Impact of landscape design on the greenhouse gas emissions of shrub willow bioenergy buffers in a U.S. Midwest corn production landscape

Short title (70 characters): Greenhouse gas emissions of willow bioenergy buffers in a U.S. Midwest landscape

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ABSTRACT

Previous studies have evaluated the economics and ecosystem services of perennial bioenergy crops when replacing grain crops on marginal (environmentally critical and/or underproductive) lands. This study used life-cycle analysis (LCA) to investigate the greenhouse gas (GHG) emissions of perennial crops when grown in targeted landscape positions and their impact in reducing nitrogen leaching. Specifically, LCA was performed to evaluate the GHG emissions of growing shrub willow on marginal lands in the Indian Creek watershed in Illinois to assess the sustainability of strategically planted willow buffer strips. Willow was grown as a short-rotation woody crop with a 21-year rotation under three scenarios including a business-as-usual (BAU) field-scale production with nitrogen fertilizer application and two unfertilized subfield buffer scenarios (landscape single subfield (LSSF) or landscape multiple subfields (LMSF)) grown alongside cornfields to reduce nitrate leaching. Each scenario also considers three field sizes, 2.0, 10.1, and 40.5 ha. The average annual GHG emissions from willow production and depot transportation were 0.32–0.77 Mg-CO_2e/ha with the lowest emissions for the LSSF scenario and highest for the BAU. The GHG emissions for the LSSF and BAU scenarios are independent of field size, while LMSF emissions increase with increasing field size, 0.41 Mg-CO_2e/ha at 2.0 ha and 0.76 Mg-CO_2e/ha at 40.5 ha. Emission results were most sensitive to the willow yield, followed by fertilizer application rate (BAU only), harvest fuel consumption, and transportation distance.

1 INTRODUCTION

Bioenergy sustainability touches many aspects of environmental performance, economic viability, and social acceptance. The feat of supplying enough renewable biomass to make a meaningful impact on energy systems is achievable,[1] and the environmental impacts of this scale of biomass production at the U.S. national level has been intensely studied in recent years.[2] Advanced bioenergy systems, particularly those based on perennial crops, present themselves as a more sustainable alternative to fossil-fuel based energy sources.[3] In addition to other benefits that they provide, they can achieve more reductions in energy use and greenhouse gas (GHG) emissions than corn grain ethanol-based systems (Argonne National Laboratory (https://greet.es.anl.gov/)). Nevertheless, environmental sustainability of an agricultural landscape as a whole is dependent upon bioenergy systems that overlap and interface with other agricultural and non-agricultural activities; therefore, the location or configuration of sustainable bioenergy production is highly dependent on the specific landforms present, as well as the adoption of specific management practices.[4, 5] In this respect, the sustainability of bioenergy crops and other agricultural activities is deeply intertwined with multiple factors including, but not limited to, nutrient use efficiency, the use of agrochemicals, and tillage practices. Combined, these factors determine how far water quality–impacting sediment and chemicals will move into surface water and groundwater systems. Likewise, agronomic practices have different impacts on soil organic carbon (SOC) and soil loss; these also depend on soil type, physical characteristics (e.g., slope, land use and land cover, and crop management schemes), and geographic area.[6-9] Several studies, for example, have found higher SOC under willow along with higher aboveground tissue carbon, and belowground tissue carbon than in other bioenergy crops (e.g. switchgrass and *Miscanthus*) or grain crops (e.g. corn and corn-soybean-wheat rotation).[10-12]

However, Bonin and Lal[11] and Zan et al.[12] noted these trends were not always present, suggesting results are site specific.

Production of switchgrass, short-rotation woody crops (SRWCs), and other perennial bioenergy crops in specific landscape positions has the potential to reduce detrimental environmental impacts relative to monocultural commodity grain crop production. It also shows promise as a tool to address agricultural externalities at large (e.g., soil erosion, nutrient and pesticide leaching, biodiversity loss), particularly in the intensively managed corn/soybean rotation landscapes in the U.S. Midwest.[6, 13-16] The ability of dedicated perennial energy crops to generate provisioning (yields) and regulating ecosystem services (e.g., clean water, pollinator services, soil health, and recreational and biodiversity functions) has supported a call for a perennialization of the U.S. Midwestern landscapes to synergistically provide bioenergy feedstock and conservation functions (see Landscape Conservation Cooperative Network (https://lccnetwork.org/), Landlabs,[17] and Green Lands Blue Waters (https://greenlandsbluewaters.net)). This approach could involve the decentralization of biomass production in small, distributed subfield areas positioned on the landscape to maximize the fit between crop productivity and environmental performance. Investigators are determining the potential for landscape design and bioenergy production to the solution of large environmental problems such as the Gulf of Mexico hypoxia,[18] which is caused in large part by the nutrient leakiness of the Midwestern agricultural systems.

In this context, previous work evaluated potential benefits in terms of water quality,[14] pollinator habitat,[19] economic value generated by the optimization of production in economically underproductive lands,[20, 21] and the creation of additional ecosystem services[22] at the watershed scale when perennial bioenergy crops are grown in particular landscape designs. In addition,

Ssegane et al.[23] examined the cost effectiveness and economics of bioenergy production in subfield marginal land in a case study centered on a small agricultural watershed in central Illinois, in the United States. They showed that although positive returns are generally affected by high land rental costs in the region, in some cases a distributed production of biomass on economically marginal land might be a better opportunity cost than growing corn- mostly because doing so would optimize the use of inputs and decrease the need for headland. They also found that when normalized based on the cost per unit of nitrogen (N) removed from water, growing a bioenergy buffer of short-rotation shrub willow would be cheaper than widely accepted conservation practices such as planting cover crops.

When growing biomass crops in distributed, parcellated acreage to meet better environmental outcomes, transportation distances could potentially increase and the use of machinery could be less efficient. However, these additional expenses could be compensated by more efficient use of nutrients and reduced annual operations (e.g., tillage, planting, and herbicide application) on the parts of fields dedicated to perennial crops. The balance of these interdependent factors determines the relative gains in the sustainability of biomass production in terms of both economics and overall GHG emissions.

Life-cycle analysis (LCA) is broadly used to assess the overall environmental impact of the entire production processes and products, and has been used extensively to calculate the emission of GHGs and other regulated gases (Argonne National Laboratory (https://greet.es.anl.gov/)). Numerous studies have used LCA to compare the GHG emission benefits of shrub willow bioenergy production to those of fossil fuels.[24-27] Other studies have evaluated the GHG emission benefits of landscape design systems. A biorefinery-scale study for a region in Michigan found that perennial grasses (i.e., switchgrass and *Miscanthus*) could lower

nitrogen leaching and provide emission reductions when planted in riparian buffers.[28] Another study evaluated production systems in Europe,[29] while Cacho et al.[5] provides an overview of bioenergy buffer feedstocks, including shrub willow, on ecosystem services, including GHG emissions.

The objective of this study was to assess whether distributed production of shrub willow biomass on targeted marginal (land vulnerable to environmental degradation and/or underproductive) areas of farm fields could reduce GHG emissions compared to business-as-usual (BAU) production of shrub willow in dedicated fields. GHG emissions were determined using LCA and a sensitivity analysis was performed to determine which parameters have the largest impact on LCA results.

2 METHODS

The landscape LCA is based on a case study of the Indian Creek watershed in Illinois, which evaluated the economic viability of growing shrub willow (*Salix miyabeana*, SX64) as a bioenergy buffer on intensively managed agricultural systems, like those in the U.S. Corn Belt. Details of the case study can be found in Ssegane et al.[23] Briefly, the case study was based on the concept of embracing future landscape design in agricultural systems to achieve multiple goals: producing food, fiber, and bioenergy feedstock on a given unit of land, while minimizing the environmental footprint. Shrub willow, a SRWC, was used as an example bioenergy crop within subfields that were considered marginal, meaning that they are considered suboptimal for commodity crop production and/or environmentally vulnerable (high susceptibility to nitrate leaching, sediment loss, flooding, etc.).[14, 15] Perennial bioenergy grasses and SRWCs can be better choices in marginal areas relative to commodity crops due to inherent physiological traits that allow them to thrive in suboptimal growing conditions.[5, 30] The Indian Creek watershed was

selected for these studies because it is representative of many watersheds in the U.S. Midwest. More than 87% of the watershed is under corn and soybean production, which results in excessive nitrate levels (>10 mg/L) in water entering the public water supply and downstream aquatic ecosystems.[31] Additional characterization of the watershed can be found in Hamada et al.[31]

2.1 Goal and Scope

This analysis investigated the GHG emissions of a landscape design system that used shrub willow as a replacement for corn on marginal land to reduce the nitrogen leaching in the watershed. Nitrate leaching and nitrous oxide (N_2O) emissions were also evaluated. The system boundary (Figure 1) of the landscape system started with shrub willow production and goes through transportation of harvested willow branches to a depot. Inputs for the production of shrub willow vary based on the landscape design approach (see Section 2.2): grown with or without nitrogen fertilizer (where buffer designs used nitrogen leached from neighboring corn on productive soils as their nutrient source, nitrogen that would otherwise end up in the groundwater and/or downstream surface water systems).[23] Energy was used for shrub willow planting and harvesting, as well as transportation to the depot. N_2O emissions were considered for decomposition of biomass left on the field and application of the nitrogen fertilizer in the BAU scenario. When shrub willow is planted as a buffer, less nitrogen leaches from the corn grown on the neighboring productive land into the groundwater and receiving surface water bodies (Figure 2). Conceptually, the root-soil system in the shrub willow buffers intercepts the leached nitrate moving downhill from corn production. Part of that nitrate is then used by the shrub willow for biomass production. Consequently, this landscape design both reduces nitrate leaching and removes the need for producers to directly apply nitrogen fertilizers to enhance

shrub willow biomass production. In addition, removing the direct application of fertilizer as an input from the shrub willow buffer production system can reduce N_2O emissions from soil microbial respiration, because less nitrate is available.

2.2 Cases and Scenarios Analyzed

The LCA was based on the three production buffer area sizes: 2.0 (practical minimum subfield), 10.1 (recommended minimum production scale), and 40.5 ha (recommended optimal production scale). This is consistent with the Ssegane et al.[23] analysis on the economics of growing shrub willow for bioenergy. Each case was evaluated with three scenarios, shown in Figure 3: (1) BAU, shrub willow grown in a single field for biomass production and requiring fertilizer application; (2) landscape single subfield (LSSF) with shrub willow planted as a buffer within a single corn field that intercepts leached nitrogen; and (3) landscape multiple subfields (LMSF) with shrub willow planted as a buffer within multiple corn fields to intercept leached nitrogen.[23] The BAU and LMSF scenarios represent two realistic options for shrub willow bioenergy feedstock production where shrub willow could be produced in a single dedicated plantation-style field (BAU) or produced across multiple cornfields as buffers in various locations such as riparian zones or upland marginal soil zones (LMSF). The LSSF scenario provides a point of comparison for BAU and LMSF scenarios; it accounts for a buffer design, but assumes production is limited to a single field (no additional travel included as in LMSF).[23]

To compute production and logistical costs for willow, Ssegane et al.[23] used EcoWillow 2.0, a publicly available model developed by the State University of New York College of Environmental Science and Forestry (Heavey (http://www.esf.edu/willow/download.htm)). An existing grain elevator close to the centroid of the Indian Creek watershed was used as a potential biomass depot, subscribing to the adaptive reuse of current infrastructure or co-location with existing transportation infrastructures (e.g., roads and railways).[23] Realistically, these subfields are distributed based on the location of marginal soil areas of individual farms within the watershed. Additional information on marginal subfield identification within the Indian Creek watershed is further described in Ssegane et al.[23] Thus, to represent reality, we calculated the proportion of the total farmland (productive corn-

corn/corn-soybean/soybean-corn plus the buffer) that was made up by the buffer for the three cases based on their actual locations within individual farms in the Indian Creek watershed. The estimated average percentages of buffer land were 71.6%, 15.6%, and 5.2%, corresponding to the 2.0, 10.1, and 40.5 ha cases, respectively. A summary of the cases and scenarios evaluated is provided in Tables

Table *1*: Cases and scenarios evaluated, with corn planted on the productive land and shrub willow or corn planted on adjacent marginal land using the following production scenarios: BAU (single dedicated field), LSSF (landscape single subfield buffer); LMSF (landscape multiple subfield buffers across the watershed). The transportation distance used for the scenarios is based on Euclidean distances between a given subfield and the depot within the Indian Creek watershed, assuming all regions of the watershed are equally accessible[23]. For the BAU and LSSF scenarios, the transportation distance used is the average of the minimum and maximum distances provided in Table S1 of the supporting information. The LMSF scenario requires additional travel between multiple subfields and therefore a most likely distance was used, which was calculated as the mean cumulative Euclidean travel route between the depot and the randomly selected subfields that made up the total acreage for each case scale (2.0, 10.1, and 40.5 ha)[23].

2.3 Life Cycle Inventory

Annual average shrub willow biomass yields and N_2O emissions for all scenarios were based on data from a field research site near Fairbury, Illinois, located in the northern part of the Indian Creek watershed. The field research site is a 6.5-ha continuous corn system where marginal soil areas were carefully classified and planted with shrub willow, which is harvested on a 3-year cycle. The site was established primarily to test the feasibility of recovering lost nutrients from agricultural fields using perennial crops while simultaneously producing biomass and commodity crops. Detailed description of the experimental site can be found in previous

studies.[14-16] N_2O emissions were measured using a static chamber.[32] The biomass yield on marginal land followed the same assumptions as Ssegane et al.,[23] an average of 12.4 Mg_{dry}/ha/yr with a 3-year harvest cycle. It was also assumed that the biomass yield would stay constant across the 21-year shrub willow crop rotation under the 3-year harvest cycle.

The materials and energy used in the Indian Creek study area for biomass production and transportation are provided in Table 2. Shrub willow was grown with a 21-year rotation, where it was harvested (branch biomass only) every third year during the dormant season after the establishment year, a common practice for SRWC. Nitrogen was applied every 3 years in the BAU scenario for a total of seven applications over the rotation. Fuel consumption for planting, harvesting, and transportation of shrub willow were provided by EcoWillow (Heavey (http://www.esf.edu/willow/download.htm)).

Application of nitrogen-based fertilizers to soil and the decomposition of biomass that contains nitrogen results in N_2O emissions due to direct release, volatilization, and leaching.[33] Ssegane et al.[23] found that nitrogen leaching from a corn only field was about 34 kg N/ha/yr and using a shrub willow buffer would reduce it by an average of 64%. As nitrate moves through the soil profile, soil microorganisms convert a portion to N_2O. As nitrate availability in the soil decreases, in part due to shrub willow interception and uptake, there is a corresponding reduction in N_2O emissions. This avoided N_2O emission was determined using the reduction percentage of the amount of nitrogen that is intercepted by the shrub willow-soil system multiplied by the leaching emission factor for indirect soil N_2O emissions of 7.5 g N_2O-N/kg N.[33]

2.4 Life-Cycle Analysis

The landscape GHG emissions were determined for all materials and energy used in the production process. It was assumed off-road diesel would be used for planting and harvesting of

willow branches while on-road diesel would be used for their transportation to the depot. Emission factors for diesel and nitrogen fertilizer production were taken directly from the GREET model (Argonne National Laboratory (https://greet.es.anl.gov/)). N_2O emissions due to nitrogen fertilizer application (15.25 kg N_2O-N/kg N) came from a meta-analysis of fertilizer applied to agricultural soils,[34] while direct and indirect N_2O emissions due to biomass decomposition (12.25 g N_2O-N/kg N) were found using the willow nitrogen content and emission factor.[33]

3 RESULTS AND DISCUSSION

3.1 Landscape-Level GHG Emissions

The landscape-level GHG emissions, provided in Mg-CO_2e/ha, from shrub willow production on the marginal land (including transporting it to the depot) are shown in Figure 4. The total GHG emissions are the highest for the three BAU scenarios at 0.77 Mg-CO_2e/ha followed by the LMSF 40.5-ha scenario at 0.76 Mg-CO_2e/ha. The emissions are the lowest for the LSSF scenarios at 0.32 Mg-CO_2e/ha. For the BAU scenarios, the largest contributor to the GHG emissions is N_2O fertilizer and decomposition at 0.42 Mg-CO_2e/ha, followed by fertilizers and chemicals at 0.14 Mg-CO_2e/ha, farming energy at 0.13 Mg-CO_2e/ha, and transportation at 0.07 Mg-CO_2e/ha. The LSSF scenario had the same transportation emissions as the BAU, but the LMSF emissions were dependent on buffer size at 0.16–0.51 Mg-CO_2e/ha, with emissions increasing with increasing buffer production acreage. The LSSF and LMSF landscape scenarios have lower nitrogen GHG emissions than the BAU, because no fertilizer is applied during feedstock growth. The credit for avoided nitrogen leaching from the productive cornfield for the LSSF and LMSF scenarios is 0.07 Mg-CO_2e/ha.

3.2 Benefits of Growing Shrub Willow on the Buffer

Growing shrub willow on the buffer in the LSSF and LMSF scenarios reduces the GHG emissions of the entire landscape by utilizing leached nitrogen from the corn/soybean rotations. Unlike corn and soybean, shrub willow uses no phosphorus or potassium fertilizer, and less fuel overall, because energy for planting is only needed once over the entire 21-year rotation. Additionally, in the BAU case, it also uses less nitrogen fertilizer than corn (16.0 kg-N/ha/yr for shrub willow vs. 94.2 kg-N/ha/yr for corn) (Argonne National Laboratory (https://greet.es.anl.gov/)). The results of this analysis are consistent with Ferrarini et al.,[35] which found that over the long term, the GHG emissions would decrease when shrub willow was produced as a buffer. An LCA analysis by Agostini et al.[36] also agreed with this finding with greater GHG emissions observed under scenarios when willow was grown in an open-field versus as a buffer strip due to fertilizer application requirements. They also noted that GHG emissions did not significantly increase when willow was grown as a buffer even with the more complex logistics assumed for production.[36] Like corn, willow can be used as a biofuel feedstock, but with substantially lower GHG emissions (Argonne National Laboratory (https://greet.es.anl.gov/)). Shrub willow is produced in a short rotation system, meaning a harvestable crop will not be produced every year, but over the long term, shrub willow production will reduce the emissions of the landscape with the largest GHG benefits from a LSSF landscape design. The LSSF scenario has lower transportation emissions than the LMSF scenario, especially when production acreage increases. The LMSF design was found to have lower emissions than the BAU scenario except at the 40.5 ha scale due to increased transportation emissions for the former, showing that any emission savings due to utilization of nitrogen from the watershed can be negated by fuel consumption during transportation.

From a practical perspective, willow production as conservation buffers to address nutrient loss would be expected to occur across multiple fields in a watershed versus just a single field, making the LMSF design more logical. Additionally, larger scale production systems such as the 40.5 ha scenario, also provides a more practical example as local biorefineries will require large amount of feedstock resources to support operations.

The transportation limitations for environmentally sustainable production of shrub willow buffers across the watershed is also mirrored by the sustainable economic constraints to moving perennial biomass to greater distances. Transportation has been identified as a major barrier to the adoption and production of perennial bioenergy crops under current logistics systems, because of the low bulk density and high fibrous nature of many perennial biomass feedstocks compared to other crops such as corn. Current research is trying to address this limitation.[37] The application of landscape design approaches using technologies such as remote/proximal sensing, geographic information systems (GIS), and landscape-based models, among others, may be useful tools in designing integrated production systems within watersheds, especially in targeting production locations for bioenergy crops to optimize feedstock production and ecosystem service provision.[5] However, a recent review by O'Neill and Maravelias[38] highlights the importance of integrating landscape design approaches with supply chain logistics to optimize production decisions and environmental impacts, while balancing spatially explicit tradeoffs. Agostini et al.[36], also argues the need to account for biogenic carbon exchanges (carbon sequestration and carbon biomass storage), which they found to change significantly the scale of GHG emissions per MJ of fuel produced, thereby shrinking the effect of GHG emissions associated with the supply chain and resulting in negative emissions for bioethanol production.

3.3 Sensitivity Analysis

Sensitivity analysis was used to investigate the impact of various input parameters on the landscape GHG emissions from producing willow and transporting it to the depot. The sensitivity analysis evaluated the fuel consumption during harvest, fertilizer application rate in the BAU scenario, nitrogen removal rate from the watershed in the LSSF and LMSF scenarios, transportation distance, and shrub willow yield. To highlight the overall effect on GHG emissions, parameters were varied by ±25% relative to the baseline input.

Results are provided in Figure 5 for producing shrub willow on a 10.1-ha field for the BAU, LSSF, and LMSF scenarios. Landscape BAU GHG emissions are most sensitive to shrub willow yield (Figure 5A), followed by fertilizer application rate. Increasing the shrub willow yield from 12.4 to 15.5 dry Mg/ha/year increases the GHG emissions from 0.77 to 1.08 Mg-CO_2e/ha, respectively. The increase in GHG emissions from a yield increase is due to additional fuel required during harvest as greater biomass yield can slow operations and increase inner-field operations such as number of trips required to move the chipped willow material from the harvester to the transport trucks. Increasing the nitrogen fertilizer application rate (every third year, following harvest) from 112 to 140 kg-N/ha increases the landscape emissions to 0.98 Mg-CO_2e/ha. Harvest fuel consumption and transport distance also influence the emissions, with a 25% parameter increase resulting in landscape emissions of 0.83 and 0.78 Mg-CO_2e/ha, respectively.

Similar trends are seen for sensitivity results of the LSSF and LMSF 10.1-ha scenarios in Figures 5B and 5C, respectively. Increasing the shrub willow yield has the largest effect on the GHG emissions with a 25% yield increase (12.4 to 15.5 dry Mg/ha/year) resulting in an increase of 0.32 to 0.52 Mg-CO_2e/ha and 0.49 to 0.79 Mg-CO_2e/ha for the LSSF and LMSF scenarios,

respectively. For the LSSF scenario, harvest fuel consumption has the next largest effect on the results, followed by the transportation distance and nitrogen removal rate. Although the nitrogen removal rate provides a large ecosystem service benefit by reducing the leaching of nitrogen, it does not have a large influence on GHG emissions. Harvest fuel consumption also has the second largest effect for the LMSF scenario followed by transportation distance. However, transportation distance has a larger effect on the GHG emissions for the LMSF scenario compared to the LSSF scenario because the baseline transportation distance is higher for the former at 36 km than 10 km for the latter. Therefore, a 25% increase in the baseline value has a larger effect.

4 CONCLUSIONS

The GHG emissions from producing willow on marginal land in the Indian Creek watershed in Illinois are lowest for the LSSF design, followed by LMSF and the BAU. Transportation distance can have a large impact on the results with the GHG emissions of the LMSF design at 40.5 ha field size comparable to the BAU even when the former receives a credit for avoided nitrogen leaching to the watershed and does not use any fertilizers during production. This suggests that landscape design approached related to strategically planting shrub willow buffers to address nutrient leaching needs to be considered at both the field-scale (to enhance nutrient loss reduction), but also at the watershed/fuel-shed scale to optimize production scale and transportation distance between production locations. Emissions are most sensitive to the willow yield (due to increased fuel requirements during harvest), fertilizer application rate for the BAU scenario, and transportation distance for the LMSF scenario. Shrub willow grown on buffer strips provides an ecosystem service that reduces nitrogen leaching and provides a GHG savings from avoided N_2O emissions. Willow must be strategically placed to

ensure GHG savings from reduced nitrogen leaching are not outweighed by transportation emissions from harvesting and delivery of the willow to the depot.

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REFERENCES

1. Langholtz MH, Stokes BJ, and Eaton LM, *2016 Billion-ton report: Advancing domestic resources for a thriving bioeconomy, Volume 1: Economic availability of feedstock*. Oak Ridge National Laboratory, Oak Ridge, TN (United States) (2016).
2. Efroymson RA, Langholtz MH, Johnson K, Stokes B, Brandt CC, Davis MR, et al., *2016 Billion-ton report: Advancing domestic resources for a thriving bioeconomy, Volume 2: Environmental sustainability effects of select scenarios from volume 1.* Oak Ridge National Lab, Oak Ridge, TN (United States) (2017).
3. Quinn LD, Straker KC, Guo J, Kim S, Thapa S, Kling G, et al., Stress-tolerant feedstocks for sustainable bioenergy production on marginal land. *BioEnergy Research* **8**(3):1081-100 (2015).
4. Dale VH, Kline KL, Wright LL, Perlack RD, Downing M, and Graham RL, Interactions among bioenergy feedstock choices, landscape dynamics, and land use. *Ecological Applications* **21**(4):1039-54 (2011).
5. Cacho J, Negri M, Zumpf C, and Campbell P, Introducing perennial biomass crops into agricultural landscapes to address water quality challenges and provide other environmental services. *Wiley Interdisciplinary Reviews: Energy and Environment* **7**(2):e275 (2018).
6. Asbjornsen H, Hernandez-Santana V, Liebman M, Bayala J, Chen J, Helmers M, et al., Targeting perennial vegetation in agricultural landscapes for enhancing ecosystem services. *Renewable Agriculture and Food Systems* **29**(2):101-25 (2014).
7. Kantola I, Masters M, and DeLucia E, Soil particulate organic matter increases under perennial bioenergy crop agriculture. *Soil Biology and Biochemistry* **113**:184-91 (2017).
8. McLauchlan K, The nature and longevity of agricultural impacts on soil carbon and nutrients: a review. *Ecosystems* **9**(8):1364-82 (2006).
9. Olson KR, Al-Kaisi M, Lal R, and Cihacek L, Impact of soil erosion on soil organic carbon stocks. *Journal of Soil and Water Conservation* **71**(3):61A-7A (2016).
10. Bazrgar, AB, Ng, A, Coleman, B, Ashiq, MW, Gordon, A, and Thevathasan, N, Long-term monitoring of soil carbon sequestration in woody and herbaceous bioenergy crop production systems on marginal lands in southern Ontario, Canada. *Sustainability 12*(9): 3901 (2020).
11. Bonin, CL, and Lal, R, Aboveground productivity and soil carbon storage of biofuel crops in Ohio. *GCB Bioenergy*, *6*(1): 67-75 (2014).
12. Zan, CS, Fyles, JW, Girouard, P, and Samson, RA, Carbon sequestration in perennial bioenergy, annual corn and uncultivated systems in southern Quebec. *Agriculture, Ecosystems & Environment 86*(2):135-144 (2001).
13. Schulte LA, Asbjornsen H, Liebman M, and Crow TR, Agroecosystem restoration through strategic integration of perennials. *Journal of Soil and Water Conservation* **61**(6):164A-9A (2006).
14. Ssegane H, and Negri MC, An integrated landscape designed for commodity and bioenergy crops for a tile-drained agricultural watershed. *Journal of Environmental Quality* **45**(5):1588-96 (2016).

15. 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 and Bioenergy* **80**:179-90 (2015).
16. Zumpf C, Ssegane H, Negri MC, Campbell P, and Cacho J, Yield and water quality impacts of field-scale integration of willow into a continuous corn rotation system. *Journal of Environmental Quality* **46**(4):811-8 (2017).
17. Jordan N, Schulte LA, Williams C, Mulla D, Pitt D, Slotterback CS, 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 (2013).
18. Incorporating Bioenergy in Sustainable Landscape Designs Workshop Two: Agricultural Landscapes (No. DOE/EE-1237) [press release]. EERE Publication and Product Library(2015).
19. Graham JB, Nassauer JI, Currie WS, Ssegane H, and Negri MC, Assessing wild bees in perennial bioenergy landscapes: effects of bioenergy crop composition, landscape configuration, and bioenergy crop area. *Landscape Ecology* **32**(5):1023-37 (2017).
20. Bonner I, McNunn G, Muth D, Tyner W, Leirer J, and Dakins M, Development of integrated bioenergy production systems using precision conservation and multicriteria decision analysis techniques. *Journal of Soil and Water Conservation* **71**(3):182-93 (2016).
21. Bonner IJ, Cafferty KG, Muth DJ, Tomer MD, James DE, Porter SA, et al., Opportunities for energy crop production based on subfield scale distribution of profitability. *Energies* **7**(10):6509-26 (2014).
22. Mishra SK, Negri MC, Kozak J, Cacho JF, Quinn J, Secchi S, et al., Valuation of ecosystem services in alternative bioenergy landscape scenarios. *GCB Bioenergy* **11**(6):748-62 (2019).
23. Ssegane H, Zumpf C, Cristina Negri M, Campbell P, Heavey JP, and Volk TA, The economics of growing shrub willow as a bioenergy buffer on agricultural fields: A case study in the Midwest Corn Belt. *Biofuels, Bioproducts and Biorefining* **10**(6):776-89 (2016).
24. Canter CE, Qin Z, Cai H, Dunn JB, Wang M, and Scott DA, *Fossil energy consumption and greenhouse gas emissions, including soil carbon effects, of producing agriculture and forestry feedstocks.* In: Efroymson, RA; Langholtz, MH; Johnson, KE; Stokes, BJ, eds 2016 billion-ton report: Advancing domestic resources for a thriving bioeconomy Volume 2: Environmental sustainability effects of select scenarios from volume 1 ORNL/TM-2016/727 Oak Ridge, TN: Oak Ridge National Laboratory: 85-137 **2017**:85-137 (2017).
25. Dias GM, Ayer NW, Kariyapperuma K, Thevathasan N, Gordon A, Sidders D, et al., Life cycle assessment of thermal energy production from short-rotation willow biomass in Southern Ontario, Canada. *Applied Energy* **204**:343-52 (2017).
26. Heller MC, Keoleian GA, and Volk TA, Life cycle assessment of a willow bioenergy cropping system. *Biomass and Bioenergy* **25**(2):147-65 (2003).
27. Krzyżaniak M, Stolarski M, Szczukowski S, and Tworkowski J, Life cycle assessment of new willow cultivars grown as feedstock for integrated biorefineries. *BioEnergy Research* **9**(1):224-38 (2016).

28. 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. *Biofuels, Bioproducts and Biorefining* **7**(5):537-50 (2013).
29. Golkowska K, Rugani B, Koster D, and Van Oers C, Environmental and economic assessment of biomass sourcing from extensively cultivated buffer strips along water bodies. *Environmental Science & Policy* **57**:31-9 (2016).
30. Davis SC, Boddey RM, Alves BJ, Cowie AL, George BH, Ogle SM, et al., Management swing potential for bioenergy crops. *GCB Bioenergy* **5**(6):623-38 (2013).
31. 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):9753-68 (2015).
32. Collier SM, Ruark MD, Oates LG, Jokela WE, and Dell CJ, Measurement of greenhouse gas flux from agricultural soils using static chambers. *JoVE (Journal of Visualized Experiments)* (90):e52110 (2014).
33. De Klein C, Novoa R, Ogle S, Smith K, Rochette P, Wirth T, et al., Chapter 11–N2O emissions from managed soils, and CO2 emissions from lime and urea application, Volume 4: Agriculture, Forestry, and Other Land Use. *In, IPCC Guidelines for National Greenhouse Gas Inventories* (2006).
34. Wang M, Han J, 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. *Environmental Research Letters* **7**(4):045905 (2012).
35. 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* **9**(1):246-61 (2017).
36. Agostini, A., P. Serra, J. Giuntoli, E. Martani, A. Ferrarini, and S. Amaducci, Biofuels from perennial energy crops on buffer strips: A win-win strategy. *Journal of Cleaner Production* **297**: 126703 (2021).
37. U.S. Department of Energy. Quadrennial Technology Review. Chapter 7: Advancing Systems and Technologies to Produce Cleaner Fuels – Biomass Feedstock and Logistics Technology Assessment. 2-17 (2015).
38. O'Neill, EG, and Maravelias, CT, Towards integrated landscape design and biofuel supply chain optimization. *Current Opinion in Chemical Engineering,* **31**:100666 (2021).

TABLES

Table 1: Cases and scenarios evaluated, with corn planted on the productive land and shrub willow or corn planted on adjacent marginal land using the following production scenarios: BAU (single dedicated field), LSSF (landscape single subfield buffer); LMSF (landscape multiple subfield buffers across the watershed).

Field Size (ha)	Buffer Size (ha)	Scenario	Transport Case	Distance to Depot (km)
2.8	2.0	BAU	Average	10
		LSSF	Average	10
		LMSF	Most likely	24
64.8	10.1	BAU	Average	10
		LSSF	Average	10
		LMSF	Most likely	36
781.9	40.5	BAU	Average	10
		LSSF	Average	10
		LMSF	Most likely	76

Table 2: Average annual materials and energy consumed in the Indian Creek study area for shrub willow production, harvest, and transportation to the depot. Shrub willow is grown in a 21-year rotation with harvest occurring every 3 years.

Input	Willow
Average annual yield (Mg-dry/ha)	12.4[a]
Shrub willow planting fuel consumption (L-diesel/ha/yr)	1.19[a]
Shrub willow harvest fuel consumption (L-diesel/ha/yr)	0.47[a]
Transport fuel economy (L/Mg/km/yr)	0.012[a]
Nitrogen (kg-N/ha/yr)	16.0[a,b]
Biomass nitrogen content (g-N/dry kg)	2.7[a]

[a] Ssegane et al.[23]

[b] Annual average nitrogen applied for the shrub willow BAU scenario only, no fertilizer is applied for LSSF and LMSF scenarios.

Figures

Impact of landscape design on the greenhouse gas emissions of shrub willow bioenergy buffers in a U.S. Midwest corn production landscape

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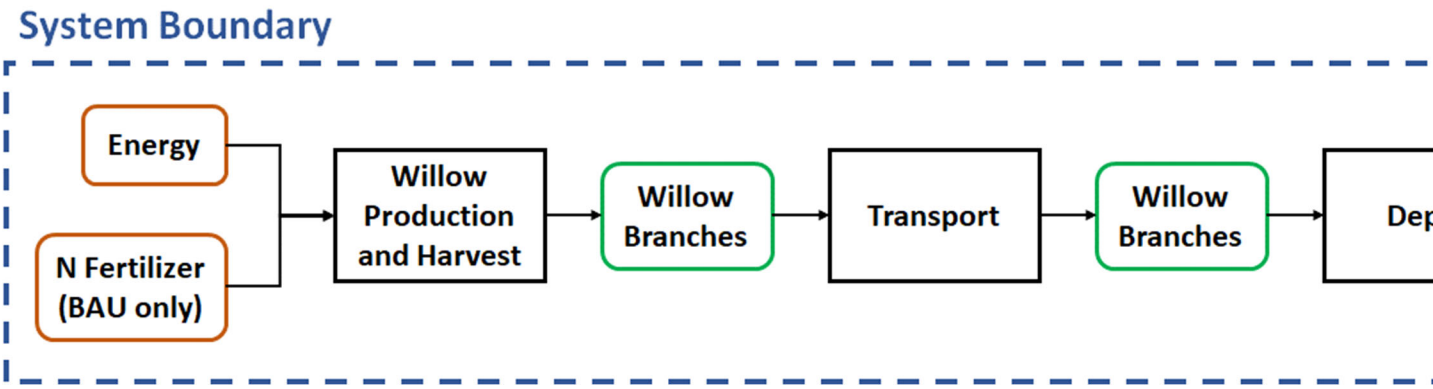

Figure 1: LCA system boundary for landscape system with willow grown as a buffer strip within a cornfield. Black boxes represent unit processes, green are biomass feedstock flows, and orange are material and energy flows.

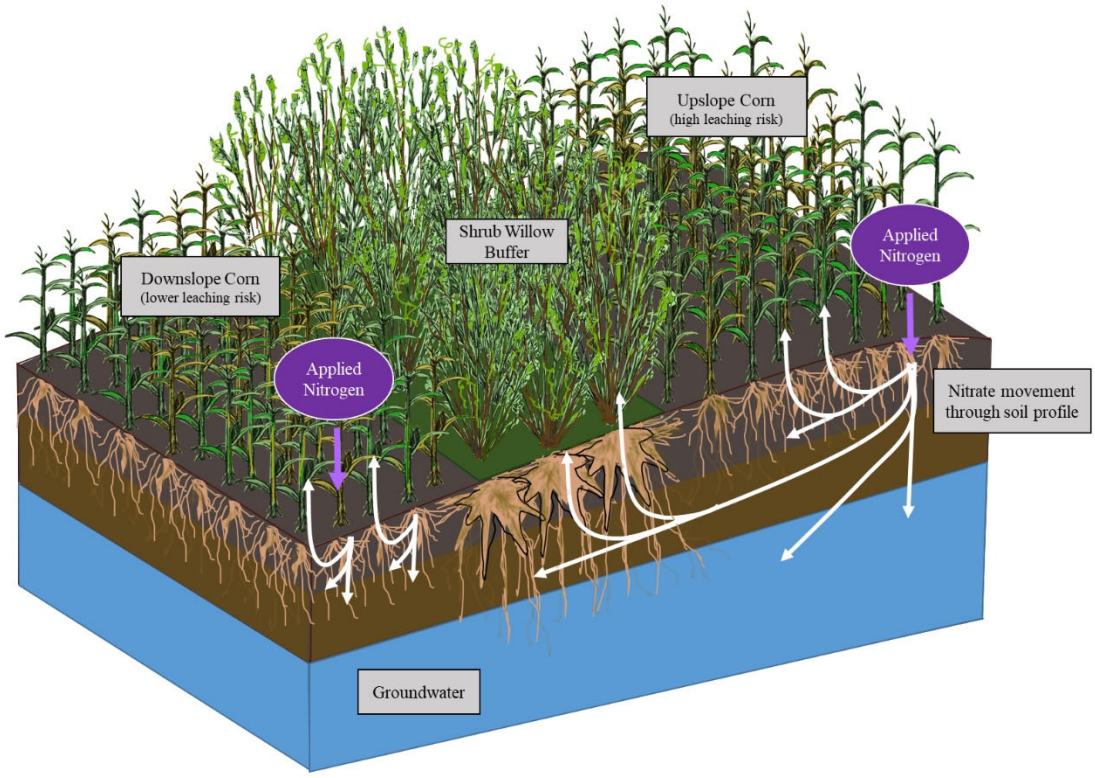

Figure 2: Shrub willow grown as a subfield buffer on marginal land within a cornfield to reduce nitrate leaching from corn production. The placement of the willow buffers within the field targets nitrate leaching from upslope corn after fertilization. The deeper roots and dense fine root mats of shrub willows can improve nitrate uptake and use for biomass production without direct fertilizer application to shrub willow buffers.

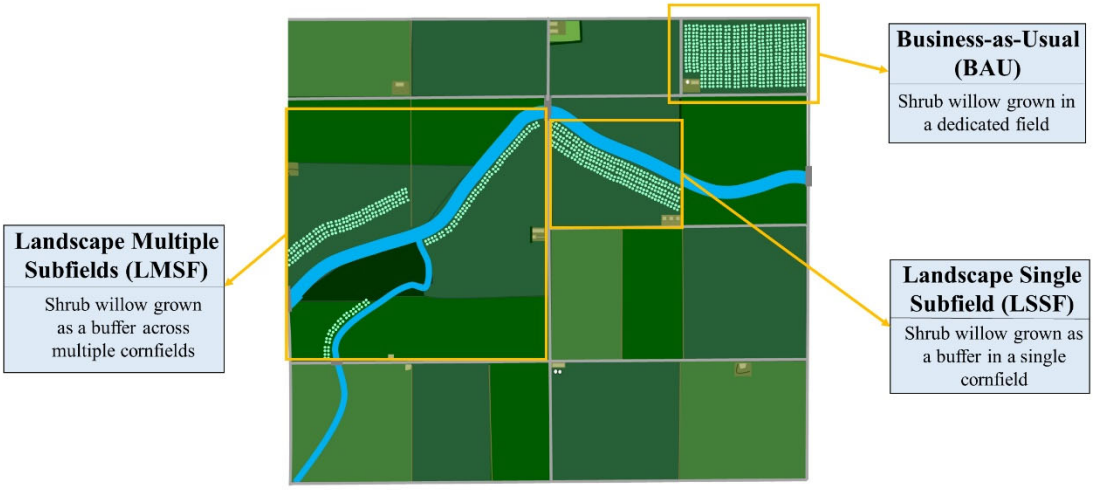

Figure 3: Three shrub willow production scenarios evaluated: (1) BAU (single dedicated field, fertilizer application, headland); (2) LSSF (landscape single subfield buffer, no fertilizer, no headland); and (3) LMSF (landscape multiple subfield buffers across the watershed). Not to scale.

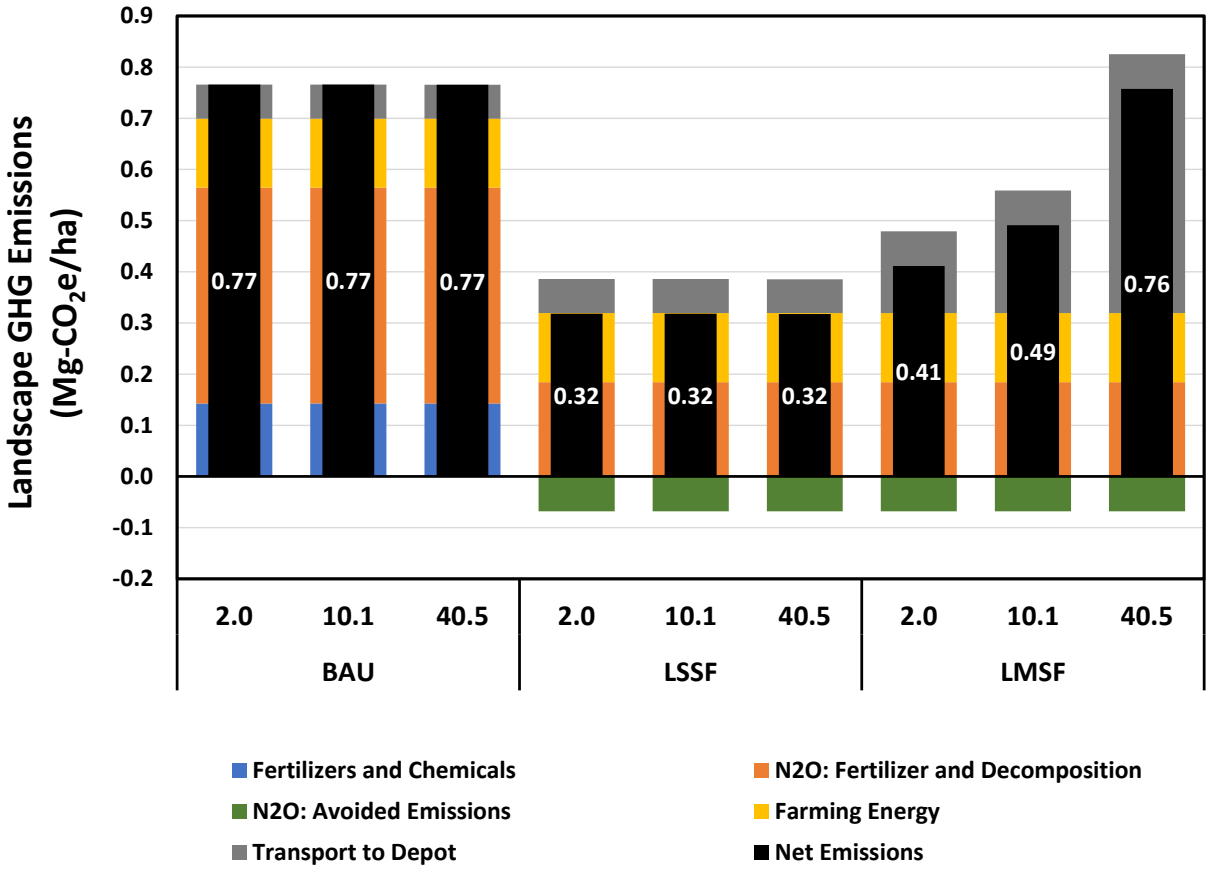

Figure 4: Landscape GHG emissions for shrub willow production in the BAU (dedicated field, fertilizer, headland), LSSF (landscape single subfield buffer, no fertilizer, no headland), and LMSF (landscape multiple subfield buffers, no fertilizers, no headlands) scenarios on 2.0-, 10.1-, and 40.5-ha fields. "N_2O Fertilizer and Decomposition" represents the N_2O released during nitrogen fertilizer application and biomass decomposition during growth.

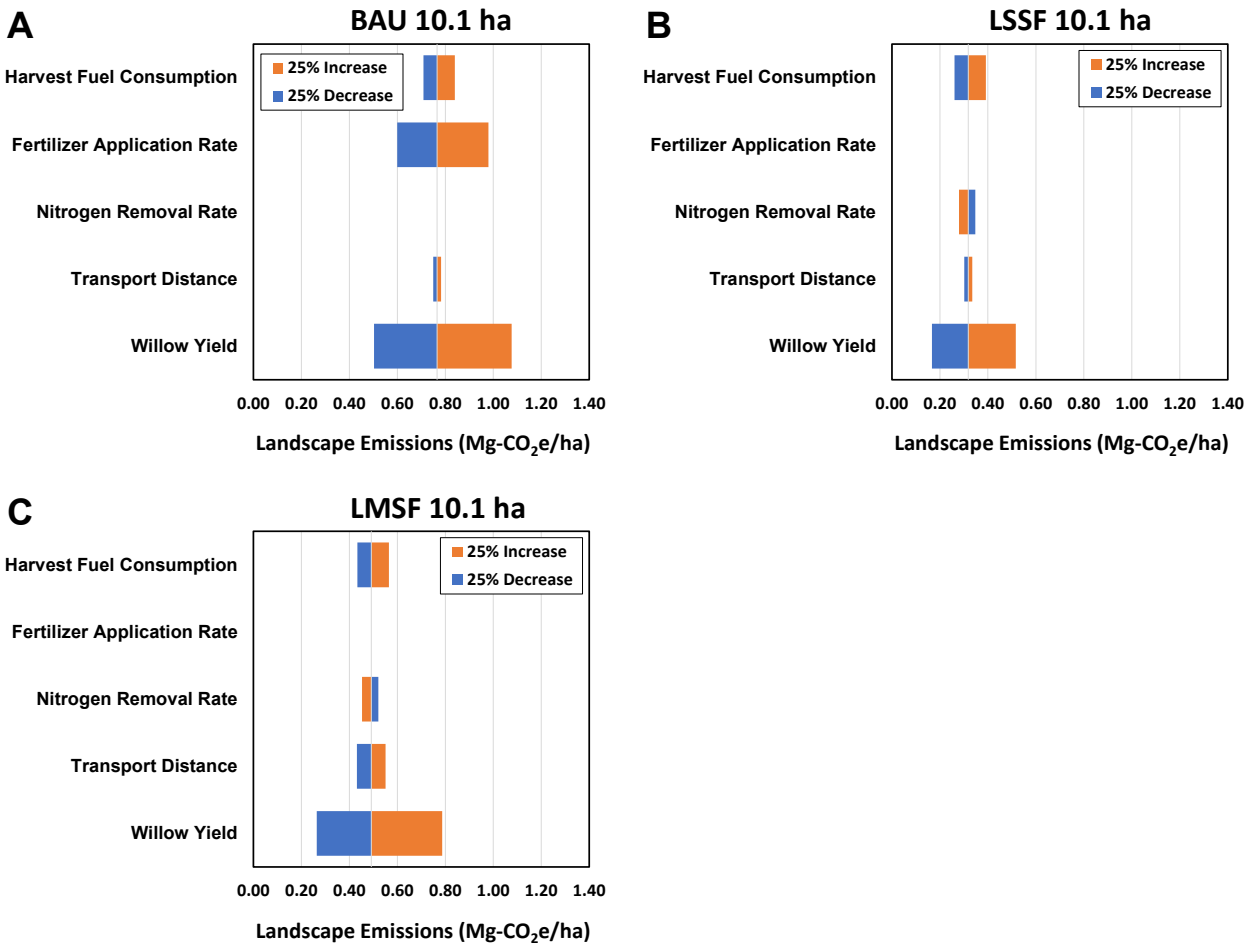

Figure 5: Sensitivity analysis for producing shrub willow on the 10.1-ha field for the (A) BAU scenario or a 10.1-ha buffer strip for the (B) LSSF and (C) LMSF scenarios. Results represent a 25% increase or decrease in the baseline parameter.