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ADVANCED REVIEW

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Positive water linkages of producing short rotation poplars and willows for bioenergy and phytotechnologies

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The production of short rotation woody crops (SRWCs) such as poplars and willows is a promising component of global bioenergy and phytotechnology portfolios. In addition to the provision of biomass feedstocks and pollution remediation, these trees and shrubs have been sustainably grown to conserve or utilize water in a variety of applications. Growing these woody plants for multiple uses supports many of the United Nation's Sustainable Development Goals (SDGs), especially *Clean Water and Sanitation* (SDG6) and *Affordable and Clean Energy* (SDG7). As a result, focusing on ecosystem services such as freshwater and biomass has become an important aspect of deploying these production systems across variable landscapes. The current review consists of an introduction of ecosystem services and the SDGs, as well as SRWCs and their applications. The middle section of the review contains case studies highlighting the positive water linkages of producing short rotation poplars and willows for bioenergy and phytotechnologies. The review concludes with a section that combines the common themes that are consistent among the case studies to address options for integrating new bioenergy feedstock production systems into rural and urban landscapes to promote environmental, social and economic sustainability.

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1 | INTRODUCTION

1.1 | Ecosystem services and Sustainable Development Goals

Society benefits in a multitude of ways from ecosystem services delivered by both natural and managed ecosystems. Some ecosystem services, such as the provision of food commodity crops and wood, are universally recognized as essential. Other essential ecosystem services, however, such as provisioning of clean water, decomposition of wastes, and pollination by insects, may be taken for granted. The lack of consistent and reliable information about many ecosystem services makes it difficult to determine if they are diminishing, and to identify contributing factors behind such trends (Martínez-Harms & Balvanera, 2012). Yet, studies have shown that many ecosystem services (e.g., provision of healthy soils and fresh water) are diminishing due to degradation and/or depletion of resources (Dodds, Perkin, & Gerken, 2013).

Biodiversity loss is an additional concern since many ecosystem services rely on the variety of life at genetic, species, and ecosystem levels, and the interaction among organisms at different levels (Cardinale et al., 2012). At the same time the growing need for energy worldwide and concerns about climate change is creating demand to expand modern biomass systems. Biomass is currently the largest source of renewable energy in the world and is projected to continue to be the largest source by 2030 (Nakada, Saygin, & Gielen, 2014). Human induced land use change (LUC) has been identified as a major cause behind biodiversity losses and diminishing ecosystem services. As a result, land management systems are being developed that provide biomass, support biodiversity, and ensure conditions for a multitude of ecosystem services. This requires multidisciplinary methods to assess impacts of land use on the conditions for ecosystem services and biodiversity, and also methods to communicate results and insights from such assessments to stakeholders involved in land use decisions (Gasparatos et al., 2018).

A central idea in the United Nations Sustainable Development Goals (SDGs) is to achieve well-being for all while protecting the environment—including, the health, diversity, and productive capacity of terrestrial and aquatic ecosystems. While there is a specific SDG focused on energy (SDG7—*Affordable and Clean Energy*), governments have declared the SDGs and their associated targets to be “integrated and indivisible” (United Nations, 2015). However, linkages among SDGs are not always well understood and science can help identify the character of these linkages, and their respective strengths. As for many other SDG challenges, the way energy is dealt with has strong implications for environment and ecosystem protection (Fritsche et al., 2017). Bioenergy is a case in point; the increasing use of biomass for energy has triggered scientific, societal, and political discussions concerning potential impacts of bioenergy on sustainable development. The link between bioenergy expansion and LUC is one of the key issues debated, and researchers have attempted to quantify positive and negative effects of bioenergy-induced LUC, although much of the conversation has been on the potential negative impacts on environment and ecosystems (Chum et al., 2015).

Policy makers are faced with striking the proper balance between energy security, equitable social and economic development, and environmental quality goals. This is a challenge fraught with uncertainties and the risks embedded in these uncertainties can be large. Governance of bioenergy has increasingly focused attention on risks (as opposed to mitigation opportunities) and feedstocks such as harvest residues and organic waste are considered preferable to energy crops because they do not require expanded land use (Miyake, Renouf, Peterson, McAlpine, & Smith, 2012). Considering well-documented LUC impacts of forest conversion and cropland expansion into uncultivated areas, such as habitat loss, greenhouse gas (GHG) emissions, and degradation of soils and water bodies, this emphasis is understandable (Lark, Salmon, & Giggs, 2015; Mladenoff, Sahajpal, Johnson, & Rothstein, 2016).

However, governance that focuses on minimizing LUC often ignores the need for addressing current land uses that cause negative impacts, and may neglect the potential for bioenergy policies to enhance ecosystem services (Baumber, 2017). A constructive approach can be to identify and promote synergies between the objective to *Ensure availability and sustainable management of water and sanitation for all* (SDG6—*Clean Water and Sanitation*) and other objectives, not the least to *Ensure access to affordable, reliable, sustainable, and modern energy for all* (SDG7—*Affordable and Clean Energy*).

This paper contributes to the accumulating body of literature that investigates options for achieving beneficial LUC with new biomass production systems that are integrated into agricultural and forestry landscapes, mitigating some of the impacts associated with current land use, and improving the way we manage land, water, and other essential resources (Ferrarini, Serra, Almagro, Trevisan, & Amaducci, 2017; Manning, Taylor, & Hanley, 2015; Souza et al., 2017). The cultivation of perennial plants can help address land use impacts such as soil erosion, compaction, salinization, sedimentation, and eutrophication of surface waters due to excess fertilization. This paper focuses on short rotation woody crops (SRWCs), but many other woody species—and also perennial grasses—can offer similar opportunities (Johnson et al., 2007).

1.2 | Short rotation woody crops

Short rotation woody crop biomass production systems are based on fast-growing species such as poplars (*Populus* L.), willows (*Salix* L.), eucalypts (*Eucalyptus* L'Hér), pines (*Pinus* L.), and other species that are mainly dedicated to the provision of biomass feedstocks for energy, pulp, and solid wood products (Vance, Maguire, & Zalesny, 2010), as well as ecosystem services associated with environmental remediation and restoration (Zalesny et al., 2016; Zalesny et al., 2016). Superior genotypes from these genera are ideal for such applications given their capability for intra- and inter-species hybridization and resulting broad genetic variability of breeding populations, which allows for selection of clones exhibiting extensive root systems, hydraulic control potential, and other application-specific traits. (Zalesny et al., 2011). General characteristics of SRWC systems include the use of clonal material (that can be selected and repeatedly propagated vegetatively from stoolbeds), short rotations (e.g., less than 20 years) and the fact that the trees are often established on marginal agricultural land and polluted sites such as landfills, brownfields, and military installations.

Compared to conventional forestry, SRWC silviculture is much more intensive, including key prescriptions such as high initial planting densities, frequent fertilization, and regular harvesting cycles (e.g., 3–5 years for bioenergy; 10–12 years for pulp; up to 20 years for sawn wood) (Stanturf, van Oosten, Netzer, Coleman, & Portwood, 2001). On the other hand, SRWC management is substantially less intensive than with traditional agricultural practices, especially conventional annual crops such as corn (*Zea mays* L.) and soybeans [*Glycine max* (L.) Merr.]. The purpose-grown trees require less fertilization and fewer harvests and subsequent planting operations (Johnson et al., 2007). Short rotation woody crops offer additional advantages over annual crops. For example, the trees can be left growing in the field (i.e., stored on the stump) until harvest and harvested throughout the year. Also, the energy returned on energy invested (EROEI) is typically 5 to 6 times greater with SRWCs than crops such as corn and soybeans (Volk, Verwijst, Tharakan, & Abrahamson, 2004). Despite different designations of these systems based on where they are grown [e.g., fast-growing plantations (Germany, USA), short rotation coppice (Germany, UK, USA), short rotation forestry (Finland), very short rotation forestry (Italy), energy forestry (Sweden), biomass production systems (USA)], they all share common goals of growing trees as fast as possible to provide targeted ecosystem services (e.g., biomass, carbon sequestration) in specialized applications.

Based on SDG6 and SDG7 described above, the objective of the current review is to provide examples of positive water linkages (e.g., selecting genotypes with high biomass production in both water-limited and water-rich sites) of producing short rotation poplars and willows for bioenergy and phytotechnologies in order to provide information about integrating new bioenergy feedstock production systems into rural and urban landscapes to promote environmental, social, and economic sustainability. In particular, case studies are described below to highlight such linkages in the north central, midwestern, southeastern, and northeastern United States, as well as northern Europe (Figure 1). The included case studies were selected from among current or recent projects undertaken by the authors, for which previously unpublished data was available or easily obtainable.

2 | POPLAR APPLICATIONS

2.1 | Biomass production in the North Central United States

Successful deployment of poplars for bioenergy and phytotechnologies requires that genotypes be properly matched to site conditions (Zalesny et al., 2009). Water use efficiency (WUE), the ratio of water used in tree metabolism to water lost through transpiration, is a key trait when assessing such genotype × environment interactions. For example, poplars with high WUE have been observed to be less susceptible to water stress than genotypes with low WUE (Yin, Wang, Duan, Luo, & Li, 2005). Thus, poplars with high WUE can be identified and selected for the purpose of ensuring high biomass productivity on water-limited sites (Monclus et al., 2005). Chemical analysis of stable isotope ratios in growth rings has proven useful in evaluating WUE in trees (Schulze et al., 2004), and such methods can be used for genotype selection. Specifically, genotypes with higher WUE exhibit greater stomatal closure, which in turn affects carbon isotope ratios as heavier isotopes are absorbed at a higher rate when the stomata are closed (Leffler & Evans, 1999). Thus, differences in WUE can be identified by differences in carbon

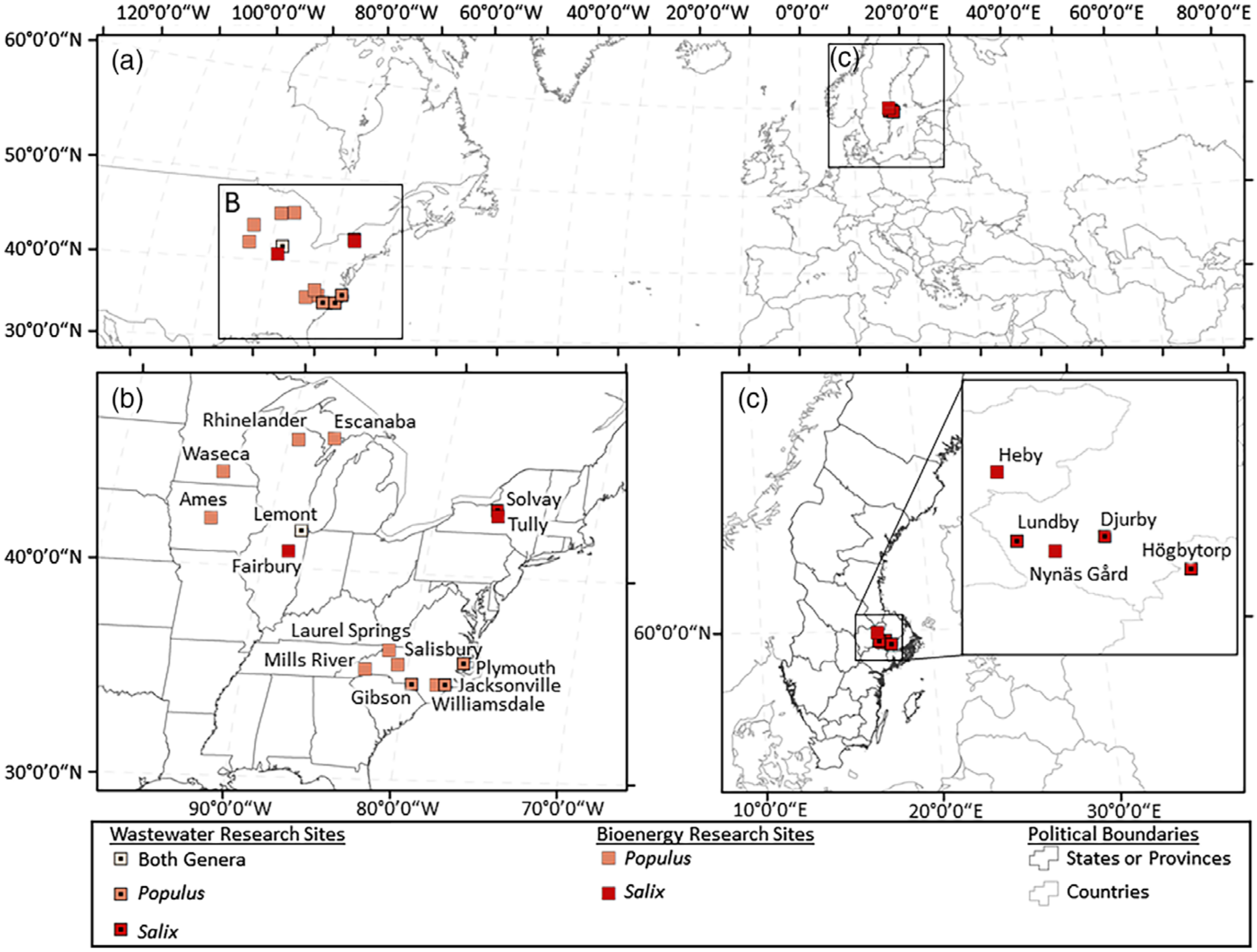

FIGURE 1 Research site locations in the United States and Sweden that were reviewed for positive water linkages of producing short rotation poplars and willows for bioenergy and phytotechnologies. Panel A provides a relative location of sites in the northern hemisphere. Panel B zooms into the north central, midwestern, southeastern, and northeastern United States. Panel C zooms into Sweden

isotope ratios in the trees, as previous research has demonstrated for various species including poplars and their hybrids (Dillen, Marron, Koch, & Ceulemans, 2008; Monclus et al., 2006; Ripullone, Lauteri, Grassi, Amato, & Borghetti, 2004).

While the studies described above have examined WUE efficiency for hybrid poplars in Europe (Dillen et al., 2008; Monclus et al., 2005, 2006) and native poplars in the United States (Leffler & Evans, 1999) and Asia (Yin et al., 2005), similar information on hybrid poplars in the United States is lacking. Therefore, in order to address this gap in current knowledge and identify differences in WUE among these regional genotypes, carbon isotope ratios were evaluated within the growth rings of seven hybrid poplar genotypes representing three genomic groups [*Populus deltoides* Bart. Ex Marsh. × *P. deltoides* 'C916000' 'C916400' 'C918001'; *P. nigra* L. × *P. maximowiczii* A. Henry 'NM2'; (*P. trichocarpa* Torr. & Gray × *P. deltoides*) × *P. deltoides* 'NC13563' 'NC13624' 'NC13649'] harvested at 10 years after planting from three contrasting sites in the north-central USA (Figure 1; Escanaba, Michigan; Waseca, Minnesota; Ames, Iowa). Overall, such differences in WUE existed, which corroborated variability observed in connection with the specific gravity of their wood (Headlee et al., 2013).

In particular, a summary of the results showed that the water-conserving strategy of closing stomata appears to have been most pronounced at Escanaba (i.e., 45.77°N), and was least at Ames (i.e., 42.05°N) (Figure 2). Overall, differences among genomic groups showed that *P. deltoides* × *P. deltoides* clones were higher water *users (i.e., low WUE)*, despite that a single clone in this group (i.e., 'C918001') was inclined to conserve water. In contrast, genotypes belonging to the F_1 backcross population [(*P. trichocarpa* × *P. deltoides*) × *P. deltoides*] were higher water *conservers (i.e., high WUE)*, even though a single clone (i.e., 'NC13563') seemed to use more water. Clone 'NM2' was intermediate, conserving more water at Escanaba (Figure 2). Overall, the linkages between water use strategies and these poplars grown for biomass are expected to be useful

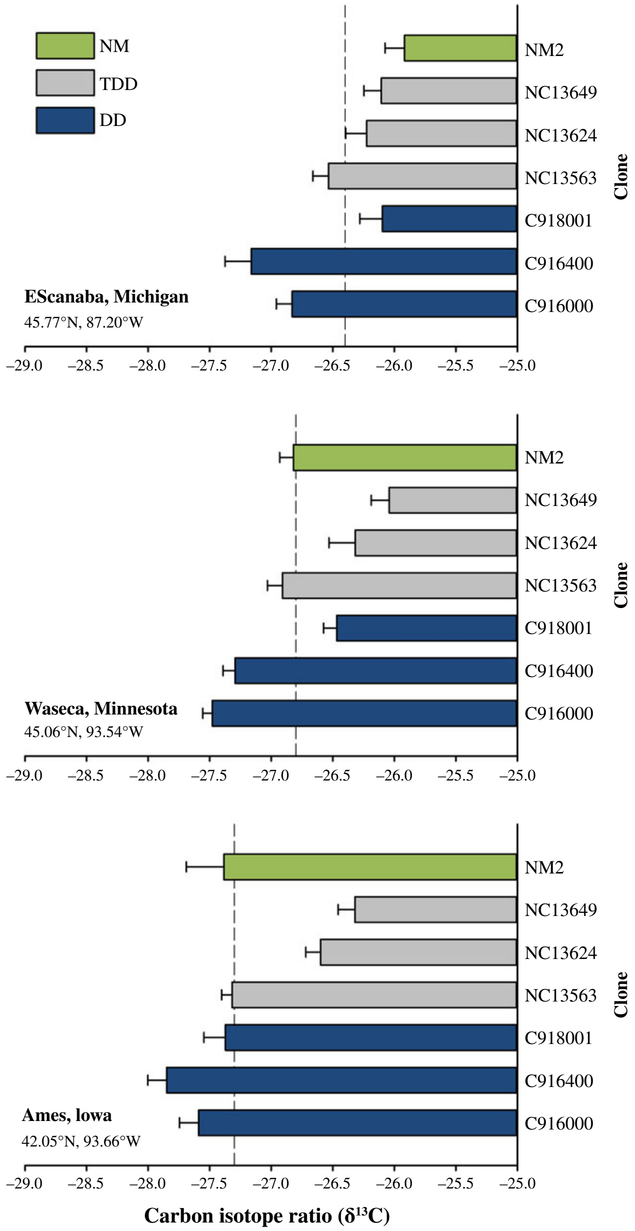

FIGURE 2 Carbon isotope ratios ($\delta^{13}C$) (± STE) averaged across growth rings from 3 to 8 years after planting of seven hybrid poplar clones grown for 10 years at three sites in the north central United States. Mean ratios for each site are indicated with a dashed line. Genomic groups are: NM = *Populus nigra* L. × *P. maximowiczii* A. Henry (green bars); TDD = (*P. trichocarpa* Torr. & Gray × *P. deltoides* Bart. ex Marsh) × *P. deltoides* (gray bars); DD = *P. deltoides* × *P. deltoides* (blue bars)

for selecting appropriate genotypes for water-limited and/or water-rich sites, depending on the specific ecosystem services desired and applications deployed. For example, Zalesny, Wiese, Bauer, and Riemenschneider (2006) reported that 3- and 4-year-old 'NM6' grown for phytoremediation of landfill leachate, where high water use was desirable, in Rhinelander, Wisconsin, USA utilized 67 and 140 L water tree^{-1} day^{-1}, respectively—indicating enhanced biomass production coupled with positive ecosystem services.

2.2 | Organics phytoremediation in the Midwestern United States

At the 317 Area of Argonne National Laboratory near Lemont, Illinois (41.70°N, 87.98°W) (Figure 1), disposal of waste solvents took place in the 1950s and 1960s by dumping the waste laboratory liquids into a gravel-filled trench near deep vaults used for temporary nuclear waste storage. Site groundwater monitoring in later decades demonstrated the spread of a plume of dissolved-phase volatile organic compounds (VOCs) and tritium, with contaminants appearing at low concentrations in seeps 300 m to the southeast in an offsite forest preserve. In the 1990s, remediation of the disposal area was initially performed using deep soil mixing with zero-valent iron addition and thermally enhanced soil vapor extraction. A system of 15 extraction wells was installed to capture groundwater downgradient of the site, where flow occurs in a deep sandy unit separated from the surface by fine-grained glacial till.

To address remaining contamination in the source area and in particular to provide hydraulic containment for the downgradient plume, site managers in 1999 chose a phytoremediation system consisting of phreatophytes. The system included about 400 willow trees comprised of three species (*Salix alba* L. 'Tristis' cv. 'Niobe'; *S. pentaphyllum* cv. 'Prairie Cascade'; *S. pentandra* L. cv. 'Laurel Leaf') in the source area and about 400 hybrid poplar trees belonging to two genomic groups (*Populus charkowiensis* Schröder × *P. incrassata* Dode 'HP308'; *P. trichocarpa* × *P. deltoides* 'HP510') targeting the downgradient plume. Later expansions brought the total number of trees close to 1,000 (Figure 3). Willows were selected to reduce contaminated soil moisture in the partially-remediated source area because of their ability to thrive in the poor soil conditions resulting from the soil mixing. Poplars were chosen to address the deeper downgradient plume because of their deep-rooting ability (Negri, Gatliff, Quinn, & Hinchman, 2003) after being installed using a specialized and patented technique, TreeWells®, with each tree in a 0.6-m diameter borehole drilled approximately 8 m through surficial glacial till to the top of the confined, roughly 1.5-m thick sand and gravel aquifer. Following the manufacturer's specifications, the boreholes of the TreeWells® were lined with plastic (open at the bottom) and backfilled with a mix of topsoil, sand, and peat. The poplars, each about 4 m tall with a small root ball, were installed with the root ball and most of the tree far below grade in order to have the roots closer to the saturated backfill. The plastic liner was folded over at the surface and secured with pea gravel, depriving the plant of rainwater and forcing the roots to seek water solely from the confined aquifer. Numerical groundwater flow modeling to assess the plantation design estimated that the poplars, once mature, would provide hydraulic containment—despite leaf-off winter conditions—based on site flow dynamics and the estimated water usage of the trees (Quinn et al., 2001).

The management effort was complemented by a comprehensive monitoring study. Site characterization included installation of over 100 monitoring wells and dozens of soil borings to characterize the subsurface at a high level of detail. Monitoring activities have included plant growth measurements, sap flow monitoring, tissue analysis, transpirate sampling, groundwater sampling, seep sampling, and probes for hourly groundwater level monitoring at numerous monitoring wells.

Sampling and analysis of leaf tissue even in the year of planting indicated the presence of VOCs, as well as the presence of trichloroacetic acid, a transformation product of the VOC trichloroethylene (TCE). Transpirate sampling through the first 6 years indicated an upward trend in overall increased tritium activity concentration as the trees reached mature size in conjunction with areas of contamination (Figure 4), which provided evidence that the tree root zones were in contact with the contaminated plume. Continuous groundwater level monitoring demonstrated small diurnal fluctuations during the initial years at a monitoring well adjacent to a TreeWell®, indicating the effect of the young trees on groundwater elevation. A sudden and dramatic response to precipitation occurs in many of the monitoring wells. This response is attributed to runoff reaching the deep waste vaults and their footing drainage system, which is in hydraulic connection with the aquifer of interest. This

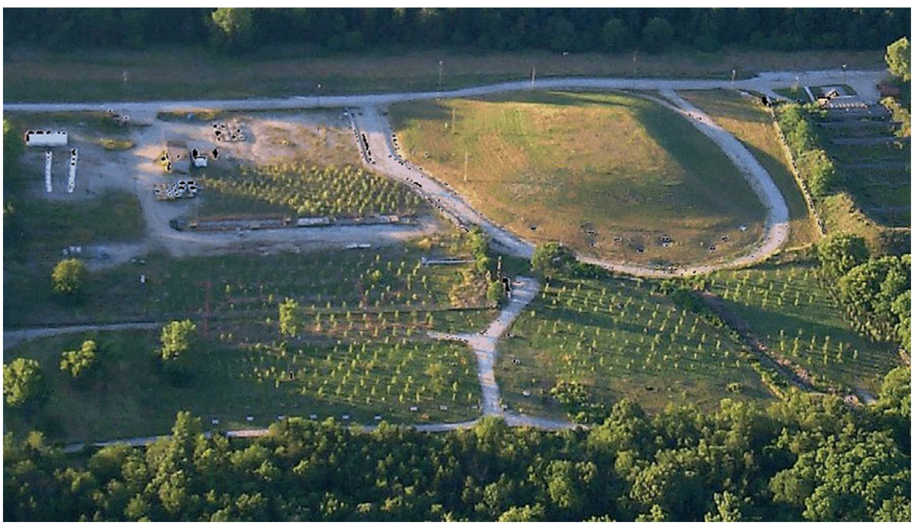

FIGURE 3 View of young trees at the 317 area of Argonne National Laboratory (Lemont, Illinois) in July 2001 (i.e., during their third growing season). Densely-planted willow is in the top left, while poplars growing in TreeWells® are across the middle ground

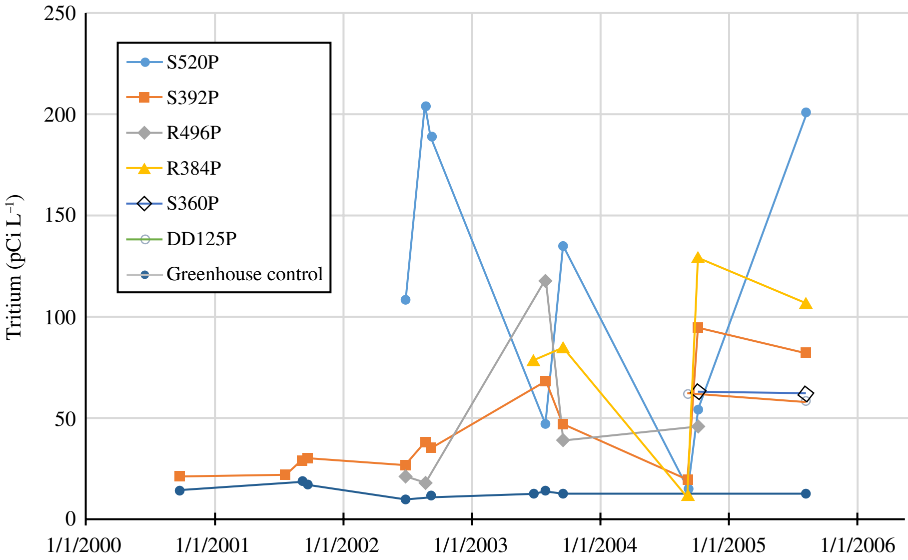

FIGURE 4 Tritium activity concentration (pCi L^{-1}) in transpirate of selected poplar trees grown at the 317 area of Argonne National Laboratory (Lemont, Illinois) (2000 to 2005)

information was not part of the initial conceptual site model (CSM), and the significance is that the groundwater flow system conveys more water than that assumed in the design of the plantation.

This phytoremediation project demonstrated the ability of the technology to target a fairly deep, isolated aquifer that could not be affected by natural vegetation or a surface-planted phytoremedial plantation. The system met criteria for green remediation (ASTM, 2016), including relying on solar energy for power, reducing greatly the burden on the extraction well system (for both pumping and treatment), and providing habitat. In 2013, however, after many years of a mature plantation, the poplars began a rapid die-off, perhaps triggered by a 2012 drought but also tied to the life expectancy of the hybrids. Approximately 20% of the trees have died annually. Although it is possible to install new trees within the existing TreeWell® boreholes and modify the design based on the new CSM, site managers have elected to rely solely on the extraction well system for hydraulic containment.

2.3 | Biomass production in the Southeastern United States

Poplar biomass production from hardwood tree plantations in the southeastern United States has great potential due to multiple species choices, genetic improvements, and exemplary productivity for selected species. However, relatively little data exist on poplar and willow hardwood productivity and associated costs of production (Kline & Coleman, 2010), as well as water implications of growing these SRWCs throughout the region. More data are needed because conventional hardwood silviculture has productivity over a narrow range of site conditions for specific species, which requires decades of growth for economic profit given that establishment costs for these hardwoods can be quite high (He, English, Menard, & Lambert, 2016).

Because of its higher productivity across more diverse site conditions within shorter rotations (<10 years), poplars offer new hardwood production alternatives where traditional wood markets are challenged by forest land conversion, wood product market competition, and climate extremes. In the Piedmont and mountainous regions, poplars offer great potential for new bioenergy and veneer markets while improving soil and water regulation services via their rapid establishment and coppice regeneration on topographically step landscapes. Silvopastoral opportunities are rich in these regions and would directly improve water quality and quantity by mitigating soil erosion/runoff, improving soil quality for infiltration, and mitigating sedimentation/eutrophication of surface waters and reservoirs.

Much of the research on poplars in the southeastern United States has been in the alluvial floodplains of the Mississippi River (Robison, Rousseau, & Zhang, 2006) and South Carolina (Coyle, Coleman, Durant, & Newman, 2006). More recent research has evaluated feedstock production on marginal agricultural lands and potentially-polluted lands such as municipal wastewater land application sites, in the coastal plain, Piedmont, and mountainous regions of North Carolina (Ghezehei, Nichols, & Hazel, 2016). Poplar trials were established to study genotype × environment interactions for biomass productivity across these three different physiographic regions within the state (Figure 1; Table 1). At all sites, poplar clones of *P. deltoides*, *P. trichocarpa*, *P. maximowiczii*, and *P. nigra* were planted in factorial or general randomized-block designs (Table 2). Soils were sub-soiled except at Williamsdale where randomized block trials included both sub-soiling and disking as treatments. Weed control included banding herbicides along tree rows and mowing between tree rows. Sites are annually evaluated for

TABLE 1 Details of location, physiography, soil type, and annual precipitation of research sites in North Carolina where poplar trials were established to study genotype × environment interactions for biomass productivity across the different physiographic regions in the southeastern United States

Site/altitude (m.a.s.l.)	County, (NC)	Latitude; longitude	Physiography	Precipitation annual (mm)	Soil texture	Planted
Salisbury 215	Rowan	35.6974; −80.6219	Piedmont	1,118	Loam	2014
Mills River 630	Henderson	35.4272; −82.5589	Southern Blue Ridge Mountains	1,261	Loam Sandy clay loam	2014
Laurel Springs 975	Ashe	36.3739; −81.2921	Northern Blue Ridge Mountains	1,244	Sandy clay loam	2014
Williamsdale 26	Duplin	34.7845; −78.1024	Coastal	1,400	Loam	2013

TABLE 2 Details of experimental designs, density, clones, and genotypes of the poplar trials established in North Carolina to study genotype × environment interactions for biomass productivity across the Blue Ridge Mountains, Piedmont, and coastal physiographic regions of the southeastern United States

Site (age)	Design	Treatments	Density (trees ha^{-1})	Parentage (genotype)
Salisbury (4 years)	Factorial	Clones (10), Spacing (2)	5,000; 2,500	**DD** (140, 176, 177, 210, 312, 356) **TD** (185, 187, 188, 229, 302, 342)
Mills River (4 years)	GRBD	Clones (16)	2,500	**DD** (140, 174, 177, 210, 373, 379, 426, 455) **TD** (185, 187, 188, 229, 302, 339, 342, 49–177)
		Clones (10)	5,000	**DD** (140, 174, 177, 373, 379, 426) **TD** (185, 188, 302, 339)
Laurel Springs (4 years)	GRBD	Clones (17)	10,000	**DD** (176, 210, 312, 356, 373, 379, 419, 426, 443) **DM** (230) **DN** (DN-34, OP-367) **TD** (185, 187, 188, 229, 339, 342)
		Clones (32)	2,500	**DD** (140, 174, 176, 177, 198, 200, 210, 224, 312, 356, 373, 379, 400, 419, 422, 426, 434, 443, 455) **DM** (230) **DN** (DN-34) **TD** (129, 185, 187, 188, 229, 302, 339, 340, 341, 342, 5,077)
Williamsdale (5 years)	Factorial	Clone (10); Soil tillage	1,495	**DD** (140, 176, 356, 373) **TD** (185, 187, 188, 229, 339) **DM** (230)

Note. Genomic groups are: DD = *Populus deltoides* Bart. ex Marsh × *P. deltoides*; TD = *P. trichocarpa* Torr. & Gray × *P. deltoides*; DM = *P. deltoides* × *P. maximowiczii* A. Henry; DN = *P. deltoides* × *P. nigra* L. GRBD = generalized randomized block design.

productivity using standard methods to measure height, outside-bark stem diameter, and wet aboveground biomass (t ha^{-1}), which is calculated using an equation developed by destructive sampling from three physiographic regions (Piedmont, Northern Blue Ridge and Southern Blue Ridge Mountains) in the southeastern United States.

Genotype was not significant for wood biomass, regardless of planting-density, at the Piedmont site (Salisbury). On the other hand, the effect of genotype on wood biomass was significant for clones planted at the coastal site (Williamsdale, 26 m. a.s.l.) and the mountain sites of Laurel Springs (975 m.a.s.l.) and Mills River (630 m.a.s.l.). On the coastal plain, three *P. deltoides* × *P. deltoides* clones (i.e., '356', '140', and '176') produced significantly greater biomass than the *P. trichocarpa* × *P. deltoides* and *P. deltoides* × *P. maximowiczii* clones at the site (Table 3). In contrast, at the mountain sites, *P. trichocarpa* × *P. deltoides* clones (i.e., '185' and '339') outperformed *P. deltoides* × *P. deltoides* genotypes for green wood biomass, although the *P. deltoides* × *P. maximowiczii* clone '230' was the greatest wood biomass producer at Laurel Springs, regardless of planting density.

Poplar productivity across mountainous, piedmont, and coastal areas of North Carolina can provide alternative forest management strategies for landowners and improve ecosystem services. As discussed above, the shorter rotations of poplars can generate sufficient stem growth to provide feedstocks for energy, mitigate wastewater management, improve carbon storage, and deliver wood product material such as veneer on marginal lands in rural areas with limited economic alternatives to declining wood product markets and non-managed hardwood forest productivity. The potential to couple poplar productivity to agroforestry is unexplored in the region, but is another potential opportunity to integrate poplar with the important nexus of food, water, fiber, and energy.

TABLE 3 Aboveground green woody biomass (t ha^{-1}) and survival (%) of the genotypes at the poplar trials established in North Carolina to study genotype × environment interactions for biomass productivity across the physiographic regions of the southeastern United States

Sites, physiography (age)	Treatments (density, trees ha^{-1})	Mean green woody biomass (t ha^{-1})	Survival (%)	Mean green woody biomass: Parentage	Mean green woody biomass: (t ha^{-1})
Williamsdale Coastal (5 years)	Disking 1,550	109 ± 65.4	79%	DD	158 **a**
				DM	113 **ab**
				TD	71 **b**
	Sub-soiling 1,550	130 ± 75.7	86%	DD	195 **a**
				DM	118 **b**
				TD	80 **b**
Salisbury Piedmont (4 years)	5,000	162 ± 73.4	82%	DD	180 **a**
				TD	152 **a**
	2,500	102 ± 61.7	83%	DD	104 **a**
				TD	97 **a**
Mills River Southern Blue-ridge mountains (4 years)	5,000	83.8 ± 60.8	93%	DD	40 **b**
				TD	150 **a**
	2,500	7.7 ± 5.9	89%	DD	5 **b**
				TD	10 **a**
Laurel Springs Northern Blue-ridge mountains (4 years)	10,000	165 ± 135	91%	DD	82 **c**
				DM	454 **a**
				DN	77 **c**
				TD	27 **b**
	2,500	74 ± 59	87%	DD	65 **ab**
				DM	155 **a**
				DN	42 **b**
				TD	85 **ab**

Note. Genomic groups are: DD = *Populus deltoides* Bart. ex Marsh × *P. deltoides*; TD = *P. trichocarpa* Torr. & Gray × *P. deltoides*; DM = *P. deltoides* × *P. maximowiczii* A. Henry; DN = *P. deltoides* × *P. nigra* L. Means with the same letter within site-treatment (density) rows were not significantly different ($p < 0.05$).

2.4 | Productivity and water reuse: Regulating nutrients and provisioning water in the Southeastern United States

Hybrid poplars, as monoculture or polyculture plantings, show great potential to produce biomass while providing positive ecosystem services for the regulation and provisioning of water from diverse sources. Poplar species and hybrids offer not only good productivity but an opportunity to match genotype to specific site conditions given the enormous number of genotypes available (Zalesny et al., 2009). The genetic flexibility of poplar varieties and clones is a great asset for climate extremes, such as water excess and water shortages, particularly in relation to hybrid poplar systems that provision fiber while providing positive water ecosystem services for storm water, aquaculture and livestock management, and wastewater management for industrial, landfill, and municipal wastewaters systems.

Hybrid poplar and cottonwood trials were established as cover crops for wastewater management in three land application facilities in eastern North Carolina; these sites are known as Gibson 2012, Gibson 2013, Jacksonville, and Plymouth (Figure 1; Table 4). The aim of these trials was to evaluate if wastewater management facilities could meet the dual objective of producing biomass while meeting regulatory guidelines for nutrient concentrations in groundwater (Shifflett, Culbreth, Hazel, Daniels, & Nichols, 2016; Shifflett, Hazel, Frederick, & Nichols, 2014). At all sites, genotypes of *P. deltoides*, *P. trichocarpa*, *P. maximowiczii*, and *P. nigra* parentage were planted in generalized randomized-block designs (Table 5). The studies evaluated wood biomass productivity of poplar clones under irrigation (Gibson, Jacksonville and Plymouth), including effects of drainage (drained versus non-drained at Plymouth) and soil bedding during stand establishment on poorly-drained soils (bedding versus no-bedding at Jacksonville). Sites were evaluated annually for aboveground green wood biomass productivity using standard methods to measure height, outside-bark stem diameter, and estimated tree productivity (dm^3 ha^{-1} yr^{-1}). Genotype was not a significant effect for biomass among clones and cottonwoods evaluated in the Gibson 2012 trial ($p = 0.32$), but genotype had a significant effect on wood biomass in the Gibson 2013 trial ($p < 0.0001$) (Figure 5).

TABLE 4 Site description of the wastewater-irrigated poplar trials established in the coastal region and sand hills of North Carolina to evaluate wastewater management and use for producing woody biomass while meeting regulatory guidelines for groundwater nutrient concentrations in the southeastern United States

Site, altitude (m.a.s.l.)	County (NC)	Latitude, longitude	Physiography	Precipitation (mm)	WW type loading (mm)	Soil texture	Year planted
Gibson, 76	Scotland	34.7676, −79.5969	Sand hills	1,300	Municipal 1,102	Loamy sands	2012, 2013
Jacksonville, 4.6	Onslow	34.7967, −77.5821	Coastal	1,300	Municipal 1,300	Sandy loam, fine sand	2014
Plymouth, 4.9	Washington	35.8555, −76.6508	Coastal	1,200	Aquaculture 550	Loam	2014

Note. m.a.s.l.: meters above sea level; WW: wastewater.

TABLE 5 Details of the experimental designs and soil preparation, density, clones, and genotypes of the wastewater-irrigated poplar trials established in the coastal region and sand hills of North Carolina to evaluate wastewater use and management for producing woody biomass while meeting regulatory guidelines for groundwater nutrient concentrations in the southeastern United States

Site (age)	Design	Soil preparation	Treatments	Density (trees ha^{-1})	Parentage (genotypes)
Gibson (4, 5 years)	GRBD	Disking	Genotypes (40)	3,590	**DD** (140, 147, 148, 176, 198, 200, 221, 224, 345, 380, 381, 406, 409, 410, 411, 412, 413, 414, 423, 427, 429, 432, 434, 444, 448, 449, 450, 451) **DM** (230) **TD** (185, 187, 188, 229, 302, 303, 304, 339, 341, 342) **Unknown** (138)
			Genotypes (10)	1,500	**DD** (140, 176, 356, 373) **DM** (230) **TD** (185, 187, 188, 229, 339)
Jacksonville (4 years)	GRBD	Bedding	Genotypes (3) Bedding (2)	2,500	**DN** (OP-367, DN-34) **TD** (49–177)
Plymouth (4 years)	GRBD	Subsoiling Disking	Genotypes (12) Drainage (2)	5,000	**DD** (140, 312, 356, 373) **DN** (DN-34, OP-367) **TD** (187, 188, 302, 339, 342, 49–177)

Note. Genomic groups are: DD = *Populus deltoides* Bart. ex Marsh × *P. deltoides*; TD = *P. trichocarpa* Torr. & Gray × *P. deltoides*; DM = *P. deltoides* × *P. maximowiczii* A. Henry; DN = *P. deltoides* × *P. nigra* L. GRBD = generalized randomized block design.

Mean depth (±1 *SD*) to water table was 1.9 ± 0.24 m for Gibson 2012 and >2.5 m for Gibson 2013; hence, depth to groundwater may influence genotype survival and success. Genotype also significantly affected biomass of trees grown in Plymouth. For some genotypes (*P. trichocarpa* × *P. deltoides* '187', '188', '302'; *P. deltoides* × *P. deltoides* '140'), drained soils (i.e., tile drainage) significantly increased growth ($p < 0.0001$; Figure 5). Drainage was also significant for wood biomass of four poplar clones planted in bedded and non-bedded treatments in Jacksonville (Figure 5). Collectively, the productivity of managed *Populus* stands can be augmented or reduced by managing surface drainage.

For genotypes across sites, comparing growth and mortality demonstrated critical relationships between water resource availability and the provisioning of woody biomass. Land applying wastewater at all three sites substantially increased hydraulic loading from 1,750 to 2,400 mm ha^{-1}, thus improving water resource availability for growth and transpiration. Despite increased water availability, trees grown in areas prone to lower water tables did not survive or grow as well as those in areas with shallow water tables (Figure 5). The provisioning of woody biomass in these managed tree plantations appears dependent on regulating services related to local hydrology. This relationship seems to be more critical for genotypes with *P. deltoides* parentage rather than genetic hybrids. This finding also demonstrates a critical relationship between poplar genotypes and water resources. Growing poplar genotypes that can survive and grow given a range of water resource availability is important to achieving positive linkages between water and SRWCs, as was also noted for poplar WUE in the north central United States.

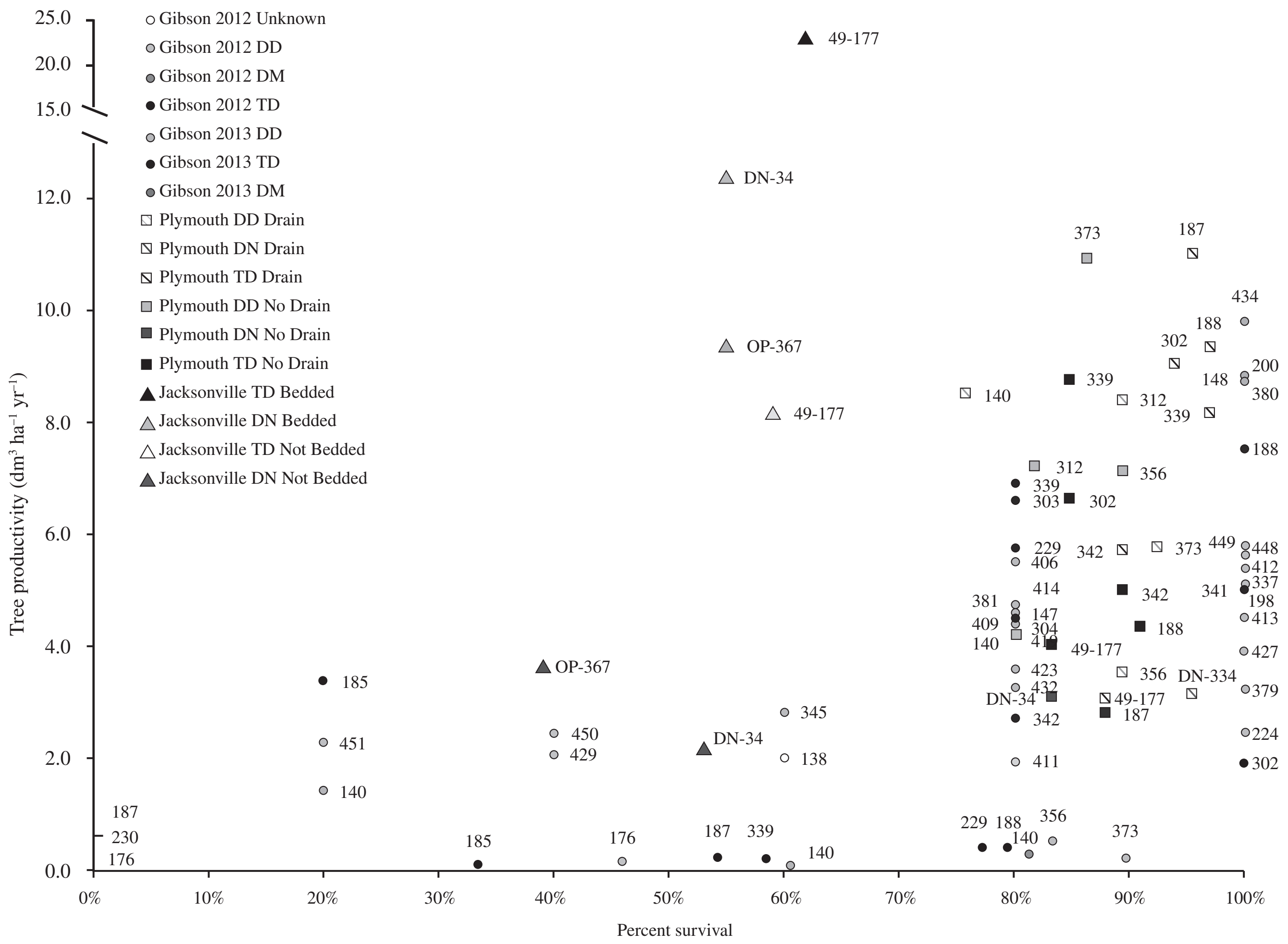

FIGURE 5 Scatter plot of poplar survival (%) and tree productivity ($dm^3\ ha^{-1}\ yr^{-1}$) by site, genomic group, and silvicultural treatments for land application sites in the southeastern United States. Genomic groups are: DD = *Populus deltoides* Bart. ex Marsh × *P. deltoides*; TD = *P. trichocarpa* Torr. & Gray × *P. deltoides*; DM = *P. deltoides* × *P. maximowiczii* A. Henry; DN = *P. deltoides* × *P. nigra* L

Water purification was an additional ecosystem service provided by these systems. In the United States, forested land application systems are designed, permitted, and managed to avoid direct surface water discharge and to meet established nutrient regulations for surface water and groundwater based on the nutrient composition of the applied water, the area available for land-application, soil quality, infiltration rates, and forest composition. At these sites, nutrient concentrations in groundwater remained below regulatory guidelines while provisioning woody biomass, sequestering carbon, and improving groundwater infiltration. The combination of these services is important to provisioning wood product, fiber, and bioenergy feedstocks as well as wildlife habitat and carbon sequestration (Nichols, 2016).

3 | WILLOW APPLICATIONS

3.1 | Bioenergy and ecosystem services in the Midwestern United States

The agricultural Midwest is responsible for excessive nutrient concentrations in local surface water and groundwater. This results in a significant cost to municipal water treatment facilities for nitrate removal, toxic algal blooms in surface water, and, ultimately, the hypoxic zone in the Gulf of Mexico (USEPA, 2008). Because of these concerns, the hypoxia task force has set a target of a 45% reduction in the nutrients reaching the Gulf of Mexico (USEPA, 2008). Among the many different changes in agricultural practices that have been proposed is the planting of perennial crops according to landscape positions where the likelihood of increased nutrient leaching is predicted (IDOA and IEPA, 2015).

Throughout the region, soil productivity varies. Economically-marginal farmland requires more fertilizer than nearby productive soil areas, which may result in greater cost to farmers while increasing nutrient losses, due in part to corn's relatively low efficiency in nutrient uptake. The economically marginal land therefore becomes environmentally marginal because of the likely impact to water resources. Conceivably, the replacement of commodity crops with better-adapted, non-fertilized bioenergy crops in marginal soil areas could eliminate the need for fertility inputs and provide ecosystem services such as improved water quality, along with a cash crop for producers (Lazarus, Headlee, & Zalesny, 2015; Zalesny, Donner, Coyle, & Headlee, 2012). Furthermore, planting of bioenergy crops in riparian buffers would allow interception of nutrients in groundwater, prior to their discharge to the surface water. In both cases, low-input SRWCs (i.e., non-fertilized, non-irrigated) or energy grasses (e.g., switchgrass, *Panicum virgatum* L.) would rely on their natural abilities to grow deep, dense root systems to uptake nutrients and survive dry periods. This integrated landscape management approach represents a scaling up of phytoremediation applications to address large-scale, non-point pollution with potential economic benefits for rural communities. Additionally, a landscape design approach will reduce the impact of both direct and indirect land use change due to the conversion from commodity to bioenergy crops, by targeting only a field's economically and environmentally marginal locations, where commodity crops are less productive.

The potential for shrub willow (*Salix miyabeana* Seemen 'SX61') to improve water quality and provide other ecosystem services is being evaluated at a site in Fairbury, Illinois (40.74°N, 88.50°W) (Figure 1). Site assessment and monitoring began in 2011 on a 6.5-ha field under corn-soy rotation, with early years under a continuous corn rotation. Shrub willow was planted in 2013 with a traditional double row planting (with a row spacing of 1.5 m between double rows, 0.75 m between rows, and 0.6-m spacing between plants on a row, resulting in a planting density of 15,300 trees ha^{-1}) in several test plots as buffers under two different soil conditions. The first location was on marginal soil where nutrient leaching was found to be the highest and corn productivity the lowest (i.e., southern experimental plots), and the second location was on fertile soil with lower nutrient leaching potential as a riparian buffer (i.e., northern control plots). The total area dedicated to willow production was 0.8 ha. The landscape design (i.e., the position of the willow plots within the field, particularly those grown on the marginal soil) targeted the leached nutrients from the upslope grain crop to serve as the nutrient source for the willow, and therefore the willow were not fertilized, unlike the corn (nitrogen, phosphorus, and potassium) and soybean (phosphorus and potassium).

Data collection at the Fairbury site covers multiple parameters including soil water, groundwater, groundwater level, biomass estimates, nutrient content of plant tissues, soil and subsoil organic carbon and nutrients, sapflow, seasonal crop productivity, greenhouse gas emissions, soil microbe diversity, and insect diversity (Ssegane, Negri, Quinn, & Urgun-Demirtas, 2015; Zumpf, Ssegane, Negri, Campbell, & Cacho, 2017). Current results show significant decreases in both nitrate leached to soil water (Figure 6) and in GHG emissions, particularly nitrous oxide, in the unfertilized willow plots. Subsurface carbon in willow plots is also on an increasing trend, particularly on the marginal soil. From a water use perspective, although data are more limited, the 2016 cumulative seasonal sap flow of willow growing on marginal soil was approximately 445.4 mm. Daily sap flow from late May to late June was the highest (around 5.33 mm day^{-1}) whereas daily water usage dropped to about 1.6 mm day^{-1} from late June to mid-October with sap flow detected through mid-November. Additionally, modeling efforts indicate the improvements that can be realized at the watershed scale in nitrate loss, sediment yield, and pollinator habitat (Graham, Nassauer, Currie, Ssegane, & Negri, 2017; Ssegane & Negri, 2016). The costs for implementing such a system were determined to be less than other conservation practices (e.g., cover crops and crop rotation) when normalized based on the cost to reduce N losses (Ssegane et al., 2016). We are currently actively assessing the valuation of various ecosystem services including nutrient management, sedimentation, carbon sequestration, terrestrial and aquatic wildlife habitat improvement, pollinator services, and water-based recreation. These findings will be added to the economics of biomass planting and harvesting to develop a complete picture of the economic, water quality, and other environmental impacts that could be achieved through integration of bioenergy crops in an agricultural landscape (Cacho, Negri, Zumpf, & Campbell, 2018; Efroymson et al., 2017; Ssegane et al., 2015, 2016). Potentially the value to farmers could be derived from science-based nutrient trading mechanisms with point-source dischargers, such as wastewater treatment plants.

3.2 | Using shrub willow to manage water and produce biomass in the Northeastern United States

Soda ash was produced in Solvay, New York (43.07°N, 76.25°W) (Figure 1) for about 100 years starting in the mid-1880s. The waste by-product from manufacture is a mixture of calcium and magnesium salts. About 600 ha of settling basins in the vicinity of the plant received waste materials during the years of operation, and range between 3 and 21 m thick (Mirck & Volk, 2010). The primary concern related to these settling basins is the leaching of salts into the area's groundwater and surface water. A shrub willow (*Salix* L.) evapotranspiration (ET) cover, in combination with a variety of leachate and seep mitigation strategies, has been implemented to address these concerns and protect human health and the environment.

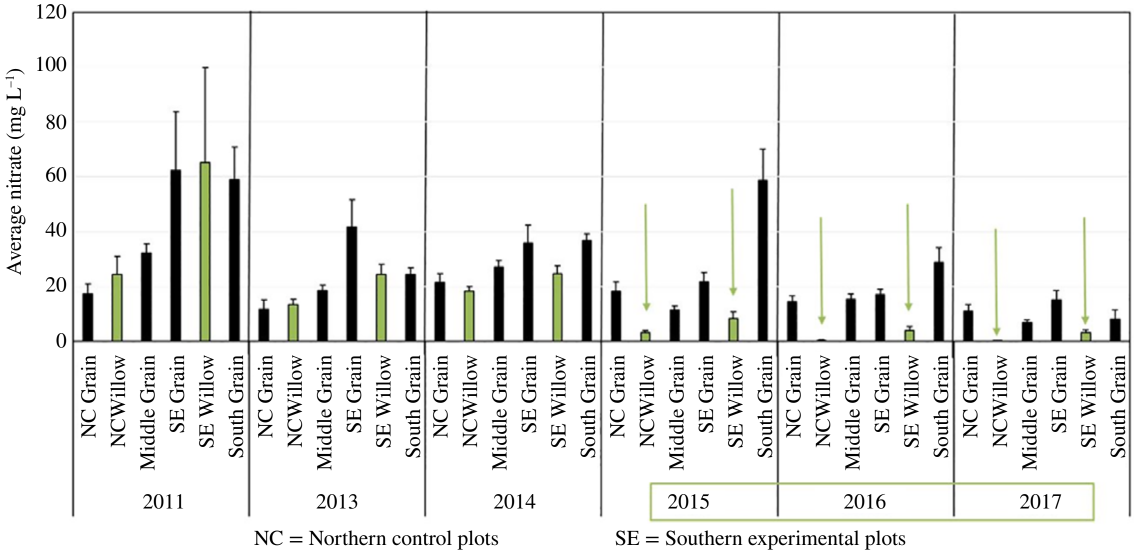

FIGURE 6 Annual comparison of nitrate-nitrite nitrogen (denoted as nitrate; mg L^{-1}) leachate in soil water at an agricultural test site in Fairbury, Illinois. Shrub willow (*Salix miyabeana* Seemen 'SX61') were planted in 2013 (with 2014 representing the first complete growing season) to improve water quality and provide other ecosystem services. Middle and South Grain refer to sampling locations outside the monitoring plots, which are included for reference. Grain was either corn (2011 to 2016) or soybean (2017)

The shrub willow ET cover is designed to manage the basic water budget (Equation (1)) at the site with the goal of minimizing the movement of salts into the surrounding ground and surface water.

$$\text{Precipitation} = \text{runoff} + \text{evaporation} + \text{transpiration} + \text{storage} + \text{percolation}. \quad (1)$$

The shrub willow ET cover increases transpiration and water storage at the site, and minimizes the amount of percolation through the basins. Shrub willow has a number of characteristics that make it an appealing choice for this application. It has a rapid growth rate, a higher transpiration rate than other plants, a long growing season (it leafs out early and drops it leaves later than most woody plants in the region), a tolerance of a wide range of site conditions, an extensive fine root system, and can be managed to produce biomass and provide other ecosystems services (Kuzovkina & Volk, 2009).

The development of a shrub willow evapotranspiration cover was initiated in the early 2000s using a phased remediation approach that started with a series of greenhouse trials, was followed by small field trials of 0.75 to 4 ha in size, and resulted a larger scale application across almost 50 ha. Initial tests indicated that it was essential to incorporate organic material into the site in order to grow willow. After testing a variety of materials, a mixture of biosolids from a local brewery and horse manure was shown to support willow growth and improve water storage capacity. Screening trials of over 40 willow cultivars identified a subset with biomass growth rates similar to rates they achieve growing on mineral soils; four cultivars exceeded 12 Mg ha^{-1} yr^{-1} (Rodzkin & Volk, 2017). Sapflow measurements at the site confirmed that even in this challenging environment shrub willow generally had high transpiration rates, but there were differences among cultivars. Some cultivars [i.e., '9870-23' ('Marcy')] have higher transpiration rates in the spring and early summer while others [e.g., '9832-34' ('Fish Creek')] had higher rates in the late summer and fall (Mirck & Volk, 2010). Despite these differences, transpiration over the entire growing season was similar, ranging from 494.0 ± 24.7 mm for 'SX61' to 532.7 ± 32.6 mm for '9870-23.' The crop coefficient (Kc) averaged across the willow varieties at the site over the entire growing season was 1.20 ± 0.05, indicating that willow transpiration was 20% higher than a well-watered grass cover for this region.

Data collected on willow growth rates and other characteristics (e.g., height growth, leaf area index, rooting depth, etc.) was used as input into the SHAW (simultaneous heat and water) model. Results from that model showed that percolation reduction under a willow ET cover over a 28-year period would be similar to a conventional clay cover. In addition to reducing percolation from the site the willow can be harvested every 3 to 4 years to generate biomass that can be used as a feedstock for renewable energy or other uses. Chemical analysis of willow biomass grown at this site shows that the material was in compliance with all 11 elements listed in the ISO standard for graded wood chip (17225-4) and would be a suitable feedstock for renewable energy generation (Table 6). Of the 19 elements tested, the willow at Solvay had statistically higher values for carbon, magnesium, potassium and phenol compared to the same willow grown on mineral soils, while the willow on the mineral soils had statistically higher levels of ash, barium, cadmium, and manganese compared to willow grown at the Solvay site. While there were statistical differences in the characteristics of willow grown on these settling basins compared to mineral soil, none of them were items that raised concerns for end users of the material.

In terms of additional ecosystem services, the installation of a shrub willow ET cover at this site also increases the structural diversity of the landscape and increases biodiversity. Campbell, Frair, Gibbs, and Volk (2012) found a higher diversity of birds and small mammals at the site along the edges of willow plantings compared to their interiors or areas comprised of other naturally regenerated vegetation. A recent assessment at the site showed that over 56 species of bees, at least 10 of which are rare or in decline in the northeastern United States (Tumminello, Volk, McArt, & Fierke, 2018). The shrub willow ET cover at this site can protect water quality in the area and simultaneously provide a wide range of other ecosystem services.

3.3 | Biomass production in Sweden

In northern Europe, Sweden was one of the first countries that considered large-scale implementation of SRWCs for energy. As a result, Sweden now has commercial plantations of poplar, hybrid aspen, and willow. Research on poplar plantation systems started in the 1930s (Rytter, Johansson, Karačić, & Weih, 2011) although their use was mainly for pulp production. Many of the existing poplar plantations were established from 1980 to 2000 on set-aside land, mainly for demonstration purposes in order to assess productivity. Despite a recent expansion in areas grown with poplar, especially in southern parts of the country (Dimitriou & Mola-Yudego, 2017), total deployment is still limited to less than 2,000 ha (Karlsson, 2017). Furthermore, willow research started in the 1970s, and the first commercial plantations were established in the 1980s, reaching 14,000 to 16,000 ha in 1996 (Mola-Yudego and Gonzalez-Olabarria, 2010). Most of these commercial systems were based on

TABLE 6 Comparison of attributes of willow biomass harvested from settling basins (Solvay, New York) and a mineral soil site (Tully, New York) and compliance of Solvay samples with ISO B1 standards for graded wood chips (17725-4). Green highlighted rows indicate attributes where there were significant differences between samples from Solvay and Tully, with the higher value in the row in bold

		Solvay		Tully		Site difference		
	Units	Mean	*SD*	Mean	*SD*	*P*-value	ISO B1 standard	Mean complies with standard
ARSENIC	mg kg^{-1}	0.02	0.005	0.01	0.000	0.2159	≤1	Complies
ASH	%	1.72	0.06	**2.06**	0.19	0.0135	≤3	Complies
BARIUM	mg kg^{-1}	1.95	0.06	**13.48**	0.92	<0.0001		
CADMIUM	mg kg^{-1}	0.49	0.01	**1.68**	0.10	<0.0001	≤2	Complies
CALCIUM	mg kg^{-1}	3,698	332	4,133	139	0.0522		
CARBON	%	**48.3**	0.05	48.1	0.12	0.0351		
CHROMIUM	mg kg^{-1}	0.98	0.01	0.98	0.02	0.1213	≤10	Complies
COBALT	mg kg^{-1}	4.95	0.06	4.90	0.12	0.4680		
COPPER	mg kg^{-1}	3.50	0.28	3.53	0.55	0.9445	≤10	Complies
IRON	mg kg^{-1}	14	7	15	3.62	0.7949		
LEAD	mg kg^{-1}	4.95	0.06	4.90	0.12	0.6669	≤10	Complies
MAGNESIUM	mg kg^{-1}	**541**	40	250	11	<0.0001		
MANGANESE	mg kg^{-1}	7.70	0.79	**29.05**	1.77	<0.0001		
MERCURY	mg kg^{-1}	0.03	0.00	0.03	0.00	0.6704	≤0.1	Complies
NICKEL	mg kg^{-1}	3.95	0.06	3.93	0.10	0.4507	≤10	Complies
NITROGEN	%	0.51	0.02	0.51	0.06	0.8970	≤1	Complies
POTASSIUM	mg kg^{-1}	**1,660**	108	1,428	40	0.0069		
PHENOL	μg kg^{-1}	**17,000**	2,943	10,200	1930	0.0083		
SODIUM	mg kg^{-1}	98	1	102	5.07	0.2476		
SULFUR	%	0.05	0.00	0.05	0.01	0.3216	≤0.1	Complies
ZINC	mg kg^{-1}	39	4	**56**	3.32	<0.0001	≤100	Complies

Note. SD: standard deviation.

clones and hybrids of *S. viminalis* L., *S. dasyclados* Wimm., and *S. schwerinii* E. Wolf. Shortly after, changes in the subsidy system and new regulations derived from the European Common Agricultural Policy resulted in a decline in the areas planted (Mola-Yudego, Dimitriou, Gonzalez-Garcia, Gritten, & Aronsson, 2014), having been reduced to 7,783 ha in 2017 (Karlsson, 2017). These plantations were usually established on agricultural land, with the highest concentration in the central (Örebro, Upplands) and southern (Skåne) parts of the country (Mola-Yudego and Gonzalez-Olabarria, 2010). Other regions in Northern Europe with significant areas planted include Denmark (5,700 ha; Jørgensen, Sevel, Georgiadis, & Ugilt Larsen, 2014) and Latvia (1,639 ha, Heino & Hytönen, 2016). In Estonia and Finland, there are 45 and 110 ha planted, respectively (Heino & Hytönen, 2016).

In general, poplars grown for energy in Sweden have been established on relatively fertile agriculture land with careful soil preparation at densities near 1,500 trees ha^{-1} (e.g., 3×3 m^2 or 3×2 m^2 spacing). In addition to fencing, site maintenance included weeding during the first 2 years, occasional thinnings, and final harvests at 15–20 years by clear felling (Christersson, 2008). The most frequent clones planted were 'OP-42' (*P. maximowiczii* Henry × *P. trichocarpa* Torr. & Gray), followed by balsam poplar (*P. balsamifera* L.) and black cottonwood (*P. trichocarpa*). Nitrogen fertilization was usually not performed (Christersson, 2008). After harvest, most of the plantations were replanted.

Willow biomass productions systems were usually established between late April and early June, with coppicing performed after the first growing season in order to promote sprouting. The most common design was double-rows, with 0.75 m within rows and 1.5 m among rows, to permit easy mechanization, resulting in densities around 13,000 cuttings ha^{-1} (Dimitriou, Rosenqvist, & Berndes, 2011). Fertilization was not a standard practice, yet recommendations varied between 70 and 120 kg N ha^{-1} yr^{-1} (Danfors, Ledin, & Rosenqvist, 1997). In addition, sludge fertilization was common (Sööder et al., 2013). Harvests were conducted every three to five years (Mola-Yudego & Aronsson, 2008) although there were cases of longer cutting cycles (i.e., over 10 years) (Mola-Yudego, 2011). Regrowth with coppicing occurred after each harvest, with no replanting taking place. However, in recent years, general management practices have shifted towards the establishment of superior genotypes with reduced initial planting densities and rotation lengths and greater levels of intensive management, such as more frequent fertilization (Mola-Yudego, 2011).

Groundwater quality in both poplar and willow systems has been investigated. For poplar, eight commercial plantations were studied from 2012 to 2015 (Dimitriou & Mola-Yudego, 2017), while 16 willow plantations were studied from 2009 to 2011 (Dimitriou, Mola-Yudego, & Aronsson, 2012). In those plantations, several groundwater pipes were installed within the plantation area as well as on nearby agricultural fields to allow for comparisons with common land uses in the area. Both poplar and willow had lower NO_3-N concentrations in their groundwater relative to that of adjacent agricultural fields [i.e., 1.55 NO_3-N mg L^{-1} (poplar) versus 7.98 mg NO_3-N L^{-1} (agriculture), and 0.36 mg NO_3-N L^{-1} (willow) versus 4.87 mg NO_3-N L^{-1} (agriculture)]. Poplar had lower PO_4-P values relative to agricultural practices (i.e., 0.0081 PO_4-P mg L^{-1} versus 0.082 mg PO_4-P L^{-1}, respectively), while that for willow was similar among both types of production systems [i.e., 0.050 mg PO_4-P L^{-1} (willow) versus 0.045 mg PO_4-P L^{-1} (agriculture)]. In general, poplar had greater NO_3-N concentrations and lower PO_4-P concentrations in groundwater compared with willow, and poplar exhibited greater overall variability (Dimitriou & Mola-Yudego, 2017), indicating possibilities to improve water quality in agricultural landscapes by growing lignocellulosic energy crops instead of annual crops.

3.4 | Wastewater treatment in Sweden

The ability of willows to reduce nitrogen leaching had been recognized in early years of the plantation implementation in Sweden described above, which led to the establishment of multifunctional plantations. For example, in the 1990s, several plantations in Sweden were established next to wastewater treatment plants, equipped with drip or sprinkler irrigation systems (Dimitriou & Aronsson, 2005). A successful example of the combined use of plantations for biomass and wastewater treatment was located in Nynäs Gård (Enköping), Sweden (59.63°N, 17.08°E) (Figure 1). This municipality was using woody biomass since the 1980s for heat generation (McCormick & Kåberger, 2005), and presented a pioneer system of combined wastewater treatment based on willow plantations. The wastewater is separated and directed to pools located adjacent to the plant and to a downstream 75-ha plantation of willow (Dimitriou & Aronsson, 2005). The wastewater is used to irrigate the fields during the growing season entailing about 120 days of irrigation annually (equivalent to a mean daily value of 2.5 mm during the growing season). This water has about 800 mg N L^{-1}, and accounts for about 25% of the nitrogen treated in the plant. The system also includes sludge from private sewages and handles about 3.75 M m^3 of water annually (Sööder et al., 2013). The system treats annually approximately 11 t N and 0.2 t P, and possible environmental hazards are being monitored; the results indicating minimal risks after wastewater application (Dimitriou & Aronsson, 2005). After the cutting cycle, the willow is harvested and the chips are delivered to the city's combined heat and power (CHP) plant, with capacity for 55 MW of heat and 24 MW of electricity. The willow biomass represents about 10 to 20% of the biofuels consumed by the power plant (Mirck, Isebrands, Verwijst, & Ledin, 2005), which is also supplied by farmers in the nearby areas (Mola-Yudego & Pelkonen, 2011). As an additional action, and in an effort to decentralize the wastewater treatment system and reduce the volumes ending up in the treatment plant, the wastewater from houses in the rural areas of the municipality is gathered in collection points, aerated for 2 months and applied in willow fields in the area (fields Djurby and Lundby in Figure 1).

In addition, landfill leachate is usually treated together with urban wastewater in the treatment plants, which is a costly operation both in economic and energetic terms, due to the transportation for treatment. One solution for this is to aerate the wastewater mixture and use it to irrigate willow plantations on restored parts of the landfills or on nearby agricultural areas (Dimitriou & Aronsson, 2005). Such irrigation contributes to the plant growth and reduces the negative effects of the high ionic strength of landfill leachate (i.e., chloride concentrations near 1,000 mg Cl L^{-1}). There are about 20 sites in Sweden where landfill leachate is used to irrigate willow plantations. Among those, trials have been established at Höybytorp (Figure 1), a field entailing about 5 ha of willow plantations, which is irrigated daily with 2 to 3 mm of wastewater. The trial comprised 400 m^2 including willow varieties 'Tora' and 'Gudrun' subject to different leachate irrigation treatments according to the estimated mean precipitation deficit (Aronsson, Dahlin, & Dimitriou, 2010). The results showed that irrigation with landfill leachate did not affect the aboveground plant growth compared to the control (i.e., without irrigation) or irrigation with tapwater. This was also found in a similar experiment in western Sweden for poplar and willow (Dimitriou & Aronsson, 2010). Relative retention of total N was found to be linear, even at loads exceeding 2,000 kg Tot-N ha^{-1}, whereas for P there were low retentions despite moderate loads (Aronsson et al., 2010).

Finally, plantations have also been used for log-yard runoff applications. In Sweden, water is applied to stored wood at sawmills and pulp mills in summer in order to preserve it from insect and fungi damage or physical damages when wood dries out. The resulting runoff water contains a range of organic compounds from the bark, as well as phosphorus. A medium-sized sawmill can consume 100,000 m^3 of water for these purposes. When incorporated with rainfall and snow, there are large volumes of runoff water that include phenolic acids, organic carbon, heavy metals and increased phosphorus concentrations. At Heby (central Sweden), about 60,000 m^3 of log-yard water is used to irrigate a 1 ha willow plantation, at a rate of 4,000 to 4,500 mm per year (Dimitriou & Aronsson, 2005), which is greater than the cases of urban wastewater and landfill leachate treatments. Experiments have shown that the total organic carbon and phenolic compounds in the ground water have decreased (Jonsson, 2004), and the growth has not been affected despite the high loads of phosphorus and total organic carbon. Nevertheless, soil saturation due to excessive irrigation affected the growth, which led to a reduction to 10 to 20 mm per day.

4 | CONCLUSION

Biomass production for energy purposes is a good example of where a holistic perspective can help to identify solutions that serve many objectives. The information presented in this review highlights the importance of relating the potential of both poplars and willows for water conservation and water usage back to the SDGs, in particular *Clean Water and Sanitation* (SDG 6) and *Affordable and Clean Energy* (SDG 7). For example, on water-stressed sites, clonal selection for water conserving (i.e., drought tolerant) genotypes can maximize biomass production without causing detrimental impacts to water supply and/or quality. In contrast, on water-rich sites (e.g., wastewater phytotechnology applications), clonal selection for genotypes that exhibit high water usage can help to combine biomass production with environmental remediation and reduced runoff from polluted sites.

Future lines of science and applications greatly depend on elucidating how genotypes can be selected to maximize the benefits of the trees. A second pertinent question is how incentives can be developed to promote bioenergy systems that, through well-chosen localization, design, management, and system integration, offer additional ecosystem services that, in turn, create added value for the systems? One way forward can be to provide information so that policy makers, regulators, and resource managers can assess the many opportunities for promoting beneficial LUC as a means of achieving SDGs.

In choosing the right genotype and by extension, the right crop for the right application, site selection also plays an important role. With a concern for the impact that bioenergy crop production expansion could have on food or product production through LUC, where these crops will be grown is a major consideration. The use of marginal land has been considered as one approach to address this issue and many of the presented case studies have shown poplar and willow production capabilities under marginal conditions, and they have addressed why understanding genotype × environment interactions is important to consider to improve productivity and provide ecosystem services.

The concept of utilizing SRWCs or other perennial bioenergy crops for multiple purposes not only expands their application but also their attractiveness for production. As some of the case studies pointed out, however, there are still limitations to SRWC application that may not directly be linked to production of the crop itself. In the case of Sweden, change in policy was a major contributing factor, while at Lemont, Illinois, it was change in land management perspective. In contrast, some of the case studies also highlighted incentives for producing SRWCs. In the mountainous regions of North Carolina, poplar was an attractive crop because it was more cost effective and had a greater production range potential than traditional hardwoods. In Fairbury, Illinois the production of willow buffers was an attractive option for areas of the field where the farmer was already losing money with an annual corn cropping system, but where they still wanted to produce a crop to maintain some level of income. The ecosystem service potential, including nitrate loss reduction, was also attractive, especially in a region where many of the surrounding watersheds were considered nitrate impaired by the Illinois Environmental Protection Agency (EPA). This highlights the importance of matching crop production to the needs of producers, landowners, communities, regions, or even countries. The case studies presented in this paper have shown how production of poplar and willow within the United States and northern Europe have been evaluated and used to address a very important global need: water quantity and quality. By taking into consideration genotype, production location, and in some cases, thinking beyond traditional applications (e.g., growing SRWCs for wastewater management and using TreeWells® for groundwater remediation), SRWCs have the potential to be produced across a variety of climate and soil conditions for numerous, complementary purposes, including bioenergy and phytotechnologies.

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CONFLICT OF INTEREST

The authors have declared no conflicts of interest for this article.

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