Modeling and Analysis

Biofpr Biofuels Bioproducts & Biorefining

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

Herbert Ssegane[†], Colleen Zumpf, M. Cristina Negri, Patty Campbell, Argonne National Laboratory, IL, USA **Justin P. Heavey, Timothy A. Volk,** State University of New York, Syracuse, NY, USA

Received March 17, 2016; revised July 8, 2016; and accepted July 11, 2016
View online at Wiley Online Library (wileyonlinelibrary.com);
DOI: 10.1002/bbb.1679; *Biofuels, Bioprod. Bioref.* (2016)

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

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

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

Correspondence to: M. Cristina Negri, Energy Systems Division, Argonne National Laboratory, 9700 South Cass Argonne, IL 60439, USA. E-mail: negri@anl.gov
[†]Current affiliation: Climate Corporation, Monsanto, St. Louis, MO, USA

SCI

Introduction

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

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

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

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

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

Methods and assumptions

Study area

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

Willow production and transport costs

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

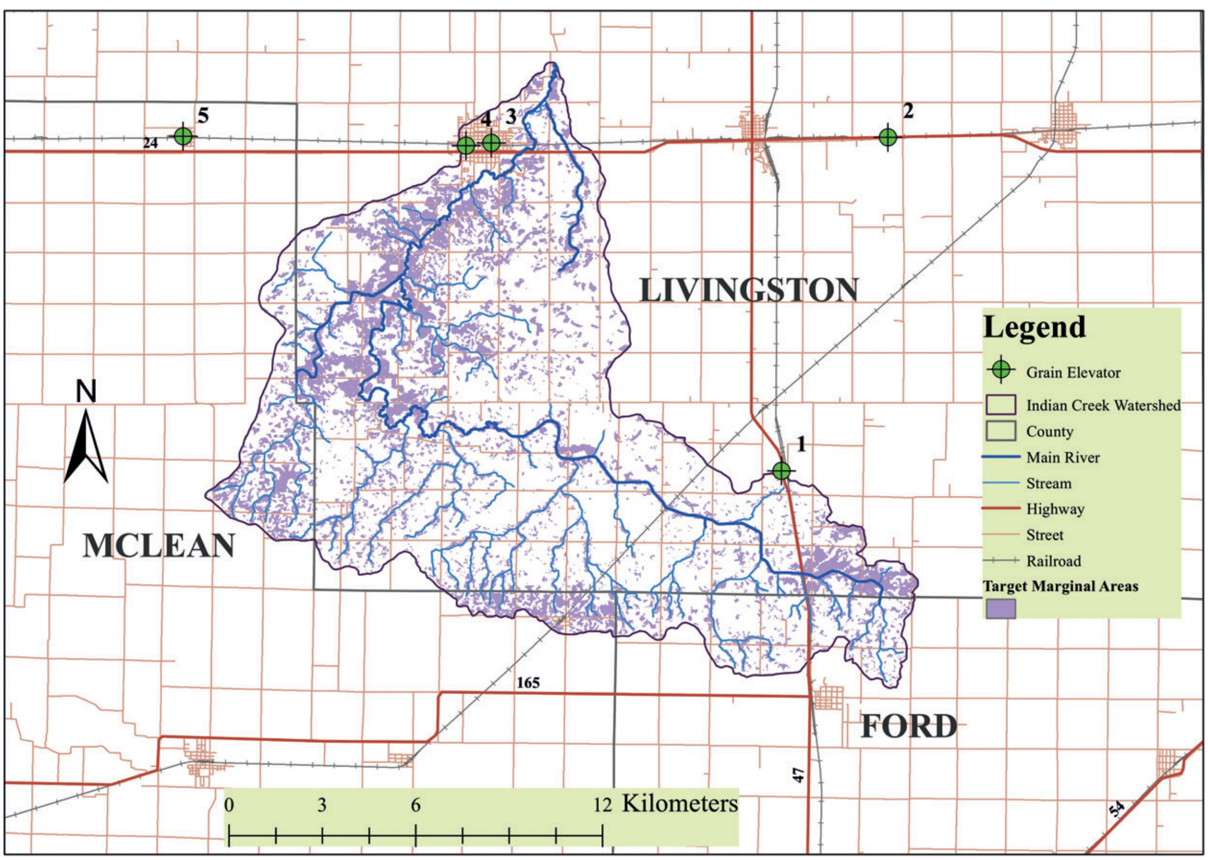


Figure 1. Locations of grain elevators and underproductive or environmentally sensitive soils in the Indian Creek watershed, IL.

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

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

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

*Volk *et al.* [48]

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

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

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

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

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

Net revenue of corn on marginal areas and opportunity costs

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

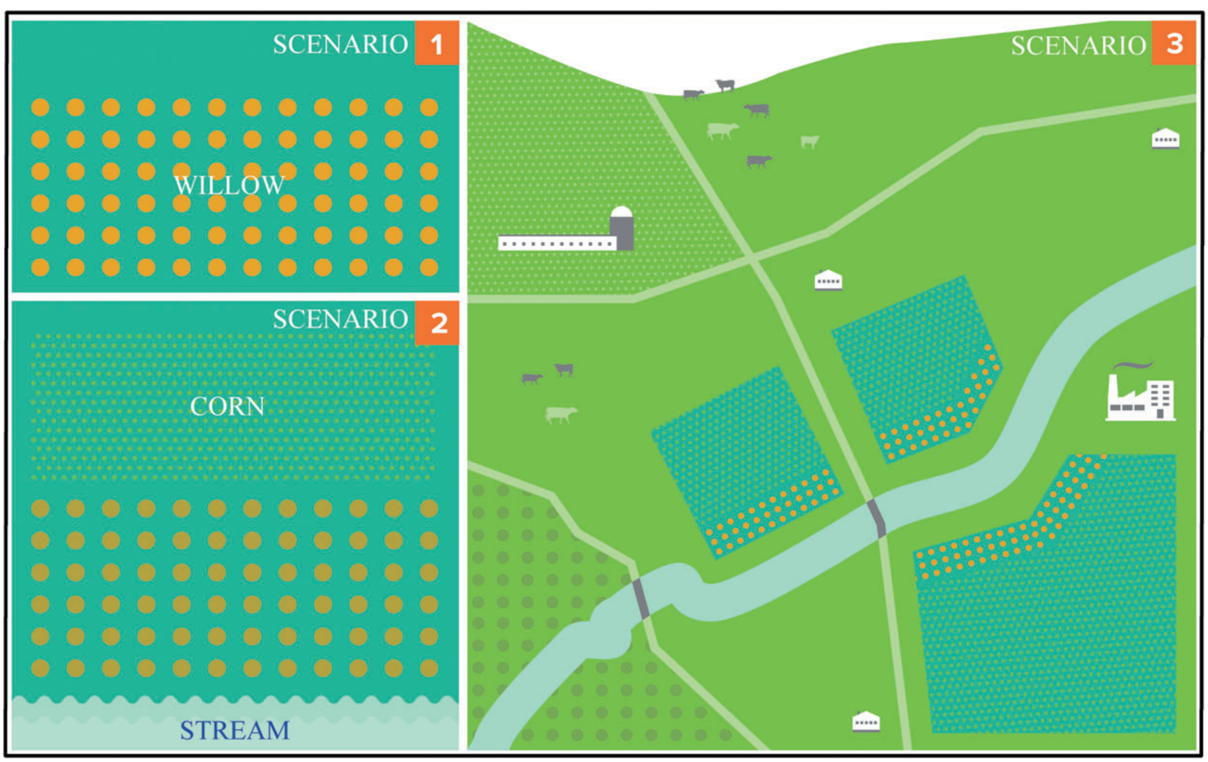


Figure 2. An infographic illustrating the three scenarios. (a) Business as usual, BAU (single field, fertilizer application, & headland); (b) Landscape: single subfield, LSSF (single subfield, no fertilizer & no headland); and (c) Landscape: multiple subfields, LMSF (multiple subfields across the watershed).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

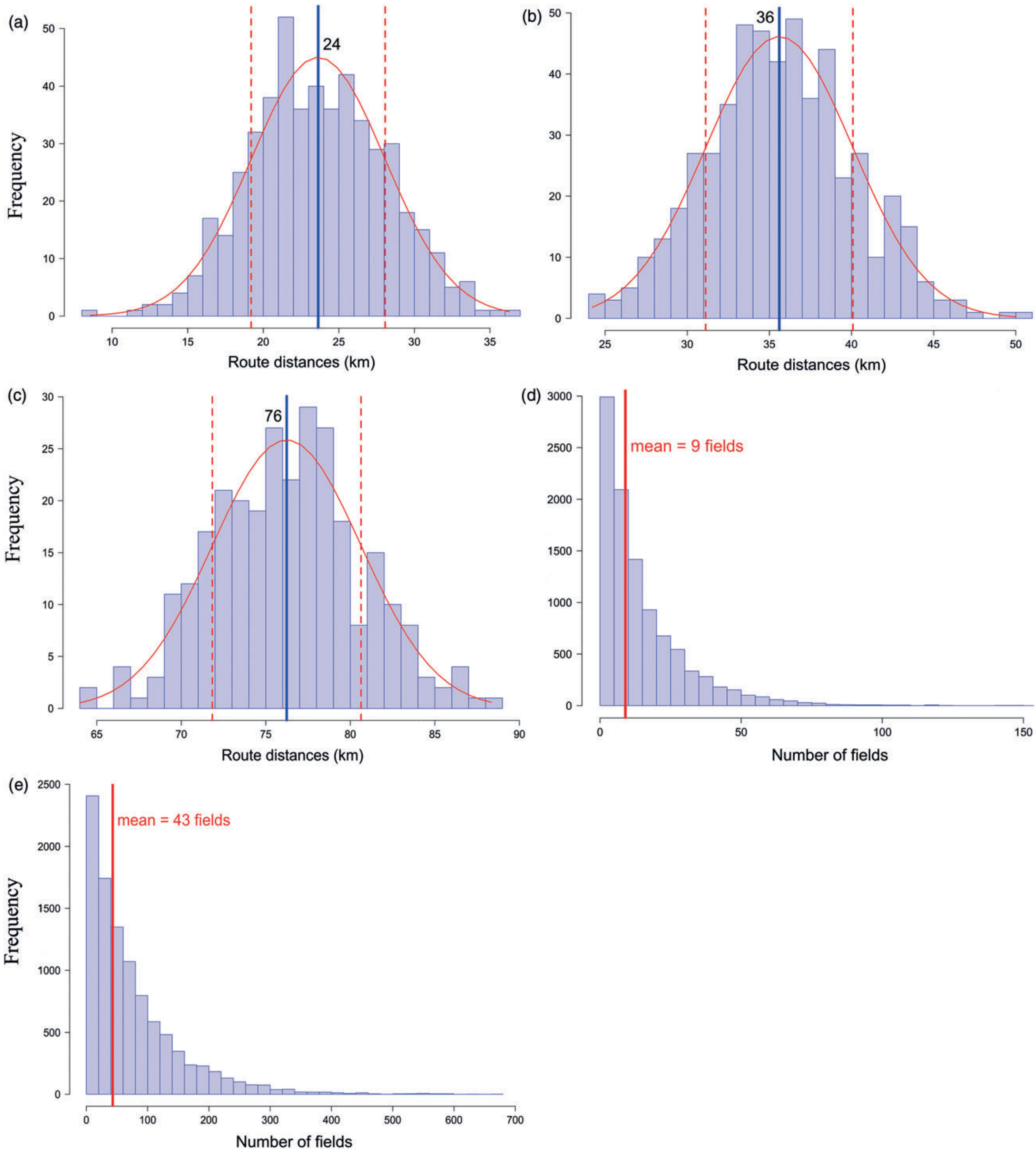


Figure 3. Histograms of simulated most likely transport distances from the subfields to Trainer Grain depot in the Indian Creek Watershed with total subfield area of 2.0 ha (a), 10.1 ha (b), and 40.5 ha (c). The most likely transport distances for Figures 2b and 2c correspond to average number of 9 subfields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

(\$1055 ha^{-1}) were estimated using a Corn-Soybean rotation tool[13] given a corn after soybean rotation option assuming low productivity land in central Illinois. The non-land costs include direct, power, and overhead costs. Annual corn and farmland cash rent prices for 2008 to 2013 were obtained from Illinois historical corn prices[32] and historical cash rent data.[33] Refer to Table S2 for annual variation of the corn and cash rent prices. Corn yields were estimated using the range of average annual corn yields from three counties that comprise the watershed (Livingston, McLean, and Ford). The annual minimum and maximum county level corn yields were reduced by 25% to estimate corn yields grown on marginal lands,[34] hence resulting in corn yield variations of 3.2 to 9.6 $Mg_{dry}\ ha^{-1}$ (50 to 152 bu ac^{-1}). The corn yield range is due to annual variation in weather conditions and differences in county average yields. Net revenue per hectare at the watershed level for corn was calculated using Eqn (1).

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

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

Cost of nitrogen loss reduction

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

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

Results

EcoWillow infield and transport economics

EcoWillow 2.0 estimated production costs and revenues consider both 13- and 22-year investment time frames. The costs reported in this study are for the 22-year time frame because it represents the complete production cycle before willow replanting and includes costs to remove stools after the final harvest at the end of the 22-year period. The annual net revenue under all production scales and scenarios varies between –\$3 and –\$15 Mg^{-1} (–\$67 to –\$304 ha^{-1}) at a biomass price of \$46.30 Mg_{wet}^{-1} (\$71.50 Mg_{dry}^{-1}: Fig. 4). A range of biomass prices (\$23.60 to 46.30 Mg_{wet}^{-1}) was run to account for variability in a potential heating market for wood chips;[41] all yielded negative returns. Therefore, willow biomass production in this watershed is a net loss, with high land cash rents (Table S3) accounting for over 50% of the total cost (Table 3).
The minimum and maximum net losses fall under the LSSF (–\$3 Mg^{-1}) and the LMSF (–\$15 Mg^{-1}) scenarios. Comparison between cases (2.0, 10.1, and 40.5 ha) shows a decrease in revenue losses for the BAU and LSSF scenarios as the total area of production increases (Fig. 4) and thus efficiency in production increases with scale. Net revenues of the LMSF scenario for cases 1 and 2 are comparable due to the limited difference in the most likely transport distance (9 vs. 25 km). However, at the 40.5 ha field size, transport costs are higher because of the increased number of fields and increased transport distance (Fig. 3).
For all cases, the LSSF scenario had the lowest negative return, or better outcome. This was followed by the BAU scenarios, highlighting the impact of the added fertilizer application and headland. The differences in annual net revenue due to differences in transport distance (minimum and maximum) for the BAU and the LSSF were \$1.3 Mg_{wet}^{-1} (\$31 ha^{-1}) and \$2 Mg_{wet}^{-1} (\$29 ha^{-1}), respectively, thus highlighting the impact of transportation. The cost difference of approximately \$5 Mg_{wet}^{-1} between BAU and LSSF is equivalent to the cost of having landscape subfields within a radius of 6 to 21 km. Therefore, the economics of a single dedicated field (BAU) located 2–18 km from the depot are comparable to those of using landscape-placed subfields at distances of 8–39 km from the depot, due to

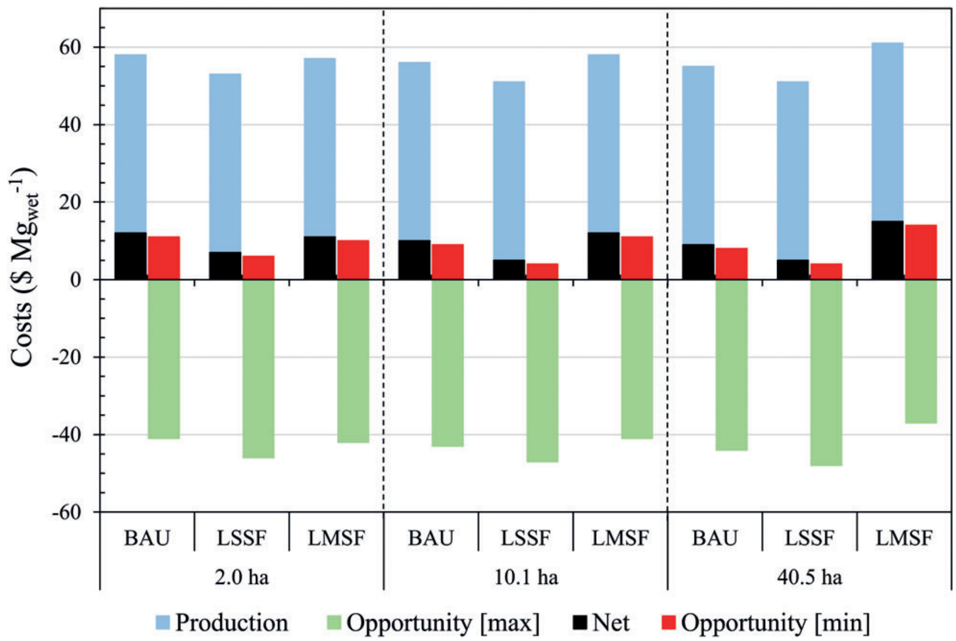


Figure 4. Comparison of production, net, and opportunity costs of willow under business as usual (BAU) and two landscape scenarios (LSSF: single subfield and LMSF: multiple subfields) across three production scales (2.0, 10.1, and 40.5 ha). Net costs are differences between production costs and revenue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

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

Opportunity costs

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

Cost of nitrogen removal

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

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

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

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

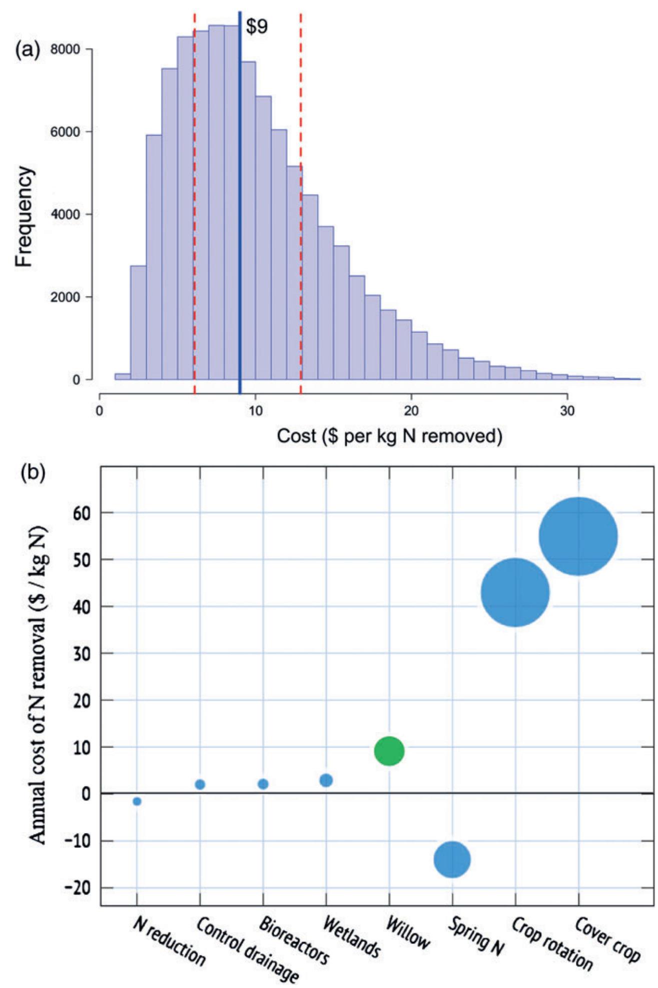


Figure 5. (a) Frequency distribution of nitrogen removal cost by shrub willow buffer in the Indian Creek watershed. Solid line represents the median (\$9) of 100,000 simulations, with the dashed lines representing the 25th (\$6) and 75th (\$13) quartiles. Minimum and maximum values are \$1.8 and \$37,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

Discussion

Monetization of ecosystem services

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

Cost comparisons with conservation practices

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

Cost comparisons with wastewater treatment

Beyond the field level, system-level nitrogen removal strategies in the form of wastewater and drinking water treatment (although not directly comparable) may be useful in placing a value on ecosystem services. The cost of treating wastewater for nitrogen removal is highly dependent on the size of the waste treatment plant, the target effluent concentration level, and the technology used.[43] For example, Washington DC's Blue Plains advanced wastewater treatment plant, a very large facility treating 1.4 billion L day^{-1} has calculated the cost of removing nitrogen from its effluent as \$1.85 kg N^{-1} removed to reduce N from 14 to 7.5 mg L^{-1}, then an additional \$8.13 kg N^{-1} to bring the concentration further down to 5 mg L^{-1}, and an additional \$113.52 kg N^{-1} removed to further reduce the concentration to 3.9 mg L^{-1}.[44] Because of economies of scale, smaller plants incur comparatively higher costs, in the vicinity of \$628 kg N^{-1} yr^{-1} for 11.36 million L day^{-1} flows to reach a 5 mg L^{-1} nitrogen effluent concentration.[45] Future research will need to inform system-level planning, encompassing an assessment of the return on investments in both point- and non-point source reductions to achieve State Nutrient Loss Reduction goals in the best interests of taxpayers and all stakeholders. In this context, bioenergy buffers should be examined as a cost-effective tool to be integrated into existing best practices.

Conclusions

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

Acknowledgements

Funding from the US Department of Energy, Office of Energy Efficiency and Renewable Energy, Bioenergy Technologies Office is gratefully acknowledged. The submitted manuscript has been created by UChicago Argonne, LLC, Operator of Argonne National Laboratory ('Argonne'). Argonne, a US Department of Energy Office of Science laboratory, is operated under Contract No. DE-AC02-6CH11357. The US Government retains for itself, and others acting on its behalf, a paid-up non-exclusive, irrevocable worldwide license in said paper to reproduce, prepare derivative works, distribute copies to the public, and perform publicly and display publicly, by or on behalf of the Government. The authors also acknowledge anonymous reviewers who provided valuable insights and recommendations.

References

1. Freeman OE, Duguma LA and Minang PA, Operationalizing the integrated landscape approach in practice. *Ecol Soc* **20**(1):24 (2015).
2. Dale VH, Kline KL, Buford MA, Volk TA, Smith CT and Stupak I, Incorporating bioenergy into sustainable landscape designs. *Renew Sustain Energ Rev* **56**:1158–1171 (2016).
3. Eranki PL, Manowitz DH, Bals BD, Izaurralde RC, Kim S and Dale BE, The watershed-scale optimized and rearranged landscape design (WORLD) model and local biomass processing depots for sustainable biofuel production: Integrated life cycle assessments. *Biofuel Bioprod Bioref* **7**(5):537–550 (2013).
4. Gopalakrishnan G, Negri MC and Synder S, Redesigning agricultural landscapes for sustainability using bioenergy crops: quantifying the tradeoffs between agriculture, energy and the environment. *Aspects of Applied Biology* **112**:139–146 (2011).
5. Jordan N, Schulte L, Williams C, Mulla D, Pitt D, Schively Slotterback C *et al,* Landlabs: An Integrated approach to creating agricultural enterprises that meet the triple bottom line. *Journal of Higher Education Outreach and Engagement* **17**(4): 175–200 (2013).
6. Ghezehei SB, Everson CS and Annandale JG, Can productivity and post-pruning growth of Jatropha curcas in

silvopastoral systems be regulated by manipulating tree spacing/arrangement without changing tree density? *Biomass Bioenerg* **74**:233–243 (2015).

7. Harmel RD, Haney RL, Smith DR, White M and King KW, USDA-ARS Riesel Watersheds, Riesel, Texas, USA: Water quality research database. *Water Resour Res* **50**(10):8374–8382 (2014).
8. Ssegane H and Negri MC, An integrated landscape designed for commodity and bioenergy crops for a tile-drained agricultural watershed. *J Environ Qual* (2016). doi:10.2134/jeq2015.10.0518
9. Ferrarini A, Fornasier F, Serra P, Ferrari F, Trevisan M and Amaducci S, Impacts of willow and miscanthus bioenergy buffers on biogeochemical N removal processes along the soil-groundwater continuum. *GCB Bioenergy* (2016). doi:10.1111/gcbb.12340
10. Gopalakrishnan G, Negri MC and Snyder SW, A novel framework to classify marginal land for sustainable biomass feedstock production. *J Environ Qual* **40**(5):1593–1600 (2011).
11. Schmer MR, Vogel KP, Varvel GE, Follett RF, Mitchell RB and Jin VL, Energy potential and greenhouse gas emissions from bioenergy cropping systems on marginally productive cropland. *PloS one*. **9**(3):e89501 (2014).
12. Ssegane H, Negri MC, Quinn J and Urgun-Demirtas M, Multifunctional landscapes: Site characterization and field-scale design to incorporate biomass production into an agricultural system. *Biomass Bioenerg* **80**:179–190 (2015).
13. Bonner I, Cafferty K, Muth D, Tomer M, James D, Porter S *et al.,* Opportunities for energy crop production based on subfield scale distribution of profitability. *Energies* **7**(10):6509–6526 (2014).
14. Brandes E, McNunn GS, Schulte LA, Bonner IJ, Muth DJ, Babcock BA *et al.,* Subfield profitability analysis reveals an economic case for cropland diversification. *Environ Res Lett* **11**(1):014009 (2016).
15. David MB, Drinkwater LE and McIsaac GF, Sources of nitrate yields in the Mississippi River Basin. *J Environ Qual* **39**(5):1657–1667 (2010).
16. Cairns J, Sonder K, Zaidi P, Verhulst N, Mahuku G, Babu R *et al.,* Maize production in a changing climate: impacts, adaptation, and mitigation strategies. *Adv Agron* **114:**1–58 (2012).
17. Ciampitti IA and Vyn TJ, Physiological perspectives of changes over time in maize yield dependency on nitrogen uptake and associated nitrogen efficiencies: A review. *Field Crop Res* **133**:48–67 (2012).
18. Kant S, Bi Y-M and Rothstein SJ, Understanding plant response to nitrogen limitation for the improvement of crop nitrogen use efficiency. *J Exp Bot* **62**(4):1499–1509 (2011).
19. Wang M, Jeongwoo H, Dunn JB, Cai H and Elgowainy A, Well-to-wheels energy use and greenhouse gas emissions of ethanol from corn, sugarcane and cellulosic biomass for US use. *Environ Res Lett* **7**(4):045905 (2012).
20. Schnitkey G, Crop Budgets, Illinois, 2015. University of Illinois, Department of Agricultural and Consumer Economics, Urbana-Champaign IL (2015).
21. NSF-DOE-EPA. NSF (National Science Foundation), DOE (US Department of Energy), and EPA (US Environmental Protection Agency), Energy-Positive Water Resource Recovery Workshop Report. Arlington, VA: 2015 April 28–29, 2015.
22. McLellan E, Robertson D, Schilling K, Tomer M, Kostel J, Smith D *et al.,* Reducing Nitrogen Export from the Corn Belt to the Gulf of Mexico: Agricultural Strategies for Remediating Hypoxia. JAWRA *J Am Water Resour Assoc* **51**(1):263–289 (2015).
23. Christianson L, Tyndall J and Helmers M, Financial comparison of seven nitrate reduction strategies for Midwestern agricultural drainage. *Water Resour Econ* **2**–3:30–56 (2013).
24. Börjesson P and Berndes G, The prospects for willow plantations for wastewater treatment in Sweden. *Biomass Bioenerg* **30**(5):428–438 (2006).
25. Hamada Y, Ssegane H and Negri MC, Mapping intra-field yield variation using high resolution satellite imagery to integrate bioenergy and environmental stewardship in an agricultural watershed. *Remote Sensing* **7**(8):9753–9768 (2015).
26. Olson K, Lang J, Garcia-Paredes J, Majchrzak R, Hadley C, Woolery M *et al.*, Average crop, pasture and forestry productivity ratings for Illinois soils. Office of Research, College of Agricultural, Consumer and Environmental Sciences, University of Illinois, Urbana-Champaign, IL (2000).
27. USDA, Web Soil Survey [Online]. USDA (2012). Available at: http://websoilsurvey.nrcs.usda.gov/ [August 28, 2013].
28. USDA, Soil Survey manual. USDA Handbook 18. [Online]. USDA (1993) Available at: http://www.nrcs.usda.gov/wps/portal/nrcs/detail/soil/planners/?cid=nrcs142p2_054262 [September 17, 2014].
29. Keefer DA, Potential for agricultural chemical contamination of aquifers in Illinois:1995 revisions. Illinois State Geological Survey Champaign, Illinois (1995).
30. Buchholz T and Volk T, Profitability of Willow biomass crops affected by incentive programs. *Bioenergy Res* **6**(1):53–64 (2013).
31. Heavey J and Volk TA, EcoWillow 2.0 – Economic Analysis of Shrub Willow Crops.: SUNY ESF, Syracuse, NY (2014).
32. University of Illinois, Illinois Average Farm Price Received Database [Online]. University of Illinois at Urbana-Champaign (2015). Available at: http://www.farmdoc.illinois.edu/manage/uspricehistory/us_price_history.html [December 16, 2015].
33. University of Illinois, Average Cash Rents by County, Illinois, 2008 to 2013. [Online]. University of Illinois at Urbana-Champaign (2015). Available at: [December 16, 2015].
34. Schmer MR, Vogel KP, Mitchell RB, Dien BS, Jung HG and Casler MD, Temporal and spatial variation in switchgrass biomass composition and theoretical ethanol yield. *Agron J* **104**(1):54–64 (2012).
35. Gentry LE, David MB, Below FE, Royer TV and McIsaac GF, Nitrogen mass balance of a tile-drained agricultural watershed in East-Central Illinois. *J Environ Qual* **38**(5):1841–1847 (2009).
36. Smith SL, Thelen KD and MacDonald SJ, Yield and quality analyses of bioenergy crops grown on a regulatory brownfield. *Biomass Bioenerg* **49**:123–130 (2013).
37. Woli KP, David MB, Cooke RA, McIsaac GF and Mitchell CA, Nitrogen balance in and export from agricultural fields associated with controlled drainage systems and denitrifying bioreactors. *Ecolog Eng* **36**(11):1558–1566 (2010).
38. Perttu K and Kowalik P, Salix vegetation filters for purification of waters and soils. *Biomass Bioenerg* **12**(1):9–19 (1997).
39. Hendricks A. Wagner AE, Volk TA, Newman DH and Brown TR, A cost-effective evaluation of biomass district heating in rural communities. *Appl Energ* **162**:561–569 (2016).
40. Liu B, Biomass production of willow short-rotation coppice across sites and determinants of yields for SV1 and SX61.

State University of New York Col. of Environmental Science and Forestry, New York (2013) 139 p.
41. Stoof CR, Richards BK, Woodbury PB, Fabio ES, Brumbach AR, Cherney J *et al.,* Untapped potential: Opportunities and challenges for sustainable bioenergy production from marginal lands in the Northeast USA. *Bioenerg Res* **8**(2):482–501 (2015).
42. Volk T, Abrahamson L, Cameron K, Castellano P, Corbin T, Fabio E *et al.,* Yields of willow biomass crops across a range of sites in North America. *Asp Appl Biol* **112**(6):67–74 (2011).
43. EPA, A compilation of cost data associated with the impacts and control of nutrient pollution. [Online]. US Environmental Protection Agency Contract No.: EPA 820-F-15-096 (2015). Available at: http://www.epa.gov/sites/production/files/2015-04/documents/nutrient-economics-report-2015.pdf [January 23, 2016].
44. DCWater, Blue Plains advanced wastewater treatment plant. [Online]. District of Columbia Water and Sewer Authority (2016). Available at: https://www.dcwater.com/news/publications/Blue_Plains_Plant_brochure.pdf [February 24, 2016].
45. BCWCTF, Comparison of costs for wastewater management systems applicable to Cape Cod. [Online]. Barnstable County Wastewater Cost Task Force (2010). Available at: http://www.ccwpc.org/index.php/component/content/article/36-wastewater-reports/78-comparison-of-costs-for-wastewater-management-systems-applicable-to-cape-cod [January 23, 2016].
46. Bracmort K, The Renewable Fuel Standard (RFS): Cellulosic Biofuels. [Online]. Congressional Research Service (2015). Available at: http://www.lankford.senate.gov/imo/media/doc/The%20Renewable%20Fuel%20Standard%20Cellulosic%20Biofuels.pdf [January 27, 2016].
47. EPA, Mississippi River/Gulf of Mexico Watershed Nutrient Task Force 2015 Report to Congress. [Online]. United States Enviromental Protection Agency (2015).Available at: http://www.epa.gov/sites/production/files/2015-10/documents/htf_report_to_congress_final_-_10.1.15.pdf [January 27, 2016].
48. Volk TA, Abrahamson LP, Buchholz T, and Eisenbies JC, Development and deployment of Willow Biomass Crops, in *Cellulosic Energy Cropping Systems*, ed by Karlen DL. John Wiley and Sons (2014). p. 201–217.

Herbert Ssegane

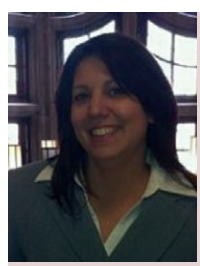
Dr Herbert Ssegane is a postdoctoral appointee in the Energy Systems Division at Argonne National Laboratory, USA. His research projects have focused on field and watershed scale modeling of surface water hydrology, hydraulics, and water quality; assessments of impacts of land use and climate change on water resources; use of GIS and remote sensing for sustainable landscape design; environmental monitoring; and statistical data analysis. His interests include fusion of computational modeling and sensor data analytics to resolve the effects of temporal and spatial variability in land management decisions and for sustainable management of natural resources.

Colleen Zumpf

Colleen Zumpf is a research associate in the Energy Systems Division at Argonne National Laboratory, USA. She holds a Master's in Environmental Biology (2015, Governors State University, USA) and a Bachelor's in Environmental Science and Biology (2012, Monmouth College, USA). Her research includes a focus on water quality and bioenergy production in agricultural landscapes, as well as the evaluation of plant response in water limited environments. Her research interests include land management impacts on ecological systems and community ecological dynamics.

M. Cristina Negri

Dr M. Cristina Negri is a principal agronomist and environmental engineer at Argonne National Laboratory, USA. She is also a senior fellow at the Energy Policy Institute and a fellow at the Institute for Molecular Engineering at University of Chicago, USA. Her research encompasses multidisciplinary projects developing technologies for environmental remediation and stewardship, including soil remediation and water treatment. Current interests are in systems approaches to environmental problems where industrial ecology concepts are applied to water and land management, both in agricultural and urban contexts.



Patty Campbell

Patty Campbell is a research chemist in the Energy Systems Division at Argonne National Laboratory, USA. She holds a BSc in Chemistry from Purdue University. She is also a limited term lecturer at Purdue University Northwest. Patty's research includes effects of extracts from the *Cnidiscolus chaymanasa* plant on the enzymatic activity of HMG-CoA reductase and nitrogen remediation and bioenergy production in agricultural landscapes. Her interests include leadership roles in programs that encourage young girls to consider a career in a STEM (Science, Technology, Engineering and Mathematics) related field.

Justin P. Heavey

Justin P. Heavey is a senior research support specialist at the State University of New York College of Environmental Science and Forestry (SUNY-ESF), Syracuse, NY. He provides a variety of extension services and contributes to research projects for the development of sustainable bioenergy supply chains throughout Northeastern USA. He also contributes to campus sustainability projects and teaches environmental and energy auditing. His interests include sustainability in higher education, sustainable vegetation systems, and ecosystem restoration.

Timothy A. Volk

Dr Timothy A. Volk is a senior research associate at State University of New York, College of Environmental Science and Forestry (SUNY-ESF), USA. His research has focused on the development of shrub willow biomass cropping systems as a feedstock for bioproducts and bioenergy and the use of willow as an alternative cover for industrial waste sites. He is actively involved in sustainability assessments of bioenergy systems, life cycle assessments and economic modeling of short rotation woody crops, regional woody biomass resource supplies, and harvesting systems for short rotation woody crops.