POTENTIAL SUITABILITY OF SUBIRRIGATION FOR FIELD CROPS IN THE U.S. MIDWEST

F. Yu, J. Frankenberger, J. Ackerson, B. Reinhart

HIGHLIGHTS

- A fuzzy rating system was created based on published criteria for subirrigation suitability.
- Maps showing potential suitability for subirrigation were created for the U.S. Midwest.
- 78,500 km² across the U.S. Midwest is potentially suitable for subirrigation.
- Maps identify potential subirrigation locations pending onsite assessment.

ABSTRACT. *Subirrigation through subsurface tile drains has potential to increase crop yields and improve water quality in tile-drained landscapes, but it has not been widely implemented. Identifying locations with high potential suitability for subirrigation may help the planning and implementation of this practice. In this study, we developed a fuzzy rating system for subirrigation suitability using the Gridded Soil Survey Geographic Database (gSSURGO). Maps of the fuzzy rating system identified locations of high potential suitability for subirrigation and highlighted physiographic regions highly conducive to the practice. We identified 78,500 km², about 9%, of agricultural land in the Midwest with high potential suitability for subirrigation where onsite investigation may be targeted. The largest areas of high potential suitability were found in Minnesota, Illinois, and Indiana. Results from the fuzzy rating analysis are provided to the public through three channels: a downloadable data repository, map service, and web map tool. Ultimately, this study can facilitate the adoption of subirrigation by highlighting areas where subirrigation may potentially be a viable practice.*

Keywords. *Controlled drainage, Fuzzy rating, Geographic information system (GIS), Gridded Soil Survey Geographic Database (gSSURGO), Midwestern U.S., Subirrigation.*

Subirrigation is the application of irrigation water below the ground surface to raise the water table to within or near the root zone. In areas with subsurface tile drainage, the same drains that remove excess water during wet periods of the year can be used to provide supplemental irrigation to the crops during dry periods, provided that the drains are close enough to achieve uniform distribution. Subirrigation of field crops in poorly drained soils, implemented together with controlled drainage in a system also called water table management, has been proposed as an efficient management system that improves water quality and sustains agricultural productivity (Belcher and D'Itri, 1994; USDA-NRCS, 2001). Subirrigation is widely used in greenhouse production (Ferrarezi et al., 2015)

and could potentially be more widely used in field crop production, which is the focus of this study.

In the limited locations where it has been implemented, subirrigation has been shown to have considerable crop yield benefits as well as water quality benefits. For example, Cooper et al. (1991, 1992) showed that subirrigation could increase soybean yield by up to 42%, and Fisher et al. (1999) found average increases of 19% in corn yield and 64% in soybean yield. Corn yield increases of 64% were found by Ng et al. (2002), and increases up to 12.9% were found by Mejia et al. (2000) in Ontario. Subirrigation has also been found to have substantial benefits in Missouri (Nelson et al., 2011; Nelson and Smoot, 2012). Water quality benefits of subirrigation include average reductions in nitrate loss of 37% to 66%, as shown by Tan et al. (1993) and Drury et al. (1996, 2009). At another site, Tan et al. (2007) and Tan and Zhang (2011) documented a 41% reduction in average annual nitrate loss and a 36% reduction in total dissolved phosphorus loss. Wesström et al. (2014) found that nitrogen and phosphorus losses were both about 50% less on average in a water table management system compared to a conventional subsurface drainage system.

Interest in supplemental irrigation of all types is growing in the U.S. Midwest, as temperature and precipitation patterns shift toward more frequent summer droughts (Melillo et al., 2014). The increasing benefits of supplemental irrigation in this region have been suggested by Baker et al.

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(2012), and Baule et al. (2017) estimated that climate change would increase the corn yield benefit of subirrigation from a historical average of 20% at three Ohio sites to about 30% by the middle of the 21st century.

There is considerable potential for subirrigation in the U.S. Midwest, where millions of cropland acres already have subsurface drainage systems, some of which could potentially be retrofitted to include subirrigation. However, subirrigation has not been widely adopted; less than 1% of irrigated acreage was served by subirrigation based on the 2008 Farm and Ranch Irrigation Survey (USDA-NASS, 2008), and subirrigation was no longer included in the 2013 survey (USDA-NASS, 2013). There are a number of barriers to adoption of subirrigation. Specific soil characteristics, which are found in areas of limited extent, are required to ensure adequate water uniformity and water table control. The ideal soil for subirrigation has high horizontal hydraulic conductivity, a restrictive layer below the drains, and nearly level topography (Evans and Skaggs, 1989; Nolte et al., 1987; Zimmer and Madramootoo, 1997; Fouss et al., 1999). Subirrigation may still be viable at sites with less than ideal soils, such as by installing additional drains to reduce drain spacing or multiple water control structures to manage the water table, but these modifications add costs. In addition, the concept is not widely known, and specialized skills are required for proper design and management of subirrigation systems. In some areas, lack of water could be a barrier, which may be overcome by storing and recycling drained water (Frankenberger et al., 2017).

Therefore, identification of areas that have the characteristics required for successful subirrigation is important to improve the decision-making process. Although onsite investigation is necessary to determine the suitability of any specific site, it would be useful to know where such investigations would most likely lead to successful identification of suitable areas. Understanding which criteria are not met can help decision-makers understand whether the limitations are due mainly to economics or to physical constraints. For example, if the limitation is due to low conductivity, subirrigation would be possible, but the required narrow drain spacing would add costs. However, if a restrictive layer is lacking, then subirrigation is likely not possible. Fuzzy rating methods offer a relatively new and innovative technique capable of developing classification schemes that incorporate the nuances involved in multi-criterion site suitability analyses (Badr et al., 2018).

The landscape characteristics required for subirrigation have been identified, and criteria have been proposed in the literature. The goal of this study is to identify and quantify land that meets these criteria across the Midwest, as well as the most common criteria that are not met, so that farmers and agencies supporting conservation practices can make better decisions about implementation. Specific objectives are to: (1) identify land suitable for subirrigation in the 12-state U.S. Midwest region using only widely available data, (2) identify the primary limiting criteria in areas that are less suitable for subirrigation, (3) quantify the amount of land suitable for subirrigation across states and major land resource areas, and (4) develop an online tool for others to use

to identify suitable sites in their locations using the results of this analysis.

This analysis can lead to improved understanding among stakeholders about site characteristics that influence subirrigation site suitability, determine the prevalence of suitable sites in the Midwest, and identify locations where site-specific investigations should be conducted, in order to improve decision-making about subirrigation implementation in the region.

METHODS

SUITABILITY CRITERIA FOR SUBIRRIGATION

Subirrigation is economically feasible on cropland when four conditions exist simultaneously: flat topography allows reasonably large management zones while keeping the depth to the water table even across the field, permeable soil allows water to move horizontally between the drains, a restrictive layer below the permeable soil limits deep seepage and causes the water table to rise to a level where crop roots can access it, and subsurface drainage exists or would be beneficial (Evans and Skaggs, 1989; Zimmer and Madramootoo, 1997; Fouss et al., 1999). Although there is wide agreement about these necessary conditions, determining the specific numeric criteria needed for a geospatial analysis is more complicated, and numerous studies have proposed differing numeric criteria. The key challenges for selecting numeric criteria in multi-state, geospatial analysis lie in selecting criteria that balance the sometimes-conflicting criteria from previous studies and that can be determined throughout the region based on widely available data. Below, we summarize the criteria for subirrigation proposed by previous studies and discuss how we reconciled differences in the criteria between studies and arrived at a final set of criteria that could be assessed using widely available data throughout the study region.

Flat Topography

To maintain a uniform depth from the surface to the water table, the surface topography should be nearly level. A field with considerable undulation of the surface could require small management zones to avoid excessive variation of the depth to the water table, which increases the cost of implementation. Evans and Skaggs (1989) stated that 2% slope is the physical limit, while 1% slope is the economical limit, and most other authors suggested slopes $\leq 1\%$ (Fouss et al., 1999; Zimmer and Madramootoo, 1997). Therefore, 1% and 2% were used to define the slope suitability criterion in this study.

Hydraulic Conductivity

Rapid horizontal conductivity allows the drains, which are also used for water supply, to be placed at an economical (i.e., wide) spacing and still maintain the water table during periods of high evapotranspiration. Suggested criteria are that horizontal conductivity should be $\geq 0.5 \text{ m d}^{-1}$ (Evans and Skaggs, 1989), $\geq 0.3 \text{ m d}^{-1}$ (Zimmer and Madramootoo, 1997), $\geq 0.37 \text{ m d}^{-1}$ (USDA-NRCS, 2001), or $\geq 0.6 \text{ m d}^{-1}$ (Belcher, 2005). Hydraulic conductivity varies with depth in the soil profile, and because most flow is in the saturated zone, deeper soil layers play an important role. In this study,

soils were rated as suitable if the average hydraulic conductivity between the 50 and 100 cm depths was $\geq 0.3 \text{ m d}^{-1}$ ($3.5 \mu\text{m s}^{-1}$ or 0.5 in. h^{-1}).

Restrictive Layer

The soil must have a restrictive layer that limits deep seepage losses and maintains the water table at the desired depth. Previous studies have stated that the restrictive layer should have a permeability of 1/10 or less of the vertical permeability in the root zone soil (Nolte et al., 1987) or that the permeability of the restrictive layer should be less than 1 mm h^{-1} (Belcher, 2005). The restrictive layer should be 2 to 6 m below the surface, but close to the drains is preferable (Evans and Skaggs, 1989; Fouss et al., 2007). Although these values are useful for onsite investigations, they cannot be obtained directly from widely available soil data for large spatial scales, as required for this analysis. The Soil Survey Geographic Database (SSURGO) contains a data field for restrictive layers (e.g., bedrock, cemented layers, dense layers, and frozen layers), but this data field is based on restriction of root growth rather than water movement, and more importantly, it only includes layers within the described soil profile. Restrictive layers that are below the described soil profile, which does not exceed 200 cm in depth, cannot be obtained directly from SSURGO. However, the natural drainage class of the soil can provide evidence of a restrictive layer sufficient for subirrigation (Evans and Skaggs, 1989; Fouss et al., 1999, 2007). High water tables exist where restricted hydraulic conductivity causes seasonally high water tables during the wet season. Therefore, the natural drainage class in SSURGO was used as a proxy for the presence of a restrictive layer, as described below.

Response to Subsurface Drainage

Subirrigation is only beneficial in soils that have or would benefit from subsurface drainage. The natural drainage class in SSURGO is often used for estimating areas with subsurface drainage (i.e., Sugg, 2007) and was used here. Because these data are also used for the restrictive layer, only three analyses were needed to address all four criteria.

DATA SOURCES

We included twelve Midwestern states in this study: Minnesota (MN), Iowa (IA), Missouri (MO), Wisconsin (WI), Illinois (IL), Indiana (IN), Michigan (MI), Ohio (OH), North Dakota (ND), South Dakota (SD), Nebraska (NE), and Kansas (KS). For North Dakota, South Dakota, Nebraska, and Kansas, we only included areas east of longitude 100° W , where most poorly drained soils are located. We also restricted our analysis to land with agricultural land use only, using data from the most recent National Land Cover Database (NLCD) version available at the time of analysis, i.e., the 2011 edition amended in 2014 (Homer et al., 2015). We included cropland as well as pasture/hay because the latter areas may also support row crops as part of a multi-year crop rotation.

We used data from the Gridded Soil Survey Geographic Database (gSSURGO; USDA-NRCS, 2019) to evaluate three key criteria for subirrigation: surface slope, hydraulic

conductivity (K_{sat}), and drainage class. The Soil Data Development Toolbox for ArcGIS (Peaslee, 2018) was used to query the gSSURGO database and generate maps of relevant soil physical and hydrologic properties, including representative slope (slope_r), hydraulic conductivity (ksat_r), and drainage class (drainagecl). All soil data were taken from the 2019 fiscal year release of gSSURGO (updated on 18 September 2018). The gSSURGO dataset represents soil as map units, which may contain a combination of unique components. The dominant component (i.e., the soil component with the highest composition percentage in a soil map unit) was used in all analyses.

In gSSURGO, K_{sat} data are available for each soil layer. To represent the relevant K_{sat} for subsurface irrigation suitability, we used the depth-weighted average K_{sat} between 50 to 100 cm depth for each dominant component. This depth range best represented the soil conditions needed for consistent lateral flow below the upper root zone, as required for subirrigation.

SOIL PROPERTY USED FOR RESTRICTIVE LAYER

The presence of a layer that restricts water movement, identified as a key criterion for subsurface irrigation suitability, can be indicated by a shallow water table or poor natural drainage. SSURGO contains two data fields that relate to soil drainage characteristics: natural drainage class and water table depth (WTD). Drainage class is a categorical rating that describes the frequency and duration of wet periods in the soil under natural drainage conditions and is identified in soil by the presence of redoximorphic features. WTD is a numeric value that represents the minimum depth to saturation. Because WTD is a continuous number, it would result in a more continuous suitability rating; however, unlike drainage class, WTD is difficult to observe in the field from traditional soil survey approaches (i.e., soil profile descriptions). Therefore, WTD in SSURGO is often inferred from drainage class based on local guidelines or heuristics that may not be consistent across states or soil survey regions (USDA-NRCS, 2017). To determine if WTD could be used as an alternative criterion to drainage class in suitability ratings, we compared ratings of soil drainage class and WTD for four states. The parameters were derived from the gSSURGO database, using SQL to query from the map unit aggregated attribute table (muaggatt), for 6,657 map units in Indiana, 10,418 in Illinois, 10,456 in Michigan, and 10,024 in Ohio. Specific parameters were the dominant drainage class for the map unit based on the composition percentage of each map unit component (drclassded), and the shallowest depth to a wet soil layer (water table) at any time during the year, expressed as centimeters from the soil surface, for components whose composition in the map unit was equal to or exceeded 15% (wtdepannmin) (USDA-NRCS, 2014).

We found that the relationship between WTD and drainage class was highly variable, both between states and within states (fig. 1). For somewhat poorly drained soils, which had the highest variability of WTD for a single drainage class, the state median WTD ranged from 30 cm in Michigan to 46 cm in Illinois. There was less variability between states

Figure 1. Relationship between depth to water table (WTD) and drainage class for three soil drainage classes (somewhat poorly drained, poorly drained, and very poorly drained) based on a total of 37,555 map units in Indiana (IN), Illinois (IL), Michigan (MI), and Ohio (OH).

for poorly and very poorly drained soils, for which the median WTD ranged from 0 cm in Michigan to 15 cm in Illinois. It was evident that states had different criteria for assigning WTD from drainage class observations. There was also a surprising variability within individual states. The greatest within-state variability was in Michigan, where the WTD assigned to somewhat poorly drained soils ranged from 0 to 90 cm, with only 50% of the map units falling in the fairly wide range of 15 to 46 cm. Michigan assigned WTD of 0 cm to almost all poorly and very poorly drained soils, while the three other states generally assigned a range of values, mostly between 0 and 15 cm depth. This lack of a consistent state-to-state relationship between drainage class and WTD suggested that WTD would be a poor substitute for drainage class, so drainage class was chosen as a more consistent measure to indicate the likely occurrence of a restrictive layer sufficient for subirrigation.

SUBIRRIGATION SUITABILITY CRITERIA USING FUZZY LOGIC

The final criterion for subirrigation suitability was a composite fuzzy score based on three component scores: slope, K_{sat} from 50 to 100 cm, and drainage class. For each of these factors, soils were given a score from 0 to 1, with 0 representing unsuitable and 1 representing suitable. For some intermediate locations, the soil or site characteristics were neither suitable nor unsuitable. For those intermediate sites, the score was allowed to vary between 0 and 1. For example, sites with a slope of 1% were considered suitable, while sites with a slope of 2% were considered unsuitable. However, sites with a slope between 1% and 2% may represent sites that are moderately suitable (i.e., these sites pose some additional slope-related challenges compared to suitable sites, but these challenges are not sufficient to make the site wholly unsuitable). For intermediate sites, the score was defined by a linear function between the suitable and unsuitable endpoints (fig. 2).

The composite subirrigation suitability score was calculated as the product of the three component scores, with final scores ranging from 0 to 1, where a score of 0 indicated completely unsuitable, and a score of 1 indicated very suitable. Multiplication was used to combine the numerical ratings to eliminate pixels with a 0 rating for any criteria (i.e., if the slope was greater than 2%, the site would have a combined score of 0 regardless of the suitability of drainage class or K_{sat}).

The key advantage of the fuzzy rating system was that, by providing some variability in scores between suitable and unsuitable, the rating system codified the uncertainty in soil ratings. Uncertainty can arise from several sources, including uncertainty in the soil map data (i.e., K_{sat}) as well as uncertainty in the rating criteria. Uncertainty in the soil map data arises from the large amount of natural spatial variability in soil properties (e.g., lateral and vertical variability in K_{sat}) as well as inaccuracies in the soil mapping technique. Uncertainty in the rating criteria arises from the fact that, despite being based on previous work on subirrigation, the component rating criteria are a best approximation. Additionally, there may be regional exceptions to these criteria. For example, in some areas, it may be common practice to use subirrigation on soils with low K_{sat} values. By allowing for uncertainty in the rating criteria with a fuzzy rating system, we can prevent these regional exceptions from being rated as unsuitable for subirrigation.

GEOPROCESSING OF SPATIAL DATABASE

We performed all geoprocessing for gSSURGO using ArcGIS (release 10.6, ESRI, Redlands, Cal.). Processing was done separately for each state before merging the data into single layers for the final published map. We used the Soil Data Development Toolbox to generate the raster layers of the numerical ratings or categories based on the query to the gSSURGO database. Pixels that were not identified as

cropland or pasture were excluded, resulting in raster grids of each soil property for only agricultural land.

Next, we created soil maps of the numerical ratings or categories for each of the subirrigation criteria. Each pixel of the numerical rating raster files was then assigned a fuzzy score that represented the degree of suitability, ranging from 1 (totally suitable) to 0 (totally unsuitable), using the functions shown in figure 2. The assigned score for each pixel of the rating files was calculated using map algebra in Python (ArcPy). Finally, we calculated the combined subirrigation suitability score for each pixel by multiplying the three criteria for each pixel.

Figure 2. Subirrigation suitability criteria including (a) representative slope, (b) hydraulic conductivity, and (c) drainage class versus suitability score based on linear functions.

To investigate underlying spatial trends in the subirrigation suitability scores, we generated histograms for the frequency and distribution of the percentage area for each of the three criteria and combined the suitability scores by state and by major land resource area (MLRA; USDA-NRCS, 2006). MLRAs are geographically associated areas that have similar characteristics of land use, elevation and topography, climate and water, and are important for agricultural planning at the state and national level. We used MLRAs to determine their possible correlation with the degree of subirrigation suitability to inform subirrigation planning. These statistics were computed using the Geospatial Data Abstraction Library (GDAL/OGR, 2019) and NumPy (Oliphant, 2006) for higher efficiency and flexible histogram bin assignment.

RESULTS

Over the entire study region, approximately 70% of the agricultural land had a combined subirrigation suitability score of less than 0.1, meaning that it was not suitable for subirrigation, while approximately 9% of the agricultural land had a suitability score of 1 (fig. 3). To show the score range more clearly in the maps, we classified the suitability scores into four categories: non-agricultural land or otherwise unsuitable lands (0.0 to 0.1), low potential suitability (0.1 to 0.5), medium potential suitability (0.5 to 0.99), and high potential suitability (0.99 to 1).

Areas of land that have a suitability score of 1 are scattered throughout the Midwest (fig. 4a). Minnesota has the largest area (22,466 km²), followed by Illinois (15,406 km²) and Indiana (12,614 km², fig. 4b). Iowa and Michigan have more than 5,000 km² of agricultural land with high potential suitability for subirrigation. Kansas, Nebraska, and South Dakota, for which only the portion of each state east of longitude 100° W was included, have suitable areas of less than 1,000 km², with Kansas having only 38 km².

The distributions and locations of land with high potential suitability for subirrigation have similarities to poorly drained areas that were previously estimated to have artificial drainage (Sugg, 2007), but not all poorly drained areas

Figure 3. Distribution of combined subirrigation suitability scores for all twelve Midwestern states.

Figure 4. Subirrigation suitability (combined fuzzy scores for the three criteria) for each of the twelve states: (a) spatial mapping and (b) histogram of the area with low, medium, or high potential suitability.

are included. For example, the Red River valley along the border of Minnesota and North Dakota is flat and requires artificial drainage, but the low K_{sat} of many of the clay soils is less than the minimum required in this study for fully suitable soils. However, subirrigation has been used in that area (Jia et al., 2017), which shows the value of using fuzzy criteria rather than strict thresholds. Subirrigation is possible in areas with low K_{sat} , although the need for more closely spaced drains would add to the installation cost, demonstrating that the K_{sat} criterion is mainly economic. Northwest Ohio is another area characterized by low to medium potential suitability due to low K_{sat} and where subirrigation has been researched (Cooper et al., 1999; Fausey et al., 1995). Of three wetland-reservoir-subirrigation sites described by Allred et al. (2014), subirrigation performed well at two of the sites; however, at the third site, the K_{sat} was too slow to

raise the water table. Modeling by Gunn et al. (2018) showed that the rise of the water table was so slow after subirrigation started that only 36 mm of water could be added all season, which did not meet crop needs. Narrower drain spacing would be required for effective subirrigation.

The areas identified with this process correspond with previous analyses. Kittleson et al. (1990) estimated that about 8,000 km² of agricultural land was potentially suitable for subirrigation in Michigan, with more than 80% of the potentially suitable area concentrated around Saginaw Bay. The results of the present study also highlight the area around Saginaw Bay as the highest concentration of potentially suitable agricultural land in Michigan.

The regional map shown in figure 4 can be useful for large-scale assessment and planning, but individual sites must be studied using site-specific analyses. Areas that do

not appear suitable at the regional scale may have many small suitable areas within them, and vice versa. For example, within the Red River valley, subirrigation is potentially suitable in many individual fields, while within the generally suitable Saginaw Bay area, many fields are less suitable (fig. 5). This illustrates the value of the detailed scale of analysis using gSSURGO, which is generally based on maps at a scale of 1:12,000.

Climate, agronomic, and other economic factors may influence suitability in ways not shown here. For example, the potentially suitable area in northwest Minnesota just east of the Red River valley meets the soil and topography-based criteria used in this study, but the climate and resulting short growing season limit the viability of the practice. This demonstrates an area that is only potentially suitable and therefore requires more detailed analysis for decision-making, including the availability of a reliable water supply and drainage outlet, as well as onsite soil analyses.

POTENTIAL SUBIRRIGATION SUITABILITY BY MAJOR LAND RESOURCE AREA

Assessing potential suitability by MLRA provides another way to identify where land that is potentially suitable for subirrigation is most likely to be found. The physiographic characteristics used to delineate MLRAs integrate the topographic and soil criteria that were considered individually in the geospatial analysis. MLRAs are denoted with either a number (e.g., 103) or a number with a letter modifier (e.g., 108a and 108b). Letter modifiers are used when an MLRA covers a large or discontinuous area. To simplify our analysis, we combined MLRAs with the same numeric designation but different letter modifiers into a single geographic unit (e.g., we combined MLRA 108a and MLRA 108b into a single unit, MLRA 108). This reduced the total number of units within the study region from 94 to 53. The resulting map (fig. 6) shows that the potential suitability for

subirrigation is highly related to MLRA. For example, MLRA 103, which contains the Des Moines lobe of the Wisconsin glaciation, has a high concentration of highly suitable land, as is readily apparent in figure 6.

For MLRAs with large areas of high subirrigation suitability scores, there are several recurring physiographic and soil features (table 1). Most commonly, areas of high subirrigation suitability are located on lake plains and glacial till plains. Lake and till plains make ideal features for subirrigation for several reasons. First, these plains tend to be level or nearly level and therefore have optimum slopes for the installation of subirrigation systems. Second, the geology of both lake and till plains tends to result in high concentrations of restrictive subsoil layers. On lake plains, clay-rich lacustrine sediments often function as restrictive layers, while on till plains, compacted or dense till layers function as restrictive layers. In either case, both physiographic types have subsoil layers that support subirrigation because these layers prevent deep percolation of irrigation water during periods when irrigation is active. Finally, it is common for lake and till plains to have a surficial layer of silty loess or sandy/loamy outwash. These surficial materials often have high K_{sat} values needed for subirrigation.

Conversely, MLRAs with small areas (i.e., <2 km²) of high subirrigation suitability scores (table 2) tend to have physiography consisting of deep soils and/or steeply sloping terrain. Commonly, these soils are not derived from glacial drift but instead developed from weathered bedrock. Where drift is present (e.g., MLRA 77), the soils lack a restrictive layer such as dense till, or these layers are too deep to impact the soil drainage class. Additionally, soils in these regions tend to have good drainage and are therefore unsuitable for subsurface drainage.

The analysis by MLRA suggests that physiographic characteristics, rather than geopolitical boundaries, should be used for making recommendations. If subirrigation suitability

Figure 5. Potential suitability at the regional scale (left) showing the Saginaw Bay area of Michigan, while at the local scale (right) specific fields that may be suitable can be identified.

Figure 6. Subirrigation suitability with major land resource area (MLRA) boundaries.

Table 1. Ten major land resource areas (MLRAs) with the greatest area of land with high potential suitability for subirrigation.

MLRA Number	MLRA Name	Physiographic Type	Highly Suitable Land	
			km ²	%
103	Central Iowa and Minnesota Till Prairie	Till plain	17,022	29
111	Indiana and Ohio Till Plain	Till plain	11,136	17
108	Illinois and Iowa Deep Loess and Drift	Till plain	11,053	16
56	Red River Valley of the North	Lake plains	6,378	19
98	Southern Michigan and Northern Indiana Drift Plain	Till plain	4,933	20
102	Rolling Till Prairie, Till Plains, and Loess Uplands	Till plain	3,621	7
99	Erie-Huron Lake Plain	Lake plains	3,311	19
95	Wisconsin and Northern Illinois Drift Plain	Till plain	3,101	12
55	Black Glaciated Plains	Till plain	2,441	4
115	Central Mississippi Valley Wooded Slopes	Till plain	2,394	7

Table 2. Ten major land resource areas (MLRAs) with the smallest area of land with high potential suitability for subirrigation.

MLRA Number	MLRA Name	Physiographic Type	Highly Suitable Land	
			km ²	%
77	Southern High Plains and Breaks	Loess and sand plain	0.0	0.0
84	North Cross Timbers	Bedrock upland	0.0	0.0
76	Bluestem Hills	Bedrock upland	0.0	0.0
74	Central Kansas Sandstone Hills	Bedrock upland	0.6	0.0
78	Central Rolling Red Plains, Eastern Part	Bedrock upland	0.9	0.1
54	Rolling Soft Shale Plain	Bedrock upland	0.9	1.7
63	Northern Rolling Pierre Shale Plains	Bedrock upland	1.4	0.1
121	Kentucky Bluegrass	Bedrock upland	1.4	0.1
80	Central Rolling Red Prairies	Bedrock upland	1.9	0.1
122	Highland Rim and Pennyroyal	Bedrock upland	2.1	0.1

ity recommendations are made on a state-by-state basis, rather than based on physiographic features, significant areas of suitable land may be overlooked. Additionally, MLRAs may be a useful basis for exploring where regional subirrigation criteria could be developed. These region-specific criteria could refine the criteria used in this study to account for unique regional circumstances or soils. MLRAs are used in a similar context in other areas, such as wetland delineation.

In wetland delineation, certain soil morphological features are only permissible as indicators of hydric soils in specific MLRAs (USDA-NRCS, 2018). By allowing certain indicators to be used only in specific regions, the criteria for hydric soils can account for locally unique soil environments without being too restrictive or permissive in areas without such soils. A similar approach could be employed with the suitability criteria for subirrigation.

MOST LIMITING CRITERION

To provide additional information for subirrigation planning and implementation, we also analyzed which criterion was most limiting. The most common limitation for the entire study region was lack of a restrictive layer, indicated by soils that are not poorly drained (71% of the total area). Another 18% of the agricultural land was primarily limited by the K_{sat} values between 50 and 100 cm depth. Steep slopes limited subirrigation suitability on 11% of the area, while areas of no limitation covered approximately 9% of the agricultural land. The most limiting criterion was strongly related to the MLRAs (fig. 7). The various limiting criteria were distributed fairly evenly across states (fig. 8).

ONLINE GIS MAPS AND DATA AVAILABILITY

This analysis resulted in eight different maps for the entire study area: subirrigation suitability, most limiting criterion, K_{sat} score, K_{sat} values, slope score, slope values, drainage class score, and drainage class. The 30 m resolution data are freely available in three ways (fig. 9).

Downloadable Data

For users interested in conducting their own analyses, the data are available as downloadable raster files from the Purdue University Research Repository (PURR). The data are organized by state, with each file about 162 to 379 MB in size, including raster pyramids for fast rendering (.ovr) and detailed

Figure 7. Map visualization of the most limiting criteria for MLRAs.

Figure 8. Limiting criteria for subirrigation suitability by state and percentage of agricultural land with no limitation (suitability score = 1).

Figure 9. Three methods to access data from this subirrigation suitability analysis.

metadata (.xml), and are distributed with the Creative Commons license 3.0 at <https://purr.purdue.edu/publications/3263/1>.

REST Map Services

The data were uploaded to an ArcGIS server through Purdue University Libraries and are available through any GIS software that links to REST services at <https://mapsweb.lib.purdue.edu/arcgis/rest/services> (in the Ag folder).

Online Tool

To make the data widely available to users without GIS tools or expertise, an online tool was developed and is available at <https://transformingdrainage.org/tools/subirrigation-suitability-tool/>. This tool uses ArcGIS API for JavaScript to provide simple web-based access to the data. The scores for overall suitability, K_{sat} , slope, and drainage class are shown as maps, while the underlying values, and the most limiting criterion, are available in interactive popup boxes by clicking on any pixel in the map.

CONCLUSIONS

This study demonstrated that approximately 78,500 km² of land is potentially suitable for subirrigation across the U.S. Midwest, and the results have been made freely available through an online tool, REST map services, and downloadable data. Onsite investigations are required to determine the feasibility of implementing subirrigation at any specific site, and this analysis identified areas where such investigations should be directed to most likely identify suitable locations. Conversely, this analysis may help save time and money by showing where subirrigation is not likely to be successful. Agro-nomic and economic feasibility, as well as the availability of a water source (groundwater or surface water) and suitable outlet, also need to be considered in site-specific feasibility analyses.

This suitability analysis used the most appropriate, widely available data, but there are limitations with this approach. Specifically, the use of SSURGO data has some limitations. One is that although the presence of a water-restricting soil layer is a key requirement for land to be suitable for subirrigation, SSURGO does not provide information on restrictive layers below the soil profile; therefore, an indirect indicator (drainage class) was used for this criterion. In addition, there are well-known inconsistencies in the SSURGO data across

survey regions, and although the NRCS is actively working to resolve these inconsistencies, they present a limitation.

The criteria used in this study were based on published values, but there is a lack of empirical data for testing them, especially considering how the criteria could potentially vary across the region. More regional field experiments in subirrigation are needed to refine the criteria and better understand the nuances across the region. For example, subirrigation could be successful with lower hydraulic conductivities in specific regions. Our results indicate that it may be beneficial to constrain regionally specific criteria using MLRAs or similar physiographic delineations. Uncertainty also arises from the fact that parameters such as hydraulic conductivity are difficult to measure, and the SSURGO data provide only broad estimates. The fuzzy rating system provides some variability between suitable and unsuitable scores and thereby takes the uncertainty in soil ratings into account.

Future studies could refine this analysis, for example by considering economic, agronomic, and climate factors. Economics play an important role in the suitability of any land for subirrigation; for example, more land might be considered suitable when crop prices are high. In addition, sensitivity analyses could be used to better understand the influence of the uncertain criteria and data that are necessarily used in such an analysis.

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