation can reduce synthetic N needs. Excessive fertilization can spur lush, weak growth or exacerbate pest issues.

Pest and Weed Control

Warm climates cause high pest pressure. Key threats include beetles, borers, sawflies, deer, and rabbits, with multiple generations yearly. IPM, resistant clones, and targeted spraying help control. Weed pressure is high; pre-emergent herbicides, mulching, or cover crops aid suppression.

Market Opportunities

Limited market but possible in riparian buffers, biochar production, soil improvement, on-farm heating, or small-scale Combined Heat and Power (CHP). Native willow species may offer opportunities for conservation and water management programs.

Costs

Establishment costs of $400-500/acre (planting stock and labor), harvest and transport costs of $40-60/ton. Viability is strongest on marginal or wet lands, with subsidies or dual-use benefits (e.g., water treatment, carbon credits) often required to offset high costs.

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