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PLANT AND ENVIRONMENT INTERACTION

Yield and Water Quality Impacts of Field-Scale Integration of Willow into a Continuous Corn Rotation System

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Abstract

Agricultural landscape design has gained recognition by the international environmental and development community as a strategy to address multiple goals in land, water, and ecosystem service management; however, field research is needed to quantify impacts on specific local environments. The production of bioenergy crops in specific landscape positions within a grain-crop field can serve the dual purpose of producing cellulosic biomass (nutrient recovery) while also providing regulating ecosystem services to improve water quality (nutrient reduction). The effectiveness of such a landscape design was evaluated by the strategic placement of a 0.8-ha short-rotation shrub willow (*Salix miyabeana* Seemen) bioenergy buffer along marginal soils in a 6.5-ha corn (*Zea mays* L.) field in a 6-yr field study in central Illinois. The impact of willow integration on water quality (soil water, shallow groundwater leaching, and crop nutrient uptake) and quantity (soil moisture and transpiration) was monitored in comparison with corn in the willow's first cycle of growth. Willows significantly reduced nitrate leachate in shallow subsurface water by 88% while maintaining adequate nutrient and water usage. Results suggest that willows offer an efficient nutrient-reduction strategy and may provide additional ecosystem services and benefits, including enhanced soil health. However, low values for calculated willow biomass will need to be readdressed in the future as harvest data become available to understand contributing factors that affected productivity beyond nutrient availability.

Core Ideas

- We assessed impacts of shrub willow integration within an agricultural landscape.
- Nitrate leachate was significantly reduced by willow buffers in an Illinois cornfield.
- Willows used water resources differently than corn with time.
- Improved soil health seen under willow will continue to be monitored.
- Influencing factors contributing to low willow biomass will be assessed in the future.

Research interests in alternative management strategies for water quality conservation in agricultural systems have grown as negative impacts of excess nutrients on the environment (Rabalais, 2002; Rabalais et al., 2002; Dale and Polasky, 2007) and human health (Rabalais et al., 2002; Townsend et al., 2003; Galloway et al., 2008; Nissim et al., 2014) are seen at multiple monitoring scales. Important ecological and societal impacts range from the hypoxic zone in the Gulf of Mexico to the 2014 shutdown of the Toledo public water system because of cyanotoxins (Kozacek, 2014), to the lawsuit by the Des Moines Water Works, IA, against surrounding agricultural Drainage Districts for nitrate pollution of drinking water (Snider, 2015). Practices to reduce nutrient loadings need to be economically viable and implementable in practice. The integration of cellulosic biofuel feedstocks into agricultural fields in marginal soils (underproductive or high environmental risk areas) may be able to address nutrient leachate. The passive reuse (recovery) of leached nutrients from neighboring grain crops in strategic cropping systems can promote enhanced biomass production without additional fertilizer application (Ssegane et al., 2015). This may provide a cost-effective solution (Ssegane et al., 2016) for state and national nutrient reduction goals (USEPA, 2013; IDOA and IEPA, 2015). Targeting marginal lands optimizes land use by reducing the competition between bioenergy and grains for land allocation, improves the economics of bioenergy crop production (Ssegane and Negri, 2016; Ssegane et al., 2016), and may provide additional benefits (Graham et al., 2016, 2017), thereby offering potential solutions for other problems within the food, energy, and water nexus. In particular, it may offer positive synergisms between the need to produce lignocellulosic feedstock, as mandated by the Renewable Fuel Standard (USDOE and USDA, 2009; USDOE, 2016), and to provide cost-effective solutions for water quality problems, as identified by State and Regional Hypoxia Task Force targets.

Shrub willows (*Salix miyabeana* Seemen) are efficient bioenergy and phytoremediation candidates due to their fast perennial growth, high biomass production, and high nutrient uptake. They can tolerate a wide range of environmental conditions, including drought, saturated soils, and high toxicity (landfill leachate), as well as stressors including herbivory, rust

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Abbreviations: LAI, leaf area index; MW, monitoring well; N-plots, northern plots; OM, organic matter; S-plot, southern plot; TN, total nitrogen; TSM, total soil moisture.

infection, and frost (Elowson, 1999; Kahle et al., 2002; Smart et al., 2005; AILE, 2007; Nissim et al., 2014). Taking into account soil and climate effects on denitrification and soil immobilization, the literature suggests that ~200 kg N ha^{-1} yr^{-1} could be treated through a soil–willow system (AILE, 2007). Therefore, the objectives of this paper were to evaluate the impacts of field-scale willow integration into a continuous corn (*Zea mays* L.) rotation system for the dual purpose of addressing water quality issues while producing bioenergy feedstock. Our purpose for the willow buffer, planted along areas considered underproductive or of high environmental risk (marginal land) to reduce land competition for grain-crop production, was to bolster its yield through the interception and uptake of leached nitrate, thereby improving water quality (Ssegane et al., 2015).

Materials and Methods

Field Site and Experimental Setup

The field site is a 6.5-ha, nontiled corn field located in Livingston County, Fairbury, IL (40.74° N, 88.50° W). The site is hydrologically isolated from neighboring fields, with Indian Creek lying west of the field and an elevated soil embankment to the east. The 5-yr average annual precipitation for Fairbury (2011–2015) was 877.3 mm (Fairbury WWTP; NOAA, 2016).

The field was set up using a randomized block design with plots of corn and willow 'SX61' blocked on lowland floodplains in Comfrey loam soil (fine-loamy, mixed, superactive, mesic Cumulic Endoaquolls), 0 to 2% slope, (northern plots [N-plots]) and upland plains in Symerton silt loam soil (fine-loamy, mixed, superactive, mesic Oxyaquic Argiudolls), 2 to 10% slope, (southern plots [S-plots]) (Supplemental Fig. S1). The S-plots represent marginal soils with a relatively deep, nitrate-enriched (NO_3/NO_2–N) water table, whereas the N-plots represent a pseudo-control situated in fertile, floodplain soil with a shallow water table and more limited nitrate leaching. Additional site characterization is found in Ssegane et al. (2015) and Ssegane and Negri (2016).

Willow and corn plots were each ~0.2 ha. Willow plots were planted in the spring of 2013 using a double-row planting system (150-cm spacing between double rows, 75 cm between rows, and a 60-cm in-row spacing) (Abrahamson et al., 2010) at a density of 15,300 cuttings ha^{-1} into a grass cover crop. Planting density was lower in the N-plots due to equipment calibration problems, which resulted in many rows being planted as single rows. Subsequent hand planting was unsuccessful, in terms of establishment. The willows were coppiced at the end of 2013, with willow harvest expected to be every 3 yr. No fertilizer was applied to the willows at or after planting; all corn crop was managed as usual, with an average fertilizer application of 248 kg N ha^{-1} yr^{-1}, with pre- and postemergent herbicide applied at rates of ~3.5 L ha^{-1} of Harness Xtra (aceteochlor) and 0.04 L ha^{-1} of Impact (topramezone methanone), respectively. Land under corn crop was conventionally tilled with no corn stover collection after harvest. Management of willow plots was limited to mowing of the herbaceous understory as an alternative to herbicide application because of foliar damage during the first year of herbicide application (a pendimethalin pre-emergent herbicide applied at 5.7 L ha^{-1} and 2.43 L ha^{-1} of Poast [sethoxydim] postemergent herbicide).

Field Monitoring and Statistical Analysis

The data collection regime followed pre-willow introduction (2011–2012) and post-willow introduction (2013–2016) periods.

Soil Moisture

Soil moisture was continuously measured in the four S-plots from 2014 to 2015 using a Sentek EnviroSCAN probe, a capacitance probe, which monitored hourly volumetric water content (VWC) at several depths between 0 and 150 cm. The probes were calibrated in air and water according to manufacturer calibration requirements. Linear regression was used to interpolate missing data using R statistical software version 3.3.1 (R Core Team, 2016) and Microsoft Excel 2016. Total soil moisture (TSM) for the full 150-cm profile was calculated using the trapezoidal formula for nonuniform increments:

$$\begin{aligned}\mathrm{TSM}\ (150\ \mathrm{cm}) = {} & 10\left(\frac{\mathrm{VWC}_{10\mathrm{cm}}}{100}\right)\\ & + 0.5\left[(30-10)\,\frac{\left(\mathrm{VWC}_{30\mathrm{cm}}+\mathrm{VWC}_{10\mathrm{cm}}\right)}{100}\right]\\ & + 0.5\left[(50-30)\frac{\left(\mathrm{VWC}_{50\mathrm{cm}}+\mathrm{VWC}_{30\mathrm{cm}}\right)}{100}\right]\\ & + 0.5\left[(100-50)\frac{\left(\mathrm{VWC}_{100\mathrm{cm}}+\mathrm{VWC}_{50\mathrm{cm}}\right)}{100}\right]\\ & + 0.5\left[(150-100)\frac{\left(\mathrm{VWC}_{150\mathrm{cm}}+\mathrm{VWC}_{100\mathrm{cm}}\right)}{100}\right]\end{aligned} \qquad [1]$$

Groundwater Monitoring

Edge-of-field and intrafield monitoring wells (MW) were used to monitor water quality (see Supplemental Fig. S1). The edge-of-field MWs (MW1, MW3, MW4, and MW5) were screened at depths between 180 and 400 cm. The intrafield MWs consisted of a shallow well (MW6S) screened between 120 and 300 cm and a deep well (MW6D) screened between 370 and 580 m. Water samples were analyzed by Servi-Tech Laboratories (Dodge City, KS) for nitrate using a copperized cadmium column that reduced nitrate to nitrite. A modified Greiss–Ilpsvay method was used to calculate nitrate concentrations, which were measured spectrophotometrically (USEPA, 1974; Promega Cooperation, 2009; Gelderman and Beegle, 2011). Any samples returned with a value less than the minimum detection level (0.2 mg L^{-1}) were reported as 0.1 mg L^{-1}. Annual nitrate loads were calculated using annual well concentrations normalized by daily average leached rainfall. The biogeochemical modeling tool DeNitrification-DeComposition (DNDC) (Li, 2012; http://www.dndc.sr.unh.edu/) was used to calculate the amount of leached rainfall entering the shallow groundwater system (18% of annual rainfall).

Soil Water

During the growing seasons of 2011 to 2016, water from the unsaturated zone at a depth of 120 to 150 cm was collected using evacuated syringes connected to MacroRhizons (by Rhizosphere) with pore size of 0.15 μm, referred to as rhizon(s). The sampling depth was selected according to the average surface-to-groundwater depth across the field, as well as the corn rooting depth, to target the leachate. Syringes were left attached in the field for up to 5 d, with the time limit set by an in-house study that assessed nitrate degradation rates without preservative. It found no significant impact of time on water nitrate levels under sun or shade conditions compared with laboratory-control preserved samples after 5 d. Soil water and groundwater were collected and analyzed on the same day. Data were analyzed using a linear mixed model fit using the statistical package lmerTest, with residuals checked for normality using R statistical software version 3.3.1 (R Core Team, 2016). Fixed factors included crop type, landscape position, and year, whereas sampling date and rhizon ID (identification number) were treated as random factors. The linear model was simplified to include only two-way interactions between fixed factors, because the three-way interaction was nonsignificant ($P = 0.38$). The average annual concentrations (least square means) were used to determine nitrate reductions in soil water as percentage over corn. Geostatistical analysis with ArcGIS Desktop 10.x (ESRI, 2016) was used to determine nutrient hotspot and nitrate leaching patterns throughout the growing season for each year using the inverse distance weighted interpolation method.

Ion-Exchange Resins

Ion-exchange resins (Rexyn I-300, research-grade resin beads) housed in a permeable polyvinyl chloride (PVC) capsule were used to measure annual soil-water nitrate and ammonium loads to the subsoil. Ion exchange resin capsules were constructed with a modified design following Susfalk and Johnson (2002) and Ventura et al. (2013) (see Supplemental Fig. S2) and placed in the S-Plots along transects upslope, within, and downslope of the plots with three replicates each. Capsules were placed in 46-cm-deep boreholes using a GeoProbe drilling system at a 45° angle (±3°) with the permeable sides of the capsule parallel to the soil-infiltration pathway. Capsules were refrigerated after extraction from the field until analysis. Resin beads were cleaned with deionized water and placed in 2 M KCl on a shaker for 1 h at 100 rpm (Ventura et al., 2013). The combination of resin beads and KCl solution was transferred to a separatory funnel with glass wool supported down by glass beads, for resin separation from extractant. The extractant was analyzed by Servi-Tech Laboratories. A Kolmogorov–Smirnov nonparametric test was used to assess crop effect.

Soil Sampling

At the beginning of each growing season (2011–2016), soil core samples to a depth of 122 cm were collected using an acetate sleeve-lined macro-core sampler (2.5-cm o.d.) attached to a GeoProbe drilling system. Approximately the top (surface) 15 cm and bottom (subsurface) 15 cm of the soil cores were collected and put on ice for chemical analysis. Soil samples were analyzed by Servi-Tech Laboratories for total N (TN) and organic matter (OM) (Grafton et al., 2015). Descriptive statistics by monitoring plot, landscape position, and soil type were calculated. Additionally, soil chemical mapping using Veris Precision Farm Mapping (Prime Meridian, Nevada, MO) was done in December of 2014 from 2400 sampling points calibrated with laboratory-analyzed soil core samples.

Vegetation Sampling and Allometric Measurements

Vegetation sampling for willow was done following a modified version of Mirck and Volk (2009). Corn (grain) and willow (single branch cut at the 30-cm height above ground) were collected at the end of the 2015 growing season. Three random corn samples were collected from each corn plot; willow plot sampling was based on transects (one sample from each of the three transects: north, middle, south). Samples were dried at 60°C until constant weight and analyzed for percentage TN by Servi-Tech Laboratories.

Stem counts and diameter measurements were taken every 200 cm along each willow transect three to four times in 2015 to calculate willow standing biomass. Stem counts included all stems growing at the 30-cm height, with two randomly selected stems being measured for diameter using a digital caliper. A stem-size class (small, medium, large) was developed on the last sampling event (18 Oct. 2015), for use with transpiration data. Small stems were usually first-year stems with diameters <1.3 cm. Medium stems, usually with developing bark, had diameters of <2.3 cm; large, mature stems were up to 4.4 cm in diameter. The number of stems per size class was counted, and one random stem per class was measured for diameter (Mirck and Volk, 2009). Willow density (plants per unit area) was quantified by counting the number of willows in each 200-cm × 250-cm consecutive plot along each transect. Corn was planted at a density of 84,016 plants ha^{-1}. Calculation of standing biomass for corn (grain) and willow (stems) was done using the following equations:

$$\text{Corn grain biomass}\left(\frac{\text{kg}}{\text{ha}}\right)=\frac{\text{Dry biomass}}{\text{plant}}\times\frac{\text{plants}}{\text{ha}} \quad [2]$$

$$\text{Willow stem biomass}\left(\frac{\text{kg}}{\text{ha}}\right)=\frac{\text{Dry biomass}}{\text{stem}}\times\frac{\text{stems}}{\text{plant}}\times\frac{\text{plants}}{\text{ha}} \quad [3]$$

Corn grain biomass was normalized by the actual yield collected at the end of the season. Crop N uptake was calculated from standing biomass and its corresponding percent N concentration using Eq. [4]:

$$\text{kg N ha}^{-1}=\text{biomass}\times\frac{\%\text{TN}}{100} \quad [4]$$

Leaf area index (LAI) was also measured for both crops using an AccurPAR LP-80 ceptometer (Decagon Devices) at the end of 2015 and throughout the 2016 growing season.

Sap Flow and Transpiration

Crop transpiration was measured using the Dynamax Flow 32-1K system at an hourly interval based on the stem heat balance relationship. The sap flow system was set up along the corn–willow interface of two S-plots, with 16 sensors of varying sizes (from 10-mm to 25-mm diameter, equally distributed between corn and willow). Transpiration was measured for 5 mo (July–November) in 2015. Sap flow sensors of 10-mm and 13-mm diameter used small-stem allometric data; sensors fitting 16 and 19 mm used medium-stem data, and the 25-mm sensor used the large-stem allometric data. Outliers (values more than two standard deviations from the mean) and missing data were filled in using a local temporal-based regression relationship using a sensor on a similarly sized stem. This approach assumes temporal similarity of the relationships between the two responses. Transpiration data at stem level were converted to transpiration at stand and canopy levels (Mirck and Volk, 2009). For corn, the entire field was assumed to have the same density and an average stem diameter (calculated from stems with sensors placed) (McChung and van Bavel, 2005).

Results and Discussion

Nitrate Concentrations in Soil-Water Leachate

Geostatistical analysis of seasonal leaching of nitrate from 2011 to 2015 across the field depicts the seasonal movement of the nitrate hotspot (Fig. 1a). Differences in hotspot locations and intensity varied by year and as a function of the timing of fertilizer application, precipitation events, and sampling. Nutrient hotspots in the southern uphill end of the field in 2011 identified the location of the buffer strip (S-plots) as having the largest impact on nutrient reduction. Soil water collected in 2011 represented premonitoring plot design, so only the impact of landscape position on seasonal nitrate was examined. The 2011 data were not directly compared with subsequent years after monitoring plot establishment due to the low number of sampling locations that fell within plot boundaries. The northern floodplain corn had a seasonal mean nitrate concentration of 23.8 mg L^{-1} (SE = 14.6 mg L^{-1}), whereas southern uphill corn had a mean concentration of 102.9 mg L^{-1} (SE = 21.3 mg L^{-1}). Therefore, prior to willow planting, nitrate concentrations were found to be significantly higher in uphill corn than on the floodplain (P = 0.005). Drought conditions in 2012 prevented adequate water collection for analysis.

Every year, the data show a similar pattern of elevated concentration in the late spring to early summer, with highest nitrate concentrations toward the southern end of the field, followed by a decline in concentrations later in the season, when subsoil water was too scarce for collection. In 2013, after willow establishment, plot comparisons by crop cover showed no significant differences in nitrate concentrations in soil water between willow and corn-crop treatments in comparable soil, indicating that starting concentrations were comparable. As willow below- and aboveground biomass began to increase after coppicing, significant nitrate reductions were seen in 2015 and 2016 (Fig. 1b). Reduction in nitrate concentrations was greater in N-plots, with

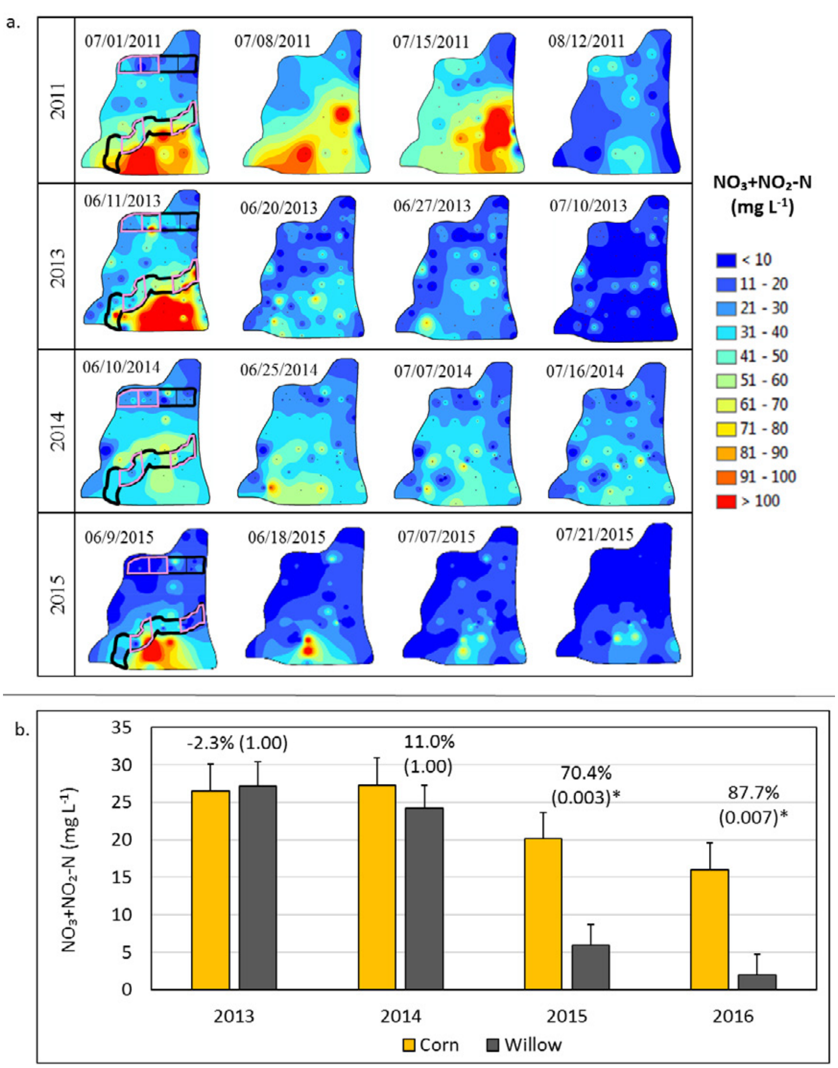

Fig. 1. Soil water NO_3+NO_2–N (nitrate) concentrations. (a.) Nutrient hotspots (2011–2015) leached nitrate concentrations post-fertilizer application before and after willow introduction. The first map in each year shows the placement of the north and south plots in reference to the upslope nutrient hotspot. Areas outlined in pink denote the willow plots; however, willows were planted in 2013, and therefore 2011 serves as a reference for starting conditions. (b.) Annual nitrate concentrations (least square mean × SE) by crop type regardless of landscape position. Percentage nitrate reduction by willow is shown above with *p*-values (* = significant difference at α = 0.05).

the exception of 2014 (8.7, 80.8, and 98.5% in 2014, 2015, and 2016) than in S-plots (12.5, 60.6, and 74.0%). This observation may be attributed to differences in transient times of soil water due to varying soil types and topography, and thus to differences in nutrient availability for plant uptake (sandy soils in S-plots vs. clay soils in the N-plots). Average nitrate concentrations in leachate from all willow plots were significantly lower in 2015 (6.0 mg L^{-1}) and 2016 (2.0 mg L^{-1}) than in 2013 (27.1 mg L^{-1}) and 2014 (24.2 mg L^{-1}), suggesting that crop uptake plays a larger role in nitrate reduction than weather (annual precipitation for 2013–2016: 1422, 1955, 1839, 1250 mm, respectively).

Annual Nitrate Loading

In 2014, willow plots had less (but nonsignificant) soil nitrate loading (71 kg NO_3–N ha^{-1}, average from plots I and III) than upslope corn from each plot (140 kg NO_3–N ha^{-1}) (Fig. 2), a loading reduction of ~49.3%. Annual soil moisture was not found to affect soil nitrate loading within plots, with the average annual TSM higher in willow plots (11 cm) than in corn plots (7.9 cm), yet nitrate loadings varied across all S-plots. No significant reduction in nitrate loading was seen between willow and corn ($P = 0.2$), suggesting that crop cover did not have a significant impact on nitrate loading in 2014. This was consistent with the 2014 soil-water nitrate concentrations for corn versus willow, with $P = 1.0$ for all plots in the first year of willow growth after coppice. However, it is noted that with a small sample size (three replicates) and high standard deviation, results may be influenced more by intrafield soil heterogeneity than the treatment. Quantitative nitrate loading analysis for 2015 and 2016 (with increased replications) will be discussed in a future paper.

Nitrate Concentrations in Shallow Groundwater

Mean nitrate concentrations in groundwater are shown in Fig. 3. On average, seven times less nitrate leached into groundwater under Comfrey soil (MW1, MW3, MW4, and MW5) than under the uphill Symerton soils (MW6S/D), with greater variability in annual nitrate loading in Symerton in-field MWs. However, it was noted that after willow establishment, MW5 (closest to the willows in the N-Plots) and MW6S/D (within a willow S-plot) showed a decline in nitrate loading (two to seven times less) by 2015 compared with 2011. Nitrate concentrations were normalized for precipitation each year, suggesting that declines in nutrient concentrations are likely a result of uptake rather than a dilution effect or influence of soil condition.

Crop Water Use

Crop water use was evaluated by fluctuations in soil moisture and differences in transpiration, shown in Fig. 4. Seasonal soil-moisture variations under corn and willow are depicted in Fig. 4a. Only the four S-plots were monitored, due to the high flooding risk in the N-plots and likely damage to the soil moisture sensors. The TSM fluctuated readily across the 2 yr, with greater fluctuations occurring during the mid- to end of the growing season (July–October) and more stability during the dormant season (baseline). The two willow plots have a higher moisture baseline than corn plots, possibly due to their lack of tillage, which alters soil permeability and exposes the soil to direct soil evaporation. Differences in baseline between all four plots may also reflect

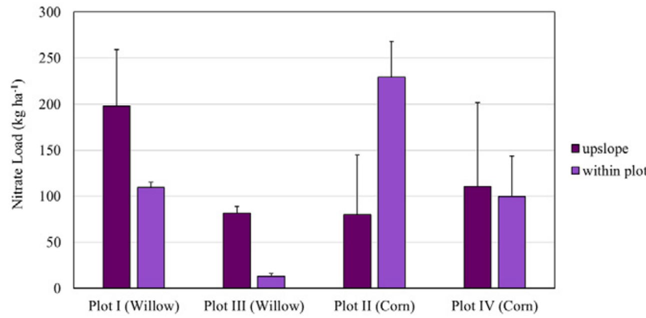

Fig. 2. 2014 annual nitrate load (mean ± SE) upslope of and within each southern plot.

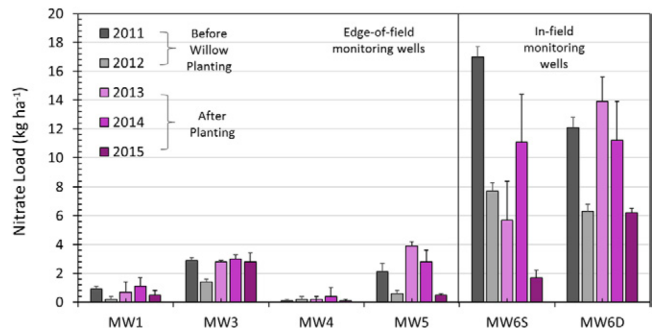

Fig. 3. 2011–2015 annual nitrate load (mean ± SE) in groundwater normalized with daily rainfall. Monitoring wells (MWs) are distinguished by field location: edge-of-field or within-field. Gray bars represent years prior to willow planting, and pink bars represent those after willow integration.

differences in site-specific soil characteristics and crop density, namely for the two willow plots, where willow establishment in Plot III was less successful than in Plot I. Results, however, suggest that willows are not depleting water resources any faster than corn. Direct water use by each crop was monitored using sap-flow instrumentation (Fig. 4b).

Regression analysis showed that soil moisture was significantly correlated to transpiration for both crops with adjusted $R^2 = 0.66$. Cumulative transpiration volume between the two crops was very similar at the beginning of July but diverged until mid-August when water uptake by corn began to decline as it reached maturity, with no transpiration measured after 24 September. Conversely, water uptake and use by willow continued past the time of corn harvest (3 October) at around the same rate until mid-October, with no transpiration measured after 16 Nov. 2015. With a longer growing season (March–November) than corn (May–October), willows have a better chance to intercept the leached nutrients from fertilizer applied during corn planting and exhibit higher total cumulative transpiration (295 mm) than corn (248 mm). However, the rate of willow transpiration for most of the monitoring period was lower than that of corn, and it was only after corn reached maturity and its water uptake declined that willow cumulative transpiration surpassed that of corn. The lower transpiration rate and higher soil moisture may suggest that willows are using water resources more conservatively than corn. The perennial nature of willows and the year-round soil coverage may also lead to more favorable conditions for water retention. Future monitoring will be required to determine if these trends will continue as the willows mature.

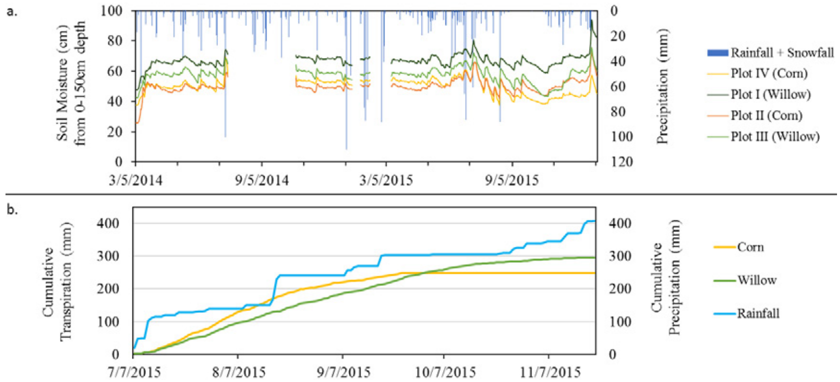

Fig. 4. (a) Daily total soil moisture (0-cm to 150-cm soil profile) under willow and corn crop covers with their corresponding daily precipitation for 2014–2015. Missing data are shown as a gap. Precipitation data are missing between 1 and 19 Sept. 2015. The dip near 26 October may be a result of tilling, which occurred that week. (b) Cumulative transpiration (sap flow) of corn and willow and cumulative rainfall in 2015.

Impact on Soil Chemistry

Soil OM and TN were evaluated by soil type, crop cover, and landscape position to determine which factors or set of factors had the largest influence on the differences in sampling locations. Soil OM from 2011 to 2016 by plot is shown in Fig. 5a. From 2011 to 2016, N-plots in Comfrey loam soils had, on average, 1.6% higher surface OM than S-plots in Symerton loam soils for all years and, on average, 0.8% higher subsurface OM (Fig. 5a). This trend was consistent with precision soil mapping in 2014, in which surface soil OM ranged between 3.0 and 4.7% across the Comfrey loam soils, but between 2.2 and 3.55% for the two Symerton soils (Fig. 5b). Evaluation of crop impact on soil OM showed an increase in subsurface OM under willow (all plots) from 0.7 to 1.3% from 2011 to 2016, whereas soil OM under corn decreased from 1.4% in 2011 to 1.1% in 2016 (with S-Plot corn being more variable). Total N in willow plots tended to stay more consistent, at 717.8 mg kg^{-1} in 2011 and 600.1 mg kg^{-1} in 2016, whereas corn plots showed a decline from 1220.7 mg kg^{-1} in 2011 to 412.1 mg kg^{-1} in 2016 (Fig. 5c). Annual fluctuations in soil TN and OM are

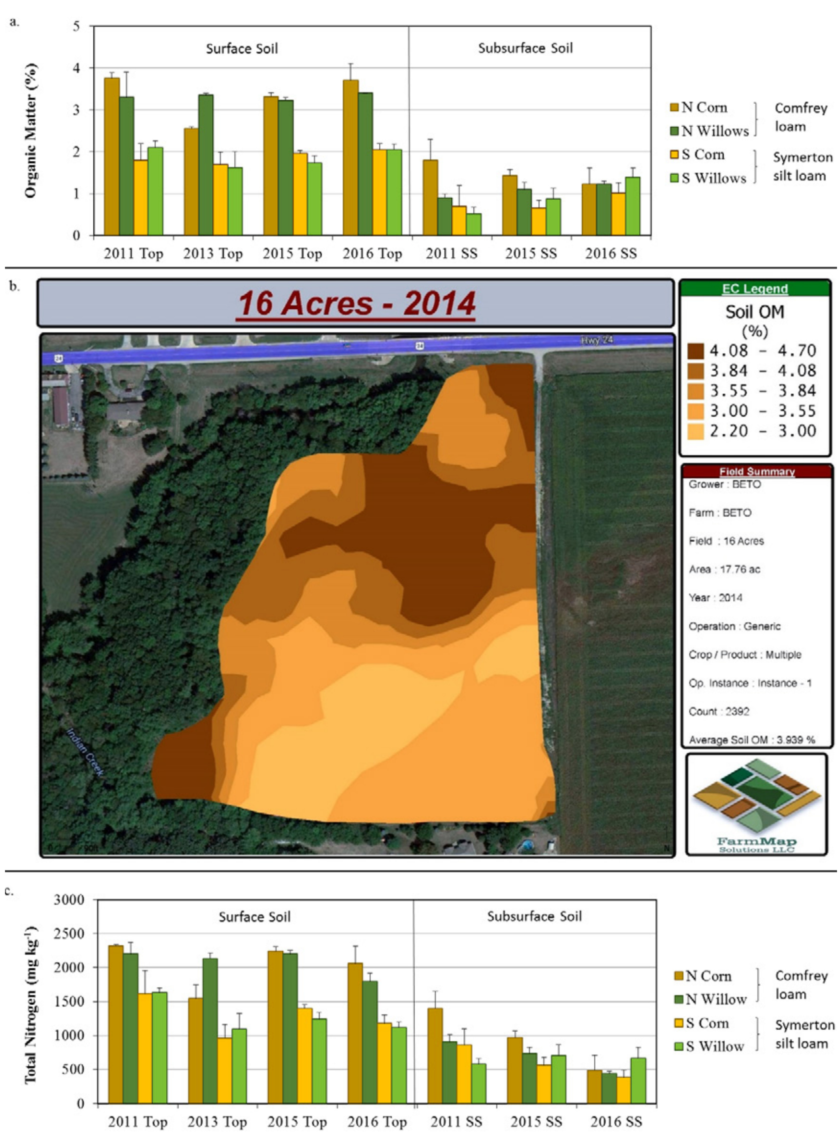

Fig. 5. (a) Soil percent organic matter (OM, mean ± SE) and (c) soil total nitrogen (mean ± SE) by landscape position (northern plots [Comfrey loam soils] vs. southern plots [Symerton silt loam soils]) before (2011–2013) and after (2014–2015) willow introduction. Soil samples were collected at the beginning of the growing season, therefore representing the impact of the previous growing season. Surface (top) soil represents approximately the top 0 to 15 cm, and subsurface represents a depth of 107 to 122 cm. Sample size varied by plot and by year. (b) Veris precision farm mapping of percentage soil OM.

similar under corn and willow crop cover. Although the site has been monitored for several years, change in soil conditions may require more time to assess trends. Additionally, although willows are known for their luxury consumption of N (AILE, 2007), which could raise concern for soil nutrient depletion, no evidence was found of that occurring in this field study at rates any faster than corn. Considering that no fertilizer was applied directly, this finding also suggests that willow likely draws its N from soil water. Isotope analysis for nutrient-source tracking will be used in the future to confirm this assessment.

Nitrogen uptake by each crop type in both landscape positions was also monitored throughout the 2015 growing season, along with its impact on biomass production (Fig. 6). Since 2015 represented second-year growth for willows, average annual N uptake and biomass are shown for corn comparison. Compared with willow, corn had three times greater N-uptake on average, which can be partially understood due to its annual lifecycle. However, this difference can also be attributed to harvestable biomass. Willow biomass (branches) in the plots as a whole was about half of that produced by corn (grain). However, the allometric calculations for willow biomass will be reevaluated once harvest data become available. Two major problems that may have contributed to these lower biomass values are poor establishment (plot heterogeneity in soil moisture, pH, or mortality from direct or indirect [drift] herbicide application) coupled with planting anomalies (single rows vs. double rows), resulting in lower planting densities than expected. For N-plots, if only areas that were planted correctly in double rows are taken into account for biomass calculations, the two plots would yield 11.4 dry Mg ha^{-1} yr^{-1} (SE = 2.5) on average and therefore be comparable with corn. For S-plots, poorer establishment in spite of multiple replanting efforts may more likely be responsible for lower biomass values than planting anomalies. However, the leading cause is unknown and could be related to limited moisture, weed pressure, herbicide toxicity, and/or lower pH. Future evaluation of willow biomass production on an individual-plant basis in association with site characterization may help to determine the effect of planting and environmental factors on biomass production in this study. Additionally, plots will be assessed for gradient effect on biomass production, comparing willows closer to corn (where nutrient leaching is likely to be higher) with those further away, which may point to a threshold for buffer width. The data do show, however, that N-plots have an advantage over S-plots in both N-uptake and biomass production. This finding follows the soil-water nitrate reductions, for which a greater N reduction was seen under the willow N-plots after 2013. Higher biomass production in N-plots can be attributed to their better soil conditions and higher moisture retention and availability in the northern Comfrey soils compared with S-plots.

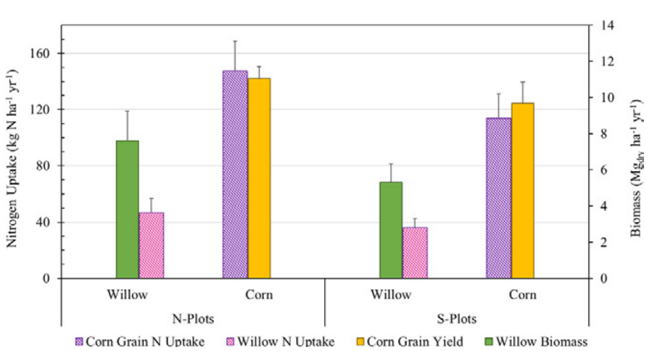

Fig. 6. Annual nitrogen (N) uptake and biomass production for corn and willow by the end of the 2015 growing season (mean ± SE).

The LAI data were inconsistent for aboveground biomass productivity. In September 2015, the average LAI values were 3.5 and 3.0 for willow and corn, respectively, regardless of landscape position. The same trend was found in July 2016, with measured LAI of 4.5 and 3.3 for willow and corn, respectively. Differences in LAI may be due to plant structure, such as differences in leaf arrangement patterns to maximize light interception.

Conclusion

Results of this 6-yr study suggest that strategic placement of shrub willows on an agricultural landscape in central Illinois was an effective strategy for nutrient reduction, in which high nitrate-reduction efficiency was seen even under lower biomass production. However, additional analysis will be required to assess the productivity of this strategy in marginal soil as a lignocellulose feedstock production system. Transpiration and TSM measurements suggest that willows consume water resources comparably with, yet more conservatively than, corn during the active growing season. The low soil-water nitrate concentrations, comparable soil TN contents, and potential increase seen in soil subsurface OM highlight the benefit of a perennial landscape for nutrient reduction, crop productivity, and soil health. Although soil type was a factor affecting nutrient dynamics and crop production, additional variation between plots can be attributed to differences in crop nutrient use, length of seasonal growth, and corresponding land management practices, including fertilization and tillage. The benefits of shrub willow integration on marginal lands for soil health and nutrient reduction arises from the altered land management practices including no-till management and year-round soil coverage. Additionally, willows can significantly reduce N leachate while maintaining a more conservative usage of water and nutrients than corn. However, further research is required to assess and improve yields when producing lignocellulosic feedstock under marginal conditions. New research, such as cultivar selection, may be required to develop alternative design approaches for marginal land.

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References

Abrahamson, L.P., T.A. Volk, L.B. Smart, and K.D. Cameron. 2010. Shrub willow biomass producer's handbook. State Univ. of New York, College of Environ. Sci. and Forestry, Syracuse, NY.

AILE. 2007. Purification function of short rotation willow coppice: Summary of experimental results. Association d'Initiatives Locales pour l'Energie et l'Environnement (AILE) Wilwater Project, Saint Brieuc, France.

Dale, V.H., and S. Polasky. 2007. Measures of the effects of agricultural practices on ecosystem services. Ecol. Econ. 64:286–296. doi:10.1016/j.ecolecon.2007.05.009

Elowson, S. 1999. Willow as a vegetation filter for cleaning of polluted drainage water from agricultural land. Biomass Bioenergy 16:281–290. doi:10.1016/S0961-9534(98)00087-7

ESRI. 2016. ArcGIS desktop: Release 10.x. Environ. Syst. Res. Inst., Redlands, CA.

Galloway, J.N., A.R. Townsend, J.W. Erisman, M. Bekunda, Z. Cai, J.R. Freney et al. 2008. Transformation of the nitrogen cycle: Recent trends, questions, and potential solutions. Science 320:889–892. doi:10.1126/science.1136674

Gelderman, R.H., and D. Beegle. 2011. Nitrate-nitrogen In: Recommended chemical soil test procedures for the North Central Region. North Central Regional Res. Publ. no. 221. Missouri Agric. Exp. Stn., Columbia, MO. p. 17–21.

Grafton, K., B. Joern, A. Mallarino, D. Mengel, J. Dahl, D. Kaiser et al. 2015. Recommended chemical soil test procedures for the North Central Region. Missouri Agric. Exp. Stn., Columbia, MO.

Graham, J.B., J.I. Nassauer, M.C. Negri, and Ssegane, H. 2016. Landscape boundary objects in socio-ecological research: Engaging stakeholders to investigate production alternatives for perennial bioenergy crops. Ph.D. diss., Univ. of Michigan, Ann Arbor.

Graham, J.B., J.I. Nassauer, W.S. Currie, H. Ssegane, and M.C. Negri. 2017. Assessing wild bee abundance in perennial bioenergy landscapes: Effects of bioenergy crop composition, landscape configuration, and bioenergy crop area. Landscape Ecol. 32:1023–1037. doi:10.1007/s10980-017-0506-y

IDOA and IEPA. 2015. Illinois nutrient loss reduction strategy. Illinois Dep. Agric., Illinois Environ. Prot. Agency. http://www.epa.illinois.gov/Assets/iepa/water-quality/watershed-management/nlrs/nlrs-final-revised-083115.pdf (accessed 15 Nov. 2015).

Kahle, P., C. Criegee, and B. Lennartz. 2002. Willow stands as an alternative method for the reduction of leachate at contaminated sites—numerical investigations. J. Plant Nutr. Soil Sci. 165:501–505. doi:10.1002/1522-2624(200208)165:4<501::AID-JPLN501>3.0.CO;2-R

Kozacek, C. 2014. Toledo issues emergency 'do not drink water' warning to residents. Circle of Blue: Water News, 2 August.

Li, C. 2012. The DNDC model. Univ. of New Hampshire, Inst. for the Study of Earth, Oceans, and Space. http://www.dndc.sr.unh.edu/ (accessed 9 May 2017).

McChung, M., and M. van Bavel. 2005. New technologies to compute transpiration and water balances for phytoremediation projects. Dynamax. ftp://ftp.dynamax.com/Presentations/IPTech-2005-Presentation.pdf (accessed 9 May 2011).

Mirck, J., and T.A. Volk. 2009. Seasonal sap flow of four Salix varieties growing on the Solvay wastebeds in Syracuse, NY, USA. Int. J. Phytoremediation 12:1–23. doi:10.1080/15226510902767098

Nissim, W.G., A. Voicu, and M. Labrecque. 2014. Willow short-rotation coppice for treatment of polluted groundwater. Ecol. Eng. 62:102–114. doi:10.1016/j.ecoleng.2013.10.005

NOAA. 2016. Climate data online search. Dep. of Commerce, NOAA. https://www.ncdc.noaa.gov/cdo-web/search;jsessionid=55E88BDD157E7DB5822944FB334B6C10 (accessed 22 Apr. 2017).

Promega Corpration. 2009. Technical bulletin: Griess reagent system instructions for use of product G2930. Promega Corporation, Madison, WI. https://www.promega.com/resources/protocols/technical-bulletins/0/griess-reagent-system-protocol/ (accessed 22 Apr. 2017).

R Core Team. 2016. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna.

Rabalais, N. N. 2002. Nitrogen in aquatic ecosystems. Ambio 31:102–112. doi:10.1579/0044-7447-31.2.102

Rabalais, N.N., R.E. Turner, and D. Scavia. 2002. Beyond science into policy: Gulf of Mexico hypoxia and the Mississippi River nutrient policy development for the Mississippi River Watershed reflects the accumulated scientific evidence that the increase in nitrogen loading is the primary factor in the worsening of hypoxia in the northern Gulf of Mexico. Bioscience 52:129–142. doi:10.1641/0006-3568(2002)052[0129:BSIPGO]2.0.CO;2

Smart, L., T. Volk, J. Lin, R. Kopp, I. Phillips, K. Cameron, E. White, and L. Abrahamson. 2005. Genetic improvement of shrub willow (Salix spp.) crops for bioenergy and environmental applications in the United States. Unasylva 56:51.

Snider, A. 2015. Water pollution: Iowa utility's lawsuit takes new stab at old nutrient problems Greenwire. http://www.eenews.net/stories/1060012531 (accessed 25 Nov. 2016).

Ssegane, H., and M.C. Negri. 2016. An integrated landscape designed for commodity and bioenergy crops for a tile-drained agricultural watershed. J. Environ. Qual. 45:1588–1596. doi:10.2134/jeq2015.10.0518

Ssegane, H., M.C. Negri, J. Quinn, and M. Urgun-Demirtas. 2015. Multifunctional landscapes: Site characterization and field-scale design to incorporate biomass production into an agricultural system. Biomass Bioenergy 80:179–190. doi:10.1016/j.biombioe.2015.04.012

Ssegane, H., C. Zumpf, M.C. Negri, P. Campbell, J.P. Heavey, and T.A. Volk. 2016. The economics of growing shrub willow as a bioenergy buffer on agricultural fields: A case study in the Midwest Corn Belt. Biofuels Bioprod. Biorefin. 10:776–789. doi:10.1002/bbb.1679

Susfalk, R., and D. Johnson. 2002. Ion exchange resin based soil solution lysimeters and snowmelt solution collectors. Commun. Soil Sci. Plant Anal. 33:1261–1275. doi:10.1081/CSS-120003886

Townsend, A.R., R.W. Howarth, F.A. Bazzaz, M.S. Booth, C.C. Cleveland, S.K. Collinge et al. 2003. Human health effects of a changing global nitrogen cycle. Front. Ecol. Environ 1:240–246. doi:10.1890/1540-9295(2003)001[0240:HHEOAC]2.0.CO;2

USDOE. 2016. 2016 billion-ton report: Advanced domestic resources for a thriving bioeconomy. Vol. 1: Economic availability of feedstocks. Oak Ridge Natl. Laboratory, Oak Ridge, TN.

USDOE and USDA. 2009. Sustainability of biofuels: Future research opportunities; report from the October 2008 workshop. USDOE, Office of Science, and USDA, Washington, DC.

USEPA. 1974. Method #:353.3. Nitrogen, nitrate-nitrite (spectrophotometric, cadium reduction). U. S. Gov. Print. Off., Washington, DC. http://monitoringprotocols.pbworks.com/f/EPA+353_3.pdf (accessed 22 Apr. 2017).

USEPA. 2013. Hypoxic zone: Looking farward: The strategy of the federal members of the Hypoxia Task Force. Mississippi River Gulf of Mexico Watershed Nutrient Task Force, USEPA, Washington DC. https://www.epa.gov/sites/production/files/2015-03/documents/hypoxia_annual_federal_strategy_508.pdf (accessed 27 Jan. 2016).

Ventura, M., G. Sorrenti, P. Panzacchi, E. George, and G. Tonon. 2013. Biochar reduces short-term nitrate leaching from a horizon in an apple orchard. J. Environ. Qual. 42:76–82. doi:10.2134/jeq2012.0250