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Saturated Bioenergy Buffers: Site Suitability Classification and Estimated Areas of Candidate Sites in the U.S. Midwest Under Three Scenarios

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Saturated Bioenergy Buffers: Site Suitability Classification and Estimated Areas of Candidate Sites in the U.S. Midwest Under Three Scenarios

by
Jules F. Cacho, John J. Quinn, Colleen R. Zumpf, and M. Cristina Negri
Environmental Science Division, Argonne National Laboratory

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EXECUTIVE SUMMARY

The loss of nutrients applied to tile-drained row-crop fields is a critically important component of agriculture's impact on surface water quality, because drain tiles provide a short circuit to ditches and creeks, resulting in rapid nutrient loss. This nutrient loss ultimately advances eutrophication and hypoxia, i.e., the creation of dead zones in bodies of water, both locally and regionally (for example, in western Lake Erie and the Gulf of Mexico). Saturated buffers help address the tile-drainage water quality problem, and incorporating bioenergy crops into saturated bioenergy buffers could provide both environmental protection and an additional source of income for farmers.

The objectives of this analysis are 1) to develop a site suitability classification approach for rapid, cost-effective identification of saturated bioenergy buffer candidate sites at multiple spatial scales and, after validation, 2) to use the approach to estimate the amount of land in the U.S. Midwest considered suitable candidates for saturated bioenergy buffer sites. To identify these sites, we will use predetermined buffer widths of 20 m and 30 m and three scenarios.

Our approach uses several biophysical parameters to identify sites that 1) are likely to be tile-drained row-crop agricultural land, 2) have conditions conducive for denitrification, and 3) have stable streambank or drainage ditch materials. We will use federally funded and maintained databases, including the Soil Survey Geographic Database (SSURGO), the National Agricultural Statistics Service (NASS), the National Hydrographic Dataset (NHD), and the National Elevation Dataset (NED). We implemented this approach in ArcGIS Desktop (ESRI, Redlands, CA, USA) and validated it using data from various saturated buffer field studies across multiple states in the U.S. Midwest.

This approach has proven to be robust in identifying suitable saturated bioenergy buffer candidate sites. It identified sites considered to be either performing or promising in reducing nitrate losses in tile drainage water with an accuracy range of 57 to 63%, depending on the criteria used. We found the areas of lands that could be dedicated to saturated bioenergy buffers in the U.S. Midwest totaled up to 225,000 ha and 342,000 ha for buffer widths of 20 m and 30 m, respectively.

This approach could be integrated as a sub-module of a larger model, such as the Scaling Up PERennial Bioenergy Economics and Ecosystem Services Tool (SUPERBEEST) to expand and enhance its capability and accuracy. The estimated areas for suitable saturated bioenergy buffer candidate sites could serve as critical information in analyses focused on assessing the use of available lands for bioenergy feedstock production without competing for lands allocated for food, feed, and fiber production or impacting natural grasslands and forestlands.

1 INTRODUCTION

The U.S. Midwest—also known as the North Central region—includes Illinois, Indiana, Iowa, Kansas, Michigan, Minnesota, Missouri, Nebraska, North Dakota, Ohio, South Dakota, and Wisconsin. This 12-state region has 229 million acres of cropland (USDA, 2019), 50 million acres of which are under tile drainage: an important component of the region's high agricultural productivity. However, excessive nutrient loading (particularly nitrate) from the region's tile-drained agricultural lands is a primary cause of water quality problems locally and regionally (for example, hypoxia in the Gulf of Mexico) (Rabalais and Turner, 2019). As an edge-of-field approach, saturated buffers (as seen in Figure 1b) have the potential to significantly improve tile drainage water quality when implemented at the regional scale (Utt et al., 2015).

Riparian buffers—the vegetated areas along the stream or drainage ditch adjacent to a cropped field—can serve a variety of functions ranging from addressing water quality issues to improving aesthetics, such as enhancing the views from a landowner's residence (Schultz et al., 2009). In the past, using riparian buffers for water quality protection/improvement has focused on non-tiled agricultural fields. Recently, however, a strong interest has emerged to understand and implement a similar approach, known as saturated buffers, in tile-drained agricultural fields. The effectiveness of riparian buffers designed for water quality protection or restoration depends on several considerations, including location, pollutant of interest, vegetation used, and other factors (Mayer et al., 2007). In non-tiled agricultural systems, a riparian buffer is effective along a low-order stream (Hawes et al., 2005). In tile-drained systems where water primarily exits an

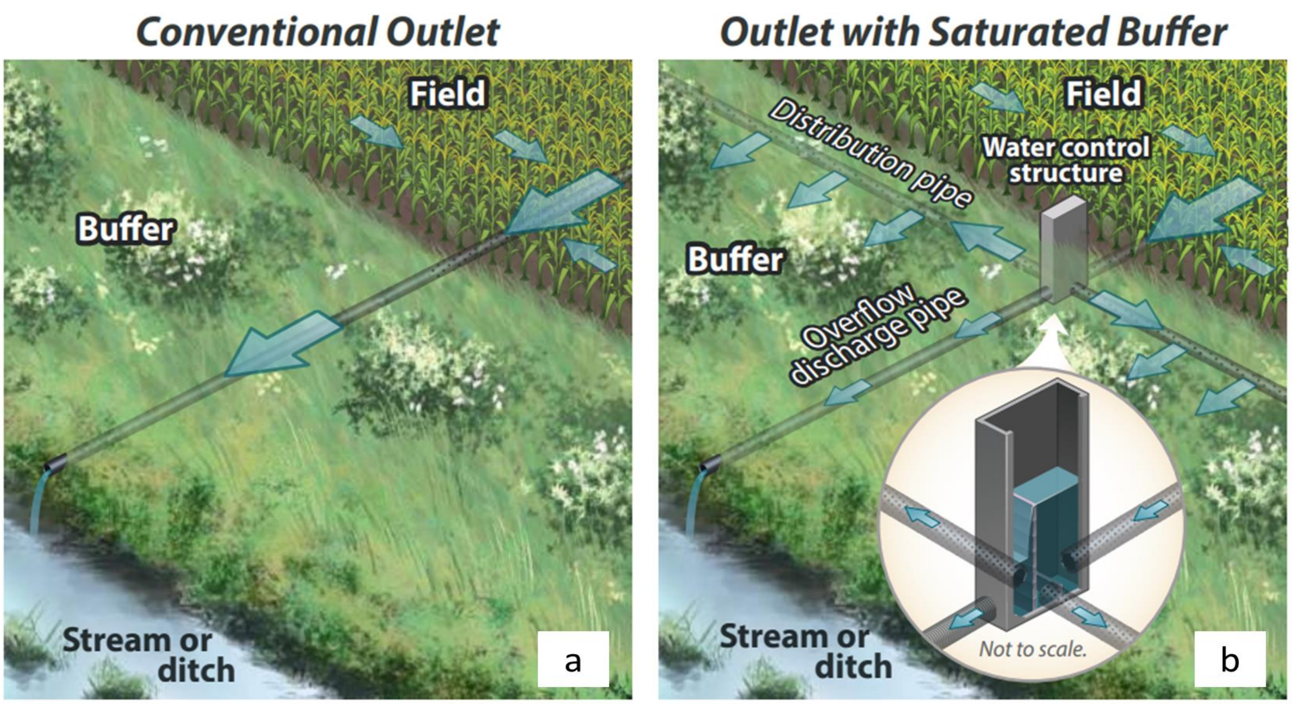

FIGURE 1 Schematic of drainage outlets under conventional drainage (a) and saturated buffer (b). (Adapted from Christianson et al. (2016) and used with permission).

agricultural field via subsurface tile drainage flow, stream order might not be a critical factor in placing a riparian buffer. Within tiled-drained agricultural landscapes, a saturated buffer has shown great potential in reducing the amount of nitrate from drainage water reaching streams (Jaynes and Isenhart, 2014).

In a saturated buffer system, much of the drainage water from a main tile is diverted via a control structure to a perforated pipe installed along the length of the buffer at a relatively shallower depth (Jaynes and Isenhart, 2014). Water from the perforated pipe seeps through the adjacent riparian area and consequently raises its water table. Allowing nitrate-rich drainage water to infiltrate the riparian soil profile instead of directly discharging into the adjacent stream reduces the nitrate by a combination of processes including denitrification, microbial immobilization, and plant uptake (Jaynes and Isenhart, 2014).

Saturated bioenergy buffers (Figure 2) adhere to the coupled ideas of resource recovery and multifunctioning landscapes. Because they maximize landscape productivity within minimum production inputs while providing environmental benefits, saturated bioenergy buffers could be considered a more sustainable variant of the saturated buffer system. Unlike saturated buffer systems that primarily rely on the natural vegetation of the riparian area for uptake of the recirculated nutrient-rich drainage water, saturated bioenergy buffer systems use perennial biomass crops (e.g., grasses and short-rotation woody crops) that can be harvested as bioenergy feedstocks for bioenergy and bioproducts. The use of perennial biomass crops under saturated bioenergy buffers is consistent with (and could be instrumental to) the success of the concerted, regional effort in the U.S. Midwest to significantly reduce the contribution of tile-drained agriculture to the Gulf of Mexico hypoxia. For instance, in Illinois alone, introducing perennial bioenergy crops in 10% of the state's tile-drained agricultural lands is projected to reduce nitrate-N loss by 90% per acre, at $3.18 per pound of nitrate-N removed (IEPA and IDOA, 2015).

As an edge-of-field multifunctional production system, saturated bioenergy buffers have the potential to improve the sustainability of overall tile-drained agricultural landscapes. In addition to water quality protection and other environmental benefits, saturated bioenergy buffers can improve the efficiency and economic viability of tile-drained agricultural landscapes by maximizing productivity for a given fertilizer input and providing additional revenue for farmers from the sale of bioenergy crops. An additional income source—a strong possibility under a thriving bioeconomy in the future—is a value proposition that would drive systemwide adoption and could further lower or offset the cost of adoption as a conservation practice. Saturated bioenergy buffers can also help address a major concern of large-scale biomass production: indirect land use change. Saturated bioenergy buffers provide another alternative approach for producing bioenergy feedstocks without displacing food croplands, helping to prevent the conversion of natural grasslands and forestlands that may otherwise be used to supplement food croplands lost to bioenergy crop production.

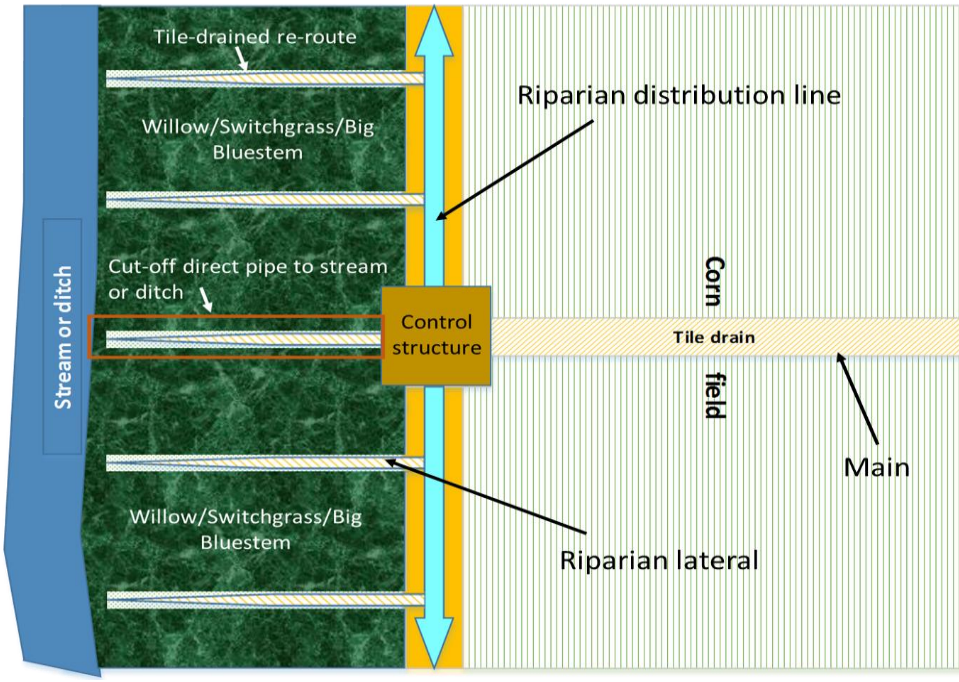

FIGURE 2 Schematic of the proposed saturated bioenergy buffer (not drawn to scale). From the drained corn/soybean field, the main collects drainage water from the laterals (not shown), which drains excess water from the cropped field. The control structure (CS) intercepts drainage water from the main and redirects it to the riparian distribution line (RDL). The RDL conveys the drainage water from the CS, where it will be distributed to the riparian zone via the riparian laterals. Bioenergy crops can take advantage of both water and nutrients for biomass production. Excess nitrate could be reduced to other nitrogen forms via denitrification. Cut-off direct pipe and overflow discharge pipe are provided to dispose of excess water via the CS during large rainfall events.

Not all tile-drained agricultural field riparian areas, however, are inherently suitable for saturated buffers or saturated bioenergy buffer systems. This fact was demonstrated by Utt et al. (2015), who conducted by far the largest field-scale study on saturated buffers (15 study sites in four U.S. Midwestern states). The team emphasized the significance of proper site conditions for saturated buffers to work. They concluded that saturated buffers are effective for reducing nitrate losses from tile drainage if proper site conditions (conduciveness for denitrification and streambank stability) and design considerations are met. A site with soil organic carbon content of ≥1% at the top 80 cm of the soil profile that is subject to periodic or constant saturated conditions is considered suitable for denitrification (Utt et al., 2015).

Methods for identifying or selecting candidate areas for riparian buffers exist. Tomer et al. (2015a) developed the most widely used method: an integral component of the Agricultural Conservation Planning Framework (ACPF) (Tomer et al., 2013, Tomer et al., 2015b). ACPF is an integrated, precision conservation planning approach for agricultural watersheds (Tomer et al., 2013), which is now packaged into a GIS-based tool (Porter et al., 2018), implemented in

ArcGIS Desktop (ESRI, Redlands, CA, USA). However, the approach for providing guidance on the suitability of a site for a saturated buffer relies primarily on such hydrologic characteristics as surface runoff potential and the depth to groundwater. No soil-based criterion is included that would indicate the suitability of a site due to the resistance of the overall soil profile to streambank erosion, although they mention closely examining the streambank for needed streambank toe stabilization especially when the bank height exceeds 3 m. Their approach is practical, and suitable for non-tile drained landscapes where surface runoff is a major component of the water balance and riparian areas are not engineered to purposely store recirculated drainage water like saturated buffers or saturated bioenergy buffers. In tile-drained watersheds where saturated buffers are more effective for reducing nutrient losses, subsurface flow is a major component of the water balance accounting to up to 90% seasonally and approximately 40% annually of watershed discharge (Macrae et al., 2007).

For saturated buffers or saturated bioenergy buffers, streambank stability is an important factor. Unlike traditional riparian buffers, in saturated buffers and saturated bioenergy buffers the entire soil profile in riparian areas is subject to a relatively longer period of saturation due to the frequency of high water table conditions caused by recirculating subsurface drainage water. As such, increased subsurface flow (e.g., seepage and preferential flow) towards the stream or drainage ditch is likely to occur frequently. The role of subsurface flow on soil erosion processes has long been recognized (Lamb et al., 2007, 2008). Sediment is one of the primary causes of stream impairment (USEPA, 2000). In many areas, the major source of stream sediment loading increase are the streambanks themselves due to mass failure (Fox and Wilson, 2010). Laboratory, field, and modeling studies have recently highlighted the contribution of subsurface flow to streambank failure (Wilson et al., 2007; Fox et al., 2006, 2007; LaSage et al., 2008; van Balen et al., 2008). Thus, it is critical to include a soil-based criterion that represents streambank stability in classifying the suitability of a site for saturated bioenergy buffer.

Our analysis takes such criteria into consideration. Our objectives are to 1) develop a framework to identify suitable locations for field-scale saturated bioenergy buffers in tile-drained agroecosystems, and 2) use the framework to estimate the average size of lands available for saturated bioenergy buffers in the U.S. Midwest based on predetermined saturated bioenergy buffer widths. Our approach is meant as a rapid and cost-effective tool for identifying tile-drained cropped farmlands at the field, watershed, county, state, and regional scales that are good candidates for sustainable implementation of saturated bioenergy buffers without having to go onsite to collect biophysical information.

2 MATERIALS AND METHODS

2.1 ENVIRONMENTAL METRICS FOR SUITABILITY ANALYSIS

Plant uptake and denitrification are the two main mechanisms for reducing nitrate loss in the drainage water being recirculated in the riparian or buffer area. Perennial biomass crops grown in the buffer area are intentionally not fertilized, and hence will depend on the recirculated water for their nutrient needs. Environmentally, site suitability is based on predefined thresholds of environmental metrics (Table 1). In addition to identifying riparian areas that are adjacent to fields under a conventional tile-drainage system, these areas require soil conditions that are conducive to denitrification (e.g., higher soil organic carbon content, high water table conditions, etc.) and provide bank stability.

TABLE 1 Suitability classes of environmental metrics for identifying tile-drained fields and suitability of adjacent riparian areas for saturated bioenergy buffers.

Environmental Metric	Classification	Suitability
1. Soil drainage	Somewhat poorly drained	1
	Poorly drained	1
	Very poorly drained	1
	Moderately well drained	0
	Well drained	0
	Somewhat excessively drained	0
	Missing data	Null
2. Topography	Very flat (≤1% slope)	1
	Flat (>1% to ≤2% slope)	1
	Moderately flat (>2% to ≤3% slope)	1
	Slightly flat (>3% to <5% slope)	1
	Not flat (≥5% slope)	0
	Missing data	Null
3. Land use land cover	Corn/soybean	1
	Others	0
	Missing data	Null
4. Soil organic carbon content in the top 76 cm	Low (<1%)	0
	Medium (1-2%)	1
	High (>2%)	1
	Missing data	Null
5. Depth to hydraulically restricting layer	1.2 - 2.5 m	1
	Otherwise	0
	Missing data	Null
6. Soil erodibility factor (whole soil profile)	Low (≤0.44)	1
	High (>0.44)	0
	Missing data	Null

2.1.1 Soil Drainage

The first step in this analysis is to identify areas under a tile-drained system. Maps showing the exact distribution of such areas are rare since farm owners typically keep such information private. However, surrogate variables including soil drainage conditions, topography, and land use land cover (to be discussed in more detail later in this report) can serve as sufficient indicators of the presence of tile drainage. In the U.S. Midwest, tile drainage essentially underlies any hydric or poorly drained soils that are used for commodity crop production (Tomer et al., 2013). In this study, we classify agricultural lands as tile-drained if the soil drainage conditions are poorly drained, average slope is less than 5%, and land use land cover is predominantly corn and soybean. Table 1 uses soil drainage data from the U.S. Department of Agriculture (USDA) Natural Resource Conservation Service (NRCS) Soil Survey Geographic (SSURGO) database to classify soil drainage.

2.1.2 Topography

Topography is a major contributing factor of a landscape's soil water conditions. High water table conditions are prevalent in relatively flat areas with abundant precipitation, like most of the agricultural fields of the U.S. Midwest. Tile drainage can lower the water table and provide more suitable soil water conditions for crop growth during the growing season. Thus, tile drainage is an integral part of the high productivity of the commodity crop production in the region (Hofstrand, 2010).

Tomer et al. (2013) considered slope as a primary factor in mapping the extent of tile-drained agricultural fields in a watershed, classifying cropped fields as tile-drained if more than 90% of the area had an average slope of less than 5%. Using this slope range (coupled with soil drainage and land use land information) could provide a logical approach to mapping the extent of tile-drained fields in the absence of actual maps. Slope information is also necessary for the accurate placement of flow control structures as a conventional tile drainage system is converted to a saturated buffer system. We used a 30-meter digital elevation model from the National Elevation Dataset (NED) maintained by the U.S. Geological Survey to generate slopes for this study. Areas that are relatively flat (<5% slope) are considered suitable (Table 1).

2.1.3 Land Use Land Cover

The focus for the land use land cover (LULC) parameter is to find a cost-effective way of identifying fields under commodity crops, which can be used along with soil drainage and topographic information for accurate classification of corn or soybean fields under tile drainage. We identified fields by using the Cropland Data Layer (CDL) dataset from the USDA National Agricultural Statistics Services database (https://nassgeodata.gmu.edu/CropScape/). The CDL dataset is a collection of LULC raster layers generated from satellite imagery collected by Landsat. These LULC layers can be used to analyze the spatial distribution of areas under commodity crops at 30-meter spatial resolution using the datasets collected beginning in 2008. In this study, an LULC layer was reclassified into two groups: corn/soybean and everything else (Table 1).

2.1.4 Soil Organic Carbon Content

As mentioned earlier, denitrification is a major pathway for reducing excess nitrate from recirculated, nutrient-rich drainage water. Reducing nitrate into various nitrogen forms (e.g., NO, N_2O, and N_2) through denitrification requires organic carbon and anaerobic conditions. In the absence of oxygen, facultative anaerobic microorganisms use nitrate and other nitrogen ionic oxides (NO and N_2O) as electron acceptors and organic carbon as electron donors (Knowles, 1982). A minimum soil organic carbon content of 2% is needed to readily sustain denitrification (Burford and Bremmer, 1975). Utt et al. (2015) used a soil organic carbon content threshold of at least 1% in the top 2.5 feet (76 cm) of the soil horizon for sustained denitrification. In this study, we used the USDA NRCS's SSURGO database to generate soil organic carbon content data. A soil is considered suitable for denitrification with a soil organic carbon content of at least 1% in the top 76 cm of the soil profile (Table 1).

2.1.5 Hydraulically Restricting Layer

A site conducive to denitrification will have a highly anaerobic condition in the soil organic carbon-rich layer of the soil profile. In this regard, Utt et al. (2015) suggested that sites show historical evidence of a high water table reaching the carbon-rich soil profile or the presence of a shallow hydraulically restricting layer. In this study, we used a shallow hydraulically restricting layer as an indicator of a site's potential to undergo a high frequency of saturated or anaerobic conditions at the carbon-rich layer. We used the SSURGO database to generate hydraulically restrictive layer data. A site is considered suitable if the hydraulically restrictive layer is from 1.2 to 2.5 m from the surface (Table 1).

2.1.6 Soil Erodibility Factor

Another important environmental sustainability parameter is streambank erosion. The U.S. Environmental Protection Agency (USEPA) identified sediment as a primary cause of stream impairment (USEPA, 2000). Protecting streambanks is critical to maintaining stream water quality since streambank failure can account for up to 85% of the sediment yield (Simon and Darby, 1999). Subsurface flow, particularly in the form of lateral seepage, is the primary cause of streambank failure (Wilson et al., 2007; Fox et al., 2006, 2007; LaSage et al., 2008; van Balen et al., 2008). Transforming the riparian areas adjacent to tile-drained commodity cropped fields into saturated bioenergy buffers has the potential to increase streambank erosion. As the water table in riparian areas rises by recirculating drainage water, increased seepage towards the streambank could occur. Additionally, the need for a shallow hydraulically restrictive layer for saturated bioenergy buffers could contribute to streambank erosion. Faulkner (2006) found that streambank erosion attributed to subsurface flow is often associated with water perched on a water-restricting layer. In this study, we used the average soil erodibility factor of the soil profile (weighted by the layer thickness) derived from the SSURGO database as an indicator of a site's susceptibility to streambank erosion. In the SSURGO database, a soil type on a map unit is assigned a soil erodibility factor by layer. Thus, to account for the relative importance of varying layer thickness, we used the average soil erodibility factor (weighted by layer thickness). In this study, a site with an average soil profile erodibility factor of 0.44 or less is considered suitable for saturated bioenergy buffers (Table 1). In addition, perennial biomass crops have deep, massive rooting systems that could hold soil particles together near the streambank.

2.2 SATURATED BIOENERGY BUFFER WIDTH

Buffer width is an important consideration in a saturated buffer's effectiveness as a conservation practice. Philips (1989) estimated that buffer width accounts for approximately 80% of a buffer's effectiveness in removing nitrate. Several U.S. state and federal agencies have recommended guidelines on minimum buffer width for effective protection of the stream ecosystem health (Belt et al., 1992; Christensen, 2000; Lee et al., 2004; Mayer et al., 2005). In general, wider buffers (those greater than 50 m) are more effective than buffers with widths of 25 meters or less (Mayer et al., 2007). Ultimately, though, the average width of a saturated bioenergy buffer (measured from the streambank edge to the boundary between the commodity crops and the perennial biomass crops) will depend on how much land an owner is willing to apportion. In this study, we used 20 meters (which is close to the average range of minimum buffer widths recommended by numerous U.S. states) to estimate potential production areas for saturated bioenergy buffers in the U.S. Midwest (Mayer et al., 2005). For comparison, we used 30 meters (which seems logical when farmers/landowners become more willing to adopt saturated bioenergy buffer production systems due to financial incentives derived from the sale of biomass and ecosystem services credits in a thriving bioeconomy).

2.3 SITE SUITABILITY CLASSIFICATION APPROACH AND VALIDATION

We determined the suitability of a row-cropped field as a saturated bioenergy buffer site using a simplified form of the Geographic Information Systems (GIS)-based Multi-criteria Decision Analysis (MCDA) technique (Malczewski, 2006). The suitability model for this analysis is shown in equation [1].

$$SBB = \prod_{i=1}^{n} w_i C_i \qquad [1]$$

where:

SBB = suitability for an SBB site; w_i = i^{th} weight of the criterion C_i;
C_i = binary raster for the i_{th} suitability criterion.

All suitability criteria specified in Table 1 are assigned equal weights—that is, all w_i values are set to 1.

In other words, all suitability criteria have equal importance in determining site suitability. Values of the suitability criteria associated with soil parameters are generated from the SSURGO database. SSURGO datasets of interest were downloaded from the Web Soil Survey (https://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm). We used Soil Data Viewer, a geospatial tool developed by the USDA NRCS, to create thematic maps for each of the soil-based suitability criteria including soil drainage, soil organic carbon content, hydraulically restricting layer, and soil profile erodibility factor. Our methods of aggregation included weighted average for quantitative parameters (e.g., soil organic carbon content, hydraulically restricting layer, and erodibility factor) and dominant component for qualitative metrics (e.g., soil drainage). The resulting thematic maps were converted into raster layers at 30-m resolution, which is also the spatial resolution of the LULC layer.

Utt et al. (2015) conducted a study in multiple U.S. Midwestern states to demonstrate and evaluate the effectiveness of saturated buffers in improving water quality tile-drainage water, particularly in reducing nitrate and phosphorus concentrations, at field scale. They conducted 15 field studies in four states: Iowa, Illinois, Indiana, and Minnesota. These study sites comprise a wide range of soil and buffer vegetation types, topographic conditions, and ditch/stream channel characteristics. We used information from that study to evaluate the potential viability or practicality of the saturated bioenergy buffer site suitability selection approach we developed for this study. In particular, we used information on the location (e.g., geographic coordinates) as well as soil organic carbon content and evidence of reducing conditions in the top 76 cm of the soil profile. We used the geographic coordinates for eight sites, along with their soil, LULC, topographic, and NHD data, to test the accuracy of the GIS-based MCDA approach for saturated bioenergy buffers (i.e., whether it can accurately classify these sites as suitable for saturated bioenergy buffers). These eight sites were chosen because they satisfied one of the following criteria:

1. Soil organic carbon content of >2% in the top 76 cm of the soil profile and high water table and high water table conditions

2. Soil organic carbon content of >2% in the top 76 cm of the soil profile and either performing or promising in nitrate removal

3. High water table conditions and either performing or promising in nitrate removal.

We implemented the GIS-based MCDA approach using the Environmental Systems Research Institute's ArcGIS Desktop 10.3.1 software package (ESRI, Redlands, CA, USA).

2.4 ESTIMATING AVAILABLE LAND AREA SUITABLE FOR SATURATED BIOENERGY BUFFERS IN THE U.S. MIDWEST

After determining the viability/accuracy of the GIS-based MCDA approach for selecting suitable saturated bioenergy buffer sites, we applied it to the entire U.S. Midwest to estimate how much land would be available that could potentially be converted into this proposed production system. Soil, LULC, topographic, and hydrologic data (e.g., stream/ditch shapefiles) were downloaded and processed for the 12 states in the region (Illinois, Indiana, Iowa, Kansas, Michigan, Minnesota, Missouri, Nebraska, North Dakota, Ohio, South Dakota, and Wisconsin). The primary source of the hydrologic data is the U.S. Geological Survey's National Hydrographic Dataset. In Minnesota's case, hydrologic data from the state's GIS database were used since the shapefiles for rivers, streams, and drainage ditches/canals are more detailed/updated at the time this analysis was conducted. Estimated areas are based on predetermined buffer widths of 20 m and 30 m (discussed in subsection 2.2) and under the assumption that the entire buffer length adjacent to the tile-drained cropped fields is converted to saturated bioenergy buffer. We also conducted three scenarios: base case, base case + 1, and base case + 2. The purpose of the base case scenario is to estimate the possible area of land in the region by converting all tile-drained lands into saturated bioenergy buffer production systems without considering other suitability characteristics, such as conduciveness to maximize denitrification and less susceptibility to streambank erosion. It only considers criteria 1-3 in Table 1. Under the base case + 1 scenario, the site characteristics indicating conduciveness to denitrification are taken into consideration using criteria 1-5 in Table 1. The base case + 2 scenario takes into consideration a site's ability to resist streambank erosion, in addition to criteria associated with denitrification (criteria 1-6 in Table 1).

3 RESULTS AND DISCUSSION

3.1 SATURATED BIOENERGY BUFFER SITE SUITABILITY APPROACH VALIDATION

The eight sites used for validating the approach to determine suitable saturated bioenergy buffer sites are shown in Figure 3 and Table 2: five from Illinois, two from Iowa, and one from Minnesota. Two Illinois sites are located in Sangamon County (Figure 3a), while the other three are in Edgar (Figure 3b), Piatt (Figure 3c), and Rock Island (Figure 3d) counties, respectively. The Iowa sites are located in Benton (Figure 3e) and Hamilton (Figure 3f) counties, while the Minnesota site is located in Dodge County (Figure 3g). Table 2 provides a summary of information on these sites. Information on other soil and biophysical data can be found in Utt et al. (2015).

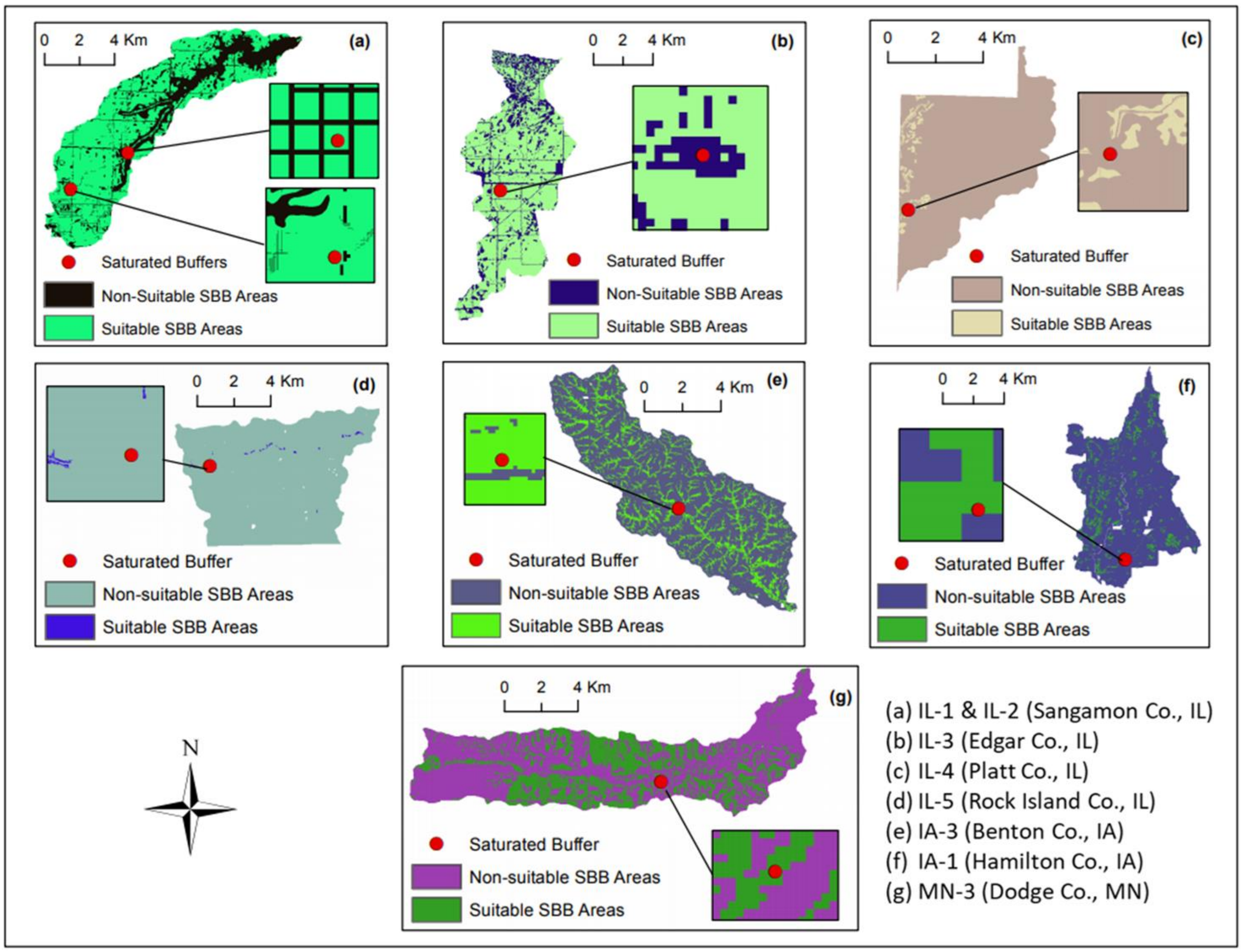

FIGURE 3 The eight saturated buffer (SB) study sites used for validating the approach for identifying suitable sites for saturated bioenergy buffers including five in Illinois (a-d), two in Iowa (e-f), and one in Minnesota (g). Site locations are indicated by the solid red dot based on the site coordinates from Utt et al. (2015). Each map on the figure indicates whether a saturated buffer site is suitable or not suitable for a saturated bioenergy buffer production system.

TABLE 2 Saturated buffer characteristics of the selected sites used for validating the proposed saturated bioenergy buffer site suitability identification approach, adapted and modified from Utt et al. (2015).

Site ID by County and State[a]	Drainage Area (ha)	Buffer Width (m)	Buffer Length (m)	Organic Matter Content (%)[b]	Periodic or Frequent Saturation of Organic Layer[c]
Sangamon, IL1 (IL-1)	10.67	~21.34	310.98	>2 (18.9 cm)	Confirmed
Sangamon, IL2 (IL-2)	25.42	~24.39	498.48	>2 (18.9 cm)	Confirmed
Edgar, IL (IL-3)	15.52	~22.87	178.35	>2 (18.9 cm)	Confirmed
Piatt, IL (IL-4)	6.95	~32.01	396.34	>2 (18.9 cm)	Confirmed
Rock, IL (IL-5)	60.43	~36.59	219.51	>2 (18.9 cm)	Confirmed
Benton, IA (IA-3)	60	~41.16	304.88	>2 (18.9 cm)	Confirmed
Hamilton, IA (IA-1)	4.69	~36.59	304.88	>3 (18.9 cm); 1-2 (18.9 cm)	Confirmed
Dodge, MN (MN-3)	11.44	10.67-45.73	304.88	>4.5% (18.9 cm)	Confirmed

[a] Parenthetical terms are site IDs from Utt et al. (2015).

[b] Parenthetical numbers represent corresponding depths from the soil surface where soil organic matter content was measured.

[c] Saturation of the organic layer as indicated by reducing conditions occurring in the layer, such as gleying of the layer materials.

Under our approach, five of eight sites (63%) were deemed suitable based on a soil organic carbon content threshold of $\geq$1.0% and the tendency of 76 cm of the soil profile to be subject to periodic or frequent saturation or reducing condition (Figure 3; Table 3). Taking into account nitrate reduction performance in addition to soil carbon content and saturation criteria, four of seven sites (57%) had sufficient data to be declared either "promising" or "performing." Three of the four suitable sites were deemed "performing," including the one Minnesota and two Iowa sites (Table 3). The fourth site classified as suitable was a Sangamon site (Table 3). The other Sangamon site, while identified as suitable for saturated bioenergy buffer, according to Utt et al. (2015) it was deemed neither performing nor promising in terms of nitrate reduction performance due to insufficient data (Table 3). Three Illinois sites were identified as not suitable for saturated bioenergy buffer, although they were found to be performing/promising for reducing nitrate in drainage water and also met the soil organic carbon content threshold and saturation/reducing condition. Of those sites, Edgar and Rock Island were classified as not suitable but performing, while Platt was classified as not suitable but promising (Table 3). Table 4 shows the suitability of each site by individual criterion/metric.

Utt et al. (2015) specified the criteria associated with conduciveness to denitrification (e.g., soil organic carbon content threshold and saturated conditions in the top 75 cm of the soil profile), but not with streambank stability. They concluded, based on streambank surveys of two study sites, that at sites with relatively stable banks, implementing SB will not cause streambank instability or failure. SB could still be implemented on sites with relatively unstable streambanks, but they recommended that careful design considerations be conducted to prevent streambank instability or failure. However, precisely determining streambank stability requires site visits and surveys. Thus, it is not practical as a first step for the rapid identification of candidate SBB sites that satisfy both requirements for maximizing denitrification and streambank stability at larger scale (e.g., watershed, county, state, and regional). As an alternative, we proposed using the soil profile erodibility factor as a key criterion for indicating streambank stability. The soil erodibility factor or coefficient is an important component for estimating soil loss, as shown by the Universal Soil Loss Equation (Renard et al., 1991). It is also an important parameter in the excess shear stress equation (Hanson, 1990a, 1990b), which is more applicable for estimating stream channel soil erosion rates (Clark and Wynn, 2007). The soil erodibility factor has been shown to be a good predictor of streambank erosion rates, particularly for fine-grained streambank soils (Clark and Wynn, 2007).

TABLE 3 Site nitrate reduction performance and suitability for saturated bioenergy buffers as predicted by the proposed approach for site selection.

Site ID by County and State	Nitrate Reduction Performance	Predicted Site Suitability[a]
Sangamon, IL1	[b]	Suitable
Sangamon, IL2	Promising	Suitable
Edgar, IL	Performing	Not Suitable
Piatt, IL	Promising	Not Suitable
Rock Island, IL	Performing	Not Suitable
Benton, IA	Performing	Suitable
Hamilton, IA	Performing	Suitable
Dodge, MN	Performing	Suitable

[a] Predicted using the proposed site suitability classification approach in this study.

[b] Cannot be determined due to insufficient water quality data.

TABLE 4 Suitability of eight study sites by individual metric, where 1 signifies "suitable" and 0 signifies "not suitable" based on the criteria listed in Table 1.

	Suitability Metrics					
SB Site	Soil Drainage	Topography	Land Use Land Cover	Soil Organic Carbon Content Top 76 cm	Depth to Hydraulically Restricting Layer	Soil Erodibility Factor
Sangamon, IL1 (IL-1)	1	1	1	1	1	1
Sangamon, IL2 (IL-2)	1	1	1	1	1	1
Edgar, IL (IL-3)	1	0	1	1	1	1
Piatt, IL (IL-4)	1	0	0	0	1	0
Rock Island, IL (IL-5)	1	0	1	0	1	0
Benton, IA (IA-3)	1	1	1	1	1	1
Hamilton, IA (IA-1)	1	1	1	1	1	1
Dodge, MN (MN-3)	1	1	1	1	1	1

The saturated bioenergy buffer site suitability classification approach proposed in this study uses both denitrification and streambank soil erosion factors to consider a site's suitability for saturated bioenergy buffer prior to implementation. Conversely, Utt et al. (2015) primarily considered factors related to denitrification only or, more specifically, on nitrate reduction performance. Although the Utt et al. study checked bank stability and found it to be unaffected by saturated bioenergy buffer implementation, this was done in only two out of 15 sites and was not considered a criterion for choosing the sites beforehand. This could explain the variability in correctly predicting saturated bioenergy buffer sites that are both considered suitable and promising or performing in terms of reducing nitrate losses. In other words, it is possible that those three sites deemed not suitable, although considered by Utt et al. (2015) to be promising or performing in removing nitrate in drainage water, have a high erodibility factor, which was supported by data in Table 4 where high streambank erodibility (erodibility factor suitability = 0) of two sites (IL-4 and IL-5) was one of the factors that indicates these two sites were not suitable as SBB sites. Nevertheless, the proposed saturated bioenergy buffer site suitability classification approach could be considered robust as it was able to correctly classify 57% to 63% of the sites being considered.

3.2 ESTIMATED AVAILABLE AREA IN THE U.S. MIDWEST FOR SATURATED BIOENERGY BUFFERS

This study bases the estimates of area available for saturated bioenergy buffers in the U.S. Midwest on two predetermined widths, 20 m and 30 m (subsection 2.2), and three scenarios, including base case, base case + 1, and base case + 2 (subsection 2.4). These estimates are shown in Table 5. Figures 4-6 show maps of the candidate saturated bioenergy buffer sites for the U.S. Midwest.

If saturated bioenergy buffers are implemented on all likely tile-drained agricultural lands (base case), total available lands range from 225,000 ha (20-m buffer width) to 342,000 ha (30 m buffer width). Focusing only on tile-drained agricultural lands with riparian areas conducive to denitrification (e.g., higher soil organic carbon content in the base case + 1 scenario), the numbers decrease to 148,000 ha (20-m buffer width) and 226,000 ha (30-m buffer width). Further, when considering both denitrification and streambank stability parameters (base case + 2), these numbers are further reduces, totaling 132,000 ha (20-m buffer width) and 201,000 (30-m buffer width). Minnesota has the most areas where saturated bioenergy buffers could be implemented, followed by Indiana and Ohio. Kansas has the least area available for such buffers.

These numbers are dependent on the completeness of data, particularly shapefiles for streams/drainage ditches. States that depend heavily on irrigation water for crop production (such as Kansas, Nebraska, North Dakota, and South Dakota) are expected to have lower numbers. For states with prevalent tile drainage, the numbers are affected by the availability of GIS data on streams/drainage ditches that intersect with agricultural lands that are classified as likely tile-drained. It is beyond the scope of this study to determine the variability of the completeness of the stream/drainage ditch GIS-data among the 12 states, but a qualitative assessment showed that Minnesota, arguably, is one of the states with the best available state GIS-data repository, including data on streams/drainage ditches. The influence of the GIS data density is apparent in Figures 4-6, and reflects part of the reason why Minnesota ranks as the top Midwestern state for such implementation.

TABLE 5 Estimated area (ha) for saturated bioenergy buffer (SBB) candidate sites in the U.S. Midwest based on two buffer widths and three scenarios (base case, base case + 1, base case + 2) summarized by state.

	20 m SBB Width			30 m SBB Width		
State	base case	base case + 1	base case + 2	base case	base case + 1	base case + 2
IA	23,406	21,092	20,863	37,958	34,057	33,653
IL	26,455	12,634	11,428	38,982	18,684	16,926
IN	35,339	16,757	12,012	53,568	24,928	17,901
KS	390	134	24	770	208	39
MI	4,254	3,278	1,482	7,368	5,650	2,509
MN	105,555	78,620	75,806	158,106	117,949	113,504
MO	4,755	2,396	1,248	8,611	4,255	2,339
ND	1,836	1,111	1,021	2,710	1,583	1,446
NE	3,660	2,329	1,798	6,258	3,961	3,040
OH	1,3454	7,262	4478	19,347	10,249	6,236
SD	1,062	764	612	1789	1,306	1,061
WI	4,453	1,926	1,564	6,468	2,794	2,254
Total	224,620	148,304	132,335	341,936	225,624	200,908

Columns may not total accurately due to rounding.

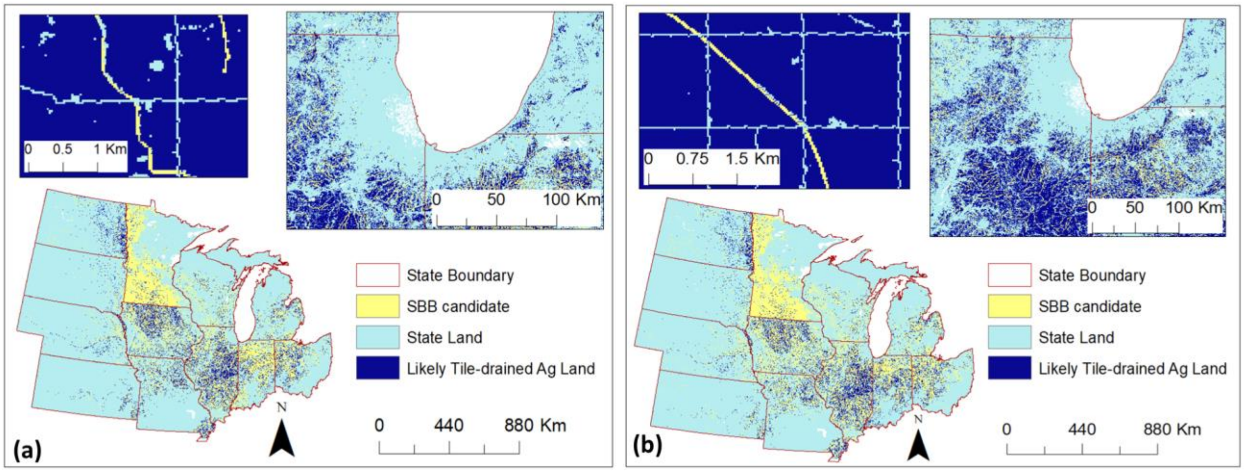

FIGURE 4 Saturated bioenergy buffer (SBB) candidate sites in the U.S. Midwest (yellow shade) mapped based on predetermined buffer widths of 20 m (a) and 30 m (b) under a "base case" scenario (implementing SBBs on all likely classified tile-drained agricultural lands).

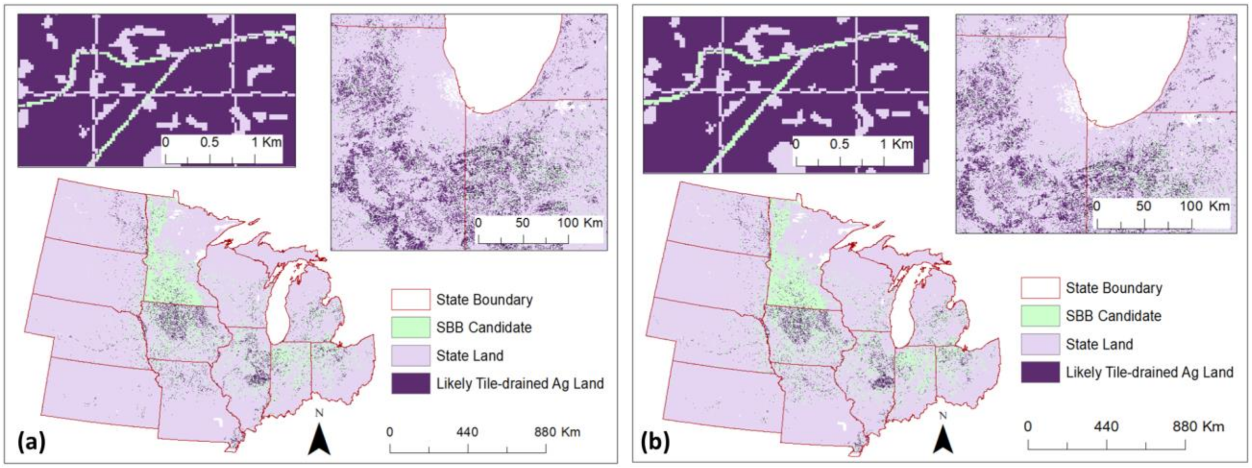

FIGURE 5 Saturated bioenergy buffer (SBB) candidate sites in the U.S. Midwest (green shade) mapped based on predetermined buffer widths of 20 m (a) and 30 m (b) under a "base case + 1" scenario (implementing SBBs on all likely classified tile-drained agricultural lands with conditions highly conducive to denitrification). Each figure shows a Midwest view, a zoom view of the region at the southern end of Lake Michigan, and a zoom view at a field/farm level.

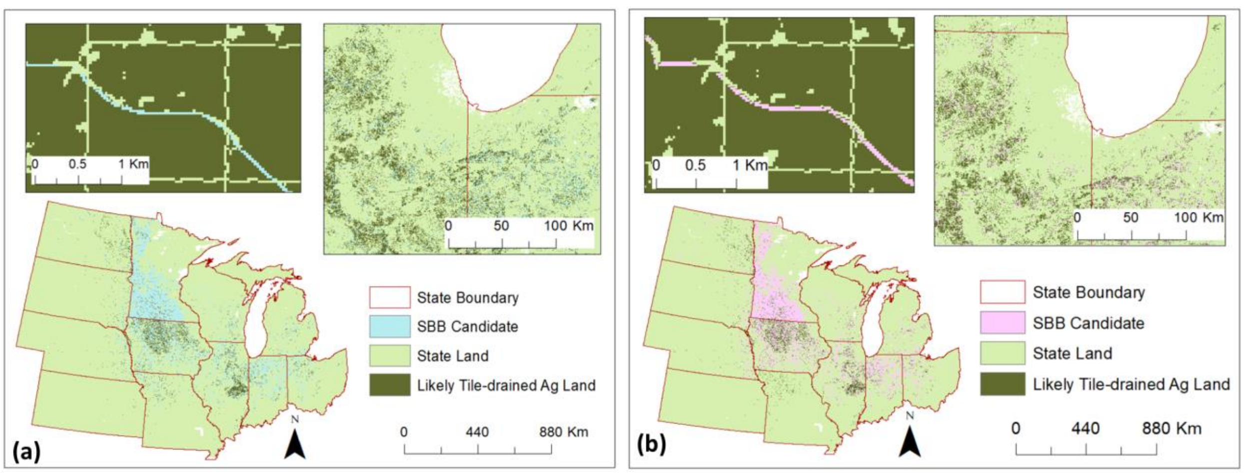

FIGURE 6 Saturated bioenergy buffer (SBB) candidate sites in the U.S. Midwest (green shade) mapped based on predetermined buffer widths of 20 m (a) and 30 m (b) under the "base case + 2" scenario (implementing SBBs on all likely classified tile-drained agricultural lands with conditions that are highly conducive to denitrification and have likely stable streambanks). Each figure shows a Midwest view, a zoom view of the region at the southern end of Lake Michigan, and a zoom view at a field/farm level.

4 CONCLUSIONS

We developed a site suitability analysis method as a first step for classifying candidate saturated bioenergy buffer sites at multiple spatial scales (field, watershed, county, state, regional). The method is robust for saturated bioenergy buffer site classification based on its performance in predicting the suitability of actual SB study sites, which were considered as either performing or promising in reducing nitrate losses in tile drainage. We implemented this approach in ArcGIS Desktop using various scenarios to estimate the available land area that could be allotted for saturated bioenergy buffer. These estimates could be critical in other analyses associated with the utilization of lands for producing more bioenergy feedstock without competing lands for food, feed, and fiber production and affecting natural grasslands and forestlands. Simultaneously, installing more saturated bioenergy buffer would improve water quality by reduced loading to surface water systems.

5 FUTURE WORK

We propose two additional works to build on our results.

1. Include the saturated bioenergy buffer site suitability classification algorithms in this study with the Scaling Up PERennial Bioenergy Economics and Ecosystem Services Tool (SUPERBEEST).

2. Conduct an analysis to estimate the yields of candidate perennial bioenergy crops under the saturated bioenergy buffer cropping system and associated water quality and other environmental benefits.

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Environmental Science Division
Argonne National Laboratory
9700 South Cass Avenue, Bldg. 240
Lemont, IL 60439-4832

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