North Dakota Statewide Irrigation Reconnaissance Study

Final Report

Submitted to

North Dakota Irrigation Association

North Dakota Department of Water Resources

Garrison Diversion Conservancy District

NDSU Office of Research and Creative Activity

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February 2025

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Executive Summary

According to the USDA National Agricultural Statistics Service's Census of Agriculture, less than one percent of cropland in North Dakota was irrigated in 2022. It was the least among the ten states that are entirely or partially covered by the Missouri River Basin and below the US average for irrigated cropland, which is 14.4% (Table ES.1). To identify the locations and areas of North Dakota croplands that have potential for future irrigation development, we conducted a statewide irrigation reconnaissance study.

Table ES.1. Irrigated cropland in the ten Missouri River Basin states (Source: USDA-NASS).

State[a]	Cropland (Thousand acres)	Irrigated Cropland (Thousand acres)	Irrigated Cropland (%)
Wyoming	2,326	1,273	54.7
Nebraska	21,218	7,966	37.5
Colorado	10,479	2,288	21.8
Montana	16,070	1,725	10.7
Missouri	14,765	1,335	9.0
Kansas	28,341	2,245	8.3
Minnesota	21,544	648	3.0
South Dakota	18,489	411	2.2
Iowa	25,882	260	1.0
North Dakota	26,260	248	0.9
Total	**185,374**	**18,499**	**10.0**
The U.S.	**382,356**	**54,930**	**14.4**

[a] Ranked from high to low by the percentage of irrigated cropland.

This statewide irrigation reconnaissance study was carried out in three phases. In Phase I, we updated the North Dakota Department of Water Resources (DWR) soil irrigability map using the most recent Soil Survey Geographic Database (SSURGO) data. In Phase II, we removed the lands that were unavailable or unsuitable for developing irrigation projects from the updated soil suitability map. In Phase III, we identified and estimated the locations and areas of cropland with irrigation potential by examining the nearby water and three-phase power availabilities. This report summarizes the methods employed and the results obtained in this study.

It is important to note the limitations of our study, which was intended to provide a statewide assessment of land in North Dakota for potential irrigation development. When assessing the potential of developing irrigation projects for specific areas, in-depth feasibility studies should be conducted to consider additional factors, including but not limited to design, cost, landowner preferences, environmental concerns, water permit applications, etc.

In terms of water availability, two sources – surface water from the Missouri River system and groundwater from the shallow glaciofluvial aquifers across the state – are considered in this study. While assuming the water from the Missouri River system is readily available for developing irrigation projects along the Missouri River corridor, we created two scenarios (best and worst) to account for groundwater availability based on the managed aquifer recharge potential map recently developed by the DWR.

In summary, considering soil suitability and water availability there are 1.8 to 2.1 million acres of cropland available for potential future irrigation development across the state. Of these lands, approximately one million acres are within the 17 counties along the Missouri River corridor for irrigation development, potentially irrigable using water withdrawn from the Missouri River system. The additional 0.8 to 1.1 million acres may be developed for irrigation by withdrawing good-quality water from shallow glaciofluvial aquifers across the state, depending upon the water availability in these aquifers, where using water from the Missouri River system for irrigation is not practical (Figure ES.1).

Figure ES.2 ranks the counties in terms of their areas of potentially irrigable croplands. The figure shows that central North Dakota counties (e.g., McLean, Emmons, Burleigh, Kidder, Morton) have the most areas of cropland for potential irrigation development under both groundwater availability scenarios. Not surprisingly, the counties in southwestern North Dakota (e.g., Adams, Billings, Bowman, Golden Valley, Hettinger, Slope) do not have much land for irrigation development, nor do Ramsey and Towner counties in northeastern North Dakota. Statewide, under the best groundwater availability scenario, 40 counties have more than ten thousand acres of cropland potential for future irrigation development, whereas, under the worst groundwater availability scenario, only 31 counties have more than ten thousand acres of cropland for potential irrigation development.

Due to data privacy concerns, we can only access three-phase power distribution lines from three North Dakota electric distribution cooperatives (i.e., Capital Electric, Dakota Valley, Northern Plains) out of the 17 North Dakota electric distribution cooperatives. In the three electric cooperatives' service areas, approximately 66 to 76 thousand acres of cropland, depending upon groundwater availability scenarios, are within a one-mile distance of the existing three-phase power lines of these cooperatives. This represents about 7.2% of the croplands with irrigation potential based on the soil suitability and water availability analyses. Twelve (12) of these 18 counties have more than 1,000 acres of croplands that are readily available for irrigation development under any groundwater availability scenario (Table ES.2).

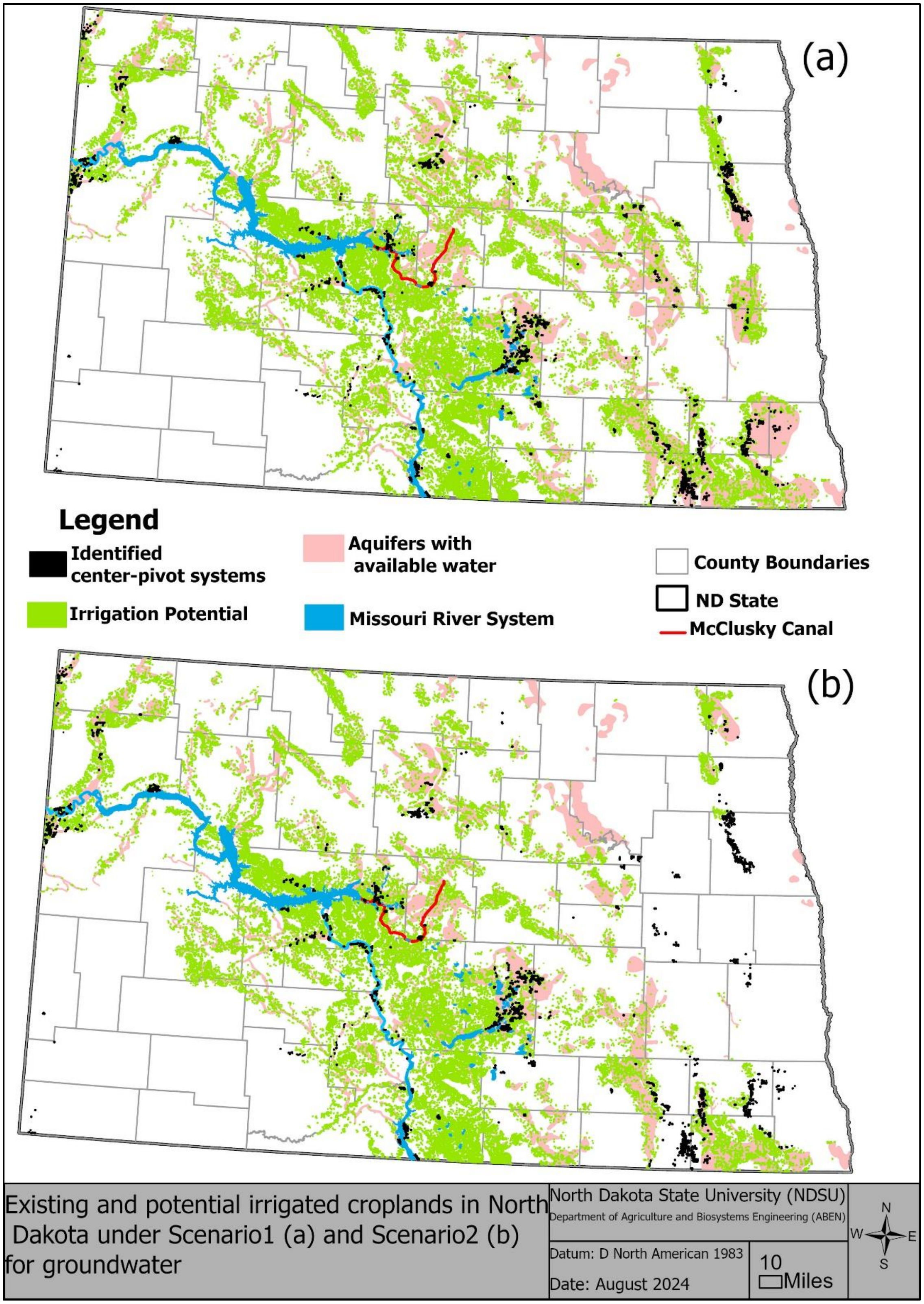

Figure ES.1. Croplands with irrigation potential using Missouri River water and groundwater under the best (a) and the worst (b) groundwater availability scenario.

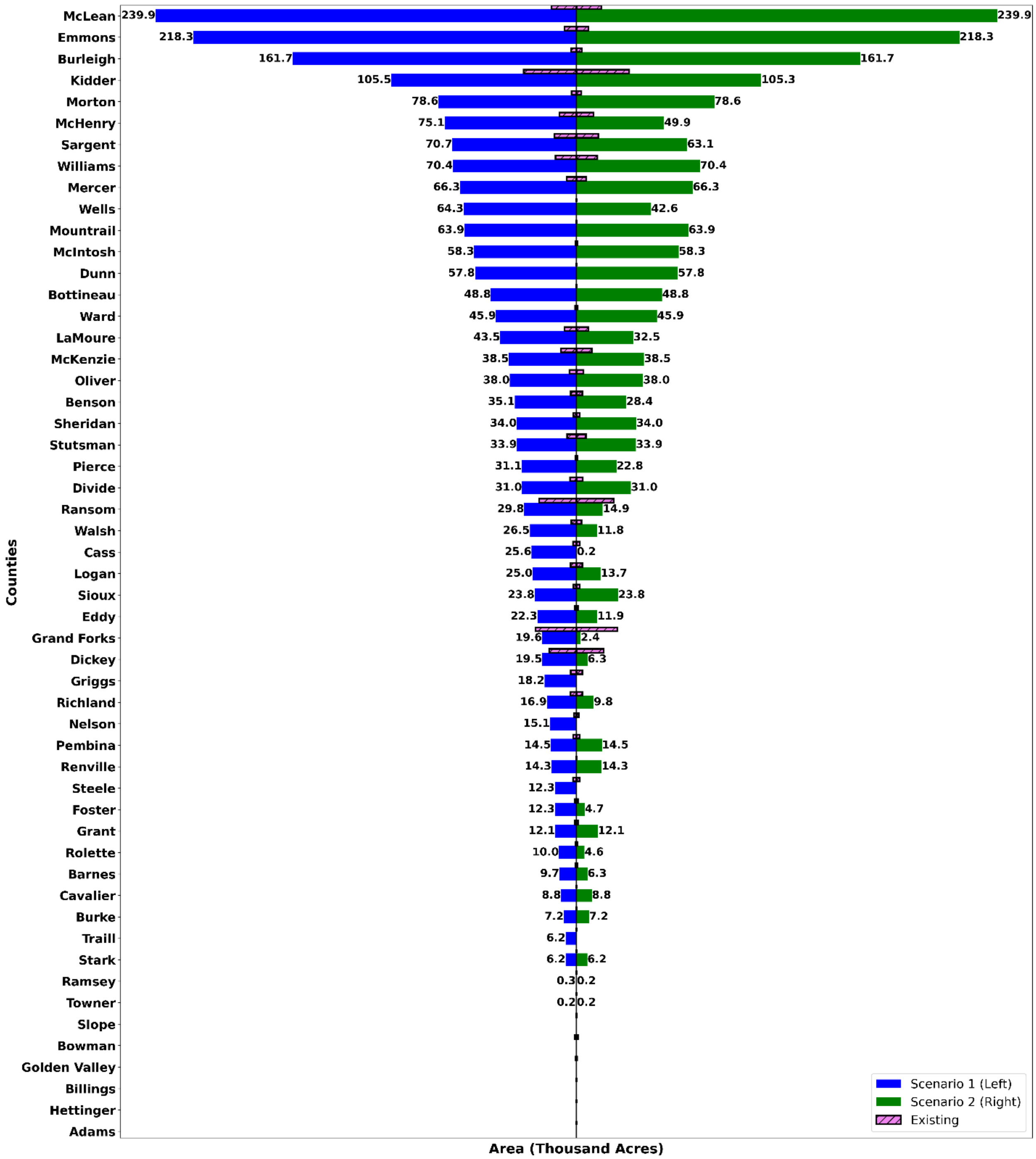

Figure ES.2. Areas of potentially irrigable croplands in North Dakota counties using Missouri River water and groundwater under the best (Scenario 1) and the worst (Scenario 2) scenarios (The numbers at the end of the horizontal bars are thousands of acres of croplands with irrigation potential in each county).

Table ES.2. Areas of land parcels with irrigation potential within one-mile distance of three-phase power lines of Capital Electric, Dakota Valley, and Northern Plains Cooperatives (acres).

County	Best groundwater availability scenario		Worst groundwater availability scenario	
	Irrigation potential[a]	Considering 3-phase power availability[b]	Irrigation potential[a]	Considering 3-phase power availability[b]
Benson	35,100	1,610	28,400	1,420
Burleigh	161,700	13,930	161,700	13,930
Dickey	19,500	5,910	6,300	3,220
Eddy	22,300	410	11,900	400
Emmons	218,300	200	218,300	200
Foster	12,300	3,170	4,700	1,120
Griggs	18,200	1,340	--	--
Kidder	105,500	7,430	105,300	7,430
LaMoure	43,500	10,230	32,500	9,070
McIntosh	58,300	200	58,300	200
Morton	78,600	280	78,600	280
Pierce	31,100	2,400	22,800	1,840
Ransom	29,800	2,240	14,900	1,080
Richland	16,900	1,570	9,800	1,190
Sargent	70,700	15,640	63,100	14,970
Sheridan	34,000	140	34,000	140
Stutsman	33,900	5,710	33,900	5,710
Wells	64,300	4,330	42,600	3,900
Total	**1,054,000**	**76,740**	**927,100**	**66,100**

[a] Considering soil suitability and water availability.

1 Introduction

According to the USDA National Agricultural Statistics Service's Census of Agriculture (NASS, 2022a), approximately 14.4% of US cropland was irrigated in 2022. In the ten states that are entirely or partially covered by the Missouri River basin, the percentages of irrigated cropland ranged from 0.94% (North Dakota) to 54.7% (Wyoming). As shown in Table 1.1, less than one-quarter of a million acres out of 26+ million acres of cropland in North Dakota were irrigated in 2022.

Table 1.1 Irrigated cropland in the ten Missouri River Basin states (NASS, 2022a).

State[a]	Cropland (Thousand acres)	Irrigated Cropland (Thousand acres)	Irrigated Cropland (%)
Wyoming	2,326	1,273	54.7
Nebraska	21,218	7,966	37.5
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[a] Ranked from high to low by the percentage of irrigated cropland.

The goal of this reconnaissance study is to identify and estimate the locations and areas of the land in North Dakota that have high potential for developing irrigation projects in the future. The study is carried out in three phases. In Phase I, we updated the North Dakota Department of Water Resources (DWR) soil irrigability map using the most recent Soil Survey Geographic Database (SSURGO) data. In Phase II, we removed the lands that were unavailable or unsuitable for developing irrigation projects from the updated soil suitability map. In Phase III, we identified and estimated the locations and areas of cropland with irrigation potential by examining the nearby water and three-phase power availabilities. This report summarizes the methods employed and the results obtained in the three phases.

It is important to note the limitations of our study, which was intended to provide a statewide assessment of land in North Dakota for potential irrigation development. However, in evaluating irrigation development for specific areas, more in-depth feasibility studies should be conducted to consider additional factors, including but not limited to design, cost, landowner preferences, environmental concerns, water permit applications, etc.

2 Phase I – Updating Soil Irrigability Maps

2.1 Classification methods

The updated soil irrigability map was developed based on the SSURGO data updated by the United States Department of Agriculture (USDA) Natural Resources Conservation Service in October 2023 (USDA-NRCS, 2024). The SSURGO datasets consist of soil map units and tabular data of soil components and their properties. The map units are linked to tabular data in the database. As outlined in the SSURGO Table Diagram (Figure 2.1), each soil map unit consists of multiple soil components. There are several options for aggregating component properties to the map unit level (USDA-NRCS, 2023). The existing North Dakota DWR soil irrigability map used a "Dominant Component" approach. However, we decided to use the "Dominant Condition" approach in this study. For a given soil property, referred to here as a "condition", the "Dominant Component" approach assigns the condition associated with the largest component within the map unit. In contrast, the "Dominant Condition" approach assigns the most frequent condition found within the map unit.

To illustrate the difference between these two methods, consider an example of a map unit with three components (USDA-NRCS, 2023). Soil A has a "severe" rating and is 45% of the map unit. Soil B has a "moderate" rating and is 30% of the map unit. Soil C has a "moderate" rating and is 25% of the map unit. Using the "Dominant Component" method, the rating value for Soil A (i.e., "severe") is used because Soil A makes up most of the map unit (45%). Using the "Dominant Condition" method, the rating value of "moderate" is used because Soil B and C both have a "moderate" rating and together they make up most of the map unit (55%).

In the NDSU Extension Bulletin AE1637 - *Compatibility of North Dakota Soils for Irrigation* (Revised March 2023), Scherer et al. (2023) categorized North Dakota soil series into 29 irrigability groups, with each irrigability group belonging to one of three Irrigation Types: irrigable (1i-7i), conditional (8c-22c), and non-irrigable (23n-29n). Therefore, there are four different *Irrigation Types*:

1) Water,
2) Irrigable,
3) Conditional, and
4) Non-irrigable.

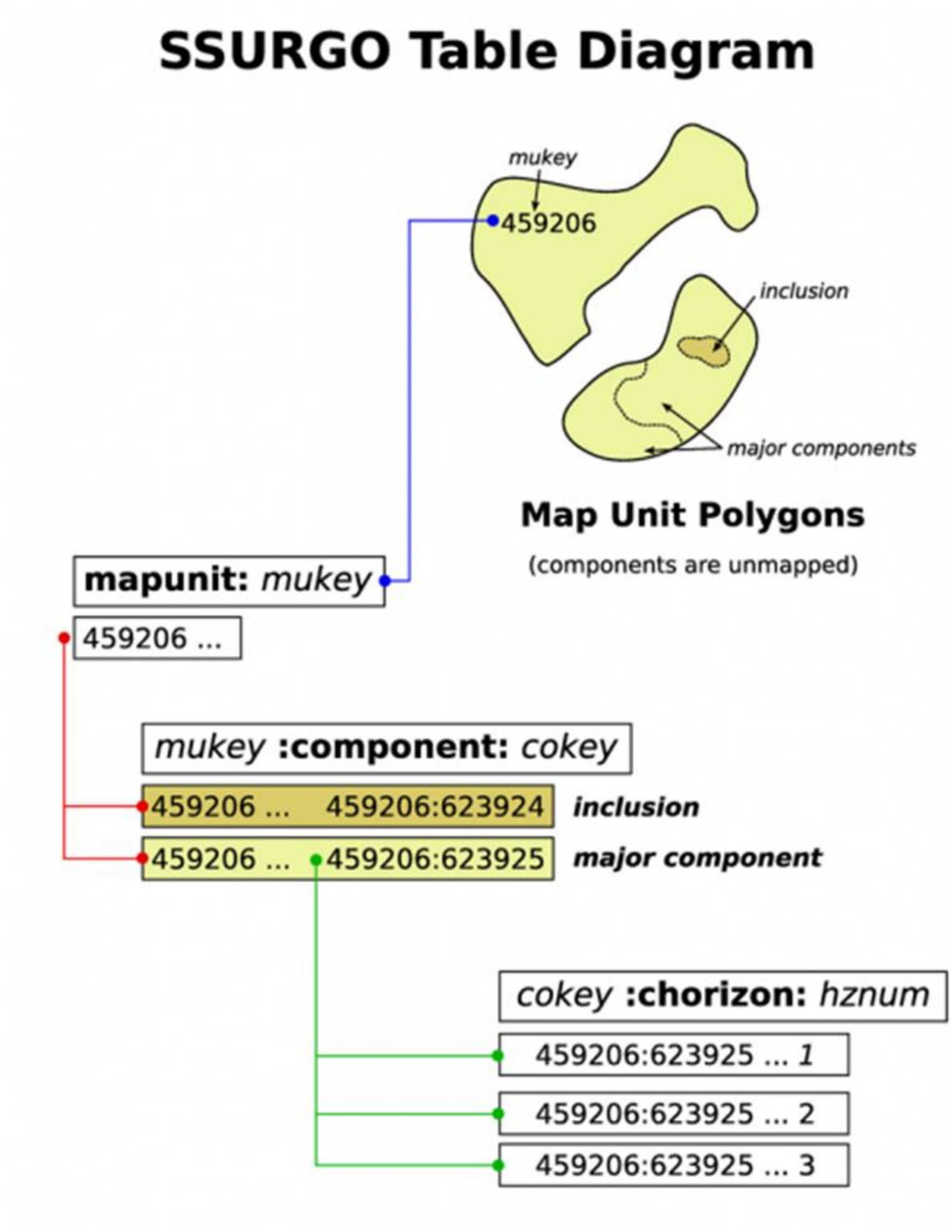

Figure 2.1. SSURGO Table Diagram.

Since there are several reasons why a soil may be classified as conditional, Scherer (undated) developed three sub-categories for conditionally irrigable soils:

i. Poor internal drainage, moderately slow and slow permeability (8c – 11c, 21c),
ii. Restricted drainage, high permeability layer with restricted layer below (12c – 14c), and
iii. Supplemental drainage required, poorly drained, high water table and salinity concerns (15c – 20c, 22c).

We have also implemented this level of specificity into this study and termed them as *Irrigation Functional Groups*: conditional – permeability, conditional – restricted, and conditional – drainage, water table, salinity. In addition, we further classified certain non-irrigable soils into a "non-irrigable due to slope" irrigation functional group, using the following criteria concerning representative slope and texture of the uppermost soil layer (Scherer et al., 2023):

a) Soil components with slopes > 6%, for soil textures that are more susceptible to erosion, including coarse sand, coarse sandy loam, fine sand, fine sandy loam, loamy coarse sand, loamy fine sand, loamy sand, loamy very fine sand, sand, sandy loam, very fine sandy loam;
b) Soil components with slopes ≥ 9%, for soil textures that are less susceptible to erosion, including those not listed above.

Therefore, there are seven different *Irrigation Functional Groups*:

1) Water,
2) Irrigable,
3) Conditional – restricted layer,
4) Conditional – permeability,
5) Conditional – drainage, water table, salinity,
6) Non-irrigable due to slope, and
7) Non-irrigable.

We included *all* soil components within a map unit to aggregate soil component irrigability ratings to the map unit level. For each map unit, we employed a two-step process with tiebreakers specified in Table 2.1 for the permissive and restrictive scenarios, respectively. In the two-step process, we first classified the soils in terms of the four irrigation types, and then in terms of the seven irrigation functional groups. During the classification process, we also needed to make assumptions about tiebreaking scenarios when determining the dominant conditions as we aggregated the soil component properties to the soil irrigability ratings at the map unit level. We made different assumptions under two different scenarios: permissive and restrictive. Under the permissive scenario, we prioritized the conditions *most* suitable for irrigation (given water is not a dominant condition), while under the restrictive scenario, we prioritized the conditions *least* suitable for irrigation (given water is not a dominant condition).

In addition, each soil description may have different local phases of slope and other properties, such as saline, wet, drained, frequently flooded, etc., that may affect the soil's suitability for irrigation. These local phase properties were not considered in the NDSU Extension Bulletin AE1637 (Scherer et al., 2023) as these local phase properties are ephemeral and may be responsive to management. In this study, we did not consider the local phase soil properties under the permissive scenario but considered them under the restrictive scenario. Given these assumptions, we expect more soils will be categorized as irrigable or conditionally irrigable under the permissive scenario than under the restrictive scenario.

Table 2.1. Assumptions underlying the permissive and restrictive scenarios.

Item	Permissive scenario	Restrictive scenario
Local phase[a]	Not considered	Considered
Dominant condition tiebreak order[b]	Prioritize the condition most suitable for irrigation, unless water is the dominant condition. **Irrigation Types:** 1. Water 2. Irrigable 3. Conditional 4. Non-irrigable **Irrigation Functional Groups:** 1. Water 2. Irrigable 3. Conditional – restricted layer 4. Conditional – permeability 5. Conditional – drainage, water table, salinity 6. Non-irrigable due to slope 7. Non-irrigable	Prioritize the conditions least suitable for irrigation, unless water is the dominant condition. **Irrigation Types:** 1. Water 2. Non-irrigable 3. Conditional 4. Irrigable **Irrigation Functional Groups:** 1. Water 2. Non-irrigable due to slope 3. Non-irrigable 4. Conditional – drainage, water table, salinity 5. Conditional – permeability 6. Conditional – restricted layer 7. Irrigable

[a]Phase criterion to be used at a local level, in conjunction with "component name" to help identify a soil component.
[b]When determining the dominant condition within a map unit, how are any ties handled? Which condition is displayed on the map?

The above classification process will produce a soil irrigability map that is based on dominant conditions within map units. In other words, only the dominant irrigation functional group (one out of the seven) within each map unit will be selected and displayed on the map, given the tiebreaker assumptions defined in Table 2.1 for each scenario. An alternative classification method is described in Appendix A.1, which will produce the relative irrigability maps under both scenarios.

2.2 Soil irrigability maps

Table 2.2 summarizes the soil irrigability classification for all soil series in North Dakota (45.3 million acres) under the permissive and restrictive scenarios. It shows that around 5.4 million acres (11.9%) are irrigable soils, about 25.1 to 27.6 million acres (55.2% to 60.9%) are conditionally irrigable soils, and about 11.2 to 13.8 million acres (24.7% to 30.5%) are non-irrigable soils. Table 2.2 also shows that the assumptions made about tiebreaking and local phase consideration under the two different scenarios did not make a big difference for almost all irrigation functional groups except for "conditional – drainage, water table, salinity". About 2.25 million acres of soils (~25%) in the "conditional – drainage, water table, salinity" group under the permissive scenario were classified as "non-irrigable" soils under the restrictive scenario. Figures 2.2 & 2.3 display the soil irrigability maps of dominant conditions under the permissive and restrictive scenarios, respectively. A close inspection of these two figures shows that this change in classification mostly occurred in Grand Forks County in northeast North Dakota.

Table 2.2. Summary of soil irrigability classification of dominant conditions.

Dominant condition	Permissive scenario map unit count	Permissive scenario million acres	Restrictive scenario map unit count	Restrictive scenario million acres
Irrigation Type				
Water	187	0.96	187	0.96
Irrigable	1666	5.41	1648	5.38
Conditional	5116	27.65	4369	25.13
Non-irrigable	2451	11.23	3216	13.78
Irrigation Functional Group				
Water	187	0.96	187	0.96
Irrigable	1666	5.41	1648	5.38
Conditional – restricted layer	810	3.36	809	3.36
Conditional – permeability	2109	15.15	2014	14.89
Conditional – drainage, water table, salinity	2197	9.14	1546	6.89
Non-irrigable	1118	4.09	1990	6.82
Non-irrigable due to slope	1333	7.14	1226	6.97

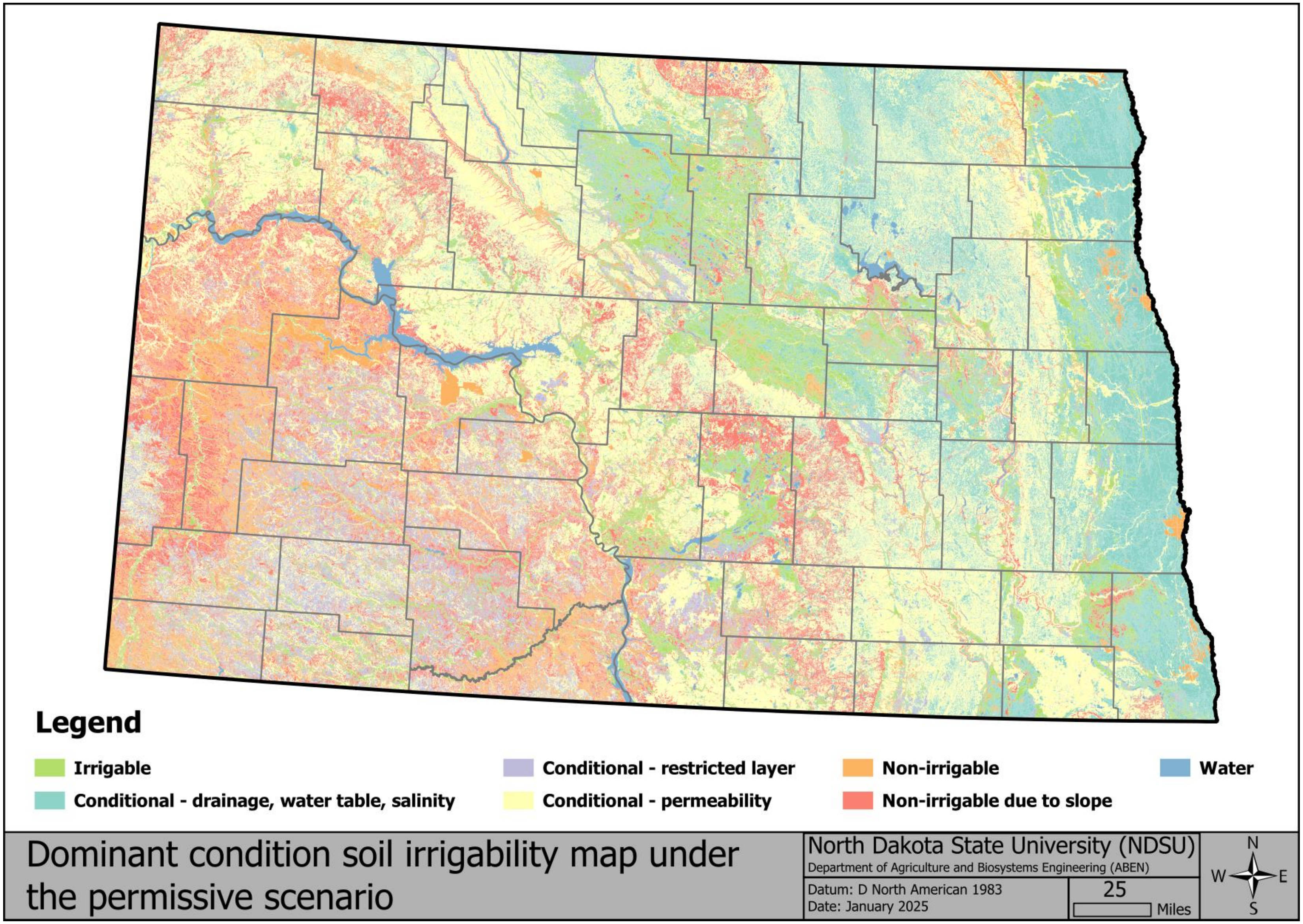

Figure 2.2. Soil irrigability map of dominant condition for the permissive scenario.

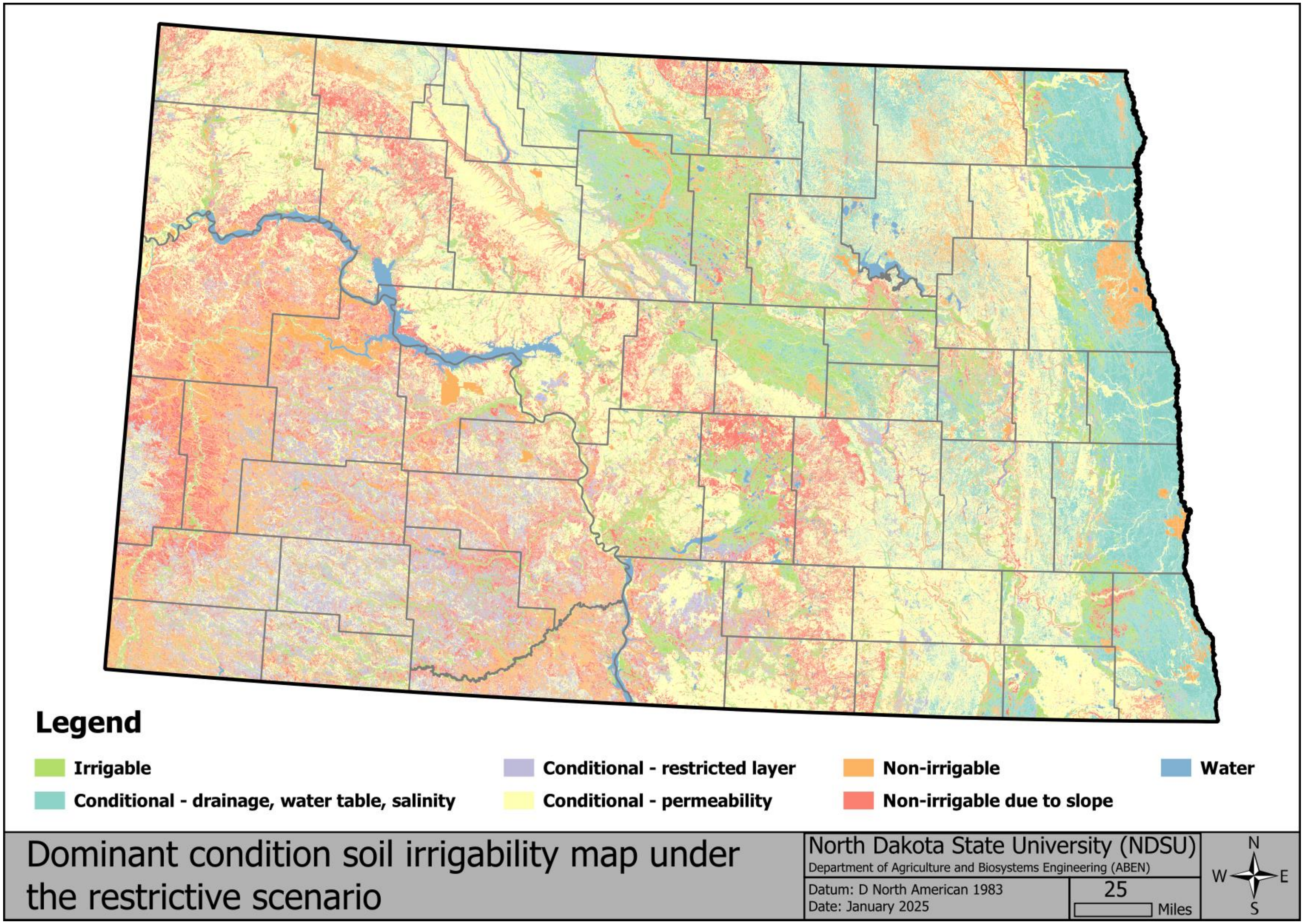

Figure 2.3. Soil irrigability map of dominant condition for the restrictive scenario.

3 Phase II – Land Availability and Suitability for Irrigation

The soil irrigability maps under the permissive and restrictive scenarios (Figures 2.2 & 2.3) are re-displayed in Figure 3.1 with the non-irrigable soils and water omitted for simplicity.

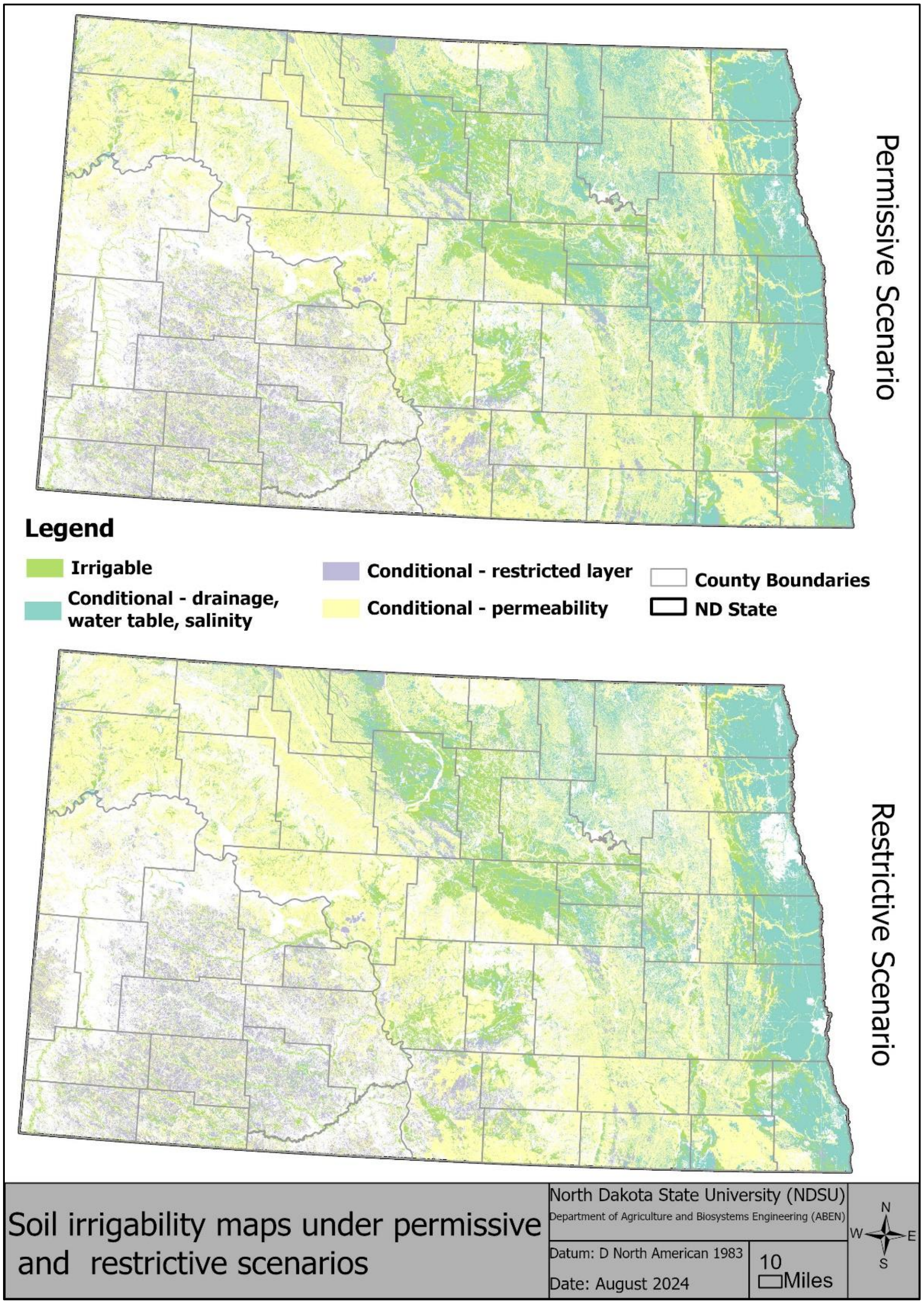

Figure 3.1. Soil irrigability maps under permissive and restrictive scenarios.

3.1 Removing unavailable land

Our goal in this phase is to remove from the irrigable and conditionally irrigable soil layers those lands that are unavailable or unsuitable for developing irrigation projects. First, we removed unavailable lands: federal and state public lands and urban areas that are prohibited from developing any irrigation projects. These lands are listed in Table 3.1 and the GIS layers of these lands were downloaded from the ND GIS Hub. Figure 3.2 shows a schematic view of these layers.

Table 3.1. Lands unavailable for developing irrigation projects.

No.	Layer Name	Description
1	City Boundaries	Geographic boundaries defining the limits of municipalities or cities, used for administrative and governance purposes.
2	National Grasslands	Federally managed lands primarily designated for the conservation and management of native grassland ecosystems.
3	National Parks	Protected areas established and maintained by federal governments to conserve the natural environment, provide recreation opportunities, and preserve cultural and historical resources.
4	National Wildlife Refuge	Protected areas designated to conserve wildlife and their habitats, managed by the U.S. Fish and Wildlife Service.
5	State Forests	Publicly owned forests managed at the state level for conservation, recreation, and sustainable timber production.
6	State Parks	Parks established and maintained by state or federal governments for recreation, conservation, and the protection of natural and cultural resources.
7	Wetlands	Areas where water covers the soil or is present near the surface for part of the year, providing crucial habitat for wildlife and contributing to flood control and water purification.
8	Surface Trust Lands	Lands held in trust by the state or federal government for specific purposes, such as supporting public schools or managing natural resources.
9	Army Corps Lands	Lands managed by the U.S. Army Corps of Engineers, primarily used for flood control, infrastructure projects, and recreation.
10	BLM Land	Lands managed by the Bureau of Land Management (BLM), used for a variety of purposes including grazing, recreation, and resource extraction.
11	Military Reservation Land	Land designated for military use, including training, defense infrastructure, and operations.
12	Reclamation Land	Land managed by the Bureau of Reclamation primarily focused on water resource management, irrigation, and reclamation of previously irrigated or developed lands.

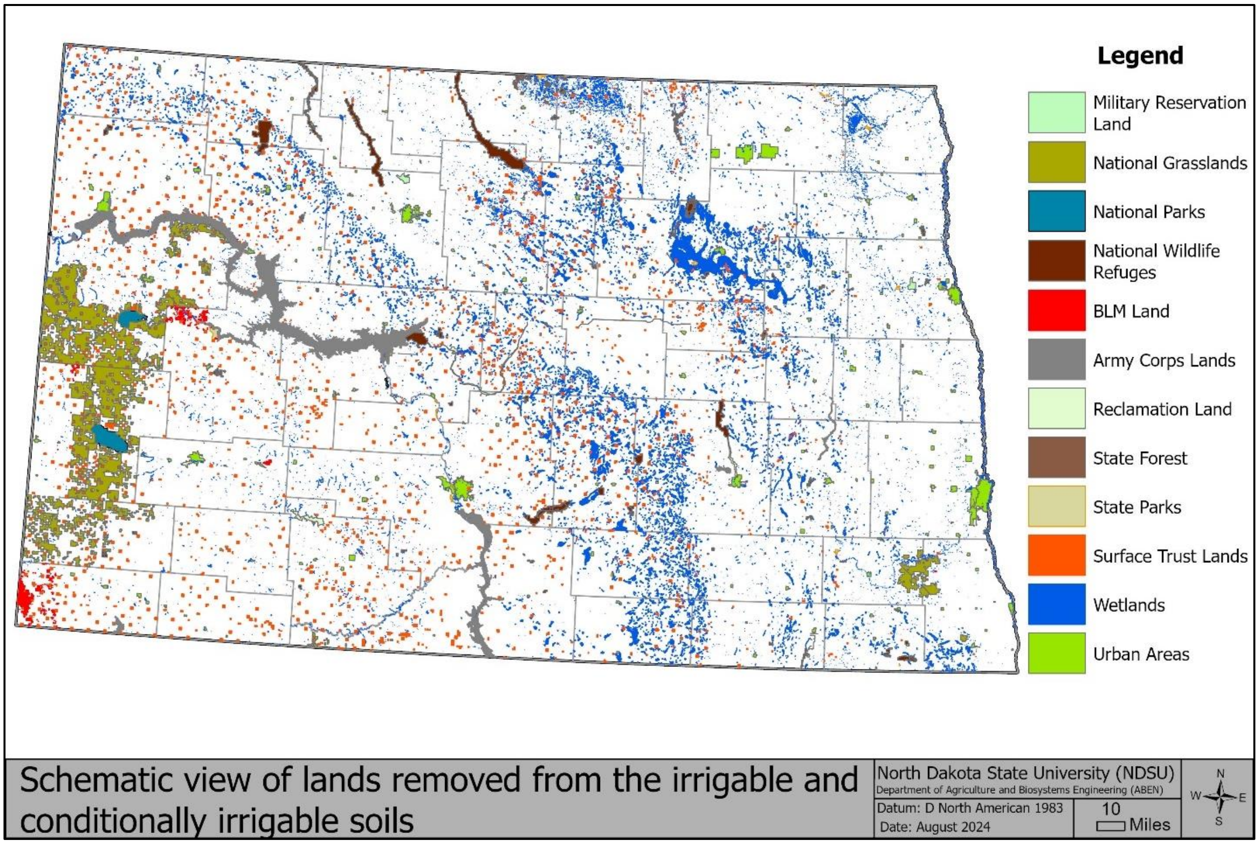

Figure 3.2. Schematic view of lands removed from the soil irrigability maps.

Figure 3.3 shows the map units of irrigable and conditionally irrigable soils, under the restrictive and permissive scenarios, after removing these land areas considered unavailable for irrigation. Table 3.2 provides a statewide summary of irrigable and conditionally irrigable acreage, which only saw a slight reduction under either scenario.

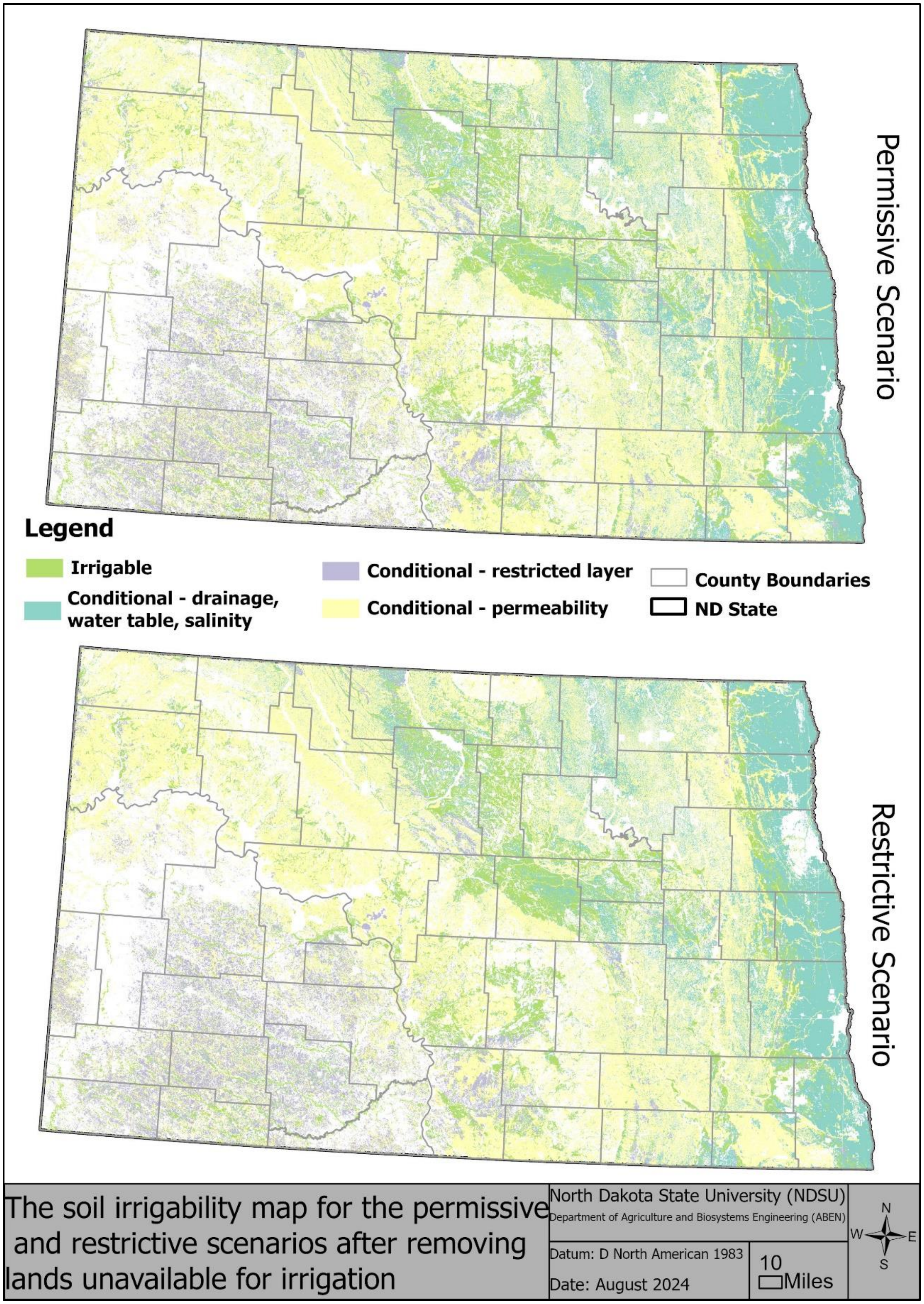

Figure 3.3. The soil irrigability map for the permissive and restrictive scenarios after removing lands unavailable for irrigation.

Table 3.2. Summary of soils after removing lands unavailable for irrigation.

Dominant condition	Permissive scenario (Million acres)		Restrictive scenario (Million acres)	
	Before	After	Before	After
Irrigation Type				
Irrigable	5.40	4.96	5.37	4.95
Conditional	27.64	24.38	25.11	23.12
Irrigation Functional Group				
Irrigable	5.40	4.96	5.37	4.95
Conditional – restricted layer	3.35	3.21	3.35	3.21
Conditional – permeability	15.15	14.15	14.88	13.93
Conditional – drainage, water table, salinity	9.14	7.02	6.88	5.98

3.2 Removing unsuitable land

Next, we removed the lands that were unsuitable for developing irrigation projects. We defined unsuitable lands as Public Land Survey System (PLSS) quarter-quarter (Q-Q) sections (Figure 3.4) featuring substantial intersections with railroads, roads, streams, rivers, overhead power transmission lines, buildings, or other structures. This is based on our assumption that a piece of land (in this case, a quarter-quarter section or 40 acres) featuring a large structure (such as a building or a wind turbine) or substantially bisected by railroads, roads, streams, rivers, or overhead transmission lines is unsuited for the installation of a center-pivot irrigation system.

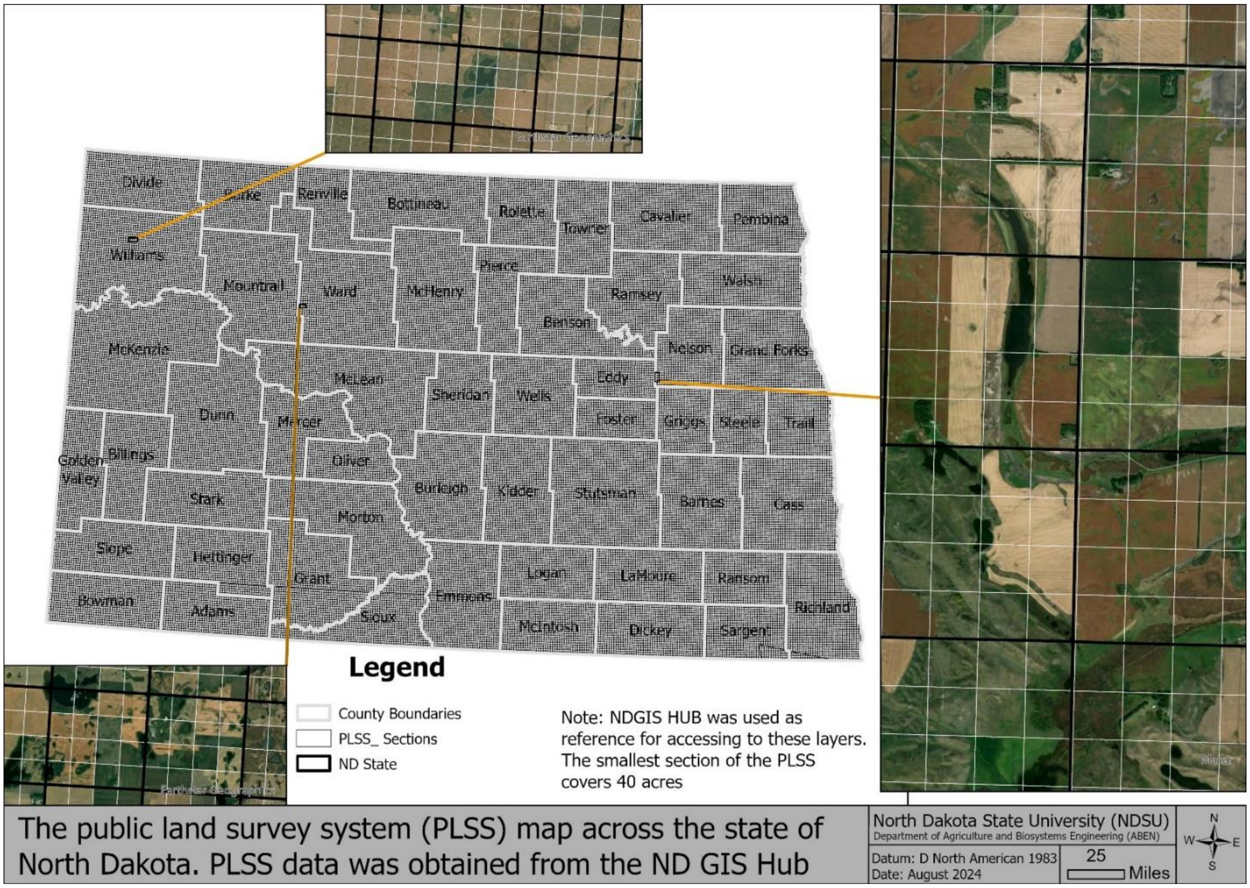

Figure 3.4. The public land survey system (PLSS) maps across the state of North Dakota. Note: The PLSS data was obtained from the North Dakota GIS Hub.

Road features, including (i) railroads, (ii) interstate, federal and state highways, and (iii) county roads, were downloaded from the ND GIS Hub and merged into a single layer (Figure 3.5). The 1:24K scale streams and rivers hydrography data (Figure 3.6) and locations of wind turbines (Figure 3.7) were also downloaded from the ND GIS Hub.

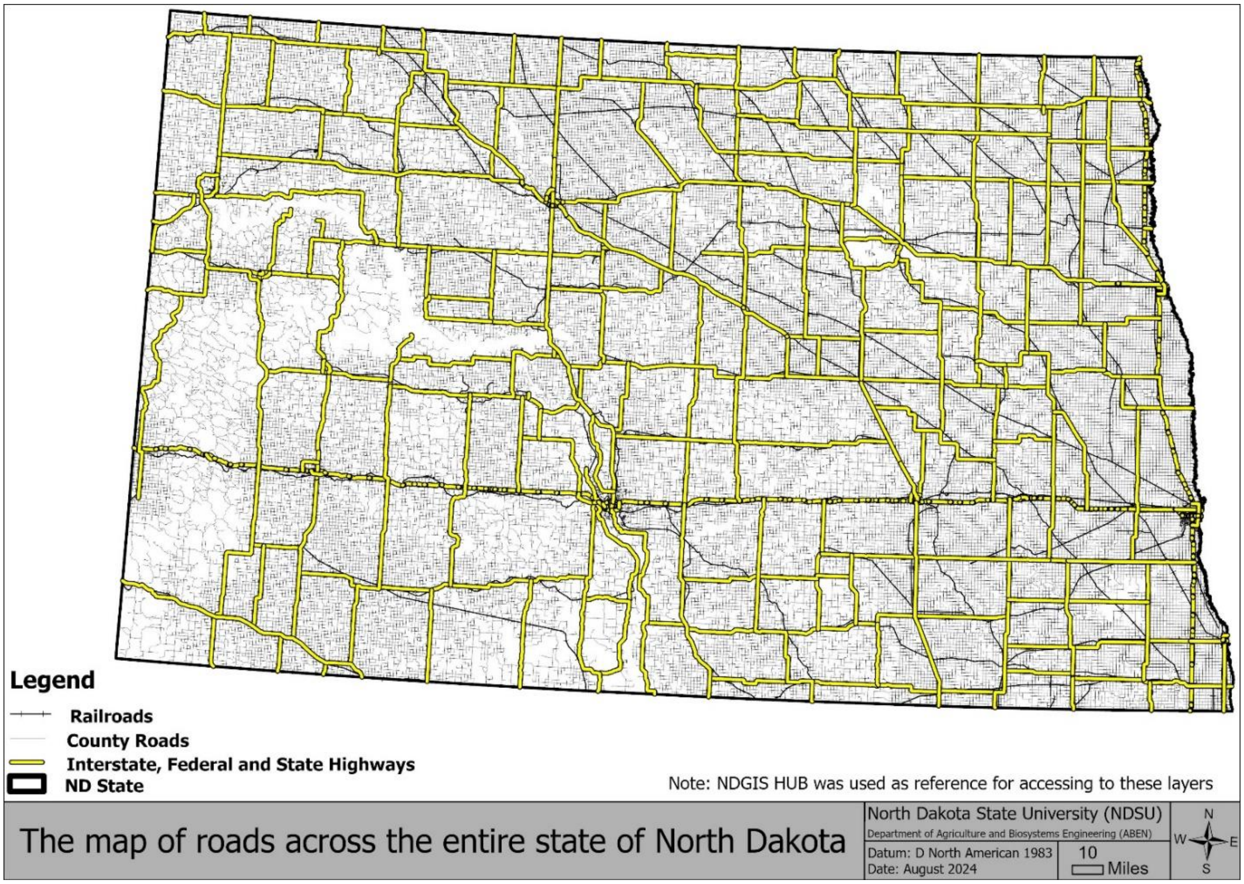

Figure 3.5. The road features across the state of North Dakota.

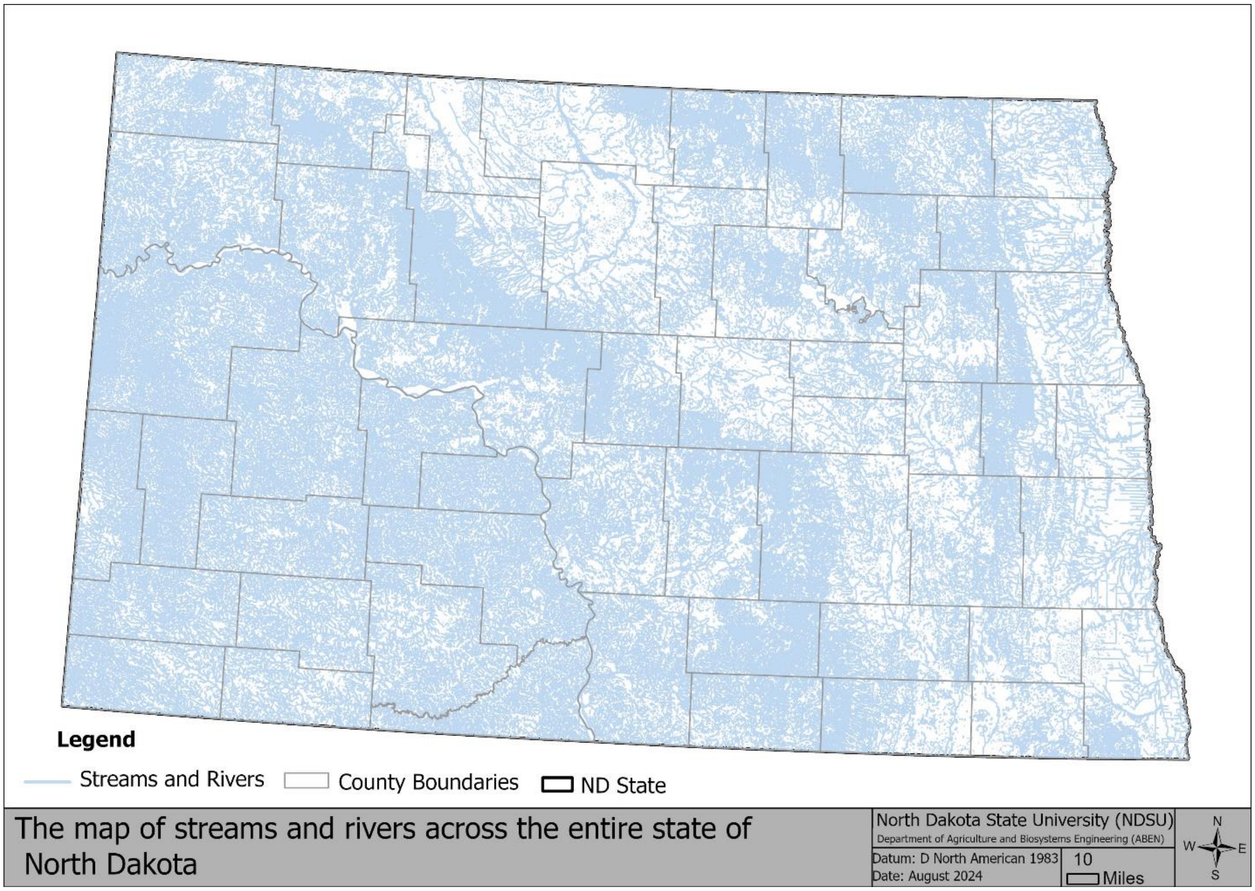

Figure 3.6. The streams and rivers across the state of North Dakota.

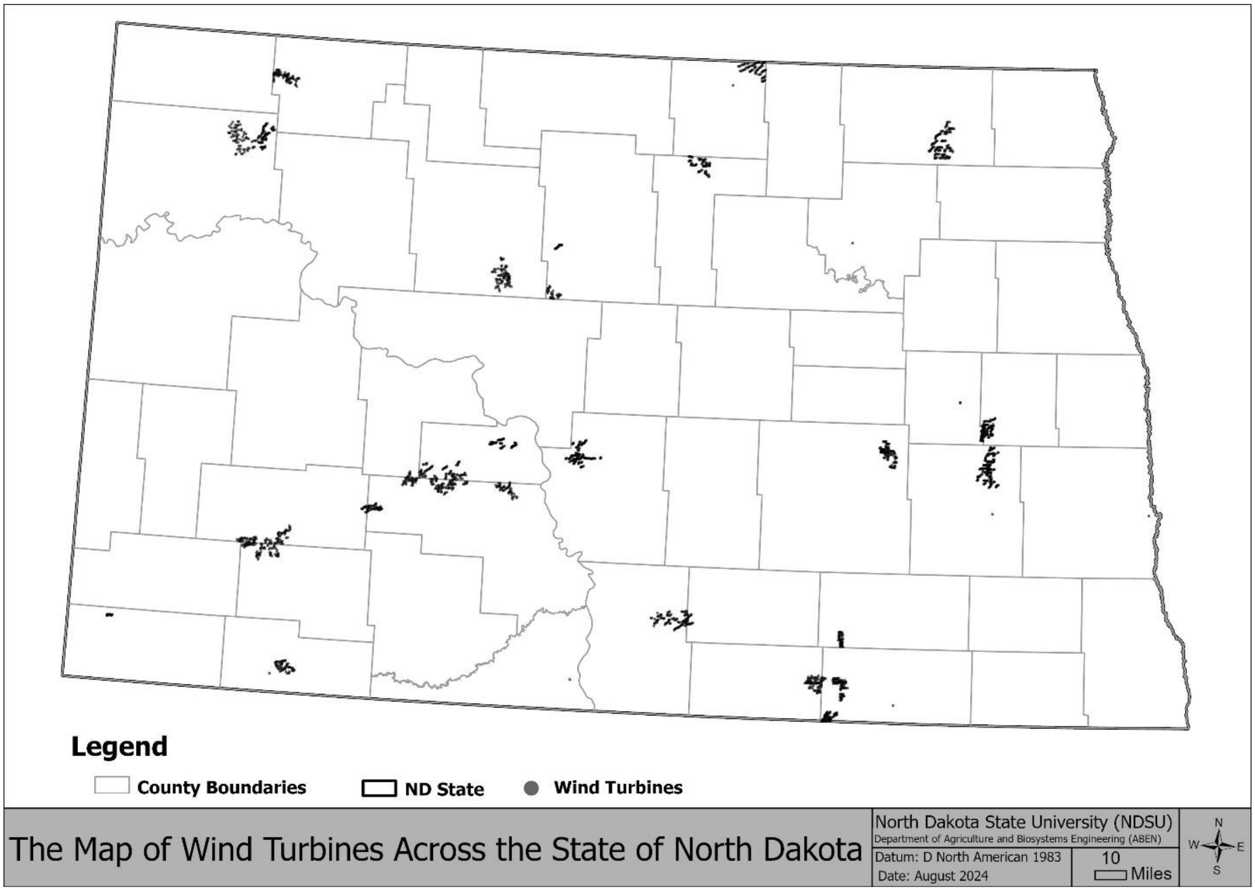

Figure 3.7. The locations of wind turbines across the state of North Dakota.

Additionally, North Dakota electric power transmission lines (Figure 3.8) were retrieved from the Climate Mapping for Resilience and Adaptation. Building structures were obtained from the FEMA's USA Structures State GDB Download Site (Figure 3.9). This dataset uses FEMA's data and displays, for the United States and its territories, all structural footprints larger than 450 square feet.

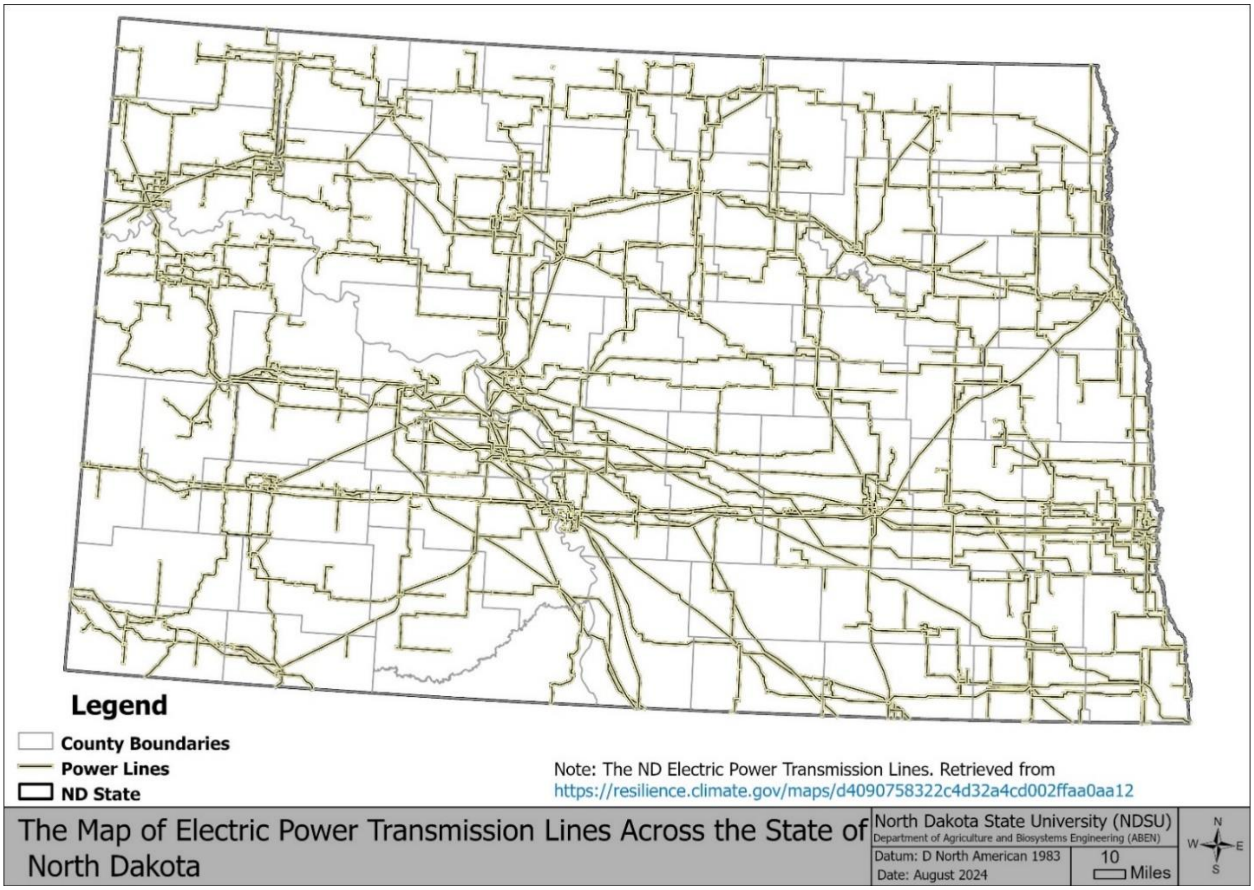

Figure 3.8. Electric power transmission lines across the state of North Dakota.

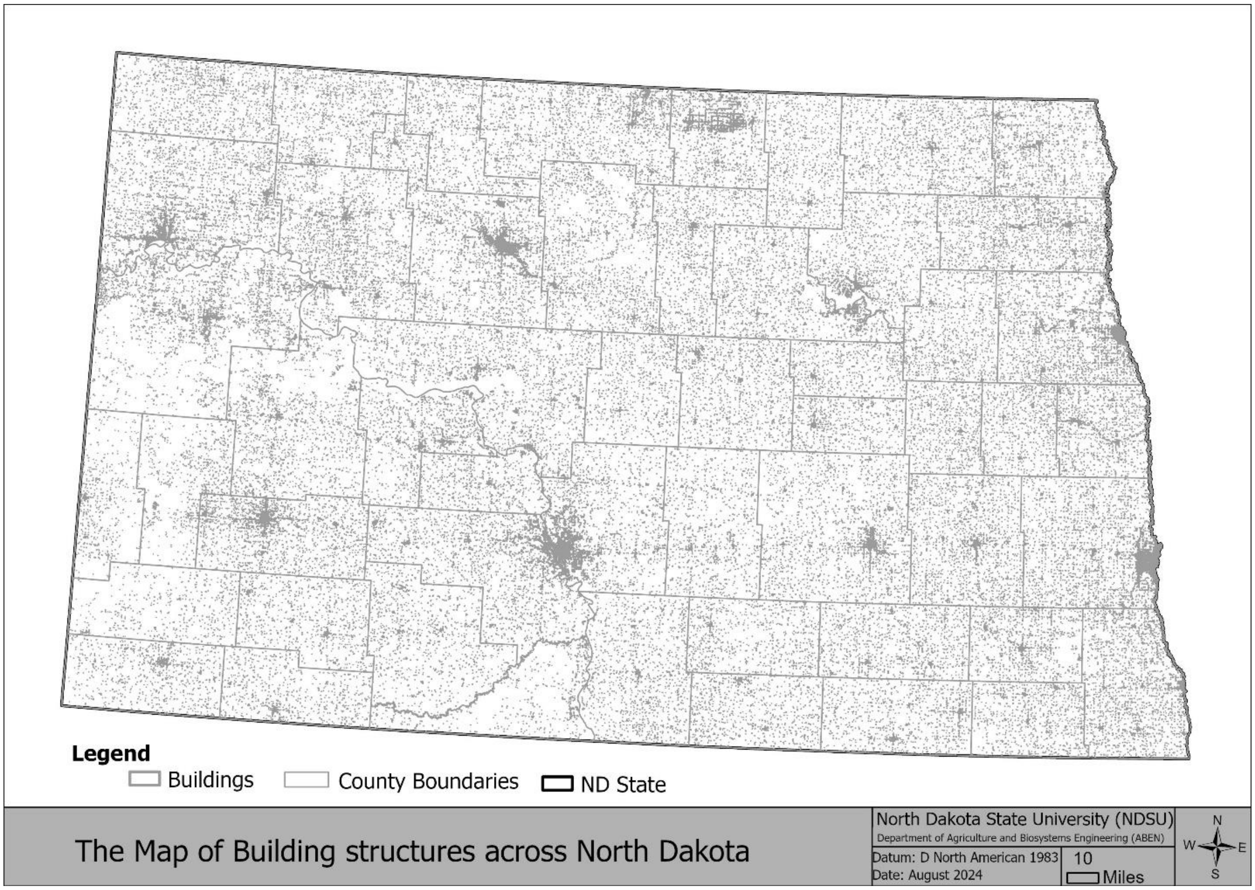

Figure 3.9. Building structures across the state of North Dakota.

Using the 'Select By Location' tool in ArcGIS Pro, we modified the PLSS Q-Q section layer by detecting and removing any parcel that contained one or more large structures such as buildings or wind turbines. Therefore, we assumed that the existence of a wind turbine or any building larger than 450 square feet on a PLSS Q-Q section would obstruct the implementation of an irrigation system. This is a conservative criterion, but we feel it is justified because many building structures are accompanied by additional infrastructure — such as driveways, windbreaks, or landscaping— that is unaccounted for in the building structures dataset. Furthermore, testing of a less conservative criterion had minimal impact on the number of PLSS parcels removed by this screening process.

Figure 3.10 illustrates the steps taken to further modify the PLSS Q-Q section layer by removing any parcel featuring substantial intersections with any of the other obstacle layers (railroads, roads, streams, rivers, or overhead transmission lines). The PLSS layer (Figure 3.10a) was converted into a polyline layer and a 70-meter buffer was created around the polylines (Figure 3.10b). All polylines of the obstacle layers outside the 70-meter buffer were selected (Figure 3.10c) and used to remove the corresponding polygons of the Q-Q sections from the original PLSS layer (Figure 3.10d). This cleared the PLSS layer of all Q-Q sections where roads, power lines, streams, and rivers transected the parcel rather than running along a parcel boundary. The 70-meter buffer distance was chosen after comparisons against two additional buffer distances: 30 meters and 50 meters. The 70-meter buffer distance demonstrated better performance in excluding the PLSS Q-Q sections that intersected substantially with roads, power lines, streams, and rivers.

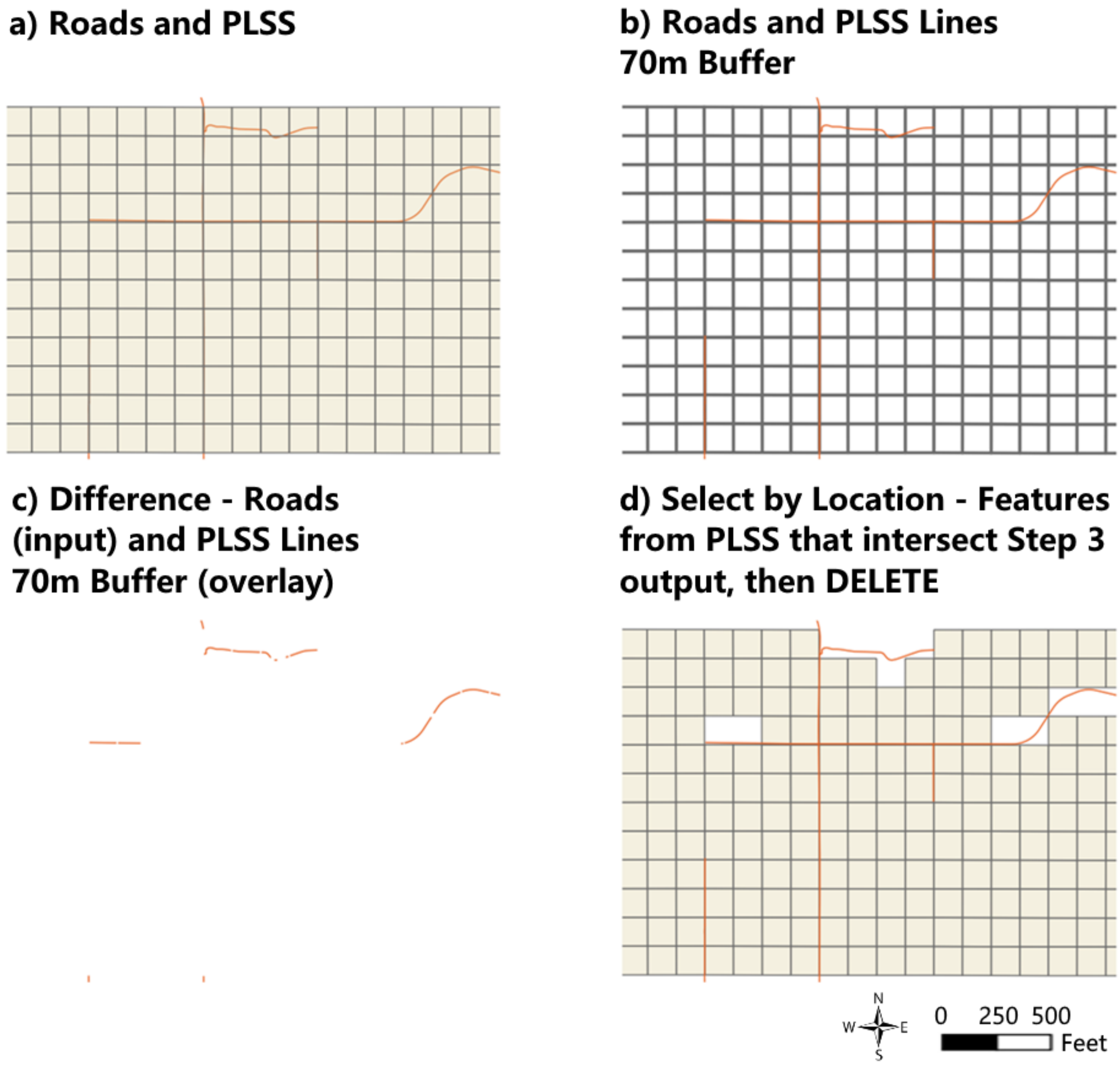

Figure 3.10. Cleaning the PLSS layer from roads, power lines, streams, and rivers.

The soil irrigability maps, minus lands unavailable for irrigation (Figure 3.3), were then clipped based on the modified PLSS Q-Q section layer. This workflow removed from the soil irrigability maps all soils within the PLSS parcels considered unsuitable for irrigation: where roads, power lines, streams, rivers, or large structures are obstacles to installing center-pivot sprinkler systems. Figure 3.11 displays the updated soil irrigability maps and Table 3.3 shows the updated statewide summary of irrigable and conditionally irrigable acreages, which were substantially reduced under both scenarios in this step.

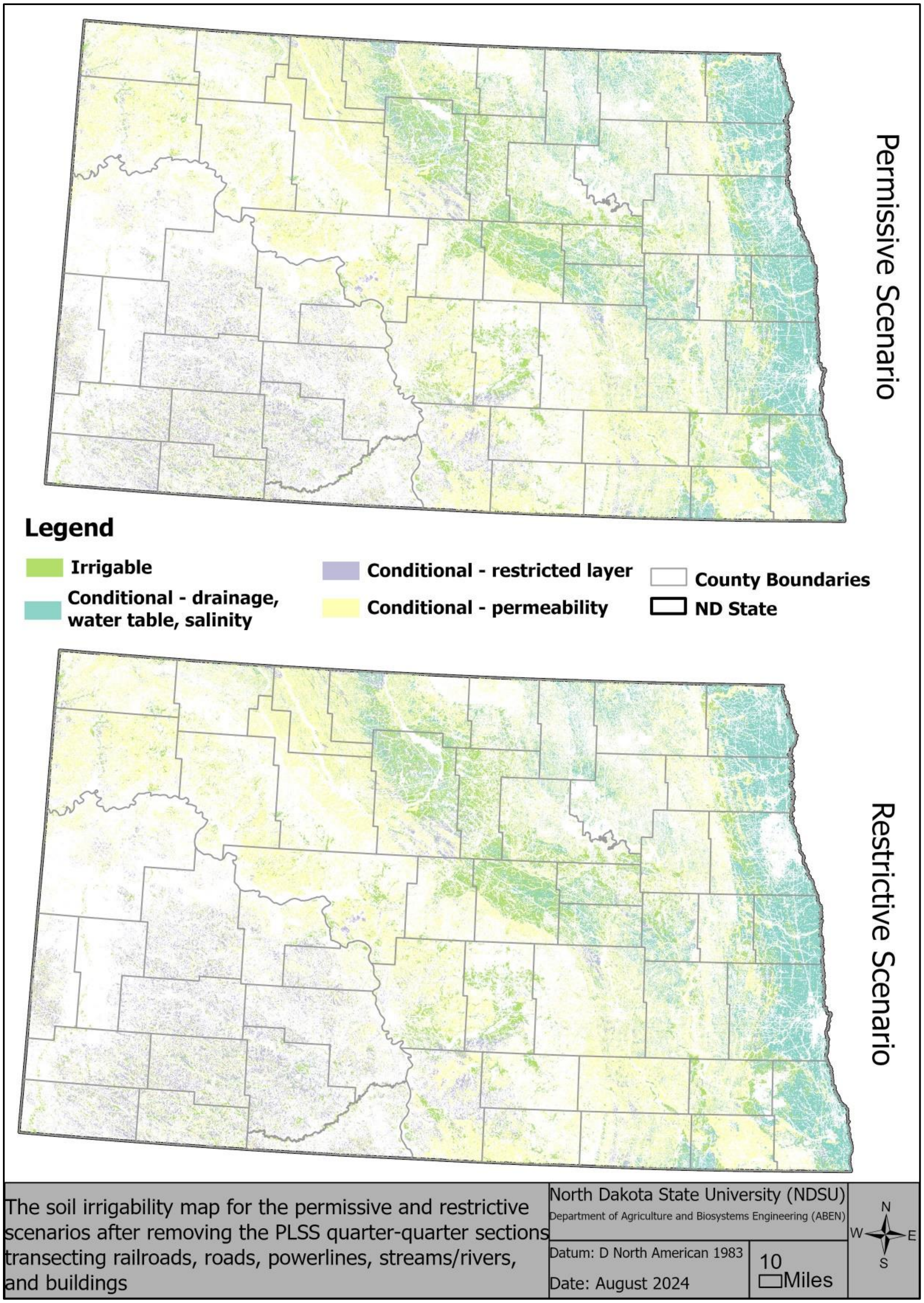

Figure 3.11. The soil irrigability map for the permissive and restrictive scenarios after removing lands unsuitable for irrigation by clearing the PLSS quarter-quarter sections transecting railroads, roads, powerlines, streams/rivers, and buildings.

Table 3.3. Soil parcels in each dominant condition after removing the PLSS quarter-quarter sections transecting railroads, roads, powerlines, streams, rivers, and large structures.

Dominant condition	Permissive scenario (Million acres)		Restrictive scenario (Million acres)	
	Before	After	Before	After
Irrigation Type				
Irrigable	4.96	3.03	4.95	3.05
Conditional	24.38	14.13	23.12	13.58
Irrigation Functional Group				
Irrigable	4.96	3.03	4.95	3.08
Conditional – restricted layer	3.21	1.89	3.21	1.89
Conditional – permeability	14.15	7.76	13.93	7.75
Conditional – drainage, water table, salinity	7.02	4.48	5.98	3.94

3.3 Summary

Figure 3.12 summarizes the statewide area reductions in irrigable and conditionally irrigable soils after removing the lands considered unavailable or unsuitable for irrigation. Table 3.4 summarizes, on a countywide and statewide basis, the areas of irrigable and conditionally irrigable soils considered available and suitable for developing irrigation projects. Statewide, there are about 17.0 million acres (~37.5%) of land available and suitable for irrigation.

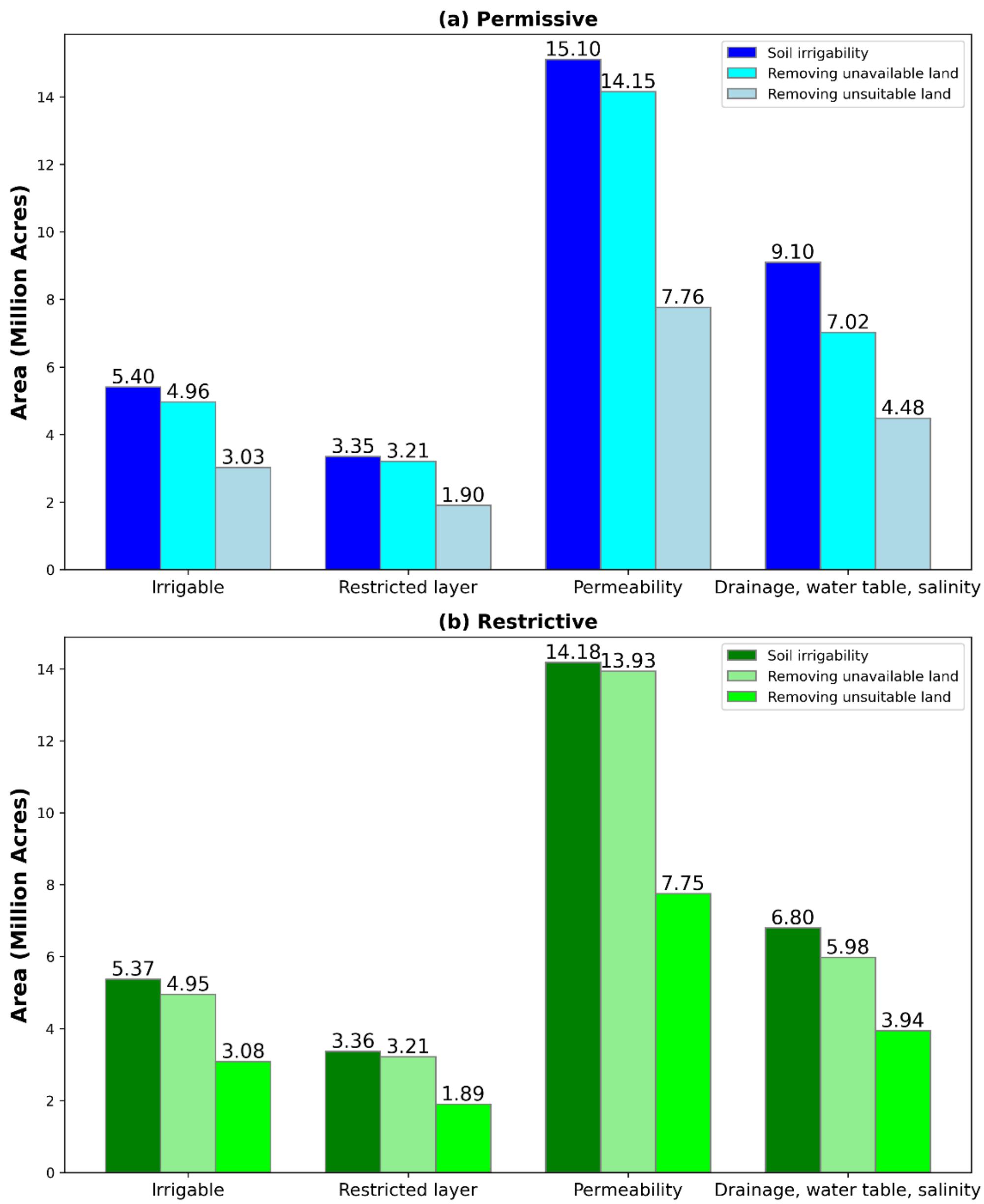

Figure 3.12. Land area reductions after removing unavailable and unsuitable lands under (a) permissive scenario and (b) restrictive scenario.

Table 3.4. Summary of irrigable and conditionally irrigable land available and suitable for developing irrigation projects.

County name	County area	Irrigable P[a]	R[b]	Conditional – restricted layer P	R	Conditional – permeability P	R	Conditional – drainage, water table, salinity P	R	Total Irrigable & Conditional P	R
	-- thousand acres---										
Adams	630	64.6	64.6	103.0	103.0	68.8	68.2	1.5	1.5	**238.0**	**237.4**
Barnes	970	33.5	33.5	4.1	4.1	259.7	262.9	173.9	143.2	**471.1**	**443.6**
Benson	910	115.0	121.4	1.4	1.4	153.2	155.3	107.5	84.2	**377.1**	**362.3**
Billings	740	9.7	9.5	28.6	28.6	6.2	6.0	0.2	0.2	**44.6**	**44.3**
Bottineau	1080	123.8	123.8	28.6	28.6	336.2	330.5	151.0	141.1	**639.7**	**624.1**
Bowman	750	41.8	41.8	113.8	113.7	38.0	37.6	0.4	0.4	**194.0**	**193.4**
Burke	720	10.8	10.8	2.6	2.6	165.0	165.0	34.0	31.0	**212.4**	**209.3**
Burleigh	1060	117.1	117.0	22.4	22.4	252.3	250.2	5.9	2.9	**397.8**	**392.5**
Cass	1130	60.2	60.2	11.6	11.6	106.7	106.7	509.7	485.0	**688.2**	**663.5**
Cavalier	960	11.2	11.2	0.0	0.0	206.1	206.0	199.6	155.8	**417.0**	**373.1**
Dickey	730	33.8	33.8	14.1	14.1	201.3	200.4	71.8	63.5	**321.0**	**311.8**
Divide	830	30.5	30.5	9.7	9.7	225.7	225.7	14.4	8.8	**280.3**	**274.7**
Dunn	1330	27.1	26.9	151.1	151.1	81.6	78.6	0.3	0.3	**260.0**	**256.8**
Eddy	410	101.7	103.7	4.9	4.9	35.7	34.8	51.6	47.5	**193.9**	**190.9**
Emmons	990	66.4	66.3	94.2	94.2	208.7	208.6	2.5	1.9	**371.9**	**371.0**
Foster	410	56.8	63.2	5.1	5.1	65.3	65.2	114.4	84.6	**241.7**	**218.1**
Golden Valley	640	6.9	6.6	72.0	72.0	49.3	48.9	0.1	0.1	**128.3**	**127.5**
Grand Forks	920	73.7	73.7	0.9	0.9	71.9	71.9	334.4	245.8	**481.0**	**392.3**
Grant	1060	84.9	84.2	198.3	198.3	42.1	41.4	2.2	2.1	**327.4**	**326.1**
Griggs	460	69.5	72.3	13.9	13.9	49.3	49.3	104.5	82.3	**237.3**	**217.9**
Hettinger	730	45.8	45.8	171.7	171.7	91.3	90.5	2.4	2.4	**311.3**	**310.4**
Kidder	910	137.9	137.9	28.1	28.1	95.1	95.1	12.9	11.2	**274.0**	**272.3**
LaMoure	740	18.8	18.8	7.6	7.6	300.2	299.9	37.0	27.5	**363.6**	**353.7**
Logan	650	44.6	44.6	19.3	19.3	91.2	91.2	4.1	3.2	**159.2**	**158.3**
McHenry	1220	271.1	270.9	70.5	70.5	155.1	155.1	128.3	112.2	**625.0**	**608.7**
McIntosh	640	49.7	49.7	13.6	13.6	155.2	155.2	4.2	2.8	**222.7**	**221.3**
McKenzie	1830	12.6	12.6	34.1	34.1	138.9	138.3	0.6	0.6	**186.2**	**185.6**
McLean	1490	80.1	80.1	14.2	14.2	406.7	406.5	6.5	4.8	**507.5**	**505.6**

County name	County area	Irrigable		Conditional – restricted layer		Conditional – permeability		Conditional – drainage, water table, salinity		Total Irrigable & Conditional	
		P	R	P	R	P	R	P	R	P	R
	---------- thousand acres ----------										
Mercer	710	23.2	23.2	34.3	34.3	89.0	88.7	0.7	0.4	**147.2**	**146.5**
Morton	1240	35.5	35.5	144.3	144.3	104.9	104.1	0.1	0.0	**284.8**	**283.9**
Mountrail	1240	35.0	34.9	3.4	3.4	309.4	309.2	15.4	12.9	**363.1**	**360.3**
Nelson	640	23.4	23.4	2.2	2.2	165.2	165.1	89.5	67.1	**280.4**	**257.9**
Oliver	470	15.7	15.7	46.4	46.4	58.6	58.4	0.7	0.5	**121.4**	**120.9**
Pembina	720	30.2	30.2	0.6	0.6	36.9	36.9	388.2	374.5	**456.0**	**442.3**
Pierce	690	203.2	210.6	8.2	8.2	58.9	59.3	68.5	51.3	**338.8**	**329.4**
Ramsey	840	3.0	3.0	0.3	0.3	161.1	161.1	131.1	101.8	**295.5**	**266.2**
Ransom	550	76.7	76.7	3.5	3.5	129.8	129.5	74.1	69.3	**284.1**	**279.0**
Renville	570	8.1	8.1	8.8	8.8	316.1	315.9	39.6	38.4	**372.7**	**371.2**
Richland	920	68.0	68.0	9.1	9.1	61.7	66.1	393.2	379.5	**532.1**	**522.8**
Rolette	600	39.3	39.4	6.7	6.7	83.2	83.3	54.8	47.4	**184.0**	**176.8**
Sargent	550	41.7	41.7	5.0	5.0	182.5	186.0	75.4	63.7	**304.6**	**296.4**
Sheridan	640	65.0	69.1	3.9	3.9	106.7	107.0	24.0	12.9	**199.6**	**192.8**
Sioux	720	33.4	32.7	64.7	64.7	47.7	47.2	0.1	0.0	**145.8**	**144.6**
Slope	780	36.2	35.9	99.8	99.8	50.7	50.3	0.2	0.2	**187.0**	**186.2**
Stark	860	25.0	24.9	158.1	158.1	40.4	39.9	0.5	0.5	**224.0**	**223.4**
Steele	460	32.0	32.0	4.1	4.1	84.0	84.0	71.5	65.3	**191.5**	**185.4**
Stutsman	1470	38.3	38.3	23.8	23.8	371.2	371.3	108.4	88.6	**541.6**	**522.0**
Towner	660	8.8	8.8	4.0	4.0	106.9	106.9	156.6	134.3	**276.4**	**254.0**
Traill	550	35.5	35.5	2.5	2.5	18.4	18.4	338.1	333.0	**394.5**	**389.4**
Walsh	830	30.7	30.7	5.1	5.1	151.1	150.3	253.2	237.3	**440.2**	**423.5**
Ward	1310	22.4	22.3	2.3	2.3	422.4	419.7	25.4	21.7	**472.5**	**466.0**
Wells	820	246.6	246.9	0.2	0.2	118.2	117.6	93.0	89.0	**458.0**	**453.7**
Williams	1370	55.3	55.0	18.5	18.5	432.8	432.7	7.6	5.1	**514.2**	**511.4**
	---------- million acres ----------										
ND State	**45.3**	**3.03**	**3.05**	**1.89**	**1.89**	**7.76**	**7.75**	**4.48**	**3.94**	**17.18**	**16.65**

[a] Permissive
[b] Restrictive

Figure 3.13 shows the areas of irrigable and conditionally irrigable soils in each county under the permissive and restrictive scenarios. The asterisk (*) on the figure indicates those counties where the acreage totals between the two scenarios differ by more than 5%.

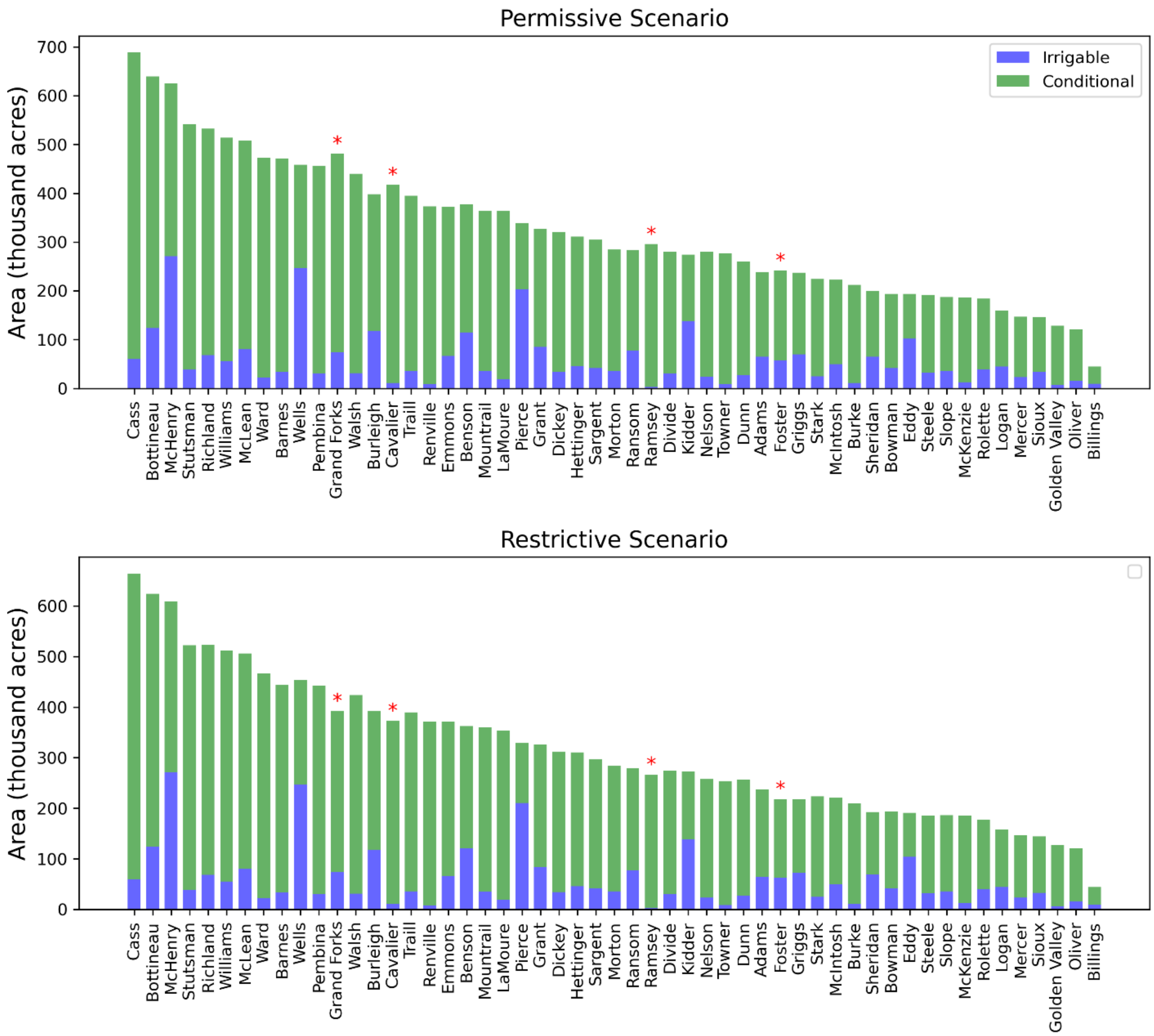

Figure 3.13. Irrigable and conditionally irrigable acreages in North Dakota counties.

4 Phase III – Water and Power Availability

4.1 Estimating existing irrigated cropland

We employed two methods to identify the existing irrigated lands in North Dakota. The first method was to apply the object detection deep learning model, Mask R CNN (convolution neural network), to process the Landsat 8 satellite images to identify and estimate the locations and irrigated areas of the existing center-pivot irrigation systems. The method is described in detail in Appendix A.2. The second method was to compile the 2017 and 2022 Census of Agriculture data (NASS, 2022b) and the active perfected irrigation permits issued by the North Dakota Office of State Engineer. It should be noted that the first method only identified the areas irrigated by center-pivot sprinkler systems. In contrast, the second method included all irrigated lands including flooding and water-spreading surface irrigation methods. The county-level results from the two methods are compared in Table 4.1. The locations of the identified center-pivot systems are shown in Figure 4.1.

Table 4.1. Estimation of existing irrigated lands in North Dakota.

County	Area	Identified center-pivot systems		NASS (2017)	NASS (2022)	Active irrigation permits
	thousand acres	count	area (acres)	area (acres)	area (acres)	area (acres)
Adams	633	0	0	0	0	179
Barnes	969	5	633	2,481	2,343	2,210
Benson	912	27	3,311	2,028	1,158	3,843
Billings	738	0	0	0	0	1,330
Bottineau	1,087	0	0	29	4	1,113
Bowman	747	8	862	878	373	2,899
Burke	722	0	0	0	0	77
Burleigh	1,068	29	3,097	4,001	5,740	9,383
Cass	1,131	16	1,953	13,871	11,724	14,081
Cavalier	966	0	0	318	2,592	33
Dickey	731	129	15,570	14,813	15,650	19,737
Divide	829	28	3,661	2,265	2,348	3,644
Dunn	1,332	0	0	788	117	3,986
Eddy	412	8	864	0	0	1,419
Emmons	996	59	6,803	10,090	8,404	15,246
Foster	414	6	801	2,788	1,681	6,500
Golden Valley	641	3	363	1,106	19	2,036
Grand Forks	921	194	23,280	27,498	25,594	30,843
Grant	1,066	14	1,028	2,146	2,793	16,751
Griggs	459	26	3,313	1,504	2,408	6,308
Hettinger	726	0	0	0	0	585

Kidder	917	240	30,126	23,722	23,888	36,338
LaMoure	737	64	6,800	5,528	5,795	8,170
Logan	647	26	3,346	2,372	718	4,112
McHenry	1,223	78	9,738	6,226	5,965	12,085
McIntosh	637	5	558	694	0	413
McKenzie	1,830	90	8,795	26,683	36,902	20,749
McLean	1,490	123	14,159	8,098	6,679	11,299
Mercer	712	43	5,504	2,431	2,326	9,738
Morton	1,245	33	2,814	4,684	5,529	4,829
Mountrail	1,242	0	0	9	450	1,584
Nelson	646	13	1,324	2,884	2,084	3,167
Oliver	468	34	3,976	2,734	4,793	7,968
Pembina	718	17	1,880	1,449	3,539	3,533
Pierce	693	4	636	782	470	628
Ramsey	842	0	0	0	0	506
Ransom	553	180	21,269	28,943	16,817	28,498
Renville	571	0	0	6	0	175
Richland	925	27	3,337	6,093	6,118	5,170
Rolette	601	4	596	967	820	793
Sargent	555	97	12,512	16,773	8,702	18,432
Sheridan	644	17	1,850	0	0	380
Sioux	722	17	1,836	0	0	361
Slope	780	1	198	0	0	1,594
Stark	858	0	0	476	35	904
Steele	458	15	1,923	6,621	5,828	9,371
Stutsman	1,471	43	5,363	4,209	4,357	7,843
Towner	667	0	0	0	0	236
Traill	552	0	0	0	0	777
Walsh	828	21	2,879	1,741	1,632	3,529
Ward	1,316	5	759	523	598	2,637
Wells	826	0	0	1,010	840	952
Williams	1,375	104	11,927	21,065	16,337	41,468
North Dakota	**45,248**	**1,853**	**219,658**	**263,327**	**244,170**	**390,439**

Table 4.1 shows that 18 North Dakota counties (Adams, Billings, Bottineau, Burke, Eddy, Golden Valley, Hettinger, McIntosh, Mountrail, Pierce, Ramsey, Renville, Rolette, Slope, Stark, Towner, Traill, and Wells) have less than 1,000 acres of irrigated land. In contrast, eight counties (Dickey, Grand Forks, Kidder, McKenzie, McLean, Ransom, Sargent, and Williams) have more than 10,000 acres of irrigated land. The remaining 27 counties have about a few thousand acres of irrigated land. It is interesting to note that Sheridan and Sioux counties each have about 2,000 acres

identified as irrigated lands but less than 400 acres of active permits and no reported irrigated acres in the NASS' Census of Agriculture. In contrast, Barnes, Cass, Foster, McKenzie, Steele, and Williams counties have considerably fewer identified irrigation acres than the reported ones. Cavalier and McKenzie counties have considerably fewer acreages of active irrigation permits than the reported acreages of irrigated land.

According to the compiled active irrigation permits, about 85% of the approved acreages are irrigated using center-pivot sprinkler systems statewide, and the remaining are using flooding and water-spreading surface irrigation methods. Approximately one-third of the approved acreages use surface water while two-thirds use groundwater as an irrigation water source (not shown in the table).

4.2 Feasible parcels for irrigation development

Since irrigation development for conditionally irrigable soils *due to poor drainage, high water table, and salinity* requires large-scale drainage for management, which would require additional infrastructure and greater long-term planning and be subject to intense regulatory scrutiny (Olson and Schuh, 1995), we excluded this type of conditional soils from further analysis. Figure 4.1 presents the soil irrigability maps under the permissive scenario after removing conditional soils due to drainage, water table, and salinity, which are mostly found in the Red River Valley counties such as Cass, Grand Forks, Pembina, Richland, Traill, and Walsh. It should be noted that after excluding this category of conditional soils, the coverages of soil irrigability maps under the permissive and restrictive scenarios are very similar. Therefore, only the results under the permissive scenario will be shown from here forward.

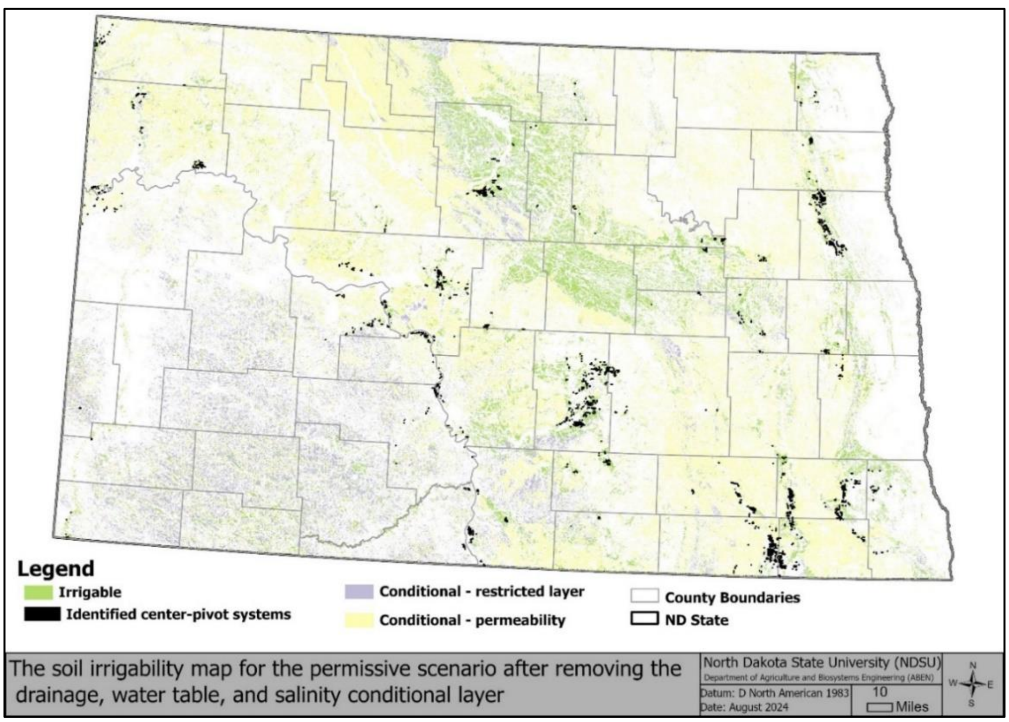

Figure 4.1. Soil irrigability maps under permissive scenarios after excluding the conditional soils due to drainage, water table, and salinity.

The modified PLSS layer served as the base for creating a feasibility map for deploying irrigation systems across North Dakota. This layer was merged into the soil irrigability map and the total areas of the irrigable and conditional soils were calculated for each PLSS unit. By dividing these areas by the total area of each PLSS unit, we obtained the percentage of land that is irrigable or conditionally irrigable for each PLSS Q-Q section (left panel of Figure 4.2). For further analysis we only accept the PLSS Q-Q sections that contain 90% or more irrigable or conditionally irrigable soils (right panel of Figure 4.2) (Scherer et al., 2023).

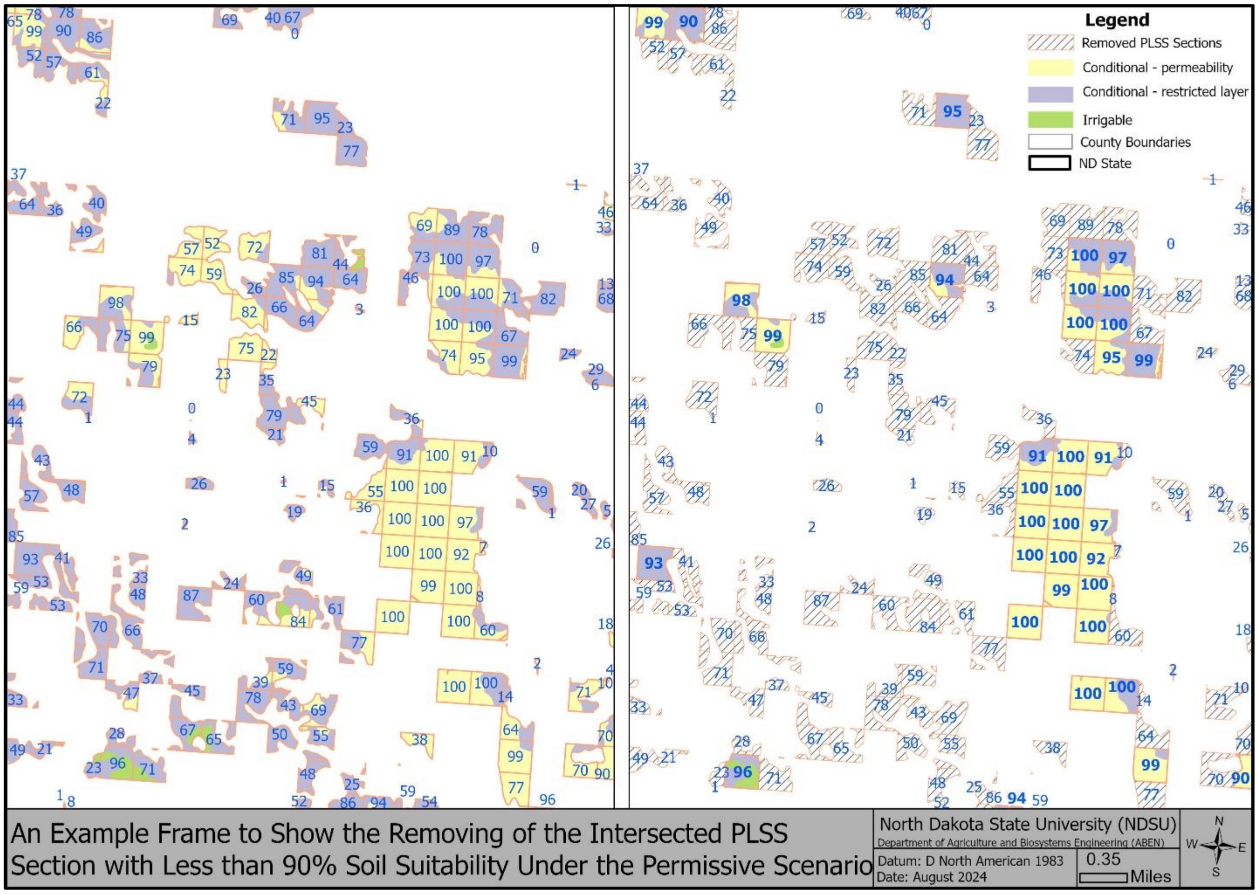

Figure 4.2. Land parcels with less than 90% of irrigable and conditional soils deemed not feasible for irrigation development.

4.3 Irrigation development potential from surface water sources

Irrigation development has two main limiting factors: suitable soil and suitable water. There are two types of water sources for irrigation development in North Dakota – surface water and groundwater. Although other lakes and streams have been permitted for irrigation water use in the past, the most reliable surface water resource for irrigation in North Dakota is the Missouri River system within the state, which includes the Missouri River mainstem, major tributaries, major lakes such as Lake Sakakawea, Lake Oahe, and Lake Audubon, and the McClusky canal which diverts water from the Missouri River (Olson and Schuh, 1995).

Therefore, in terms of surface water availability, we only consider lands near the Missouri River system for irrigation development in this study. The proximity requirements for surface water include (1) static lift for water transport cannot exceed 260 feet, and (2) irrigation must be within five miles of the water source (Olson and Schuh, 1995).

The static lift limit refers to the elevation difference between the water surface and the highest point along the water delivery path to the land. We adopted the Relative Elevation Model (REM) method to calculate the static lift for the lands in the Missouri River corridor. The details of the REM method are further explained in Appendix A.3. The PLSS Q-Q sections within 5 miles of the Missouri River system and McClusky Canal were selected as shown in Figure 4.3.

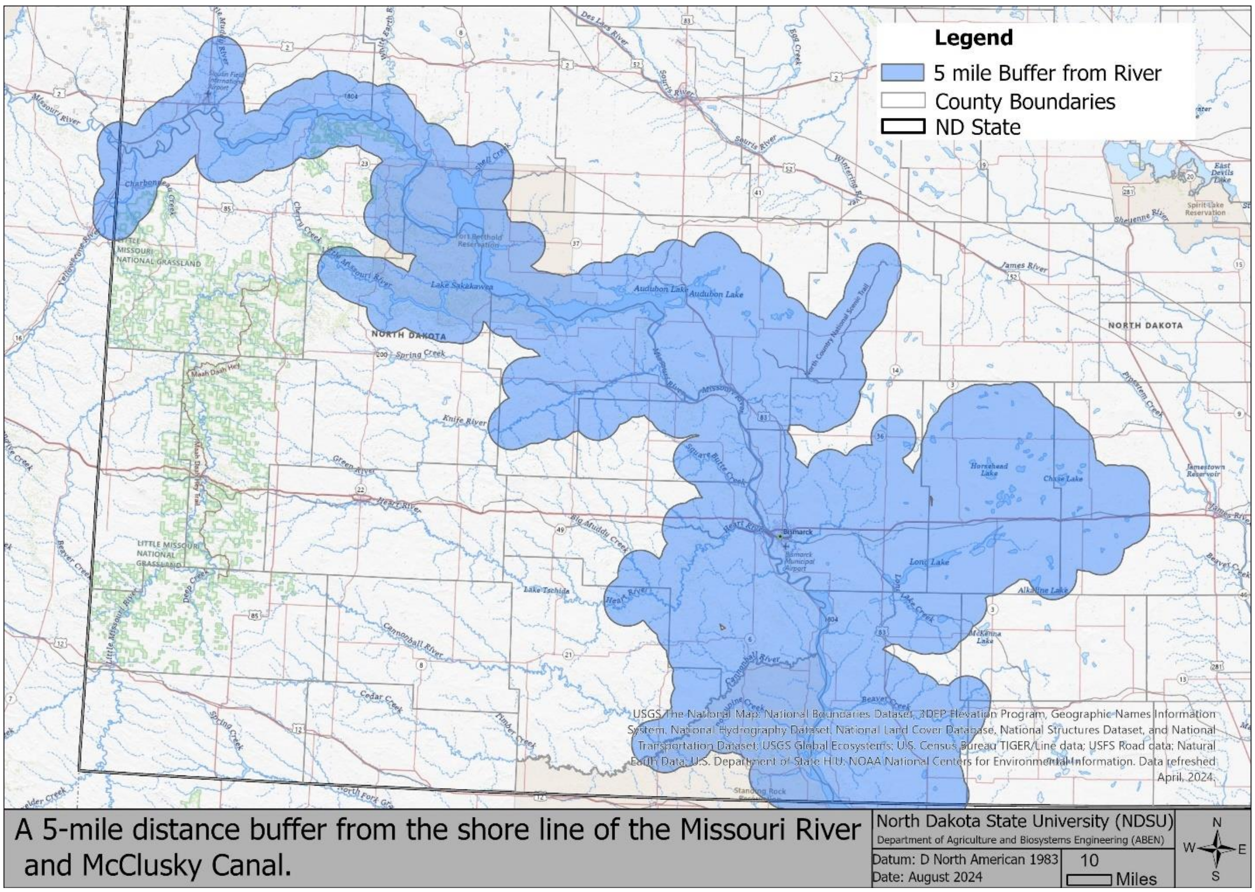

Figure 4.3. A 5-mile distance buffer from the shorelines of the Missouri River system, including mainstem, major tributaries and lakes, and McClusky Canal, within North Dakota.

Figure 4.4 shows the PLSS Q-Q parcels that meet the following conditions: (1) within 5 miles of the Missouri River system or McClusky Canal, (2) having no more than 260 ft of static lift along their straight-line path to the river system or canal, and (3) having 90% or more of their areal extent[1] consisting of irrigable or conditional soils under permissive scenarios. These land parcels have the potential to develop irrigation projects.

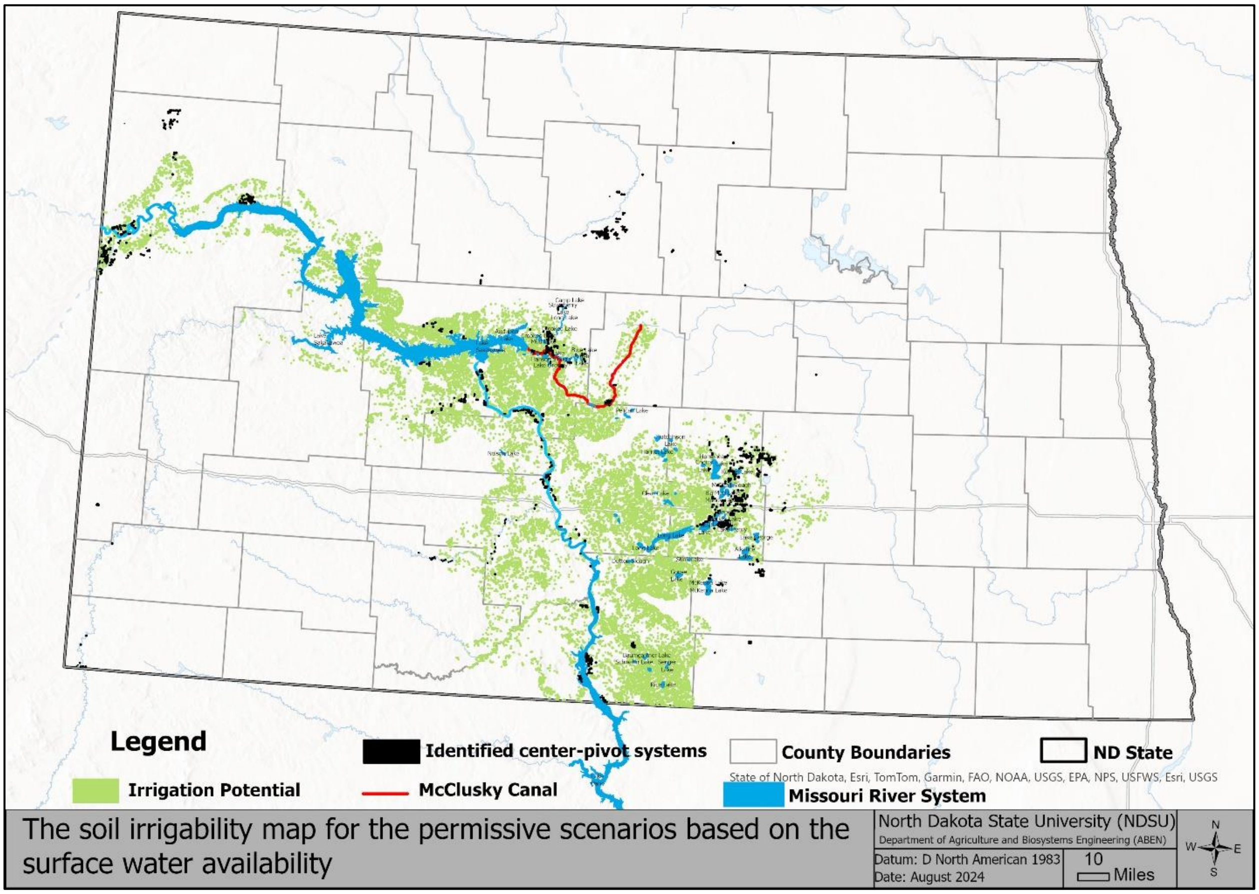

Figure 4.4. The potential lands for irrigation development along the Missouri River corridor.

Table 4.2 summarizes the areas for each class of soil irrigability across these parcels in the 17 counties along the Missouri River system and McClusky Canal. Results for the restrictive scenario are similar and not shown here. In this region, there are about 1.05 million acres of land that may be irrigated using the water from the Missouri River. Burleigh, Emmons, Kidder, and McLean counties have the most land areas, whereas Dunn, Grant, Logan, and McIntosh have the least areas.

[1] We adopted the dominant condition, rather than the dominant component, method in the SSURGO database to create the soil irrigability maps. This approach may not represent the exact spatial coverage under some peculiar situations.

Table 4.2. Areas of land parcels for potential irrigation development along the Missouri River corridor under the permissive scenario.

County	Conditionally Irrigable Soils Permeability	Conditionally Irrigable Soils Restricted Layer	Irrigable Soils	Total
	---thousand acres---			
Burleigh	91.9	7.6	49.5	149.0
Dunn	3.1	2.3	1.1	6.5
Emmons	137.5	44.1	38.3	219.9
Grant	1.3	5.3	5.6	12.2
Kidder	45.2	10.1	64.7	120.0
Logan	4.2	1.5	1.9	7.6
McIntosh	0.6	0.6	0.6	1.9
McKenzie	26.3	0.3	1.4	28.0
McLean	175.3	8.4	34.0	217.7
Mercer	43.1	10.3	11.1	64.5
Morton	31.5	26.6	11.5	69.6
Mountrail	26.2	0.7	2.3	29.2
Oliver	17.2	9.1	4.8	31.1
Sheridan	8.2	0.1	9.8	18.2
Sioux	8.2	8.0	8.4	24.6
Stutsman	8.0	0.1	5.1	13.2
Williams	29.4	0.9	7.3	37.6
	---million acres---			
Total	**0.66**	**0.14**	**0.26**	**1.05**

4.4 Irrigation development potential from groundwater sources

The unconsolidated glaciofluvial aquifers across North Dakota generally have good water quality, and most of them can be and have been developed for irrigation water use. The shapefile of these aquifers resulting from the Department of Water Resources' managed aquifer recharge (MAR) project (Patch, 2024) was used to evaluate groundwater suitability for irrigation by considering both quality and quantity. For groundwater quality, aquifers with a median TDS (Total Dissolved Solids) concentration less than 1,500 mg/L were considered good for irrigation, while those with a median TDS concentration greater than 1,500 mg/L were considered unsuitable for irrigation (Figure 4.5).

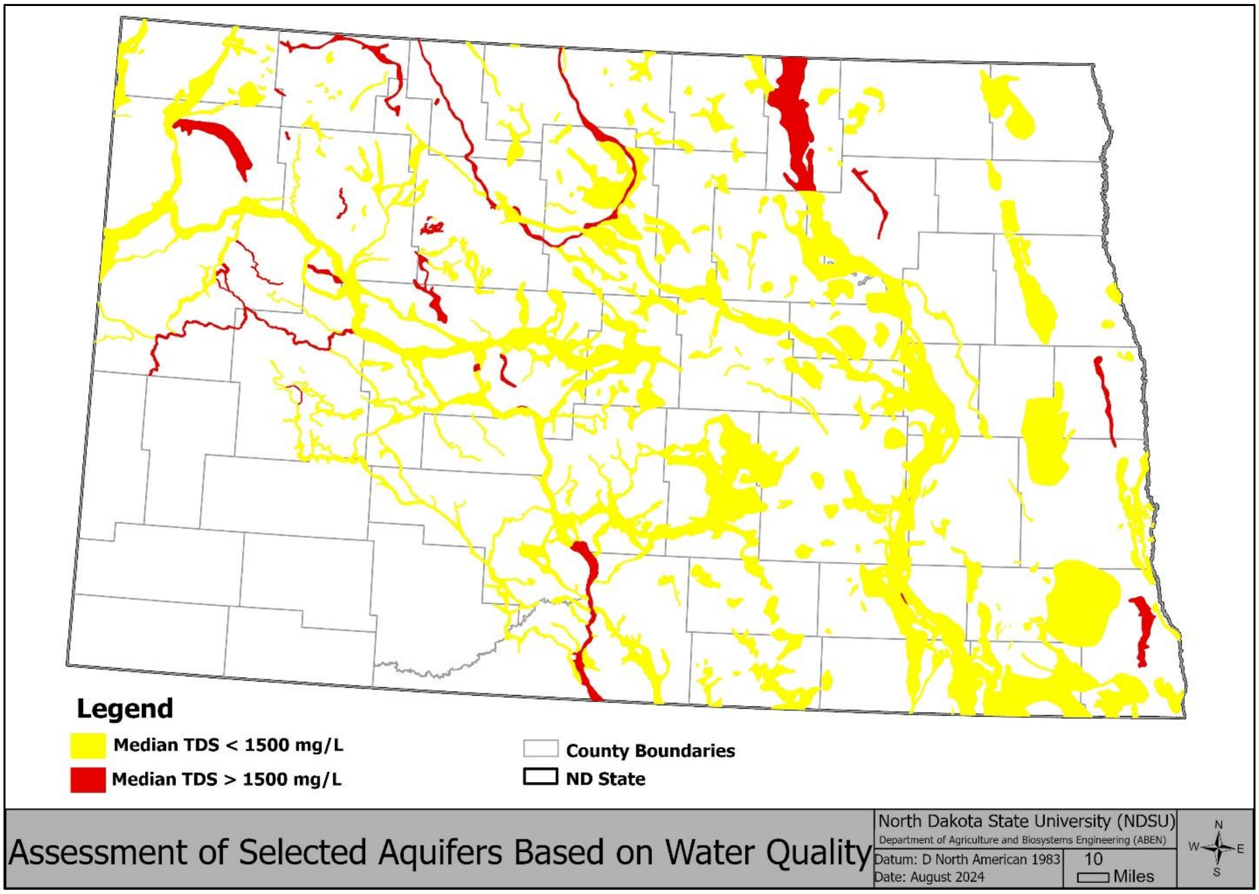

Figure 4.5. Water quality of the glaciofluvial aquifers in North Dakota. TDS - Total Dissolved Solids.

For groundwater quantity, aquifers were ranked as "Excellent", "Very Good", "Good", "Fair", or "Poor" in terms of the aquifer's recharge potential, with higher recharge potential reflecting less water availability (Figure 4.6). The aquifers with MAR rankings of "Excellent" and "Very Good" were deemed insufficient for irrigation, whereas the aquifers with MAR rankings of "Fair" and "Poor" were considered abundant for irrigation. For the aquifers ranked as "Good", there exists significant development but no current need for substantial MAR enhancement. This rating is given when MAR could be generally effective and appropriate in limited site-specific areas and during drought cycles. Aquifers in this category typically have stable (or rising) water-level trends but may be susceptible if future large-scale development may lead to downward water-level trends. However, with MAR enhancement, these aquifers may allow additional appropriation to occur without violating the prior appropriation doctrine (Patch, 2024). Examples of these aquifers include Elk Valley-Inkster-Fordville, Page, Sheyenne Delta, Spiritwood-LaMoure, Spiritwood-Oakes, Oakes, New Rockford, and Central Dakota.

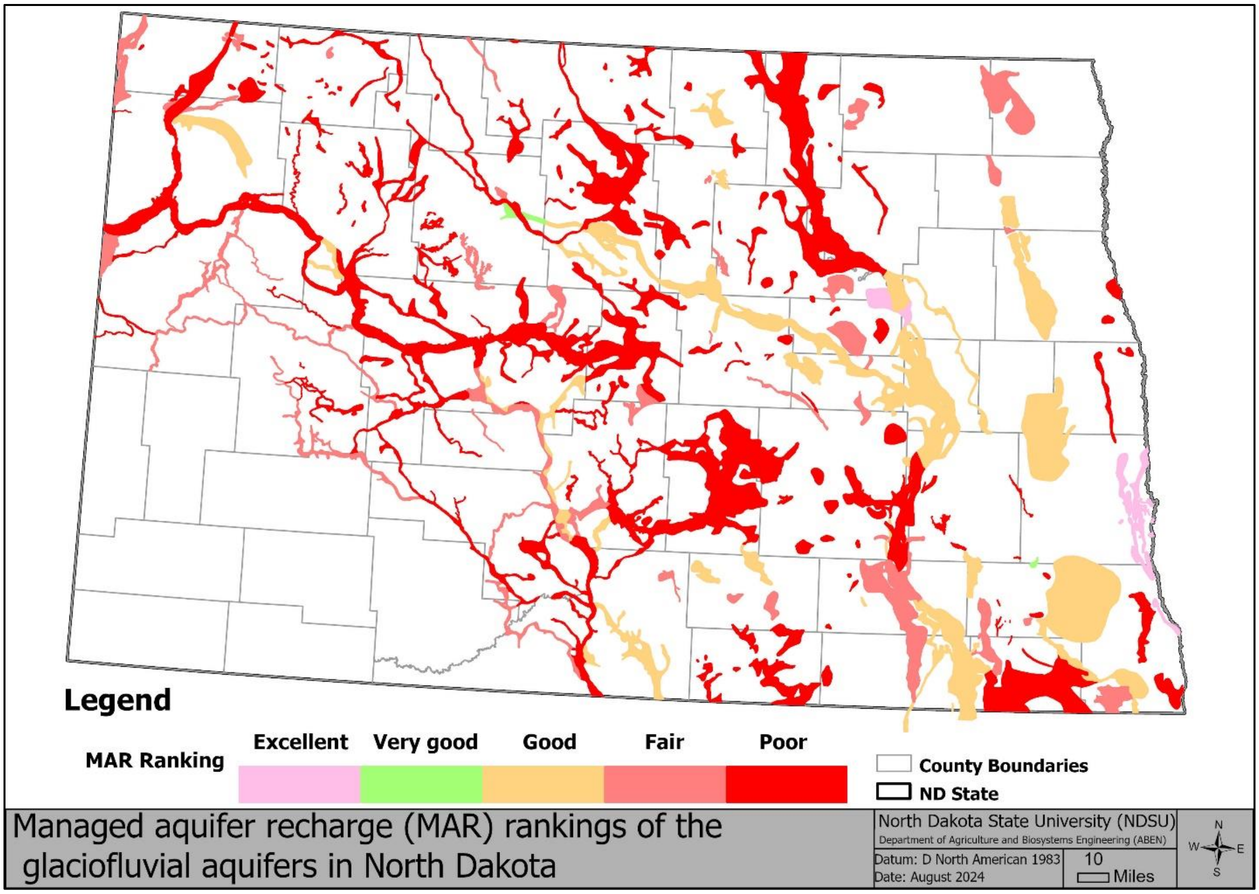

Figure 4.6. Managed aquifer recharge (MAR) rankings of the glaciofluvial aquifers in North Dakota.

Therefore, we created two scenarios to account for groundwater availability. In Scenario 1, the aquifers with good quality (i.e., median TDS < 1500 mg/L) *and "Good", "Fair", and "Poor"* MAR rankings are considered available for irrigation, while in Scenario 2, the aquifers with good quality *and "Fair" and "Poor"* MAR rankings are available for irrigation water use (Figure 4.7). These two scenarios may be considered the best (Scenario 1) and the worst (Scenario 2) scenarios regarding groundwater availability.

Also, since the water from the production wells in an aquifer may be transported to irrigate lands outside the aquifer's coverage to a certain distance (Tom Scherer, personal communication, October 2024), we created a 2-mile buffer around the aquifers with good and sufficient groundwater for Scenario 1 and Scenario 2, respectively (Figure 4.8).

In the next step, the PLSS Q-Q sections that have 90% or more of their areal extent consisting of irrigable or conditional soils (excluding conditional soils – drainage, water table, and salinity) were clipped against the boundaries of the 2-mile buffer around these aquifers. The resulting layer identifies the land parcels suitable for irrigation using groundwater under Scenario 1 and Scenario 2, respectively (Figure 4.9).

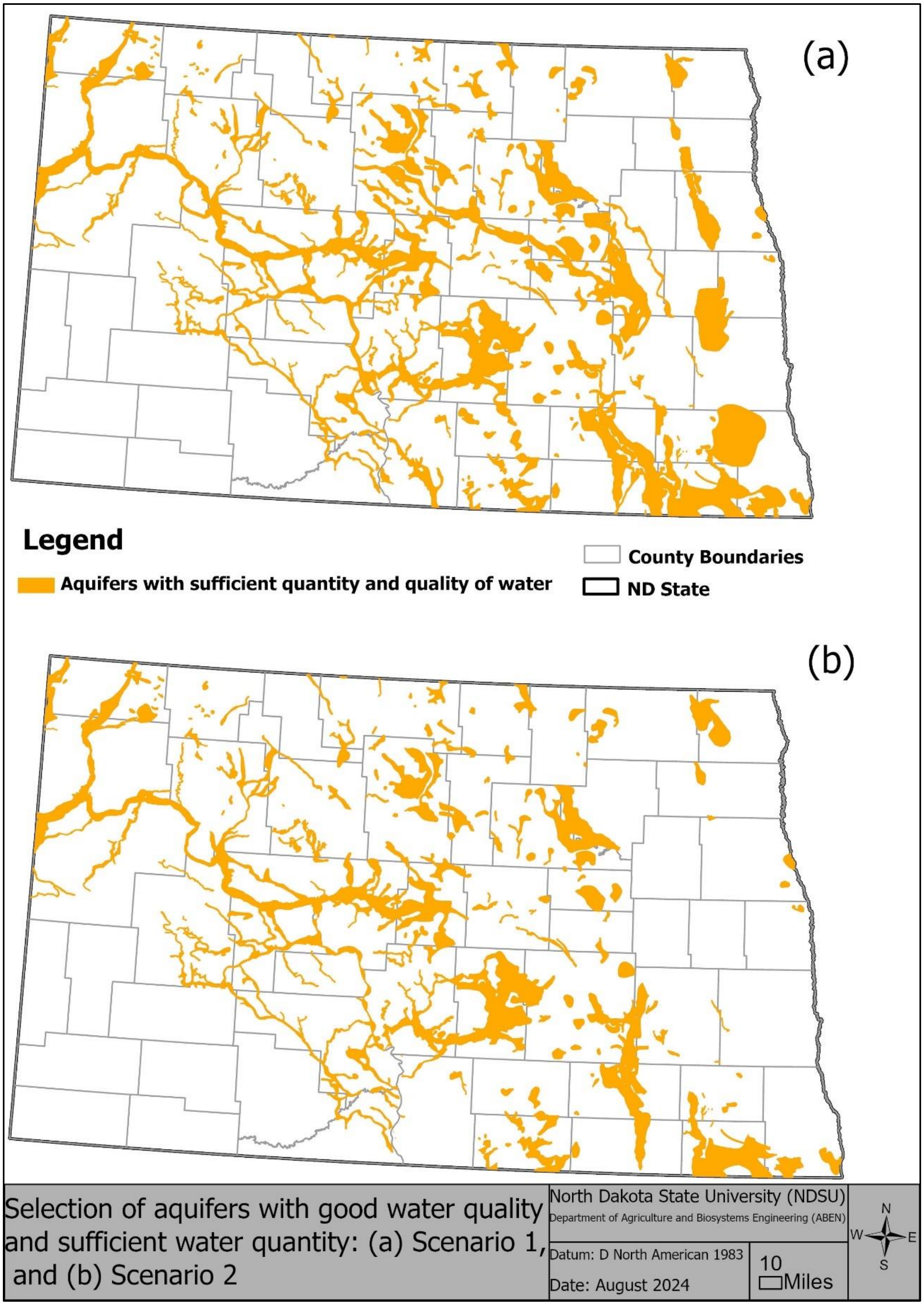

Figure 4.7. Selection of aquifers with good water quality and sufficient water quantity: (a) Scenario 1 and (b) Scenario 2.

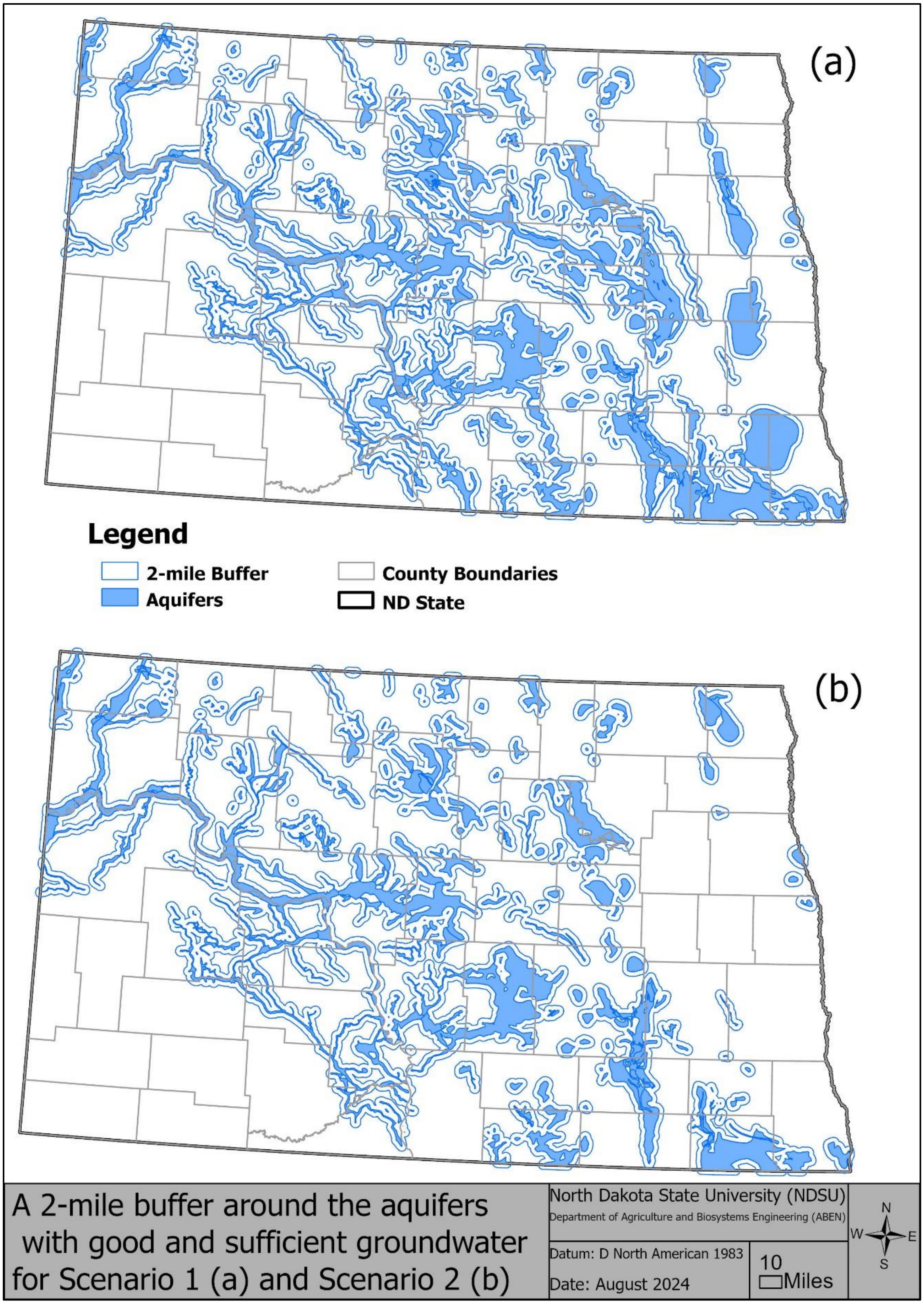

Figure 4.8. Two-mile buffers around aquifers under (a) Scenario 1 and (b) Scenario 2.

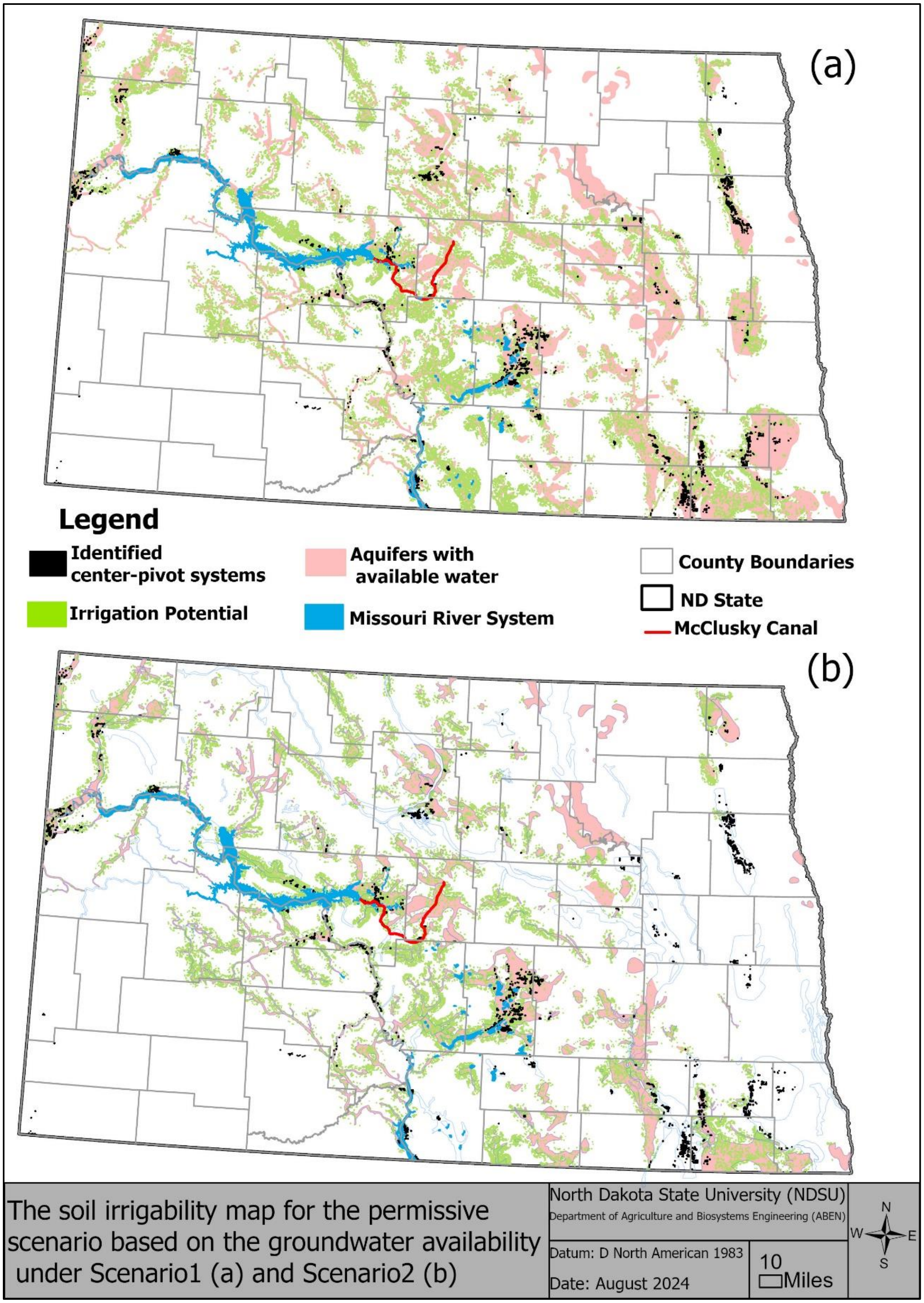

Figure 4.9. Land parcels with irrigation potential based on groundwater availability under (a) Scenario 1 and (b) Scenario 2.

Finally, for the 17 counties along the Missouri River corridor, the overlapping areas of land irrigable using water from the Missouri River and land irrigable using groundwater were removed. The lands that are currently being irrigated were also removed to obtain the total area of land with irrigation *potential* across the state. The calculation details of removing the overlapping areas and existing irrigated lands are shown in Tables A.2 & A.3 in Appendix A.4.

The total areas of land that may be *potentially* irrigated using water from the Missouri River and groundwater (both scenarios) for each county are summarized in Table 4.3 and redisplayed in Figure 4.10. When overlaying these land parcels with the 2023 USDA Cropland Data Layer (https://nassgeodata.gmu.edu/CropScape/), all of these lands are related to cropland and pasture land uses.

In summary, there are 1.8 to 2.07 million acres of cropland available for potential irrigation development across the state. Of these lands, approximately one million acres are within the 17 counties along the Missouri River corridor for irrigation development, potentially irrigable using water withdrawn from the Missouri River system. The additional 0.8 to 1.06 million acres may be developed for irrigation by withdrawing good-quality water from shallow glaciofluvial aquifers across the state, depending upon the water availability in these aquifers, where using water from the Missouri River system for irrigation is not practical.

Table 4.3. Areas of land parcels for potential irrigation development using Missouri River water and groundwater under two scenarios.

County (1)	Missouri River (2)	------------- Scenario 1 ----------- Groundwater (3)	Total[a] (4)	------------- Scenario 2 ------------ Groundwater (5)	Total[b] (6)
	-- thousand acres				--
Adams		0.	0.	0.	0.
Barnes		9.7	9.7	6.3	6.3
Benson		35.1	35.1	28.4	28.4
Billings		0.	0.	0.	0.
Bottineau		48.8	48.8	48.8	48.8
Bowman		0.	0.	0.	0.
Burke		7.2	7.2	7.2	7.2
Burleigh	149.0	12.7	161.7	12.7	161.7
Cass		25.6	25.6	0.2	0.2
Cavalier		8.8	8.8	8.8	8.8
Dickey		19.5	19.5	6.3	6.3
Divide		31.0	31.0	31.0	31.0
Dunn	6.5	51.3	57.8	51.3	57.8
Eddy		22.3	22.3	11.9	11.9
Emmons	216.8	1.5	218.3	1.5	218.3
Foster		12.3	12.3	4.7	4.7
Golden Valley		0.	0.	0.	0.

Grand Forks		19.6	19.6	2.4	2.4
Grant	12.1	0.	12.1	0.	12.1
Griggs		18.2	18.2	0.	0.
Hettinger		0.	0.	0.	0.
Kidder	105.1	0.4	105.5	0.2	105.3
LaMoure		43.5	43.5	32.5	32.5
Logan	7.5	17.5	25.0	6.2	13.7
McHenry		75.1	75.1	49.9	49.9
McIntosh	2.0	56.3	58.3	56.3	58.3
McKenzie	26.1	12.4	38.5	12.4	38.5
McLean	210.8	29.1	239.9	29.1	239.9
Mercer	63.0	3.3	66.3	3.3	66.3
Morton	69.1	9.5	78.6	9.5	78.6
Mountrail	29.2	34.7	63.9	34.7	63.9
Nelson		15.1	15.1	0.	0.
Oliver	29.9	8.1	38.0	8.1	38.0
Pembina		14.5	14.5	14.5	14.5
Pierce		31.1	31.1	22.8	22.8
Ramsey		0.3	0.3	0.2	0.2
Ransom		29.8	29.8	14.9	14.9
Renville		14.3	14.3	14.3	14.3
Richland		16.9	16.9	9.8	9.8
Rolette		10.0	10.0	4.6	4.6
Sargent		70.7	70.7	63.1	63.1
Sheridan	17.5	16.5	34.0	16.5	34.0
Sioux	23.8	0.	23.8	0.	23.8
Slope		0.	0.	0.	0.
Stark		6.2	6.2	6.2	6.2
Steele		12.3	12.3	0.	0.
Stutsman	10.7	23.2	33.9	23.2	33.9
Towner		0.2	0.2	0.2	0.2
Traill		6.2	6.2	0.	0.
Walsh		26.5	26.5	11.8	11.8
Ward		45.9	45.9	45.9	45.9
Wells		64.3	64.3	42.6	42.6
Williams	33.3	37.1	70.4	37.1	70.4
	---------- million acres ----------				
North Dakota	**1.01**	**1.06**	**2.07**	**0.79**	**1.80**

[a] Total area of potential irrigation land under scenario 1 is column (2) + column (3).
[b] Total area of potential irrigation land under scenario 2 is column (2) + column (5).

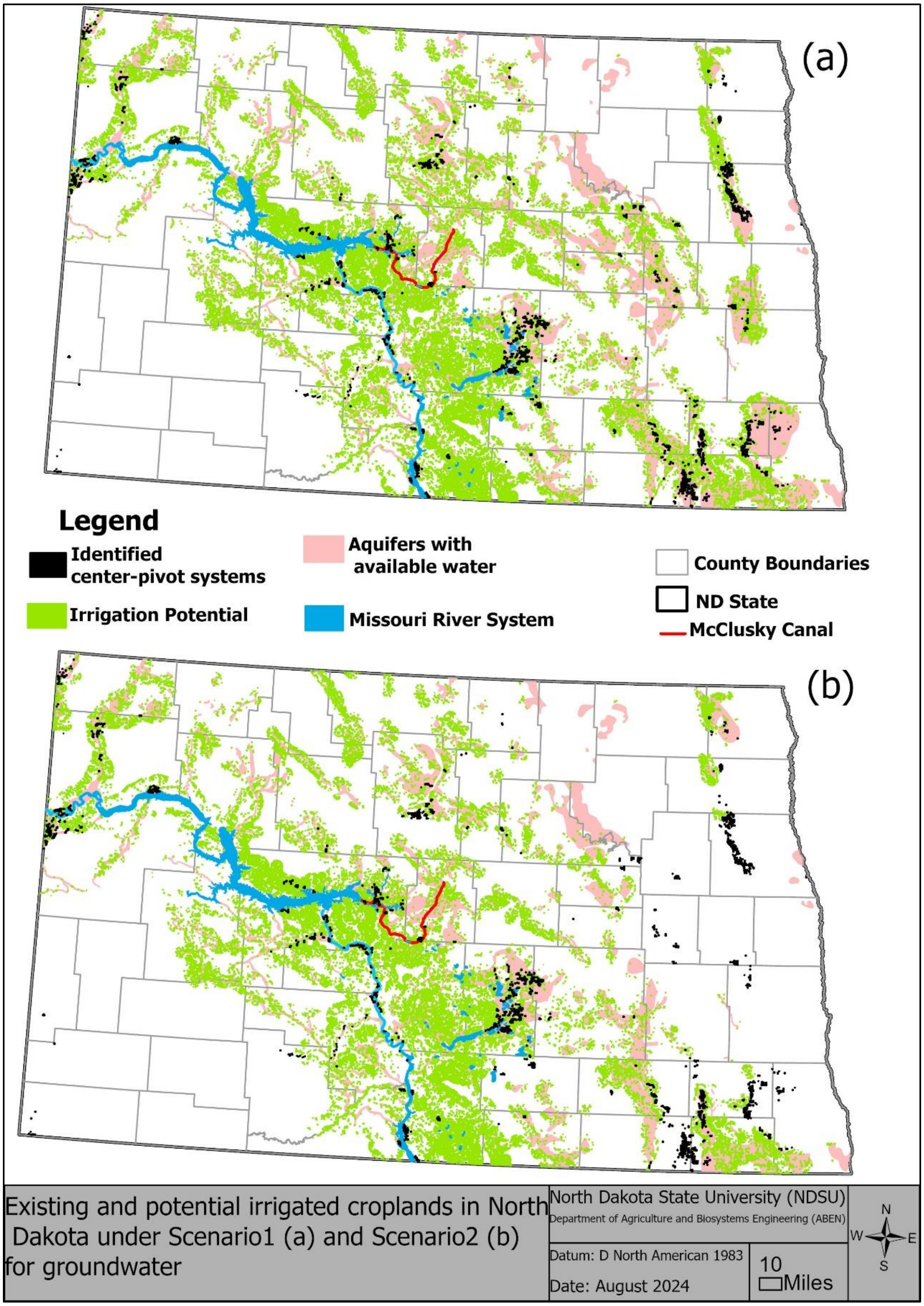

Figure 4.10. The map of croplands with irrigation potential using Missouri River water and groundwater under (a) Scenario 1 and (b) Scenario 2.

The counties are ranked in terms of the total areas of potentially irrigable croplands in Figure 4.11, which shows that central North Dakota counties (e.g., McLean, Emmons, Burleigh, Kidder, Morton) have the most areas of cropland for potential irrigation development under both groundwater availability scenarios. Not surprisingly, the counties in southwestern North Dakota (e.g., Adams, Billings, Bowman, Golden Valley, Hettinger, Slope) do not have much land for irrigation development, nor do Ramsey and Towner counties in northeastern North Dakota. Statewide, under Scenario 1, 40 counties have more than ten thousand acres of cropland potential for future irrigation development, whereas, under Scenario 2, only 31 counties have more than ten thousand acres of cropland for potential irrigation development.

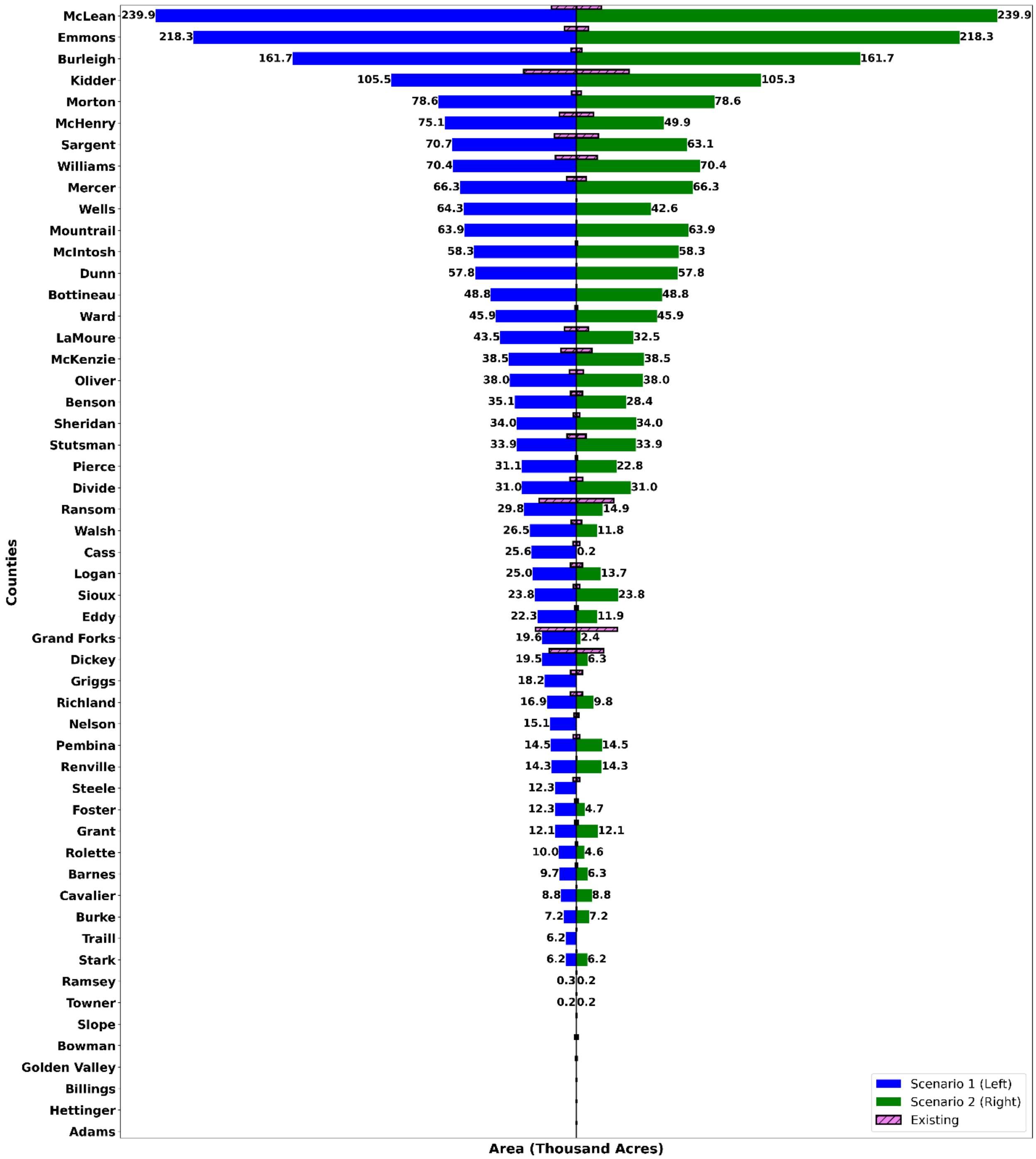

Figure 4.11. Areas of potentially irrigable lands in North Dakota counties using the Missouri River water and groundwater under two scenarios.

4.5 Irrigation development potential from power availability

Three-phase power electricity is generally the preferred source of power for irrigation pumps, over internal combustion engines, due to advantages such as lower pumping costs, less maintenance, greater reliability, and ease of operation. However, if the existing power lines are more than one mile from the pump site, it may not be economical due to high construction costs and repayment for the extension of power lines (Scherer, 2022).

Due to data privacy concerns, we can only access three-phase power distribution lines from three North Dakota electric distribution cooperatives (i.e., Capital Electric, Dakota Valley, Northern Plains) out of the 17 North Dakota electric distribution cooperatives (Figure 4.12). After creating a 1-mile buffer around the three-phase power lines provided by these three electric cooperatives, we clipped the layer of irrigation potential land against the electric availability layer to obtain the locations and areas of cropland with irrigation potential based on soil suitability and water and power availabilities. Figure 4.13 shows the locations of these lands and Table 4.4 summarizes the areas of these land parcels with the highest potential for future irrigation development.

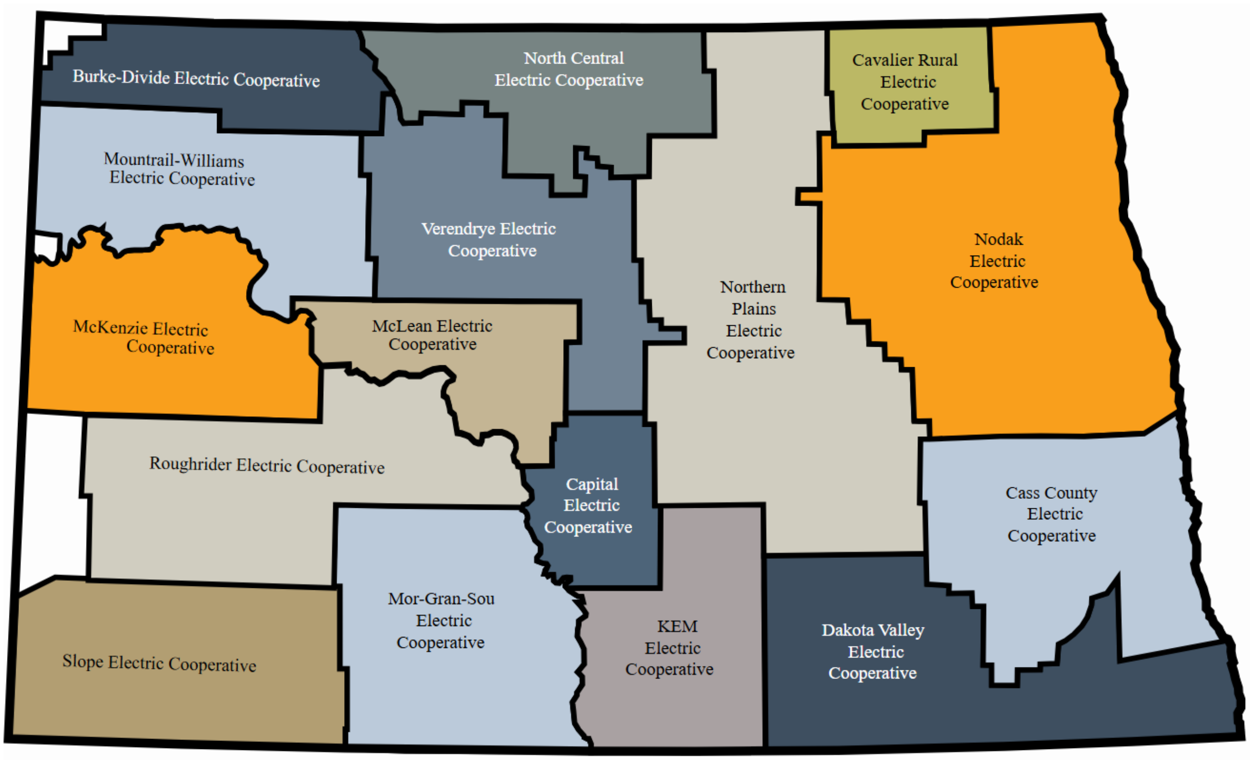

Figure 4.12. North Dakota's electric distribution cooperatives (Source: North Dakota Association of Rural Electric Cooperatives).

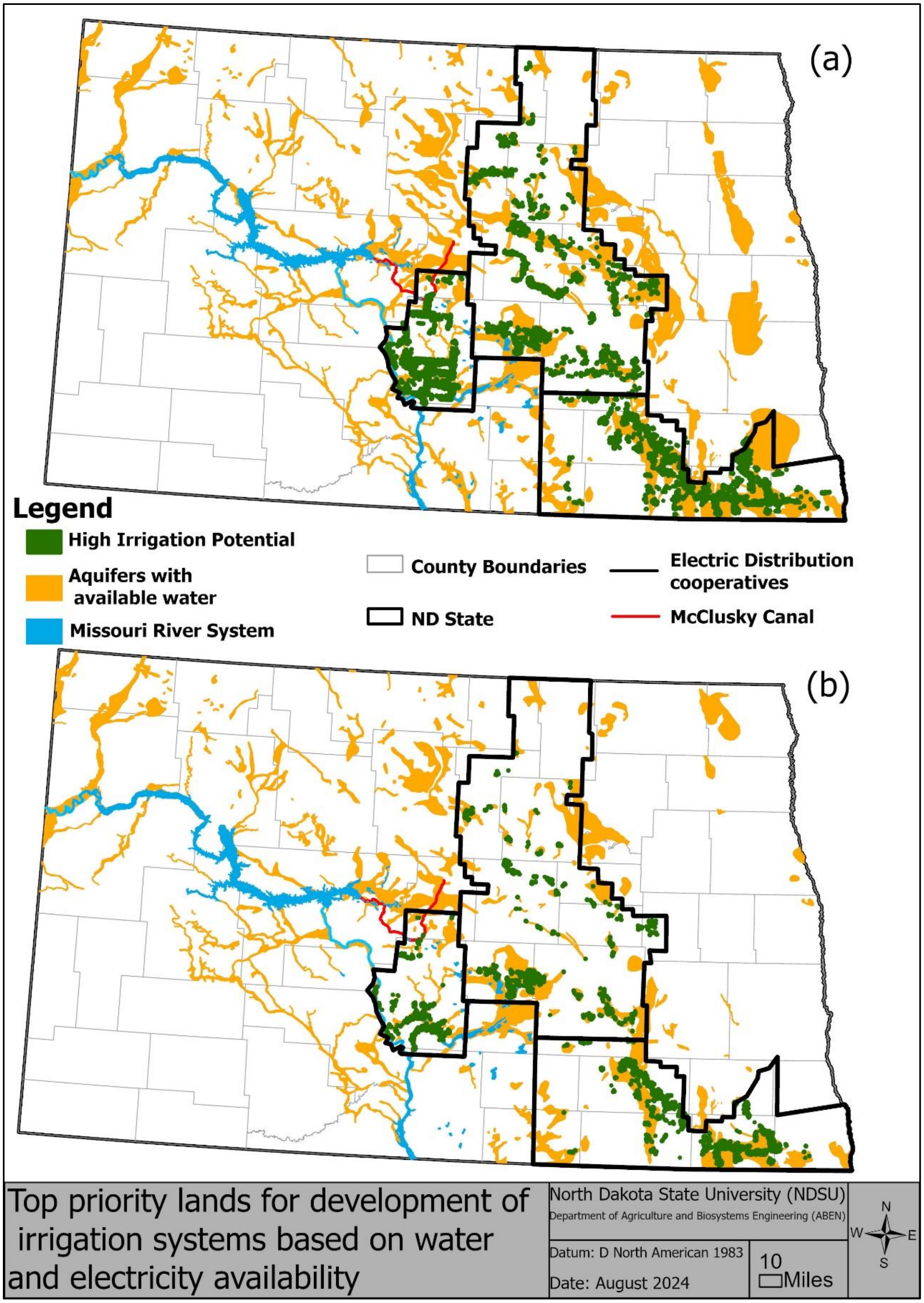

Figure 4.13. Croplands with irrigation potential within one mile from three-phase power lines of Capital Electric, Dakota Valley, and Northern Plains Cooperatives, under (a) Scenario 1 and (b) Scenario 2.

Table 4.4 shows that in the three above-mentioned electric cooperatives' service areas, approximately 66 to 76 thousand acres of cropland, depending upon groundwater availability scenarios, are within a one-mile distance of the existing three-phase power lines of these cooperatives. This represents about 7.2% of the croplands with irrigation potential based on the soil suitability and water availability analyses. Twelve (12) of these 18 counties have more than 1,000 acres of croplands that are readily available for irrigation development under either groundwater availability scenario.

Table 4.4. Areas of land parcels with irrigation potential within one-mile distance of three-phase power lines of Capital Electric, Dakota Valley, and Northern Plains Cooperatives.

County	Scenario 1 (acre)		Scenario 2 (acre)	
	Irrigation potential[a]	Considering 3-phase power availability[b]	Irrigation potential[c]	Considering 3-phase power availability[b]
Benson	35,100	1,610	28,400	1,420
Burleigh	161,700	13,930	161,700	13,930
Dickey	19,500	5,910	6,300	3,220
Eddy	22,300	410	11,900	400
Emmons	218,300	200	218,300	200
Foster	12,300	3,170	4,700	1,120
Griggs	18,200	1,340	--	--
Kidder	105,500	7,430	105,300	7,430
LaMoure	43,500	10,230	32,500	9,070
McIntosh	58,300	200	58,300	200
Morton	78,600	280	78,600	280
Pierce	31,100	2,400	22,800	1,840
Ransom	29,800	2,240	14,900	1,080
Richland	16,900	1,570	9,800	1,190
Sargent	70,700	15,640	63,100	14,970
Sheridan	34,000	140	34,000	140
Stutsman	33,900	5,710	33,900	5,710
Wells	64,300	4,330	42,600	3,900
Total	**1,054,000**	**76,740**	**927,100**	**66,100**

[a] These numbers are taken from Column (4) of Table 4.3.
[b] Areas are rounded to tens, and the counties with areas less than 100 acres are not listed.
[c] These numbers are taken from Column (6) of Table 4.3.

5 Acknowledgement

This study is supported by the North Dakota Irrigation Association, North Dakota Department of Water Resources, Garrison Diversion Conservancy District, and NDSU Office of Research and Creative Activity (ND Economic Diversification Research Fund). We want to express our gratitude to Dr. Tom Scherer and Dr. David Franzen for their expertise and assistance in updating the soil irrigability maps. We also would like to thank Andrew Nygren, Rod Bassler, Paul Moen, and Patrick Fridgen for their help with water resources data in North Dakota. Dr. James Kim is affiliated with the United States Department of Agriculture's Agricultural Research Service.

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A. Appendices

A.1. Soil relative irrigability

An alternative approach to classifying soil irrigability according to dominant conditions is to assign a numerical value for each soil component based on its Irrigation Functional Group (see Table A.1) and calculate the weighted average across all soil components within each map unit. The relative irrigability analysis assumes that soils within the *Conditional – drainage, water table, and salinity* functional group are more difficult to manage than any other conditionally irrigable soils. The numerical values for all functional groups are listed in Table A.1, which were chosen to mimic the McClusky Canal irrigation feasibility study report (Garrison Diversion Conservancy District, 2016).

Table A.1. Numerical values assigned to soil irrigation functional groups for relative irrigability analysis.

Irrigation Functional Group	Numerical value
Irrigable	3
Conditional – permeability	2
Conditional – restricted layer	2
Conditional – drainage, water table, salinity	1
Non-irrigable	0
Non-irrigable due to slope	0
Water	0

Figures A.1 and A.2 display the statewide soil relative irrigability maps under the permissive and restrictive scenarios, respectively. Figures A.3 and A.4 show the relative irrigability rating by dominant conditions under the permissive and restrictive scenarios, respectively.

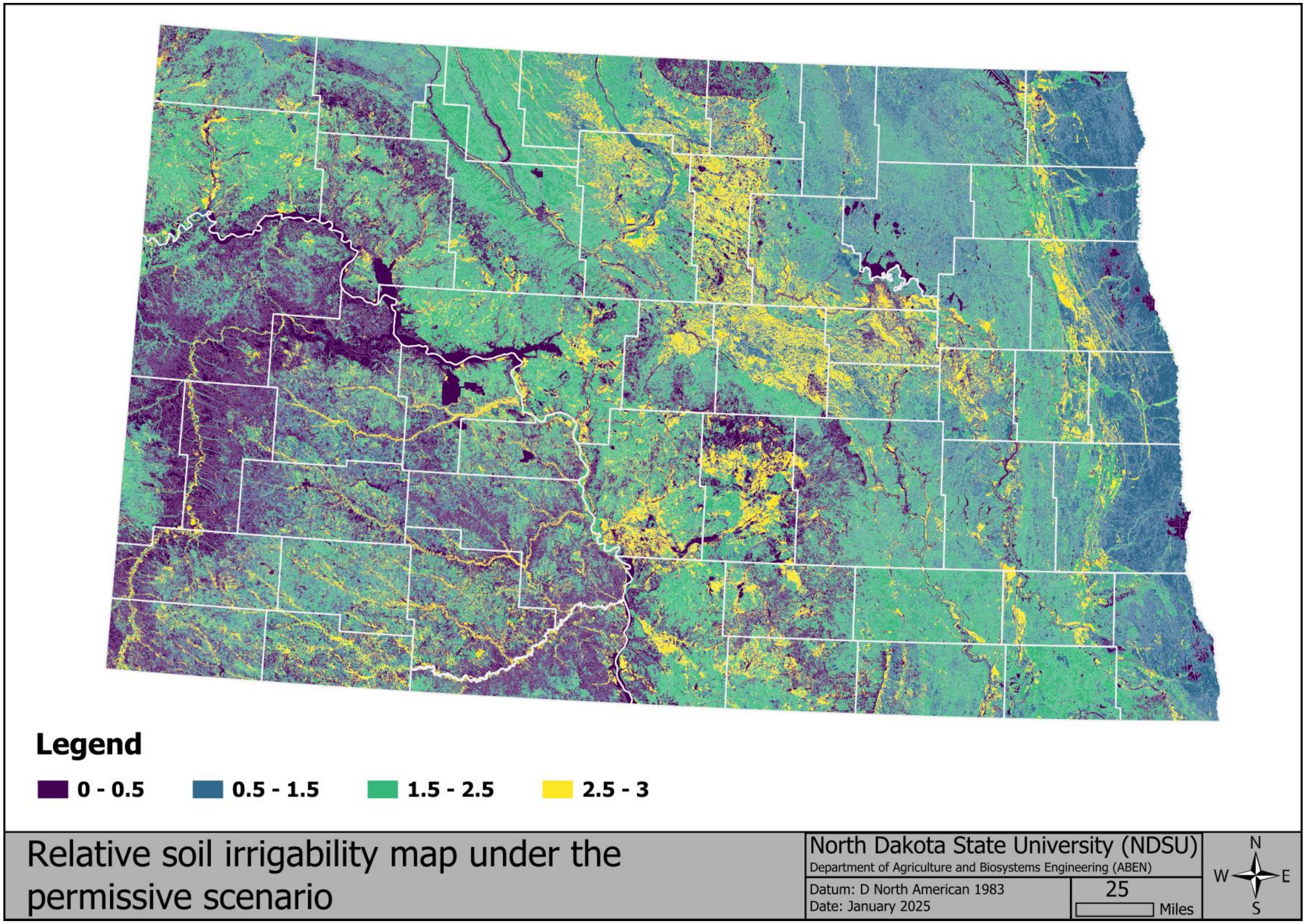

Figure A.1. Soil relative irrigability map under the permissive scenario.

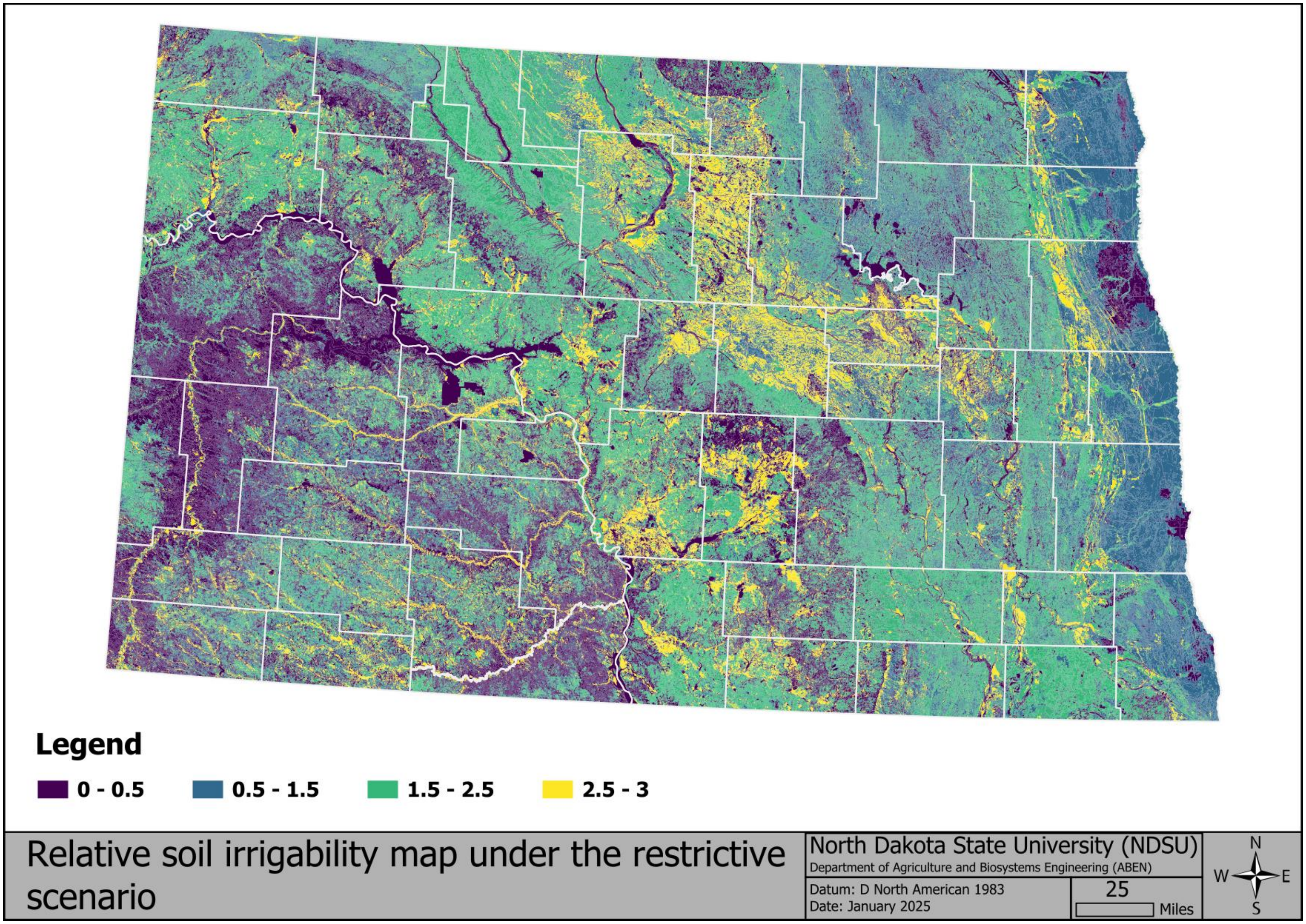

Figure A.2. Soil relative irrigability map under the restrictive scenario.

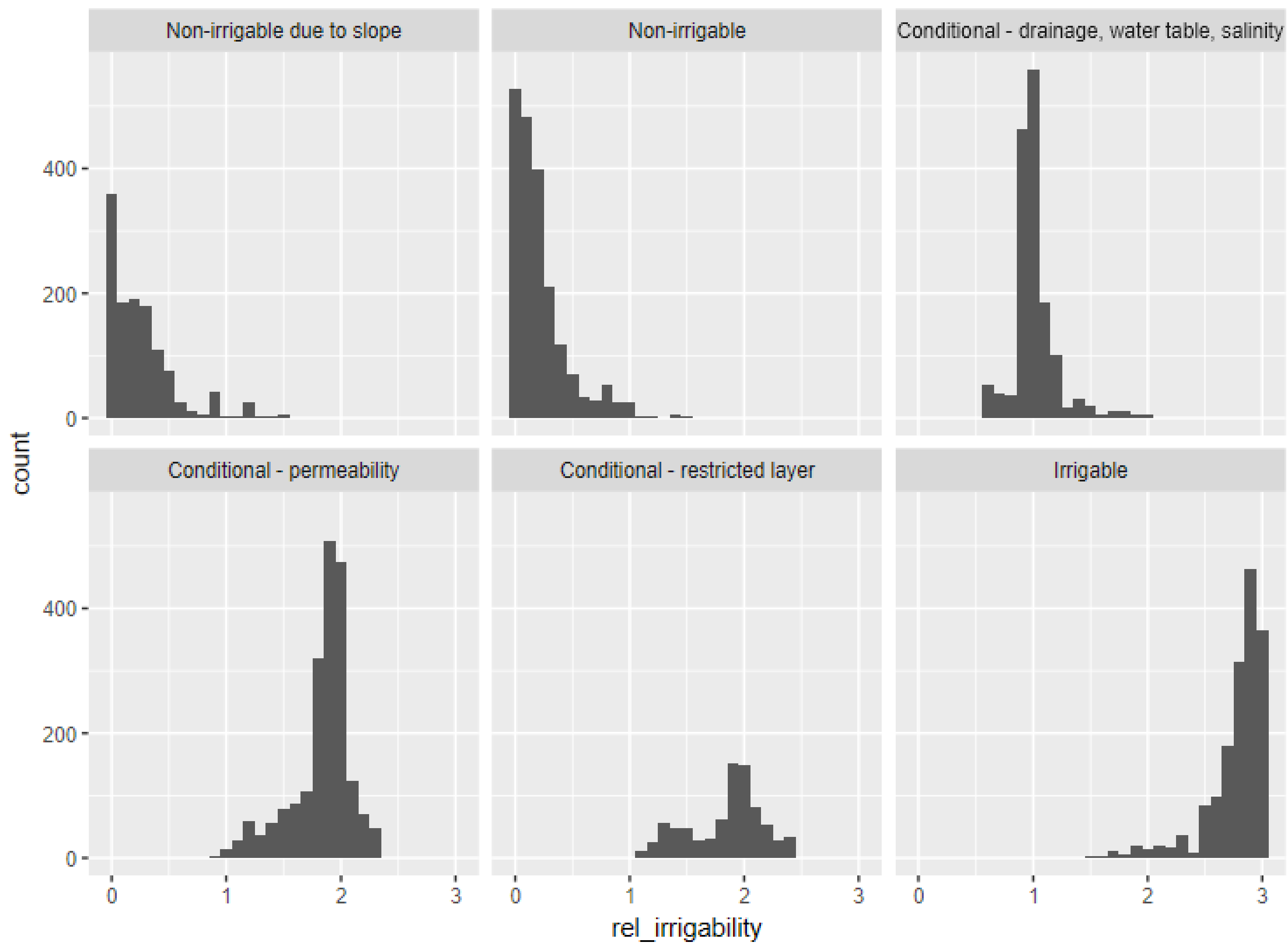

Figure A.3. Relative irrigability rating by the dominant condition under the permissive scenario.

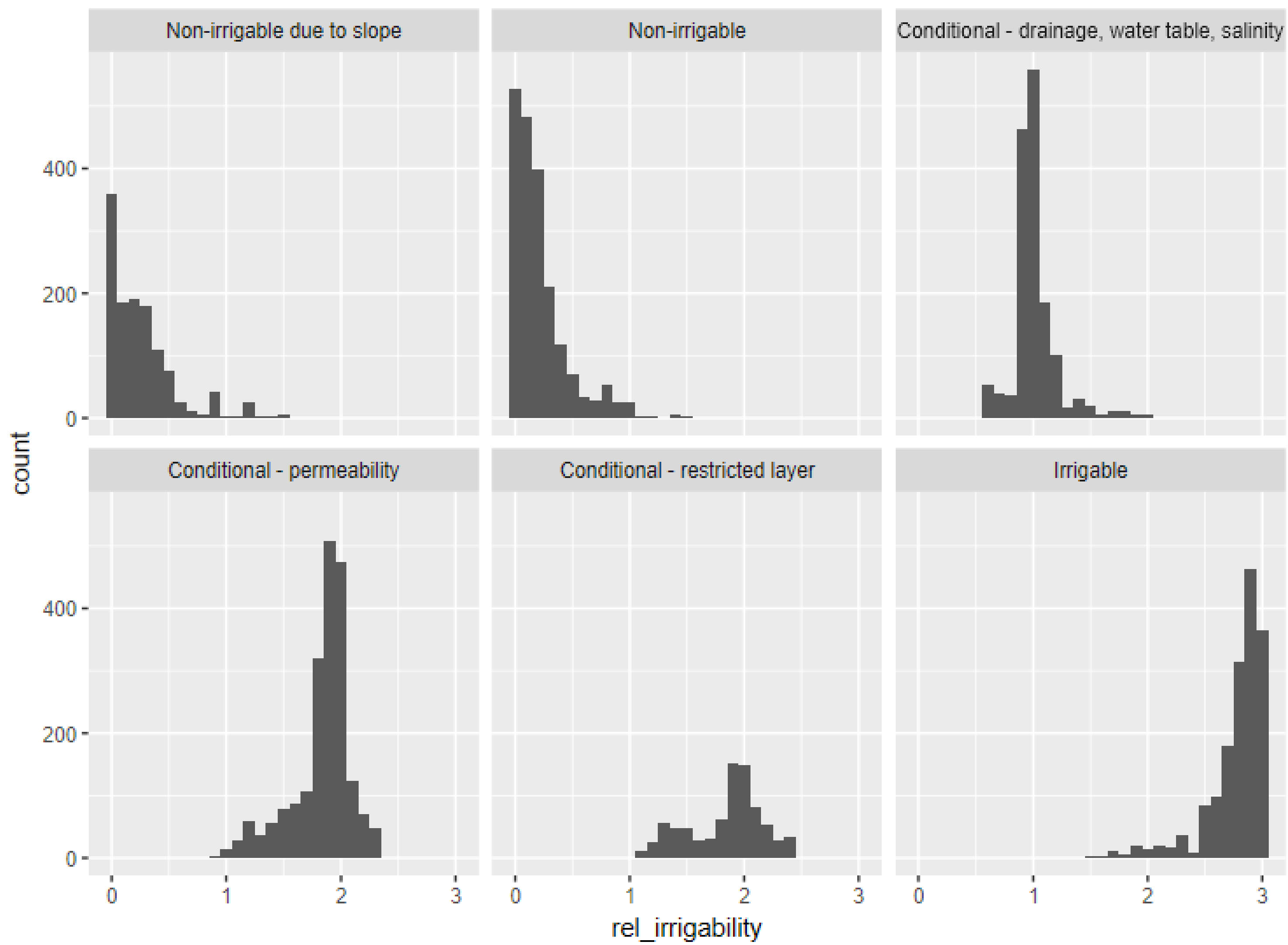

Figure A.3. Relative irrigability rating by the dominant condition under the restrictive scenario.

A.2. Identifying the existing center-pivot sprinkler systems

To identify the existing center-pivot sprinkler systems we employed the object detection deep learning model to process the Landsat 8 satellite images covering North Dakota. We downloaded 14 frames of the panchromatic band of Landsat 8 images captured in summer 2024, with a spatial resolution of 15 meters, from the GloVis website (Figure A.5 & Figure A.6).

Figure A.5. The coverage of the state of North Dakota by 14 frames of Landsat 8 images.

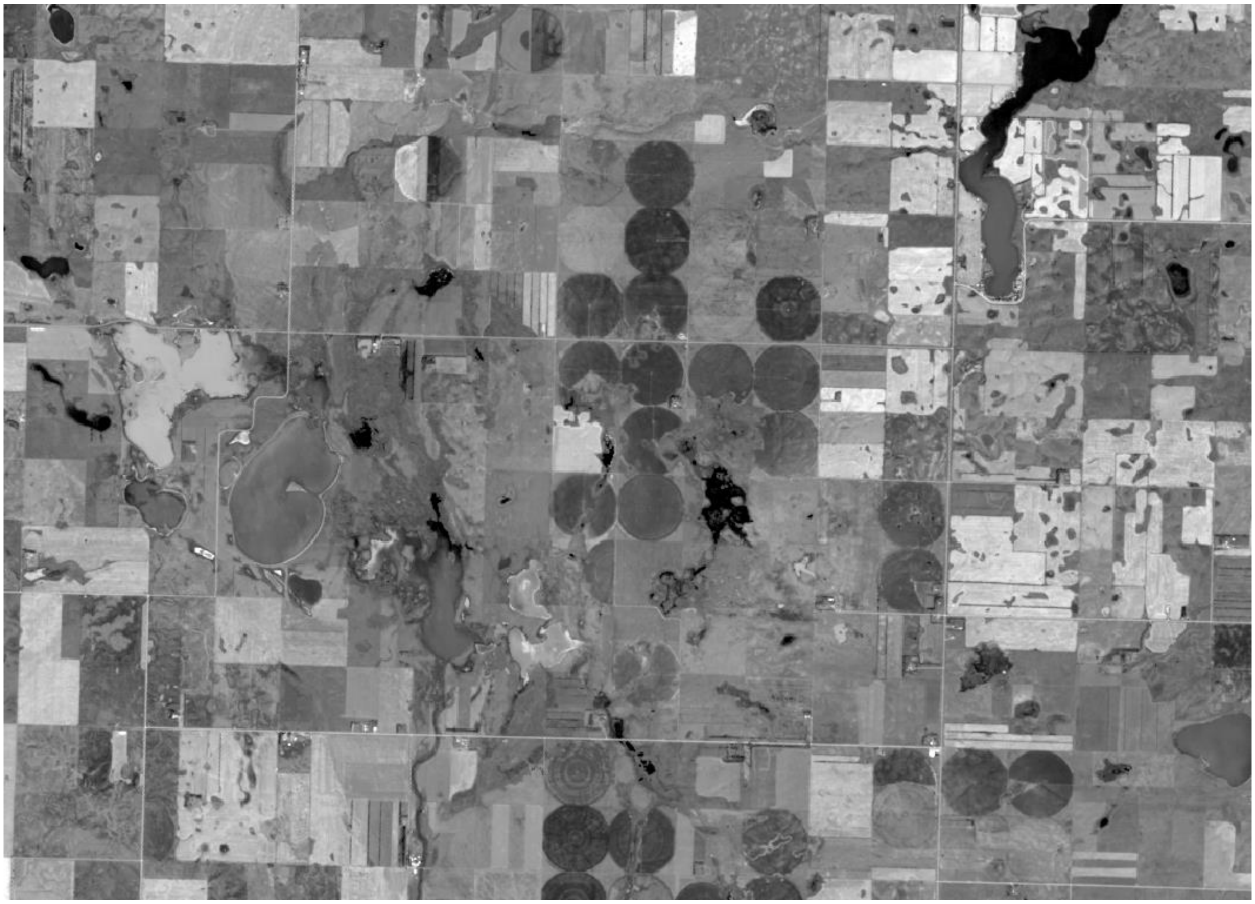

Figure A.6. Signatures of center-pivot, sprinkler irrigation systems on the panchromatic band of Landsat 8 images.

After downloading the 14 frames of Landsat 8, we created an orthomosaic image in ArcGIS Pro (version 3.3.0) and used the Image Analysis package to export a training dataset (85% of the data) and a testing dataset (15% of the data) to train and test the Mask R-CNN object detection model for identifying the center-pivot, sprinkler irrigation systems. The ResNet-152 was used as the backbone model, with a batch size of 4 and 300 epochs. Overall, the trained deep learning model was able to locate the existing center-pivot systems with 75% accuracy from the Landsat 8 imagery (Figure A.7).

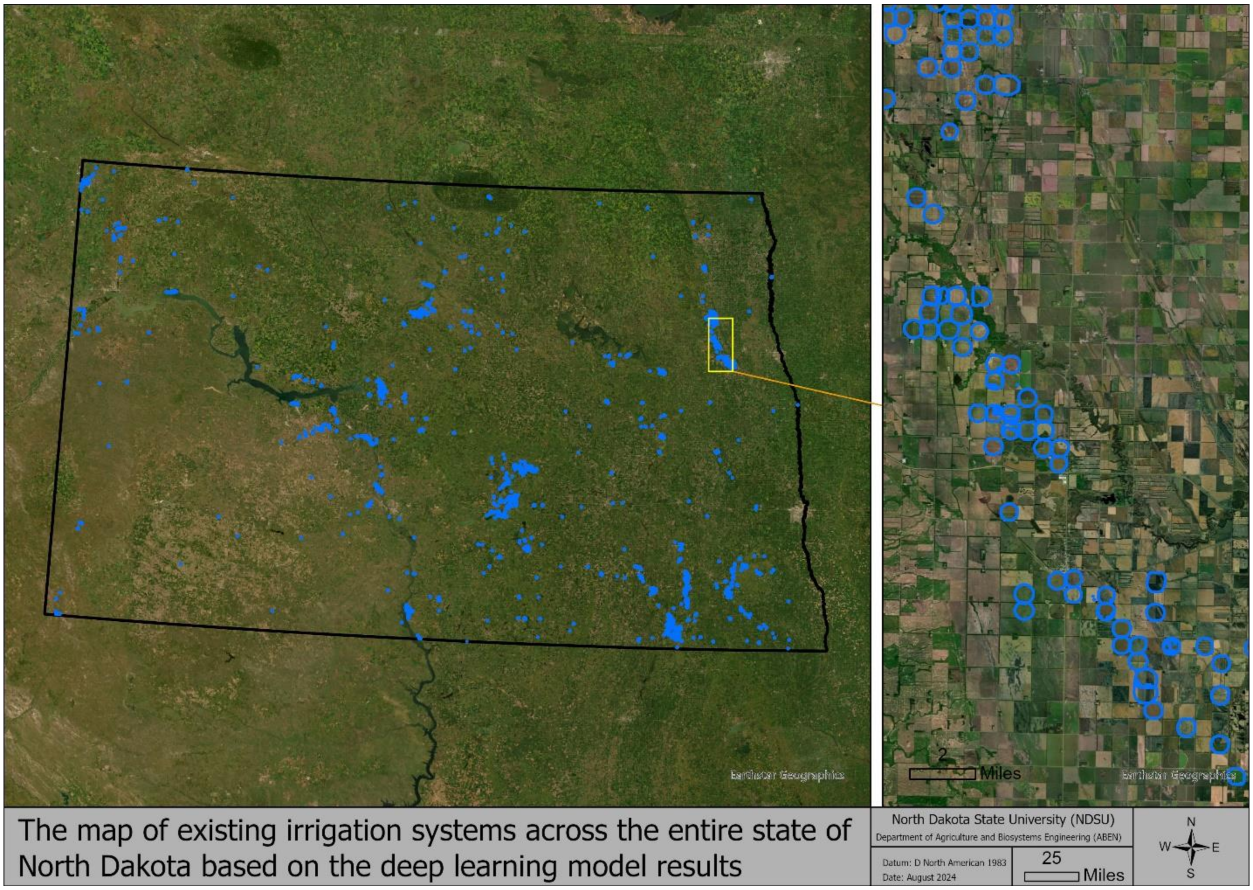

Figure A.7. The map of existing irrigation systems across North Dakota based on the deep learning model results.

To improve the accuracy of the existing layer of irrigation systems identification, we manually inspected the presence of the center-pivot systems based on the Landsat images and Google Images by dividing the state of North Dakota into 499 grids of equal size of 99,841 acres. The inspection was conducted at a zoom level of 1:12,000. By the systematic manual inspection, we corrected the shapes of irrigation systems detected by the deep learning model, identified irrigation systems that the model failed to detect, and removed polygons that were mistakenly identified as irrigation systems by the model. It should be noted that this method can only identify the circular pattern of a parcel of land actively irrigated by a center-pivot sprinkler system. It cannot identify an idle center-pivot sprinkler system or linear sprinkler system or any other type of irrigation system such as flooding and water-spreading surface irrigation systems.

A.3. Relative elevation model (REM)

A REM is a digital elevation model adjusted to show the elevation of land relative to a specific feature, such as a river or water body, rather than sea level. This approach highlights subtle topographic changes, making it especially useful for visualizing landforms, floodplains, and geomorphological features that may otherwise blend into the surrounding terrain. By calculating the elevation difference between each point in the terrain and a nearby baseline (e.g., water surface), REMs reveal detailed structural patterns that are valuable in environmental analysis, hazard assessment, and ecosystem monitoring. Figure A.8 shows the steps taken to calculate the REM in ArcGIS Pro.

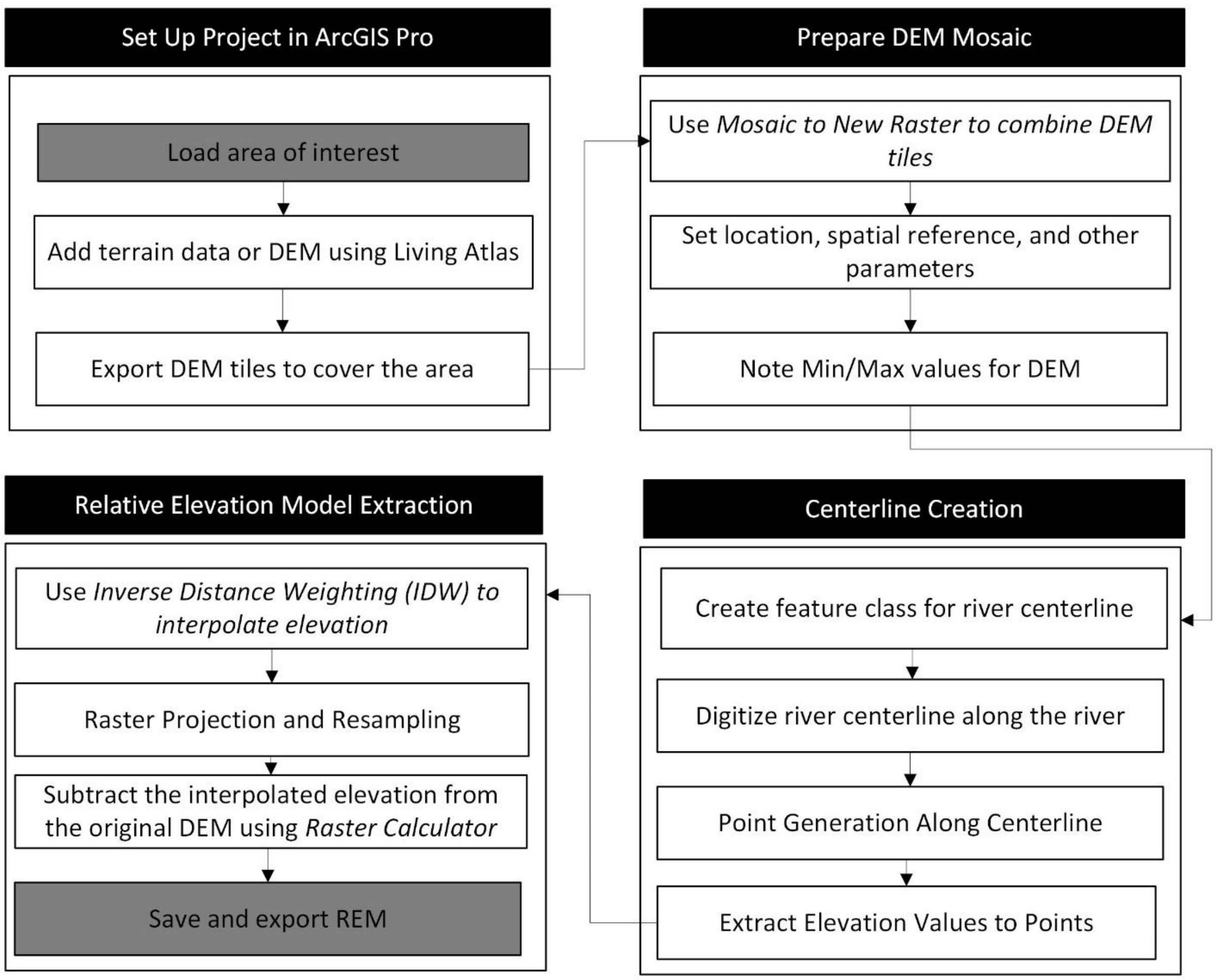

Figure A.8. Flowchart of calculating Relative Elevation Model (REM) in ArcGIS Pro.

To conduct this analysis, a digital elevation model (DEM) with a spatial resolution of 0.24 meters was downloaded from the ND GIS Hub website and used as the base dataset. Figure A.9 shows a graphical overview of the DEM of the Missouri River system vs. a REM.

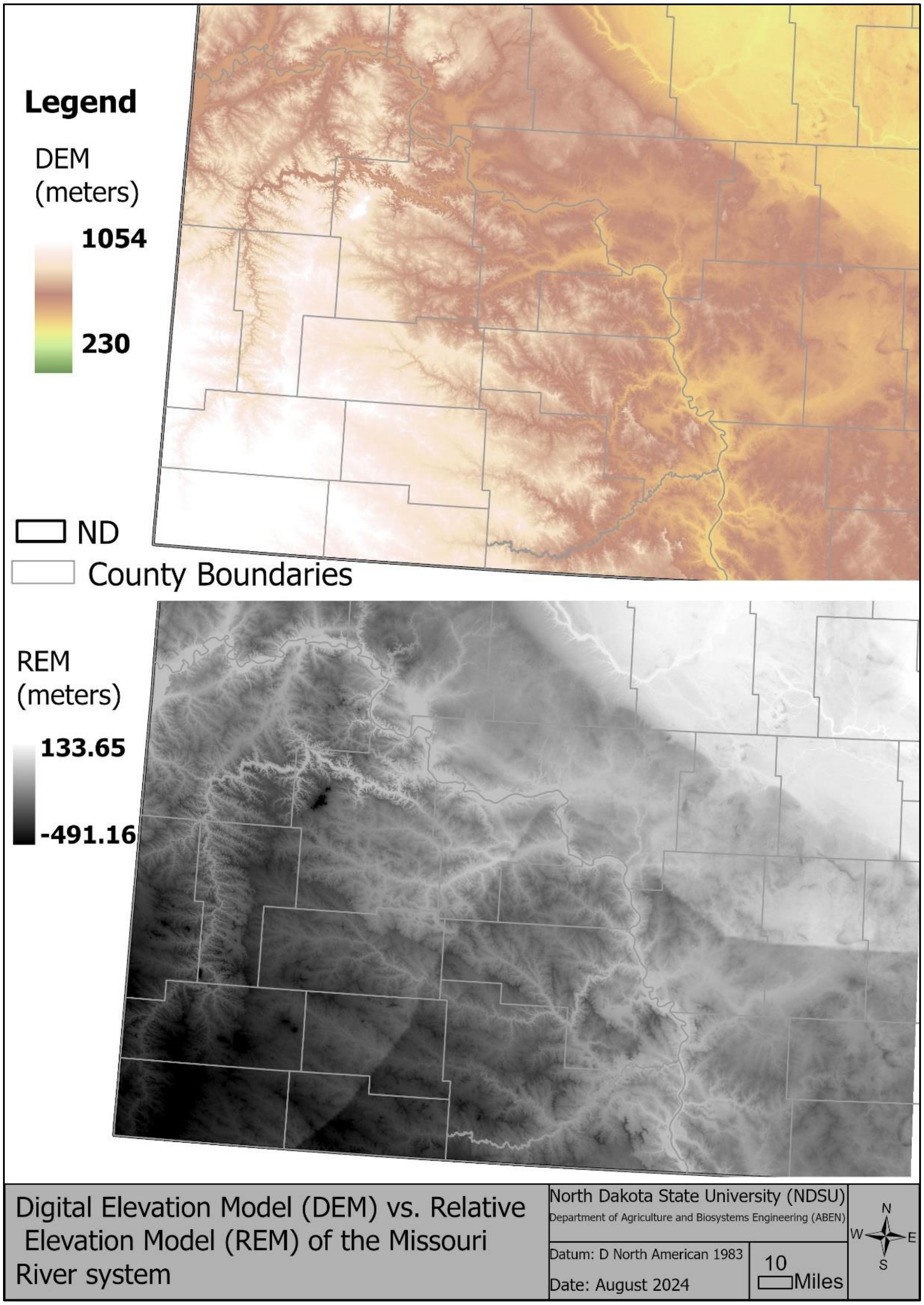

Figure A.9. Digital Elevation Model (DEM) vs. the Relative Elevation Model (REM) of the Missouri River system.

A.4. Calculating total irrigation potential lands

Table A.2 and A.3 show the details of calculating the total irrigation potential lands in North Dakota under two scenarios by removing the overlapped areas in the 17 counties along the Missouri River corridor and the existing irrigated lands in all counties.

Table A.2. Areas of land parcels for potential irrigation development using water from the Missouri River and groundwater aquifers (Scenario 1).

County	Ground-water[a]	Missouri River	Overlap	Combined[b]	Existing Irrigated Lands[c]	Irrigation Potential[d]
	----------thousand acres----------					
Adams	0.			0	0	0
Barnes	10.3			10.3	0.6	9.7
Benson	38.2			38.2	3.1	35.1
Billings	0.			0	0	0
Bottineau	48.8			48.8	0	48.8
Bowman	0			0	0	0
Burke	7.2			7.2	0	7.2
Burleigh	124.8	149	110	163.8	2.1	161.7
Cass	27.4			27.4	1.8	25.6
Cavalier	8.8			8.8	0	8.8
Dickey	25.9			25.9	6.4	19.5
Divide	32.6			32.6	1.6	31
Dunn	52.19	6.5	0.89	57.8	0	57.8
Eddy	23			23	0.7	22.3
Emmons	101.8	216.8	94.9	223.7	5.4	218.3
Foster	13.1			13.1	0.8	12.3
Golden Valley	0			0	0	0
Grand Forks	35.9			35.9	16.3	19.6
Grant	3.6	12.1	3.4	12.3	0.2	12.1
Griggs	18.2			18.2	0	18.2
Hettinger	0			0	0	0
Kidder	114.1	105.1	88.7	130.5	25	105.5
LaMoure	48.9			48.9	5.4	43.5
Logan	26.1	7.5	5.4	28.2	3.2	25
McHenry	83.8			83.8	8.7	75.1
McIntosh	56.68	2	0.08	58.6	0.3	58.3
McKenzie	31.5	26.1	13	44.6	6.1	38.5
McLean	169.7	210.8	128	252.5	12.6	239.9
Mercer	40.7	63	34.2	69.5	3.2	66.3
Morton	42.5	69.1	31.2	80.4	1.8	78.6

Mountrail	47.8	29.2	13.1	63.9	0	63.9
Nelson	16.4			16.4	1.3	15.1
Oliver	25.2	29.9	14.5	40.6	2.6	38
Pembina	14.8			14.8	0.3	14.5
Pierce	31.2			31.2	0.1	31.1
Ramsey	0.3			0.3	0	0.3
Ransom	45.8			45.8	16	29.8
Renville	14.3			14.3	0	14.3
Richland	17.5			17.5	0.6	16.9
Rolette	10.6			10.6	0.6	10
Sargent	75.5			75.5	4.8	70.7
Sheridan	34.6	17.5	16.7	35.4	1.4	34
Sioux	13.8	23.8	12.4	25.2	1.4	23.8
Slope	0			0	0	0
Stark	6.2			6.2	0	6.2
Steele	13.9			13.9	1.6	12.3
Stutsman	34.3	10.7	6.8	38.2	4.3	33.9
Towner	0.2			0.2	0	0.2
Traill	6.2			6.2	0	6.2
Walsh	27.4			27.4	0.9	26.5
Ward	46.7			46.7	0.8	45.9
Wells	64.3			64.3	0	64.3
Williams	69.3	33.3	21.8	80.8	10.4	70.4
	-- **million acres** --					
North Dakota	**1.8**	**1.01**	**0.60**	**2.22**	**0.15**	**2.07**

[a] By subtracting the areas of this column from the “Overlap” column and the areas in the “Existing Irrigated Lands” column the third column in Table 4.3 (Scenario 1) can be calculated.
[b] Calculated by adding the areas in the “Groundwater” and “Missouri River” columns and subtracting the areas in the “Overlap” column.
[c] Identified land areas irrigated using center-pivot sprinkler systems, which is smaller than the actual area of irrigated croplands estimated at ~250 thousand acres.
[d] Calculated by subtracting the “Existing Irrigated Land” column from the “Combined” column.

Table A.3. Areas of land parcels for potential irrigation development using water from the Missouri River and groundwater aquifers (Scenario 2).

County	Ground-water[a]	Missouri River	Overlap	Combined[b]	Existing Irrigated Lands[c]	Irrigation Potential[d]
	-- thousand acres --					
Adams	0			0		0
Barnes	6.4			6.4	0.1	6.3
Benson	29.3			29.3	0.9	28.4

Billings	0			0		0
Bottineau	48.8			48.8		48.8
Bowman	0			0		0
Burke	7.2			7.2		7.2
Burleigh	117.6	149	102.9	163.7	2	161.7
Cass	0.2			0.2		0.2
Cavalier	8.8			8.8		8.8
Dickey	7			7	0.7	6.3
Divide	32.6			32.6	1.6	31
Dunn	52.2	6.5	0.9	57.8		57.8
Eddy	11.9			11.9	0	11.9
Emmons	29.7	216.8	22.5	224	5.7	218.3
Foster	5.3			5.3	0.6	4.7
Golden Valley	0			0		0
Grand Forks	2.9			2.9	0.5	2.4
Grant	3.4	12.1	3.4	12.1		12.1
Griggs	0			0		0
Hettinger	0			0		0
Kidder	112	105.1	86.8	130.3	25	105.3
LaMoure	35.3			35.3	2.8	32.5
Logan	6.2	7.5		13.7		13.7
McHenry	52.6			52.6	2.7	49.9
McIntosh	56.7	2	0.1	58.6	0.3	58.3
McKenzie	31.1	26.1	12.9	44.3	5.8	38.5
McLean	156.9	210.8	115.3	252.4	12.5	239.9
Mercer	40.8	63	34.2	69.6	3.3	66.3
Morton	42.5	69.1	31.2	80.4	1.8	78.6
Mountrail	45.6	29.2	10.9	63.9		63.9
Nelson	0			0		0
Oliver	25.2	29.9	14.5	40.6	2.6	38
Pembina	15.3			15.3	0.8	14.5
Pierce	22.9			22.9	0.1	22.8
Ramsey	0.2			0.2		0.2
Ransom	21.1			21.1	6.2	14.9
Renville	14.3			14.3		14.3
Richland	9.9			9.9	0.1	9.8
Rolette	4.7			4.7	0.1	4.6
Sargent	66.6			66.6	3.5	63.1
Sheridan	34.3	17.5	16.4	35.4	1.4	34
Sioux	13.8	23.8	12.4	25.2	1.4	23.8
Slope	0			0		0
Stark	6.2			6.2		6.2
Steele	0			0		0

Stutsman	34.4	10.7	6.8	38.3	4.4	33.9
Towner	0.2			0.2		0.2
Traill	0			0		0
Walsh	12			12	0.2	11.8
Ward	46.6			46.6	0.7	45.9
Wells	42.6			42.6		42.6
Williams	68.8	33.3	21.8	80.3	9.9	70.4
	---million acres ---					
North Dakota	**1.38**	**1.01**	**0.49**	**1.90**	**0.10**	**1.80**

[a] By subtracting the areas of this column from the "Overlap" column and the areas in the "Existing Irrigated Lands" column, the sixth column in Table 4.3 (Scenario 2) can be calculated.
[b] Calculated by adding the areas in the "Groundwater" and "Missouri River" columns and subtracting the areas in the "Overlap" column.
[c] Identified land areas irrigated using center-pivot sprinkler systems, which is smaller than the actual area of irrigated croplands estimated at ~250 thousand acres.
[d] Calculated by subtracting the "Existing Irrigated Land" column from the "Combined" column.