Circular 179

Midwestern Climate Center Soils Atlas and Database

by Steven E. Hollinger

Illinois State Water Survey
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ADDENDUM

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CONTENTS

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ABSTRACT

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INTRODUCTION

The Midwestern Climate Center (MCC) uses soils data for the Midwest region to simulate soil moisture (Kunkel, 1990) and corn and soybean yields (Kunkel and Hollinger, 1991). The results of these simulations are made available to Midwestern Climate Information System (MICIS) subscribers. The original soils database was developed using a limited number of important agricultural soils in each of the MCC region's crop reporting districts (CRDs). An average set of soil properties was developed from these soils to reflect the soil of each CRD. Because the soils used represented a small portion of a CRD's total area, the soil model results only provide a general indication of the actual soil conditions.

Recently, the State Soil Geographic (STATSGO) database (Soil Conservation Service, 1993) for the 12 states of the North Central region (Illinois, Indiana, Iowa, Kansas, Michigan, Minnesota, Missouri, Nebraska, North Dakota, Ohio, South Dakota, and Wisconsin) and Kentucky became available from the U.S. Department of Agriculture-Soil Conservation Service (USDA-SCS). The STATSGO database includes geographically referenced soil map units that contain up to 21 different soil components in each map unit. A STATSGO map unit is an aggregation of related, more detailed soil descriptions that reflect the major toposequences and natural vegetation of a state. Map units vary in size and shape, and the total number in each county and state depends upon the size and complexity of the topography and natural vegetation. Map units were summarized on a county basis and then an average set of soil properties was developed for each of the 1,172 counties in the 13-state region.

This report explains 1) the application of the STATSGO database to soil moisture modeling and mapping, 2) the procedure used to develop the average set of soil properties for each county, and 3) the spatial distribution/patterns as maps of different soil characteristics across the 13-state region on a county by county basis.

METHODS AND PROCEDURES

Soil component and layer data for each map unit in the 13 states were obtained from the STATSGO database and loaded into a PARADOX® database in order to retrieve the variables necessary to run the soil moisture and crop models (table 1). The variables listed in this table were retrieved for the soil components in all map units in each state. Variables listed in the bottom half of table 1 were collected for each soil layer described in the STATSGO database and then subdivided into nine soil layers. The top soil layer was 10 centimeters (cm) thick, the second soil layer was 15 cm thick, and the remaining seven soil layers were each 25 cm thick.

The soil moisture and crop yield models require soil water characteristics and ancillary soil information to define the maximum possible root depth. A description follows of the specific STATSGO soil variables required, along with a description of how they were obtained from the STATSGO database, and how they were used with the soil texture vs. water-holding capacity functions to describe soil water characteristics (Ritchie et al., 1987).

Table 1. Soil Characteristics in County Soils Database

Soil Variable	*Description*
State identification code	Federal Information Processing Standard (FIPS) code for state
Map unit identification number	5 character map unit identification
Sequence number	Number of components in map unit
S5id	Soil pedon identification
Component name	Common name of soil component
Component, percent	Soil component in STATSGO map unit
Type of drainage	Drainage description of the soil component
Nonirrigated agricultural use capability	Suitability of land for nonirrigated agricultural use class
Irrigated agricultural use capability	Suitability of land for irrigated agricultural use class
Prime farmland classification	Class describing component as either prime or nonprime farmland
Slope, percent	Percent slope of soil surface
Water table depth, cm	Minimum season depth of water table below the soil surface
Bedrock depth, cm	Distance from surface to bedrock
Root depth, cm	Distance from surface to a root growth restricting layer
Layer top	Depth to top of each soil layer (nine soil layers)
Layer bottom	Depth to bottom of each soil layer (nine soil layers)
Rock fragments > 10 inches, percent	Rock (> 10 inches) content of soil layer
Rock fragments > 3 - 10 inches, percent	Rock (> 3 inches but < 10 inches) content of soil layer
Sand, percent	Sand content of soil layer
Silt, percent	Silt content of soil layer
Clay, percent	Clay content of soil layer
Liquid limit, percent of saturation	Water content at which soil becomes semifluid
Plastic limit, percent of saturation	Water content at which soil begins to crumble
Available water capacity, in. of water/in. of soil	Water available to plant roots per inch of soil
Bulk density, Mg/m^3	Mass of soil, air, and water per unit volume
Organic matter, percent	Organic matter content of soil layer
Permeability, mm/hr	Rate at which water passes through the soil layer

Note: Soil variables apply to entire soil profile (top half of table) and to individual soil layers in soil profile (bottom half of table).

Soil Water Characteristics

Soil water characteristics were computed for each soil layer from the STATSGO database. The computed water-holding characteristics were the upper and lower limits of water availability and the air entry water potential, defined as the water potential at which the largest water-filled pores just drain (Campbell, 1985).

The volumetric lower limit of water availability was computed using the method described by Ritchie et al. (1987). For soils with sand content greater than 75 percent, the lower limit of available water (0_1, in percent) was

$$\theta_l = 18.8 - 0.168\ Sn \quad \textbf{(1)}$$

where Sn is the percent of sand in the soil layer. If the silt content of the soil layer was less than 70 percent and the sand content was less than 75 percent, then θ_l was

$$\theta_l = 3.62 + 0.44\ Cl \quad \textbf{(2)}$$

where Cl is the percent of clay in the soil layer. For soils with a silt content greater than or equal to 70 percent,

$$\theta_l = 5.0 + 0.0244\ Cl^2 \quad \textbf{(3)}$$

The volumetric upper limit of water availability (θ_u) was computed as

$$\theta_u = \theta_l + \theta_a \quad \textbf{(4)}$$

where θ_a is the volumetric plant-available water from the soil layer database. If θ_a was zero or was not available from the soil layer database, θ_a was computed from the sand and silt (Sil) content of the soil (Ritchie et al., 1987). If the sand content of the layer was greater than or equal to 75 percent, θ_a was computed as

$$\theta_a = 42.3 - 0.381\ Sn \quad \textbf{(5)}$$

otherwise

$$\theta_a = 10.79 + 0.05004\ Sil \quad \textbf{(6)}$$

The upper and lower plant-available water limits were further adjusted for soil organic matter content and rock fragments greater than 2 millimeters (mm). When organic matter was less than 8 percent, the limit for upper available water content was adjusted by

$$\theta_u = \theta_u + 0.23\ O_m \quad \textbf{(7)}$$

where O_m is the percent of organic matter in the soil layer. The lower limit of plant-available water was adjusted by

$$\theta_l = \theta_u - \theta_a \quad (8)$$

Where O_m exceeds 8 percent, no equations exist to adjust the upper limit of plant-available water. When rock fragments greater than 2 mm were found in the soil layer, the upper limit of plant-available water was adjusted by

$$\theta_u = \frac{\theta_u \, S_v}{100} \quad (9)$$

and the lower limit of plant-available water was adjusted by

$$\theta_l = \frac{\theta_l \, S_v}{100} \quad (10)$$

where S_v is the percent of soil volume occupied by rocks greater than 2 mm. S_v was computed by

$$S_v = 100 - \left(\frac{\dfrac{1}{1 + 2.65[100 - S_4]}}{100 \, S_4 \, \rho_b} \right) \quad (11)$$

where S_4 is the percent by weight of rock fragments greater than 2 mm in size and p_b is the moist soil bulk density in Megagrams per cubic meter (Mg/m^3). When the upper and lower plant-available water limits were adjusted because of rock fragment content in the soil, the available water content was also adjusted by

$$\theta_a = \theta_u - \theta_l \quad (12)$$

The air entry water potential was computed using equations presented by Campbell (1985). The air entry water potential adjusted for the effects of bulk density (Ψ_e) is given by

$$\psi_e = \psi_{es} \left(\frac{\rho_b}{1.3} \right)^{0.67b} \quad (13)$$

where Ψ_{es} is the air entry water potential for a soil with a bulk density of 1.3 Mg/m^3 and b is the slope of the natural logarithm of the water potential versus the natural logarithm of the volumetric water content curve. Ψ_{es} is given by

$$\psi_{es} = -0.5 \, d_g^{-0.5} \quad (14)$$

where d_g is the geometric particle diameter in mm, which is computed from sand, silt, and clay content by

$$d_g = \exp\,[\sum m_i \ln d_i] \tag{15}$$

where m_i is the mass fraction of the sand, silt, or clay, and d_i is the arithmetic mean diameter of sand (1.025 mm), silt (0.026 mm), and clay (0.001 mm) particles. The slope of the water potential versus the volumetric water content is given by

$$b = -2\ \psi_{es} + 0.2\ \sigma_g \tag{16}$$

where o_g is the geometric standard deviation of the particle diameter given by

$$\sigma_g = \exp\,[\sum m_i (\ln d_i)^2 - (\sum m_i \ln d_i)^2]^{0.5} \tag{17}$$

Finally, the volumetric water content of the soil liquid (L_v) and plastic (P_v) limits were converted from mass water content by

$$L_v = L_l\ \rho_b \tag{18}$$

and

$$P_v = P_l\ \rho_b \tag{19}$$

and where L_l is the soil liquid limit, and P_l is the soil plastic limit both obtained from the STATSGO database.

Maximum Root Depth

The maximum root depth of each soil was limited either by the depth to bedrock or to a root restricting soil layer with a bulk density greater than 1.6 Mg/m^3. It is assumed that the roots of most crops cannot penetrate soil layers with bulk densities greater than 1.6 Mg/m^3. Exceptions to this assumption occur if the layer is fractured or penetrated by soil fauna, such as earthworms. The number of roots in such layers is severely restricted, however.

Average County Soil Properties

A set of average soil properties was defined for each county in the North Central region of the United States. The set of soil properties was computed as an average of each of the soil components, weighted by the percent of the county represented by each soil type. Soil types in each county were determined using the STATSGO database (SCS, 1993) and the Geographic Resources Analysis Support System (GRASS) software to geographically reference the map units containing up to 21 different soil components (soil phases). Using the GRASS routine **r.report,** the acreage occupied by each map unit in each county was determined as well as the percent of the total county area occupied by the map unit. The percent of area occupied by each soil type in a county was then determined by multiplying the percent of the soil type in the map unit by the percent of county acreage represented by the map unit.

Only arable soil components from the STATSGO database were used in computing the weighted average. Arable soils were defined as those classified as prime or potentially prime farmland soils with nonirrigated or irrigated agricultural capability classes 1-4—which include drained, flood-protected, irrigated, and drained/flood-protected lands—and those components representing more than 0.01 percent of the county area were included in the computation of the weighted average. Agricultural capability classes 5-8 represent soils with severe limitations that make tillage impractical or impossible. These soils are generally restricted to use for grazing purposes. Not including agricultural capability classes 5-8 and non-prime farmland eliminates many of the more steeply sloping soils, rockier soils, and very shallow soils. Therefore, the resultant average soil properties may be significantly different than would be expected if the total landscape were included in the analysis. Further, agronomic agriculture may be practiced on soils that are not included in the average soil properties; however, soils excluded represent marginal soils that do not significantly contribute to the overall agricultural production of a county or state.

The percent of each soil component in a county was calculated with the assumption that all soil components in a state map unit are distributed with the same proportion in each county as defined in the map unit. This assumption plus the limitation of including only soil components that comprise more than 0.01 percent of a county's area results in minor soil components of a map unit being included in only those counties where the parent map unit comprises a major portion of the county. Consequently, only the more predominant soils in each map unit are included in the computation of the average soil properties for a county.

The STATSGO database is designed for use in regional and state planning purposes rather than county planning for which the soil resolution is too coarse to be accurate. Therefore, the average soil properties of a county are, at best, an approximation of the actual soils. Although not totally accurate, such an approximation provides a better overall picture of the soils of a county than anything available at this time. When these average soil properties are used in soil moisture and crop yield models, the results contain uncertainties. However, for the purposes of the Midwestern Climate Center, to provide spatial and temporal estimates of regional soil moisture and crop yields, the average soil properties derived from the STATSGO database provide a better estimate and spatial representation than an average set of characteristics summarized from CRDs. County by county representation of moisture storage levels also offer a format more easily used by the agricultural community.

RESULTS

Average soil properties were defined for 1,172 of the 1,175 counties in the 13 states that comprise the North Central region. The three counties without a set of average soil characteristics are located in Kentucky and South Dakota. Martin County is in the highly dissected Appalachian region of Kentucky, which lacks significant acreage of prime farmland. Jones County is in the Badlands region of South Dakota, and Lawrence County is in the Black Hills region of South Dakota. The exclusion of these counties as "agricultural" does not imply that agronomic agriculture is not being practiced in these counties, but rather implies that soils where agronomic agriculture is normally practiced comprise a very small percentage of the total county area.

Using this concept of an average set of soil properties, generalized maps[1] of soil characteristics were developed for the Midwest region. It is important to remember that the weighted average reflects only those soils that represent prime farmland, or the soils that have no severe restrictions for tillage purposes. Because only a percentage of the total land area in each county is used in the mean soil characteristics calculation (figure 1), the average soil properties in a given county may not reflect the actual diversity of soils in a particular county or among counties in a state. For example, the average surface slope calculated using the procedure with the prime farmland filter, described above, shows less surface slope variation than the average surface slope for all soils (prime and nonprime) in a county (figure 2).

Slope

The average surface slope of prime farmland soils in each county is shown in figure 2. The state mean slopes of prime farmland are 2.2 percent across the region (table 2) with a state minimum of 1.6 percent (South Dakota) and a state maximum of 2.8 percent (Wisconsin). The least variation in slope occurs in Illinois and Iowa, and the largest variation occurs in South Dakota. State statistics in this table and all tables that follow are based on the typical county values.

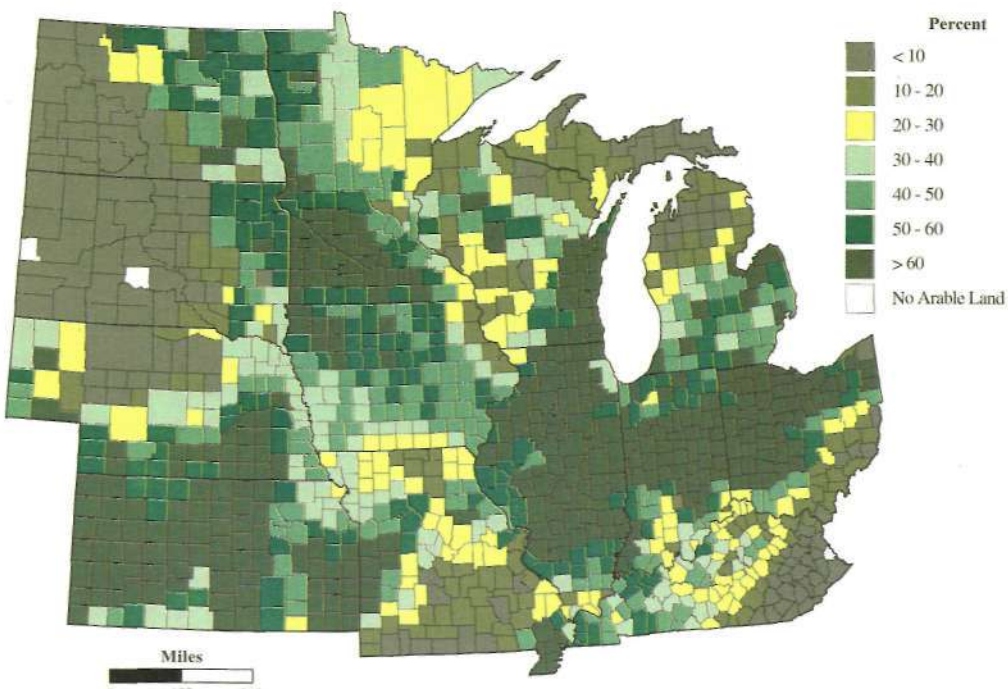

Figure 1. Percent of total county area that is comprised of arable land in the North Central region of the United States

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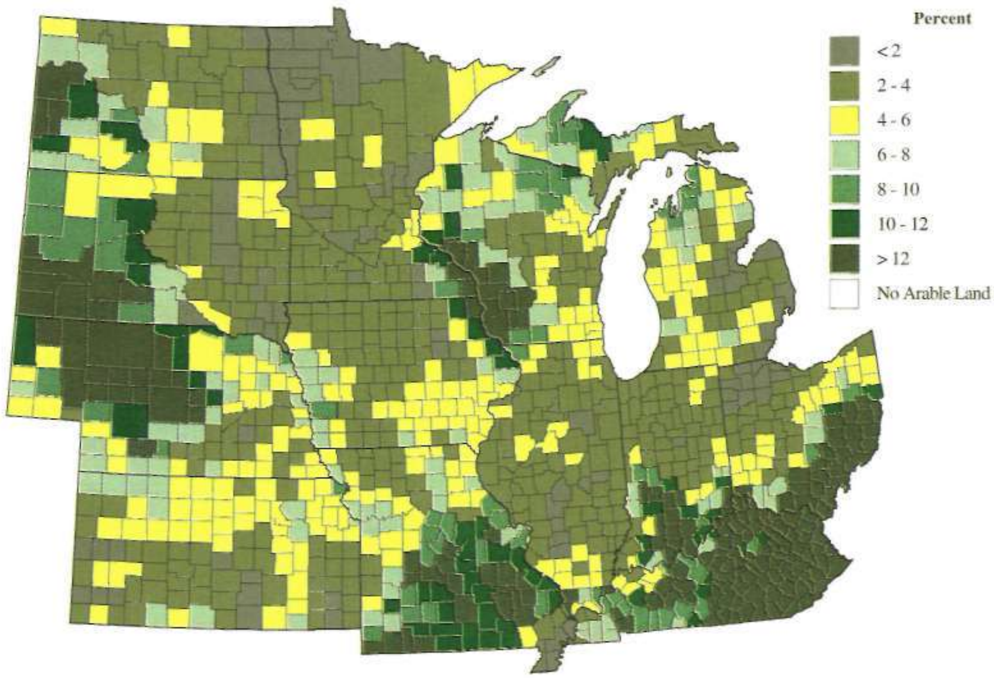
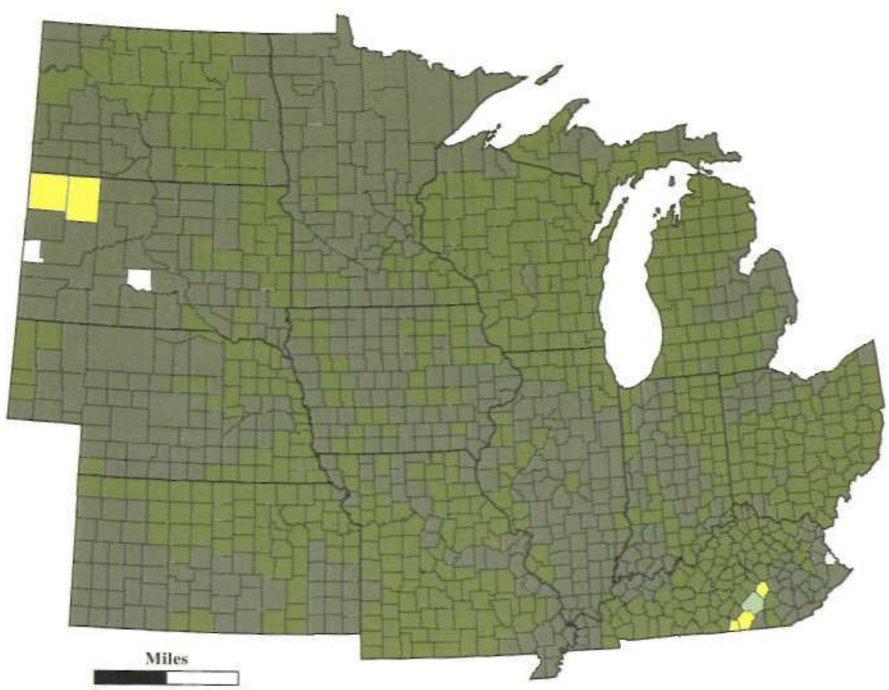
[1]Maps are Albers Equal Area Projections and were created using ATLAS-GIS software on a 486 PC.



a. Total county land



b. Arable land

Figure 2. Weighted average surface slope (in percent) of a) the total county land area and b) the arable land area in each county in the North Central region of the United States

Table 2. Slope of Prime Farmlands across the 13-State Region

State	Weighted Average (percent)	Standard Deviation (percent)	Range (percent)	
			Maximum	Minimum
Illinois	1.9	0.3	1.2	3.3
Indiana	2.2	0.5	1.2	3.4
Iowa	1.9	0.3	1.3	2.6
Kansas	2.0	0.6	0.7	4.0
Kentucky	2.6	0.9	1.0	6.2
Michigan	2.5	0.8	0.9	3.9
Minnesota	1.7	0.6	1.5	3.6
Missouri	2.2	0.5	0.6	3.0
Nebraska	1.9	0.7	0.2	3.5
North Dakota	2.0	0.8	0.5	3.3
Ohio	2.5	0.7	0.7	4.0
South Dakota	1.6	1.1	0.0	5.9
Wisconsin	2.8	0.5	0.7	3.6
Region	2.2	0.7	0.0	6.2

Slope differences affect the rate of runoff from melting snow and rainfall. For example, steeper landscape slopes result in less potential infiltration of water into the soil surface and greater potential for surface soil erosion due to water.

Drainage Class

Soil drainage classes describe the occurrence of seasonal high water tables. Crops grown on excessively drained soils require more frequent rains or irrigation than crops grown on more poorly drained soils. Because poorly drained soils often result in extended periods of soil saturation, crops grown on these soils must be able to tolerate wet root conditions. The natural drainage classification of prime farmland or land that can be classified as prime farmland if adequately drained by field tiles is shown in figure 3.

The majority of the prime farmland soils in the region were moderately well drained to somewhat poorly drained (table 3). Soils in Kansas, Kentucky, Nebraska, North Dakota, and South Dakota are well drained to moderately well drained.

Water-Table Depth

The depth to the water table refers to the closest distance between the water table and the soil surface during the year. Throughout most of Illinois, Indiana, Minnesota, Missouri, and Ohio, under arable land this distance is less than 100 cm (table 4). The mean depth to the water table in the rest of the North Central region is generally greater than 100 cm. There are counties in every state where the average depth to the seasonal water table is < 100 cm at some time during the year and counties where the water table is rarely within 100 cm of the surface (Figure 4). The majority of counties in Kansas, Nebraska, North Dakota, and South Dakota have water tables deeper than 150 cm from the soil surface.

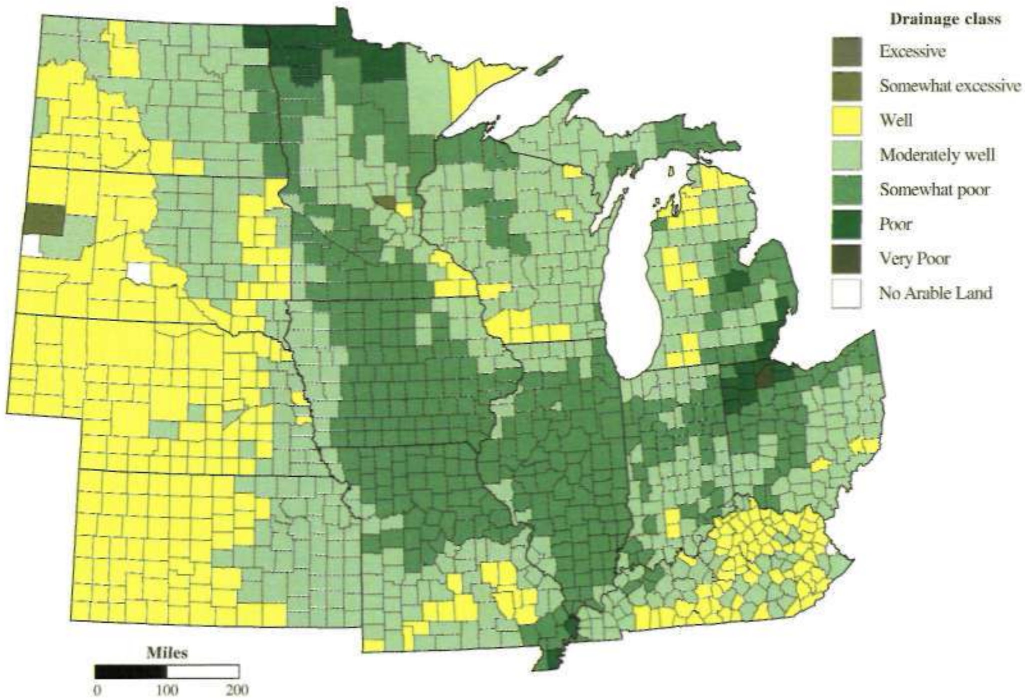


Figure 3. Weighted average of drainage classification of prime farmland or farmland without severe restrictions for tillage purposes

Table 3. Drainage Classes of Prime Farmland across the 13-State Region

State	Weighted Average	Range	
		Minimum	Maximum
Illinois	4.8	4	5
Indiana	4.4	3	5
Iowa	4.7	4	5
Kansas	3.4	3	4
Kentucky	3.5	3	5
Michigan	4.2	3	6
Minnesota	4.5	5	6
Missouri	4.4	3	6
Nebraska	3.2	3	4
North Dakota	3.8	3	6
Ohio	4.6	3	7
South Dakota	3.4	2	4
Wisconsin	4.0	3	5
Region	4.1	2	7

Note: 1 = excessively drained. 2 = somewhat excessively drained, 3 = well drained, 4 = moderately well drained. 5 = somewhat poorly drained. 6 = poorly drained, 7 = very poorly drained.

Table 4. Depth to Water Table across the 13-State Region

State	Weighted Average (cm)	Standard Deviation (cm)	Range (cm)	
			Minimum	Maximum
Illinois	83	22	43	142
Indiana	90	22	30	139
Iowa	103	20	60	152
Kansas	146	40	67	189
Kentucky	125	29	56	180
Michigan	101	41	21	178
Minnesota	88	32	67	175
Missouri	91	29	40	159
Nebraska	150	32	62	183
North Dakota	150	32	64	183
Ohio	74	29	13	125
South Dakota	152	29	31	189
Wisconsin	120	29	46	172
Region	111	40	13	189

Note: Soils data from soil survey records normally record soil properties only to a depth of 152 cm, but the actual depth to the water table may be significantly greater.

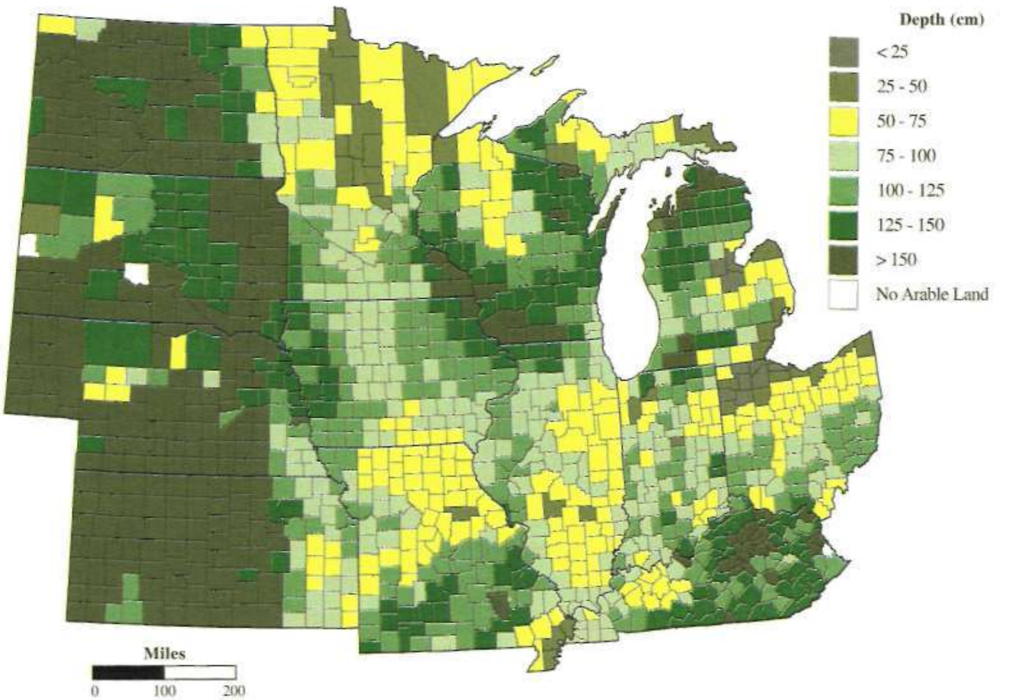


Figure 4. Weighted average of the minimum depth to the water table during the year

Depth to Bedrock

The average depth to bedrock under prime farmland soils across the region exceeds 141 cm (table 5). Soil surveys normally record soil properties only to a maximum depth of 152 cm; the actual depth to bedrock is often significantly greater than this maximum depth, however. Across most of the loess belt in Illinois, Indiana, and Ohio, the depth to bedrock exceeds 150 cm (figure 5). The shallowest agricultural soils primarily occur in Minnesota on fluted bedrock surfaces and mine spoils, in Nebraska along the Pine Ridge Escarpment and Tablelands, and in South Dakota on residual Pierre Shale. The impact of low available water-holding capacity in shallow soils with limited rooting depth is often exaggerated by higher rock fragment contents. Consequently, yields on these soils are often less than average unless the crop is irrigated.

Maximum Root Depth

The maximum root depth was determined in two ways: the depth to bedrock or the depth to a soil layer with a moist bulk density greater than 1.6 Mg/m^3. Maximum rooting depths (table 6) of arable soils varied across the region from a low of 15 cm (South Dakota and Wisconsin) to greater than 150 cm (9 of the 13 states), with a mean of 124 cm. The maximum depth reported in the STATSGO database is 152 cm although rooting depths may actually be even deeper. Only Michigan and Wisconsin have average rooting depths less than 100 cm. North Dakota has the most counties with rooting depths greater than 150 cm (figure 6).

Table 5. Depth to Bedrock across the 13-state Region

State	*Weighted Average (cm)*	*Standard Deviation (cm)*	*Range (cm)*	
			Minimum	*Maximum*
Illinois	152	1	142	152
Indiana	149	7	101	152
Iowa	145	8	114	152
Kansas	144	11	90	152
Kentucky	144	8	121	152
Michigan	144	18	62	152
Minnesota	124	27	117	152
Missouri	147	7	125	152
Nebraska	134	27	36	152
North Dakota	147	15	78	152
Ohio	149	5	125	152
South Dakota	122	51	15	152
Wisconsin	140	14	97	152
Region	142	20	15	152

Note: Soils data from soil survey records normally record soil properties only to a depth of 152 cm, but the actual depth to bedrock may be significantly greater.

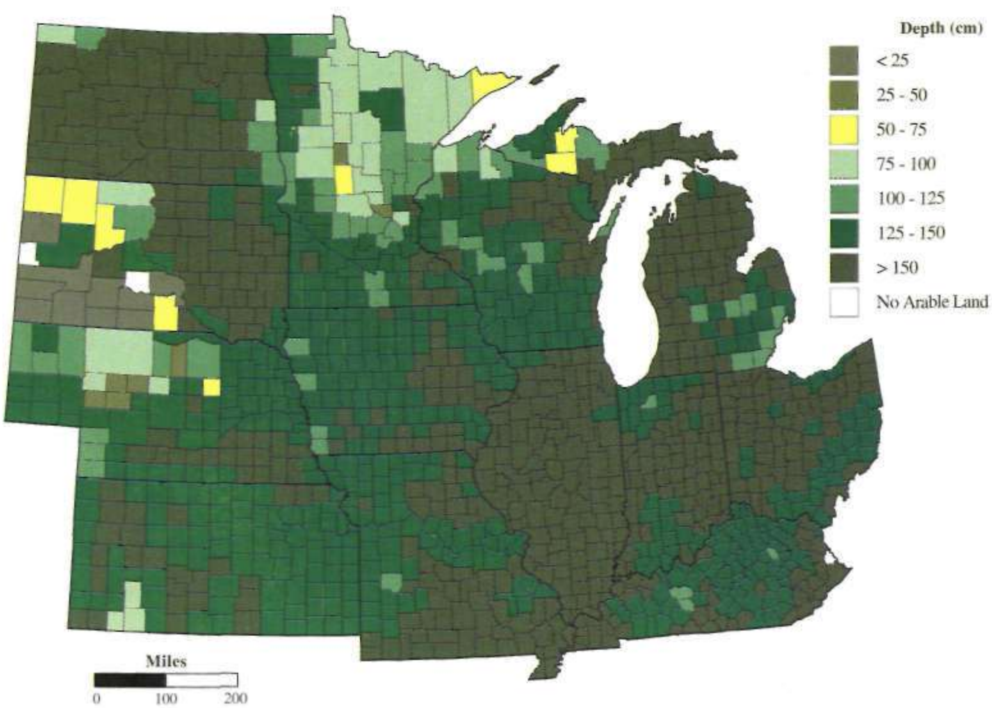


Figure 5. Weighted average of depth to bedrock

Table 6. Root Depth across the 13-State Region

State	*Weighted Average (cm)*	*Standard Deviation (cm)*	*Range (cm)*	
			Minimum	*Maximum*
Illinois	139	11	109	152
Indiana	121	21	66	147
Iowa	126	21	80	152
Kansas	142	12	90	152
Kentucky	137	10	112	152
Michigan	99	19	43	148
Minnesota	103	26	97	141
Missouri	141	8	120	152
Nebraska	127	31	28	152
North Dakota	144	15	78	152
Ohio	118	20	82	152
South Dakota	112	46	15	152
Wisconsin	99	17	15	140
Region	124	26	15	152

Note: Soils data from soil survey records normally record soil properties only to a depth of 152 cm, but the actual maximum root depth may be significantly greater.

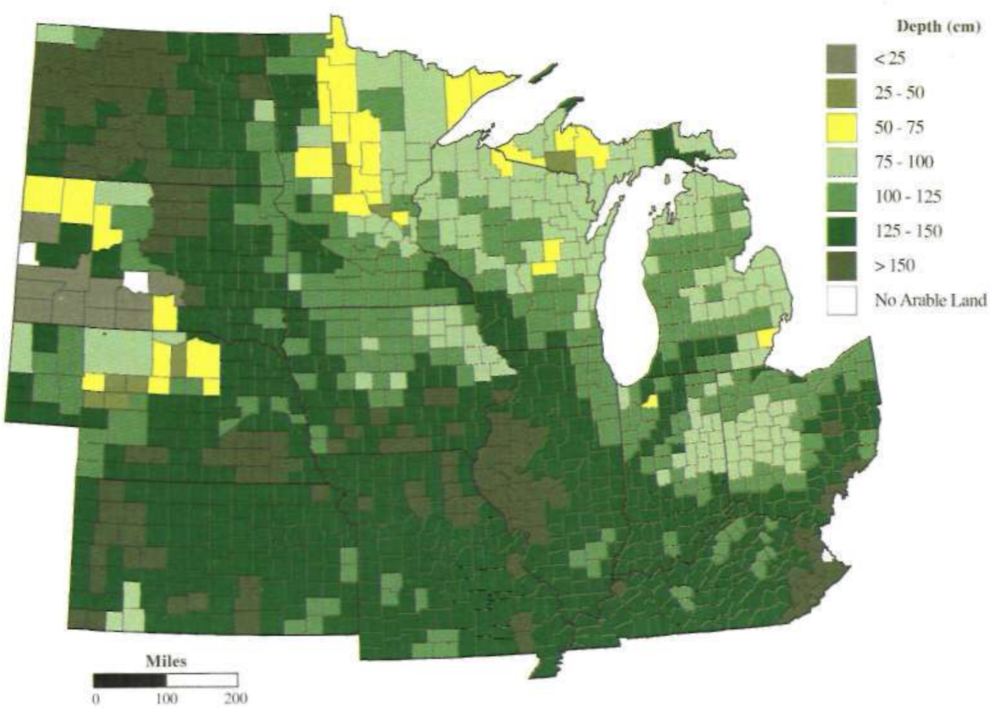


Figure 6. Weighted average of the maximum root depth

Rock Fragments

Soils containing significant amounts of rock fragments have an impact on agricultural tillage, planting, and harvesting. Therefore, most prime farmland will have few rock fragments greater than 2 mm in size in the surface layer. Generally, across the region rock fragments comprise less than 3 percent of the surface soil by weight (table 7). The rockiest soils are located in northern Minnesota, Michigan, and Wisconsin, in southwestern South Dakota (Black Hills Region), in southern Missouri (the Ozarks), and eastern Ohio and Kentucky (figure 7).

Soil Texture

Silt is the major component of prime farmland soils throughout the region (figure 8), but exceptions are found in the Sandhills of Nebraska and South Dakota, and in Minnesota, Wisconsin, Michigan, northwestern Indiana, and south-central Kansas. Although sandy soils occur throughout the region, they do not comprise a significant portion of the land area in the counties and subsequently are not represented on the maps. The heaviest clay soils are found primarily in eastern Kansas, Missouri, central Kentucky, and northwestern Ohio. The percent of sand, silt, and clay comprising the soil at the different soil profile depths is shown in tables 8 (sand), 9 (silt), and 10 (clay). The average sand content in various soil layers across the region ranges from 18 to 20 percent, the average silt content from 47 to 57 percent, and the clay content from 21 to 26 percent. Therefore, the average texture class for the agricultural soils across the region is a silt loam.

Table 7. Rock Fragment Content of Surface Layer across the 13-State Region

State	*Weighted Average (percent)*	*Standard Deviation (percent)*	*Range (percent)*	
			Minimum	*Maximum*
Illinois	1	1	0	3
Indiana	3	2	0	10
Iowa	1	1	0	3
Kansas	1	1	0	4
Kentucky	4	3	0	18
Michigan	8	3	1	28
Minnesota	7	8	3	47
Missouri	2	3	0	10
Nebraska	1	1	0	7
North Dakota	3	2	0	7
Ohio	5	3	0	17
South Dakota	3	3	0	13
Wisconsin	6	6	0	44
Region	3	4	0	47

Note: Rock fragments were greater than 22 mm in size.

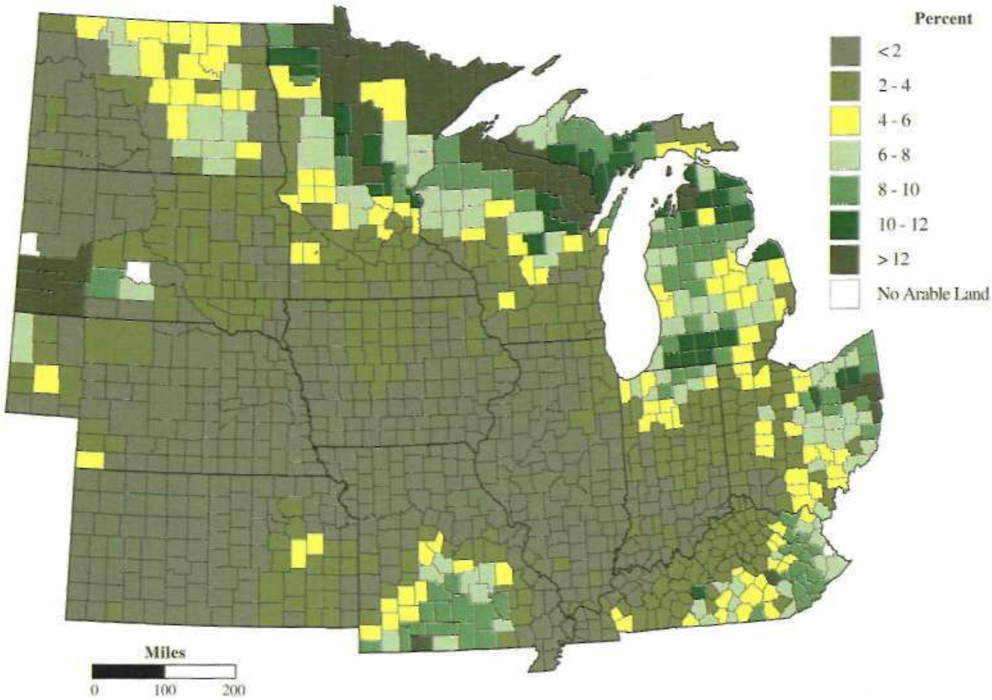


Figure 7. Weighted average of rock fragment content (> 2 mm) in the surface (0- to 25-cm) soil layer

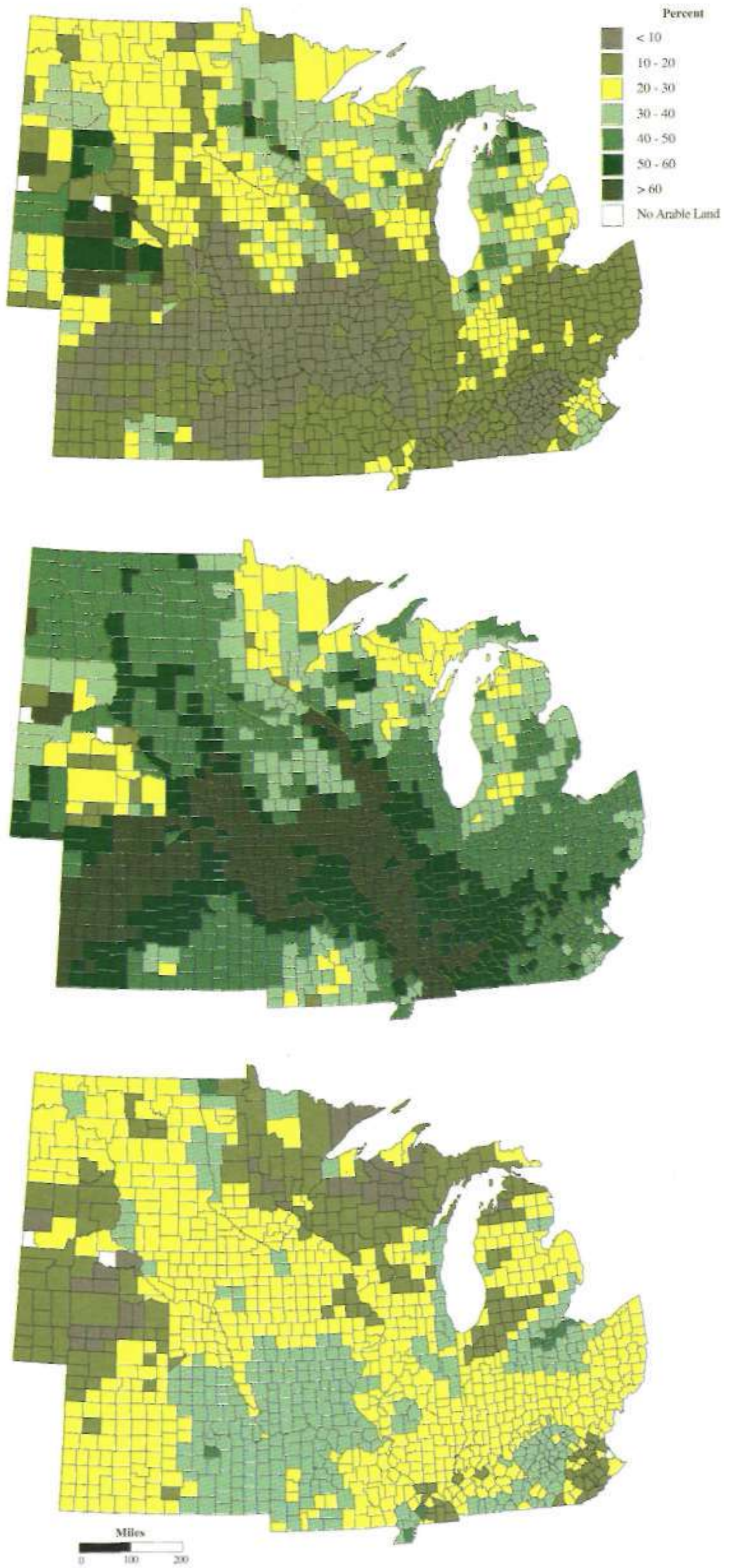
Plastic Index

Sowers (1965) defines the liquid limit (upper plastic limit) as the water content at which soil becomes semifluid, like softened butter. The lower plastic limit is the water content at which soil begins to crumble on being rolled into a thread 3 mm in diameter. The numerical difference between the liquid limit and plastic limit is the plastic index, which is related to the soil clay content and the clay mineralogy. The ease with which soil is compacted is related to the amount of water in the soil, and is greatest, for a given compaction effort, at a water content of 80 percent of saturation (Hillel, 1980). The ease of compaction decreases as the soil dries. For agricultural purposes, minimum compaction should occur if tillage occurs when water contents of the soil are near or below the plastic limit.

The mean liquid limit for the region is 4.2 cm of water in the top 10-cm soil layer (table 11). The mean plastic limit is 1.5 cm of water in the top 10-cm soil layer (table 12). The variation of the liquid limit, the plastic limit, and the plastic index across the region is shown in figure 9. The largest plastic indexes are found in northwestern Iowa, southwestern Minnesota, and northeastern Ohio.

Organic Matter Content

Organic matter content in soils provides essential nutrients to crops and helps determine soil structure. Soils low in organic matter and low in clay often display poor structure and are prone to severe compaction. In the top 10 cm of the region's soils, the mean organic matter content is 3.2 percent and ranges



a. Sand

b. Silt

c. Clay

Figure 8. Weighted average of the a) sand, b) silt, and c) clay content in the 0- to 150-cm soil layer

Table 8. Sand Content in Each Soil Layer across the 13-State Region

	Weighted Average (percent)						*Standard Deviation (percent)*					
State	*10*	*25*	*50*	*100*	*150*	*200*	*10*	*25*	*50*	*100*	*150*	*200*
IL	7.9	7.9	7.9	8.6	10.8	12.5	3.2	3.1	1.8	8.6	4.3	4.9
IN	19.9	19.9	19.2	19.5	21.2	22.4	7.7	8.0	4.6	7.7	7.8	8.9
IA	12.1	12.1	12.6	13.1	14.5	15.4	9.2	9.2	2.5	10.2	11.2	11.5
KS	13.2	12.9	12.4	12.2	12.4	12.5	7.0	7.0	3.0	7.0	7.4	7.7
KY	13.7	13.8	13.5	13.6	13.4	12.9	7.0	7.4	5.8	7.8	7.8	7.0
MI	40.8	40.4	33.7	34.9	34.1	33.8	9.9	9.3	7.4	8.1	8.1	8.4
MN	26.0	25.9	26.1	27.2	28.5	29.2	11.6	11.6	16.1	11.1	11.2	11.3
MO	11.4	11.2	10.8	10.4	10.8	11.2	6.2	6.0	9.4	5.2	10.8	4.9
NE	20.2	20.0	19.5	20.0	21.1	21.8	18.4	18.3	18.2	18.6	19.6	20.1
ND	20.0	20.7	22.2	23.6	24.5	25.5	4.1	3.9	4.4	4.9	5.5	6.6
OH	16.5	16.3	15.6	15.5	16.1	16.5	2.7	2.7	2.3	2.3	2.8	3.2
SD	26.5	26.7	26.8	27.8	28.7	29.5	17.9	18.1	18.1	18.1	17.9	17.8
WI	22.5	21.8	21.3	23.5	26.4	28.1	11.3	10.3	9.3	8.8	9.1	9.4
Region	18.4	18.3	17.9	18.2	19.1	19.7	18.4	12.7	17.9	12.3	19.1	12.6

	Range (percent)											
	Minimum						*Maximum*					
State	*10*	*25*	*50*	*100*	*150*	*200*	*10*	*25*	*50*	*100*	*150*	*200*
IL	2.7	2.7	2.7	2.7	2.9	3.1	16.6	16.7	16.7	19.0	22.2	25.3
IN	10.4	10.3	9.8	9.8	11.5	11.4	52.1	55.6	55.4	57.0	58.9	59.8
IA	3.2	3.2	3.2	3.2	3.3	3.4	31.4	31.5	31.5	32.9	35.4	36.6
KS	4.9	4.8	4.9	5.1	5.3	5.4	41.6	41.6	41.0	41.4	43.5	44.7
KY	5.7	5.7	5.6	6.1	6.3	5.9	37.6	36.4	35.0	37.3	34.5	30.9
MI	20.3	50.1	20.3	19.1	18.1	16.9	58.8	58.5	58.4	54.3	53.1	52.8
MN	19.9	20.0	21.0	22.6	23.7	24.4	69.0	68.7	67.7	71.2	72.8	73.7
MO	3.5	3.5	3.5	3.5	3.9	4.2	26.9	26.4	24.8	24.2	24.9	26.9
NE	3.6	3.6	3.6	3.5	3.4	3.3	72.4	72.2	72.9	74.0	75.8	76.8
ND	10.5	10.3	9.9	9.7	9.7	9.8	32.7	31.6	31.9	32.8	35.0	39.0
OH	8.9	9.1	9.1	9.7	9.6	9.2	28.8	28.4	26.1	24.2	23.9	23.7
SD	6.3	6.0	5.9	6.4	6.9	7.3	76.0	79.4	81.0	81.7	82.0	82.1
WI	4.8	4.6	4.6	4.9	5.5	5.8	51.2	47.4	46.0	44.8	46.1	46.0
Region	2.7	2.7	2.7	2.7	2.9	3.1	76.0	79.4	81.0	81.7	82.0	82.1

Note: The soil surface is the top of all soil layers and the bottom of the soil layers are at depths of 10, 25, 50, 100, 150, and 200 cm, respectively.

Table 9. Silt Content in Each Soil Layer across the 13-State Region

	Weighted Average (percent)						*Standard Deviation (percent)*					
State	*10*	*25*	*50*	*100*	*150*	*200*	*10*	*25*	*50*	*100*	*150*	*200*
IL	68.3	68.3	65.9	62.1	59.5	58.1	4.5	4.5	4.5	5.0	6.0	6.8
IN	58.2	57.7	54.0	50.7	47.7	45.5	7.8	8.1	8.8	8.8	7.8	7.2
IA	59.7	59.6	58.5	55.5	54.3	53.6	9.7	9.6	9.4	10.6	11.9	12.6
KS	61.6	60.7	57.0	54.2	53.3	52.6	6.3	6.3	6.8	8.6	9.8	10.6
KY	63.1	62.1	59.1	55.5	50.7	46.8	8.2	8.4	8.2	8.1	8.1	8.6
MI	37.7	37.4	35.6	34.7	34.4	34.2	8.8	8.0	6.6	5.5	6.0	6.5
MN	45.8	45.3	43.7	40.8	38.9	38.0	11.3	11.5	11.4	11.0	10.7	10.7
MO	63.6	62.2	57.8	52.5	48.9	46.6	5.7	6.4	7.2	9.2	11.8	13.7
NE	58.4	57.8	56.6	55.8	55.0	54.5	13.9	13.3	12.5	12.9	14.1	14.9
ND	54.5	53.2	50.7	48.3	47.0	46.0	2.8	2.9	3.1	2.9	2.8	3.2
OH	56.7	55.7	50.4	46.6	44.4	42.6	4.9	4.9	5.2	4.7	4.2	4.4
SD	49.6	48.8	46.7	45.0	43.7	42.8	13.2	13.2	12.3	11.8	11.6	11.7
WI	55.6	55.2	51.6	44.7	39.3	36.3	12.0	11.9	11.1	9.6	9.1	8.9
Region	57.3	56.6	53.7	50.5	48.2	46.6	11.8	11.8	11.4	11.3	11.7	12.2

	Ranee (percent)											
	Minimum						*Maximum*					
State	*10*	*25*	*50*	*100*	*150*	*200*	*10*	*25*	*50*	*100*	*150*	*200*
IL	54.8	54.8	52.0	47.2	45.0	40.7	74.7	74.5	73.1	71.5	70.1	69.1
IN	31.5	28.2	26.9	24.2	22.5	21.6	70.4	70.0	67.9	64.7	58.7	57.5
IA	44.0	43.9	42.4	25.8	32.1	30.1	72.8	72.3	70.0	69.5	69.4	69.7
KS	39.6	39.4	36.9	32.3	29.4	27.9	71.4	71.5	70.8	71.0	71.8	72.2
KY	37.2	36.8	36.2	32.3	30.1	28.9	74.7	74.0	73.1	73.0	72.7	72.3
MI	23.4	23.8	23.7	23.8	22.5	17.9	59.0	55.1	52.9	47.3	45.8	45.0
MN	47.8	47.2	44.6	39.9	37.9	37.1	75.4	75.1	73.5	7.1.7	70.3	69.5
MO	46.0	44.4	38.2	31.0	19.9	13.5	73.4	72.7	70.9	69.3	67.4	66.5
NE	19.9	20.2	20.0	19.5	18.3	17.6	75.8	71.8	69.1	70.4	71.8	72.3
ND	47.7	47.5	45.3	43.8	43.5	39.9	63.5	63.5	62.9	61.0	60.6	60.5
OH	45.0	44.3	40.6	39.3	34.3	29.5	69.8	69.8	65.6	61.2	56.9	53.9
SD	17.5	15.6	14.0	13.3	13.0	12.9	66.5	66.3	65.9	66.2	66.2	66.1
WI	24.7	25.8	26.3	24.5	21.3	18.5	71.8	71.4	69.6	67.0	63.4	62.4
Region	17.5	15.6	14.0	13.3	13.0	12.9	75.8	75.1	73.5	73.0	72.7	72.3

Note: The soil surface is the top of all soil layers and the bottom of the soil layers are at depths of 10, 25, 50, 100, 150, and 200 cm, respectively.

Table 10. Clay Content in Each Soil Layer across the 13-State Region

	Weighted Average (percent)						*Standard Deviation (percent)*					
State	*10*	*25*	*50*	*100*	*150*	*200*	*10*	*25*	*50*	*100*	*150*	*200*
IL	22.7	22.8	25.1	27.8	27.1	26.1	2.6	2.6	2.9	3.2	3.2	3.1
IN	19.1	19.6	23.3	24.9	24.4	23.6	2.8	2.8	4.0	3.9	3.9	4.2
IA	27.2	27.3	28.0	28.7	27.6	26.9	3.5	3.4	3.1	3.8	4.2	4.2
KS	24.1	25.2	29.2	30.9	29.9	29.2	4.2	4.1	4.7	5.5	5.4	5.3
KY	18/. 7	19.6	22.6	24.8	26.0	25.6	2.3	2.6	4.0	5.6	6.8	7.0
MI	13.4	14.0	18.0	20.6	20.7	20.6	3.8	3.9	5.5	6.1	6.4	6.7
MN	21.3	21.7	22.8	23.2	22.6	22.3	7.4	7.4	7.1	6.8	6.8	6.9
MO	22.8	23.8	27.6	30.4	31.2	31.4	4.3	4.1	4.7	5.2	4.8	4.3
NE	20.7	21.4	23.1	23.1	21.9	21.1	5.9	6.5	7.2	7.8	7.8	7.8
ND	22.2	22.7	23.8	24.5	24.6	24.4	5.4	5.2	5.0	4.8	5.1	5.3
OH	21.7	22.6	27.2	28.7	27.7	26.7	4.9	5.0	5.5	5.5	5.6	6.0
SD	21.2	21.7	23.5	23.5	22.7	22.1	6.2	6.3	7.0	7.4	7.2	7.3
WI	15.7	16.2	19.3	20.6	19.4	18.5	4.5	4.7	6.5	7.7	8.2	8.4
Region	21.0	21.6	24.4	25.9	25.5	24.9	5.7	5.7	6.1	6.6	6.8	7.0

	Range (percent)											
	Minimum						*Maximum*					
State	*10*	*25*	*50*	*100*	*150*	*200*	*10*	*25*	*50*	*100*	*150*	*200*
IL	15.3	15.7	16.8	18.2	18.3	18.2	30.3	30.4	32.4	35.0	34.7	34.5
IN	9.9	9.7	10.7	11.2	10.5	9.9	26.9	27.6	33.6	34.7	34.2	33.6
IA	17.5	17.6	18.8	19.4	18.6	17.9	35.6	35.5	34.9	34.8	35.0	34.0
KS	16.9	17.0	19.3	20.7	19.9	18.9	31.7	33.5	37.2	41.4	40.3	39.8
KY	12.8	13.6	12.7	12.1	11.2	10.2	23.4	24.7	28.3	33.1	35.4	37.9
MI	7.6	7.6	7.8	8.5	7.9	7.6	27.5	28.1	32.3	34.4	35.7	36.4
MN	12.0	12.1	14.2	16.9	17.4	17.4	44.5	44.9	46.6	48.1	49.0	49.5
MO	15.4	16.3	17.0	18.9	20.3	20.2	37.6	38.3	44.2	46.3	44.2	42.3
NE	7.6	7.6	7.1	6.5	5.9	5.6	31.5	34.7	36.7	37.1	35.3	34.1
ND	16.6	16.8	17.2	16.3	15.9	15.6	38.7	38.5	38.3	38.7	39.3	39.5
OH	16.6	17.0	19.9	21.2	20.3	17.3	38.3	39.2	42.7	44.3	43.3	42.9
SD	5.0	5.0	5.0	5.0	5.0	4.9	29.9	29.8	30.6	33.6	32.4	31.8
WI	6.9	6.7	7.1	7.4	7.4	6.7	25.6	28.4	35.4	39.1	37.3	37.0
Region	5.0	5.0	5.0	5.0	5.0	4.9	44.5	44.9	46.6	48.1	49.0	49.5

Note: The soil surface is the top of all soil layers and the bottom of the soil layers are at depths of 10. 25. 50. 100, 150, and 200 cm, respectively.

Table 11. Cumulative Volumetric Water Held in Each Soil Layer with Soil Moisture at the Liquid Limit across the 13-State Region

	Weighted Average (cm)						*Standard Deviation (cm)*					
State	*10*	*25*	*50*	*100*	*150*	*200*	*10*	*25*	*50*	*100*	*150*	*200*
IL	4.4	10.9	24.1	53.4	79.4	103.6	0.3	0.8	1.8	4.4	6.8	8.4
IN	3.9	9.8	22.4	48.1	71.8	93.5	0.5	1.1	2.9	6.1	9.9	14.4
IA	5.4	13.6	27.8	56.4	83.0	109.0	0.5	1.3	2.4	5.9	10.2	14.3
KS	4.6	12.0	27.1	56.4	82.2	107.1	0.7	1.7	3.8	8.6	12.7	16.6
KY	3.7	9.6	21.5	46.9	72.7	94.5	0.4	1.1	2.9	8.1	14.1	18.5
MI	3.2	8.5	20.1	45.0	68.1	90.7	0.6	1.4	3.8	8.5	14.4	21.1
MN	4.4	11.2	23.3	47.8	70.7	93.5	1.1	2.6	5.2	9.8	14.8	19.9
MO	4.5	11.7	26.0	46.3	86.1	115.2	0.8	1.8	3.7	7.9	10.7	13.7
NE	4.2	10.7	22.5	45.5	66.7	86.9	0.7	2.0	4.6	10.4	15.8	21.3
ND	4.1	10.4	22.0	46.4	70.5	93.6	0.7	1.9	3.7	7.1	11.1	16.3
OH	4.4	11.3	25.5	53.5	78.9	102.1	0.7	1.9	4.2	8.8	14.2	21.3
SD	4.0	10.2	22.0	45.3	68.0	90.0	1.0	2.5	4.3	11.7	18.9	27.8
WI	3.6	9.2	21.3	44.7	62.4	79.4	0.6	1.5	4.5	11.3	19.4	27.8
Region	4.2	10.8	23.7	50.2	74.8	98.0	0.9	2.1	4.5	9.6	15.2	21.1

	Range (cm)											
	Minimum						*Maximum*					
State	*10*	*25*	*50*	*100*	*150*	*200*	*10*	*25*	*50*	*100*	*150*	*200*
IL	3.8	9.5	19.7	41.8	62.1	77.9	5.2	13.0	28.1	60.8	91.9	123.3
IN	1.9	4.6	10.0	19.6	25.6	31.3	5.1	12.9	30.1	63.3	95.1	126.4
IA	3.7	9.5	19.9	40.6	58.4	74.8	6.6	16.5	32.5	65.6	98.9	130.2
KS	3.6	9.2	20.0	40.6	60.0	79.0	6.2	15.7	33.9	72.7	107.9	139.8
KY	2.6	6.6	13.3	26.8	37.1	45.4	5.1	13.1	27.2	59.5	93.0	123.4
MI	1.9	4.7	11.0	24.1	32.8	39.3	5.3	13.5	30.2	65.8	103.2	140.5
MN	2.9	7.4	16.5	28.4	59.8	80.9	6.1	15.5	33.1	70.1	108.1	146.1
MO	3.4	8.8	19.3	41.1	65.1	88.2	6.7	17.0	35.3	70.2	105.3	139.1
NE	2.9	7.1	13.8	27.3	32.1	36.3	5.5	14.3	30.3	62.5	91.5	118.7
ND	3.0	7.7	15.9	36.1	53.5	57.5	6.2	15.7	32.6	97.1	102.5	137.9
OH	3.3	8.4	18.7	39.4	54.9	62.2	6.9	17.7	38.1	79.0	119.4	158.8
SD	0.0	0.0	0.0	0.0	0.0	0.0	5.1	13.0	27.3	57.8	88.8	119.5
WI	1.7	4.6	9.9	21.1	31.9	41.8	4.9	12.8	33.8	73.6	108.4	146.6
Region	0.0	0.0	0.0	0.0	0.0	0.0	6.9	17.2	38.1	79.0	119.4	158.8

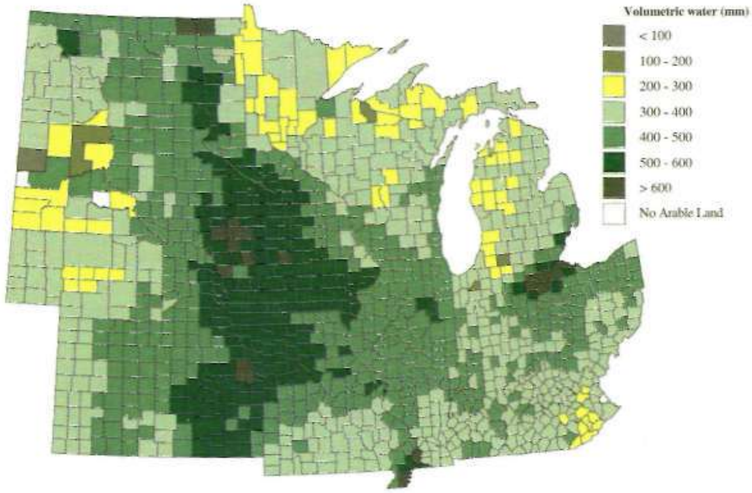
Note: The soil surface is the top of all soil layers and the bottom of the soil layers are at depths of 10, 25, 50, 100, 150, and 200 cm, respectively.

Table 12. Cumulative Volumetric Water Held in Each Soil Layer with Soil Moisture at the Plastic Limit across the 13-State Region

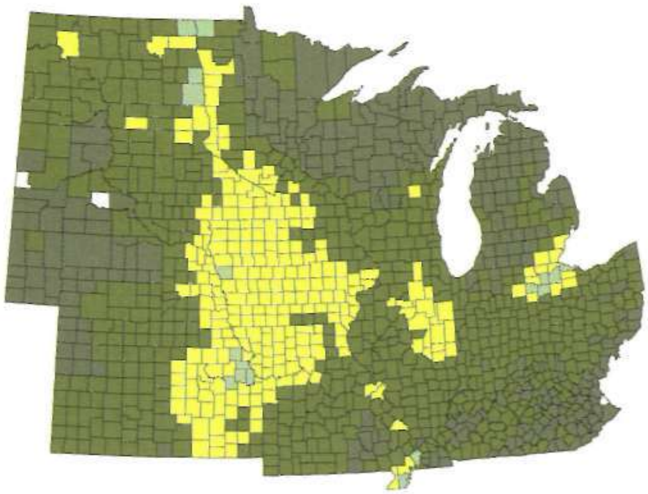
	Weighted Average (cm)						*Standard Deviation (cm)*					
State	*10*	*25*	*50*	*100*	*150*	*200*	*10*	*25*	*50*	*100*	*150*	*200*
IL	1.7	4.2	10.1	24.5	36.3	46.8	0.3	0.8	1.9	4.2	6.4	7.9
IN	1.3	3.4	8.8	19.7	29.1	37.5	0.3	0.7	2.1	4.1	5.8	8.1
IA	2.3	5.8	12.3	26.4	38.9	50.9	0.4	0.9	1.8	4.5	7.5	10.2
KS	1.8	5.0	12.5	26.8	38.7	50.2	0.6	1.5	3.1	7.2	11.4	15.5
KY	1.0	2.7	7.2	17.2	28.0	36.9	0.2	0.5	1.7	5.1	9.5	12.9
MI	0.9	2.4	7.3	17.7	26.9	36.0	0.4	0.9	2.6	5.8	9.6	13.6
MN	1.6	4.0	9.1	19.5	28.9	38.1	0.7	1.7	3.6	7.2	10.7	14.3
MO	1.7	4.6	11.4	26.7	41.7	56.3	0.6	1.4	3.2	7.0	9.5	11.9
NE	1.4	3.8	9.0	18.4	26.1	33.2	0.4	1.8	1.7	8.7	13.0	17.0
ND	1.7	4.3	9.4	20.0	30.0	39.6	0.5	1.4	2.8	5.6	8.8	12.6
OH	1.5	3.9	10.2	22.3	32.7	42.3	0.6	1.6	3.6	7.1	11.0	15.6
SD	1.4	3.7	8.3	17.4	26.2	34.8	0.6	1.4	3.1	6.7	10.6	14.9
WI	1.1	2.9	8.1	18.4	25.9	33.0	0.4	1.0	3.6	8.1	13.7	18.7
Region	1.5	3.9	9.6	21.5	32.1	42.0	0.6	1.6	3.4	7.4	11.4	15.5

	Range (cm)											
	Minimum						*Maximum*					
State	*10*	*25*	*50*	*100*	*150*	200	*10*	*25*	*50*	*100*	*150*	*200*
IL	1.0	2.5	5.3	12.0	18.0	25.3	2.3	5.9	13.0	30.6	45.9	61.5
IN	0.4	1.1	2.9	6.6	8.7	10.6	2.2	5.6	14.4	30.4	45.5	60.5
IA	1.2	3.1	7.0	15.6	22.4	28.4	3.4	8.6	17.2	35.3	53.5	71.1
KS	0.9	2.4	6.8	14.7	9.2	26.4	3.4	8.6	18.9	40.1	59.4	77.7
KY	0.5	1.4	3.4	6.8	8.6	10.9	2.0	5.2	11.1	25.3	43.2	55.1
MI	0.4	1.2	2.9	3.4	18.3	10.9	2.4	6.3	14.9	32.5	50.2	67.9
MN	0.6	1.4	4.1	2.9	23.8	24.8	3.1	7.9	17.2	39.6	62.5	85.4
MO	0.9	2.4	5.9	4.1	4.4	31.7	3.5	8.9	18.7	37.2	55.9	75.3
NE	0.4	0.9	1.7	5.9	15.7	5.0	2.7	7.2	15.7	33.5	49.4	64.7
ND	0.9	2.2	5.2	1.7	18.1	18.1	3.2	8.3	17.4	36.5	55.6	74.6
OH	0.8	2.1	5.3	5.2	1.3	19.7	3.6	9.3	20.8	43.5	66.3	89.1
SD	0.0	0.0	0.0	5.3	0.0	0.0	2.2	5.7	11.9	23.6	36.5	49.7
WI	0.4	1.0	2.4	0.0	7.3	8.6	2.1	5.6	18.3	41.3	58.7	78.7
Region	0.0	0.0	0.0	0.0	0.0	0.0	3.6	9.3	20.8	43.5	66.3	89.1

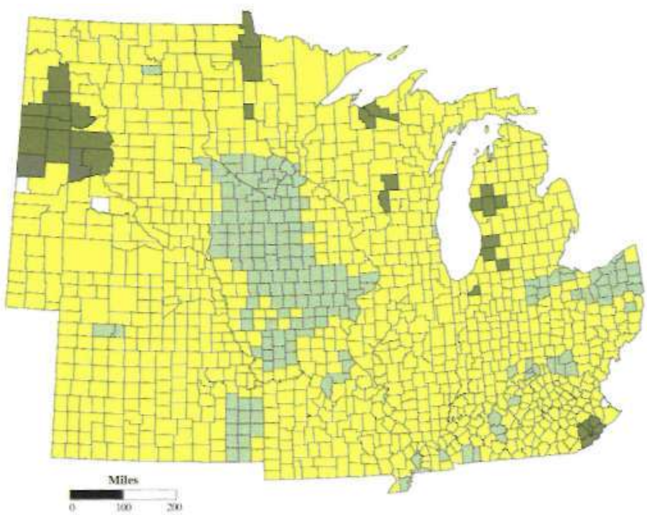
Note: The soil surface is the top of all soil layers and the bottom of the soil layers are at depths of 10, 25, 50, 100, 150, and 200 cm, respectively.



a. Liquid limit



b. Plastic limit



c. Plastic index

Figure 9. Weighted average of the volumetric water held at the a) liquid limit, b) plastic limit, and c) plastic index for the 0- to 10-cm soil layer

from 0.8 to 30.5 percent (table 13). Soils high in organic matter (peat and muck soils) are found in Minnesota, northern Wisconsin, the western region of Michigan's upper peninsula, North Dakota, South Dakota, and Iowa (figure 10). Many of the high organic matter soils in northern Minnesota have an organic matter

Table 13. Organic Matter Content of the Top Two Soil Layers across the 13-State Region

State	*Weighted Average (percent)*	*Standard Deviation (percent)*	*Range (percent)*	
			Minimum	*Maximum*
Illinois	3.1	0.9	1.5	4.6
Indiana	2.4	0.4	1.7	4.0
Iowa	4.4	0.7	2.6	5.6
Kansas	2.5	0.5	1.6	3.7
Kentucky	2.5	0.4	1.5	3.6
Michigan	2.7	1.4	1.6	14.5
Minnesota	5.5	4.6	3.3	35.3
Missouri	2.6	0.8	1.5	4.6
Nebraska	2.6	0.7	1.4	4.1
North Dakota	5.1	0.5	4.1	6.2
Ohio	2.7	0.6	1.7	4.4
South Dakota	4.0	1.2	0.8	5.5
Wisconsin	2.9	1.1	1.8	9.8
Region	3.2	1.8	0.8	35.3

Note: The bottom of the top soil layer is at a depth of 25 cm.

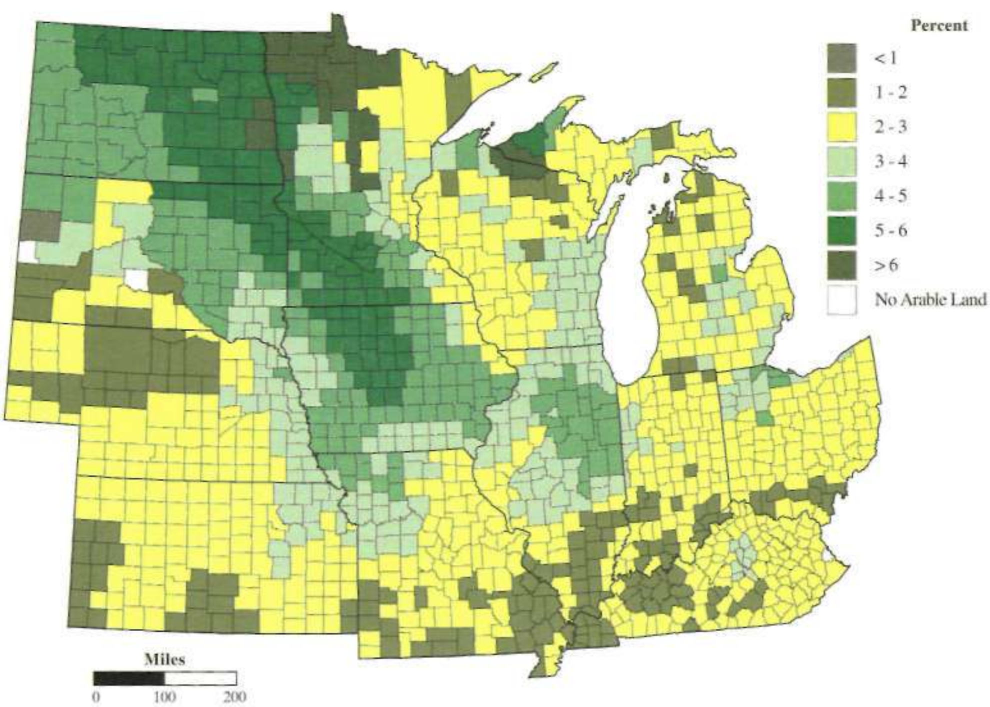


Figure 10. Weighted average of organic matter content in the 0- to 10-cm soil layer

content greater than 10 percent. Soils with the lowest organic matter content are found in South Dakota, the Sandhills of Nebraska, and scattered counties in southern Kansas, Missouri, Illinois, Indiana, and Kentucky.

Bulk Density

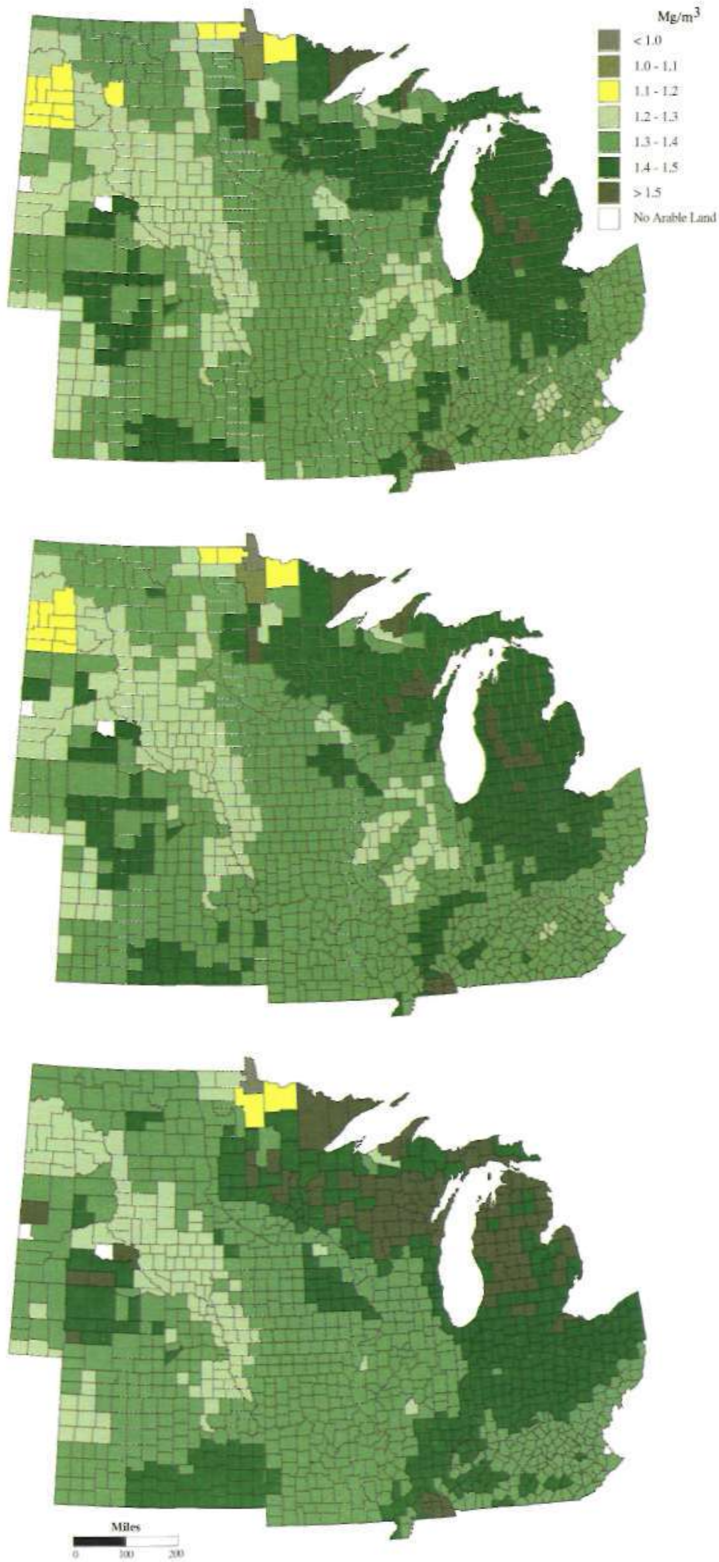
Soil bulk density plays a major role in determining the amount of water that a soil can hold and how well plant roots can penetrate to deeper depths. Bulk densities greater than 1.6 Mg/m^3 greatly limit the root growth. The mean bulk density of the region's soils (table 14) ranges from 1.36 Mg/m^3 (top 10 cm of the soil), to 1.46 Mg/m^3 (0- to 200-cm soil profile). The bulk density from the surface to different depths increases with depth (figure 11). Soils with the greatest natural bulk densities are located in the till plains

Table 14. Soil Bulk Density of Each Soil Layer across the 13-State Region

	Weighted Average (Mg/m^3)						*Standard Deviation (Mg/m^3)*					
State	*10*	*25*	*50*	*100*	*150*	200	*10*	*25*	*50*	*100*	*150*	200
IL	1.34	1.34	1.37	1.41	1.44	1.46	0.04	0.05	0.04	0.05	0.05	0.05
IN	1.39	1.40	1.44	1.49	1.52	1.54	0.03	0.03	0.03	0.04	0.06	0.06
IA	1.34	1.35	1.36	1.38	1.41	1.43	0.04	0.04	0.04	0.06	0.07	0.08
KS	1.36	1.36	1.37	1.38	1.38	1.38	0.05	0.05	0.05	0.06	0.06	0.06
KY	1.35	1.36	1.39	1.43	1.44	1.44	0.06	0.06	0.06	0.06	0.07	0.07
MI	1.46	1.48	1.51	1.55	1.57	1.58	0.04	0.04	0.03	0.04	0.04	0.04
MN	1.36	1.37	1.40	1.45	1.48	1.50	0.09	0.10	0.10	0.09	0.10	0.10
MO	1.35	1.35	1.36	1.39	1.39	1.39	0.02	0.02	0.02	0.03	0.03	0.03
NE	1.35	1.35	1.35	1.36	1.38	1.39	0.06	0.06	0.06	0.06	0.07	0.07
ND	1.30	1.30	1.33	1.37	1.39	1.40	0.06	0.05	0.05	0.04	0.03	0.03
OH	1.39	1.40	1.45	1.50	1.54	1.55	0.04	0.04	0.04	0.05	0.06	0.07
SD	1.27	1.29	1.31	1.35	1.39	1.41	0.07	0.07	0.07	0.07	0.07	0.06
WI	1.40	1.42	1.47	1.52	1.55	1.57	0.05	0.06	0.06	0.07	0.07	0.07
Region	1.36	1.37	1.39	1.43	1.45	1.46	0.07	0.07	0.07	0.08	0.09	0.09

	Ranee (Mg/m^3)											
	Minimum						*Maximum*					
State	*10*	*25*	*50*	*100*	*150*	*200*	*10*	*25*	*50*	*100*	*150*	*200*
IL	1.27	1.27	1.29	1.32	1.34	1.35	1.42	1.42	1.45	1.49	1.53	1.55
IN	1.32	1.33	1.35	1.39	1.40	1.40	1.46	1.46	1.49	1.56	1.62	1.66
IA	1.26	1.26	1.27	1.28	1.30	1.31	1.42	1.43	1.45	1.50	1.56	1.59
KS	1.23	1.23	1.22	1.24	1.27	1.29	1.45	1.45	1.46	1.49	1.50	1.51
KY	1.29	1.30	1.33	1.34	1.34	1.34	1.63	1.64	1.66	1.74	1.77	1.78
MI	1.23	1.26	1.28	1.31	1.32	1.33	1.52	1.54	1.56	1.63	1.69	1.72
MN	1.34	1.34	1.36	1.41	1.44	1.45	1.57	1.59	1.61	1.64	1.70	1.74
MO	1.29	1.29	1.29	1.31	1.32	1.33	1.41	1.41	1.43	1.45	1.46	1.47
NE	1.25	1.24	1.25	1.25	1.26	1.26	1.48	1.48	1.51	1.53	1.56	1.57
ND	1.20	1.20	1.22	1.28	1.33	1.33	1.40	1.41	1.41	1.45	1.46	1.47
OH	1.30	1.30	1.33	1.36	1.39	1.39	1.47	1.48	1.51	1.57	1.62	1.64
SD	1.21	1.22	1.24	1.28	1.30	1.31	1.50	1.50	1.53	1.57	1.58	1.58
WI	1.27	1.31	1.34	1.37	1.38	1.39	1.50	1.54	1.59	1.61	1.60	1.68
Region	1.20	1.20	1.22	1.24	1.26	1.26	1.63	1.64	1.66	1.67	1.77	1.78

Note: The soil surface is the top of all soil layers and the bottom of the soil layers are at depths of 10. 25, 50. 100. 150. and 200 cm, respectively.

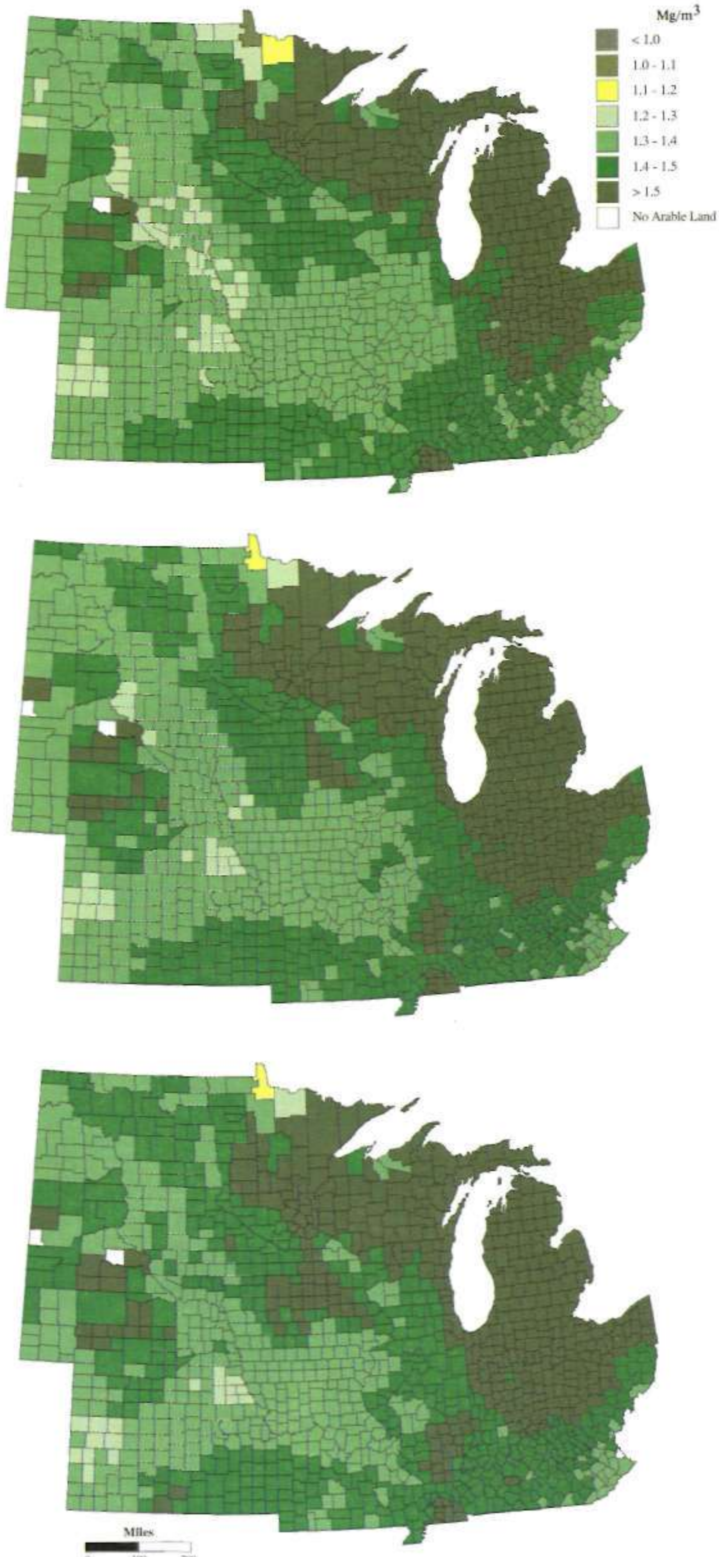


a. 0-10 cm

b. 0-25 cm

c. 0-50 cm

Figure 11. Weighted average of soil bulk density for the six soil layers: a) 0- to 10-cm, b) 0- to 25-cm, c) 0- to 50-cm, d) 0- to 100-cm, e) 0- to 150-cm, and f) 0- to 200-cm



d. 0-100 cm

e. 0-150 cm

f. 0-200 cm

Figure 11. Concluded

of Minnesota, Wisconsin, Michigan, Indiana, Ohio, and southern Illinois where dense till and loess with fragipans exist, in sandy regions of north-central Nebraska, and in the Badlands of South Dakota.

Plant-Available Water

Plant-available water is the amount of water held by the soil that plants can use. It is assumed to be equal to the amount of water held between the field capacity (drained upper limit) and the wilting point (drained lower limit). The mean volumetric plant-available water, in cm, is provided for each soil thickness for each state and the region in table 15. Soils in Illinois, Iowa, Kansas, and Nebraska tend to have the

Table 15. Cumulative Volumetric Plant-Available Water Held in Each Soil Layer across the 13-State Region

	Weighted Average (cm)						*Standard Deviation (cm)*					
State	*10*	*25*	*50*	*100*	*150*	*200*	*10*	*25*	*50*	*100*	*150*	*200*
IL	2.2	5.5	10.4	19.1	27.1	35.0	0.1	0.2	0.4	1.0	2.0	3.2
IN	2.1	5.2	9.6	17.1	23.0	28.4	0.2	0.4	0.8	1.7	2.8	3.9
IA	2.1	5.3	10.3	19.0	27.4	35.8	0.1	0.2	0.4	1.2	2.3	3.5
KS	2.1	5.1	9.4	17.7	26.0	34.0	0.1	0.4	0.7	1.7	3.1	4.7
KY	1.9	4.8	9.4	17.3	23.7	29.0	0.2	0.5	0.9	1.5	2.3	3.6
MI	1.6	3.9	7.3	13.8	19.5	25.0	0.2	0.5	0.9	1.6	2.6	3.9
MN	1.9	4.6	8.7	15.9	22.5	29.0	0.3	0.7	1.4	2.9	4.8	6.7
MO	2.1	5.0	9.2	16.4	23.4	30.2	0.2	0.4	0.8	2.0	3.7	5.7
NE	2.0	4.9	9.3	17.7	25.7	33.7	0.3	0.6	1.2	2.5	14.4	16.4
ND	2.0	4.9	9.4	17.7	25.6	33.4	0.1	0.3	0.6	1.0	1.2	1.6
OH	1.9	4.8	8.6	15.0	19.8	24.3	0.2	0.5	0.9	1.5	2.2	3.0
SD	1.8	4.5	8.7	16.5	23.9	31.0	0.3	0.8	1.5	3.0	4.5	6.3
WI	1.9	4.7	8.7	15.2	19.9	24.5	0.3	0.7	1.3	2.4	3.4	4.5
Region	2.0	4.9	9.2	16.9	23.8	30.4	0.3	0.6	1.2	2.4	4.1	16.0

	Range (cm)											
	Minimum						*Maximum*					
State	*10*	*25*	*50*	*100*	*150*	*200*	*10*	25	*50*	*100*	*150*	200
IL	2.0	5.0	9.1	16.1	22.1	*21.1*	2.3	5.7	10.9	20.7	30.6	40.3
IN	1.4	3.3	6.6	12.1	16.0	19.7	2.2	5.6	10.6	19.8	27.9	36.6
IA	1.9	4.8	9.6	16.5	22.2	27.9	2.3	5.6	11.1	21.3	31.3	41.6
KS	1.8	4.4	8.2	14.9	20.1	25.0	2.3	5.7	10.7	20.5	30.7	41.0
KY	1.2	3.1	6.5	12.0	15.5	18.2	2.2	5.4	10.6	20.1	29.6	38.9
MI	1.2	2.8	5.4	9.8	12.1	14.4	2.0	5.0	9.3	17.2	24.9	32.5
MN	1.8	4.4	8.4	14.8	20.1	25.2	2.3	5.6	10.9	20.8	30.4	39.8
MO	1.4	3.6	7.0	10.2	13.4	16.3	2.3	5.6	11.0	20.8	30.4	40.0
NE	1.2	3.0	5.5	9.9	13.7	17.4	2.3	5.7	10.7	20.5	30.5	40.6
ND	1.7	4.2	7.9	15.3	22.5	29.3	2.3	5.6	10.7	20.2	29.5	39.1
OH	1.4	3.5	6.2	11.5	16.1	19.2	2.2	5.5	10.2	18.9	26.1	33.2
SD	0.8	2.0	4.0	8.0	12.0	16.0	2.2	5.3	10.3	19.9	29.4	38.8
WI	1.0	2.2	4.3	7.7	10.9	14.1	2.3	5.6	10.7	20.1	27.9	36.0
Region	0.8	2.0	4.0	7.7	10.9	14.1	2.3	5.7	11.1	21.3	31.3	41.6

Note: The soil surface is the top of all soil layers and the bottom of the soil layers are at depths of 10. 25, 50, 100. 150, and 200 cm, respectively.

highest plant-available water capacities, while soils in Michigan, northern Indiana, Ohio, Minnesota, Wisconsin, the Sandhills of Nebraska, and western South Dakota have the lowest plant-available water capacity. Total plant-available water increases as the root depth increases. State average, variation, and maximum and minimum values of field capacity and wilting point are presented in tables 16 and 17, respectively. The regional variation of field capacity (drained upper limit), wilting point (drained lower limit), and plant-available water for the 0- to 150-cm layer is shown in figure 12. Other soil layers have similar water-holding capacities.

Table 16. Cumulative Volumetric Water Content in each Soil Layer with Soil Moisture at the Drained Upper Limit (Field Capacity) across the 13-State Region

	Weighted Average (cm)						*Standard Deviation (cm)*					
State	*10*	*25*	*50*	*100*	*150*	*200*	*10*	*25*	*50*	*100*	*150*	200
IL	3.9	9.6	18.7	36.0	51.6	66.8	0.2	0.5	0.8	1.6	3.1	4.9.
IN	3.4	8.4	16.7	31.6	44.2	55.6	0.3	0.7	1.3	2.5	4.0	5.6
IA	3.9	9.7	19.1	36.3	52.4	68.3	0.2	0.5	1.1	3.0	5.6	8.1
KS	3.6	9.1	18.1	35.5	51.8	67.7	0.3	0.6	1.0	1.7	2.9	4.6
KY	3.2	8.0	16.3	31.9	45.8	57.5	0.3	0.8	1.7	3.4	5.5	7.4
MI	2.5	6.3	12.9	26.0	37.6	49.1	0.4	0.9	1.8	3.7	6.2	9.0
MN	3.2	8.0	15.7	29.8	42.7	55.4	0.6	1.5	2.9	5.9	9.2	12.7
MO	3.6	8.9	17.5	33.6	48.9	63.9	0.4	0.9	1.8	4.4	7.1	9.9
NE	3.5	8.6	16.8	32.4	46.8	60.9	0.6	1.4	2.8	5.9	9.6	13.6
ND	3.4	8.5	16.7	32.3	47.4	62.2	0.2	0.6	1.0	2.1	3.3	4.9
OH	3.3	8.2	16.4	30.7	42.4	53.2	0.2	0.6	1.2	2.4	4.1	6.2
SD	3.2	8.0	15.9	30.7	44.4	57.8	0.6	1.5	3.2	6.3	9.4	13.0
WI	3.0	7.5	14.3	27.6	37.5	46.9	0.5	1.3	2.5	5.3	8.2	11.2
Region	3.4	8.4	16.7	32.2	46.1	59.4	0.5	1.3	2.5	4.9	7.9	11.1

	Range (cm)											
	Minimum						*Maximum*					
State	*10*	*25*	*50*	*100*	*150*	*200*	*10*	*25*	*50*	*J 00*	*150*	*200*
IL	3.3	8.1	16.3	31.7	43.9	53.8	4.2	10.5	20.4	38.8	57.9	77.3
IN	2.2	5.4	10.7	20.4	27.8	34.8	3.7	9.4	18.7	35.8	50.0	65.1
IA	3.5	8.3	16.2	29.7	40.3	50.5	4.3	10.6	20.7	40.1	59.0	78.8
KS	2.9	7.3	14.8	29.6	40.5	50.9	4.0	9.9	19.7	38.2	56.3	74.5
KY	2.2	5.5	11.3	20.5	26.4	31.0	3.5	8.9	17.9	36.4	53.0	68.0
MI	1.9	4.4	8.7	16.4	21.4	26.4	3.4	8.4	16.8	32.5	47.0	62.8
MN	2.7	6.6	13.3	25.5	36.3	46.7	3.9	9.7	19.2	38.6	58.4	78.3
MO	2.9	7.3	13.5	22.4	32.1	41.4	4.1	10.2	20.3	39.4	57.6	76.6
NE	1.9	4.7	8.8	16.3	22.8	29.3	4.2	10.2	20.2	39.5	57.8	76.5
ND	3.0	7.6	15.1	27.8	39.8	51.8	4.1	10.0	19.4	37.9	56.7	75.6
OH	2.7	6.7	13.3	24.3	32.8	37.6	3.7	9.2	18.1	35.4	51.4	67.2
SD	1.4	3.3	6.6	13.1	19.5	26.0	3.9	9.6	19.0	37.0	54.1	71.2
WI	1.5	3.5	6.8	12.8	18.4	24.0	4.1	10.2	19.5	37.2	52.9	69.1
Region	1.4	3.3	6.6	12.8	18.4	19.6	4.3	8.4	20.7	40.1	59.0	78.8

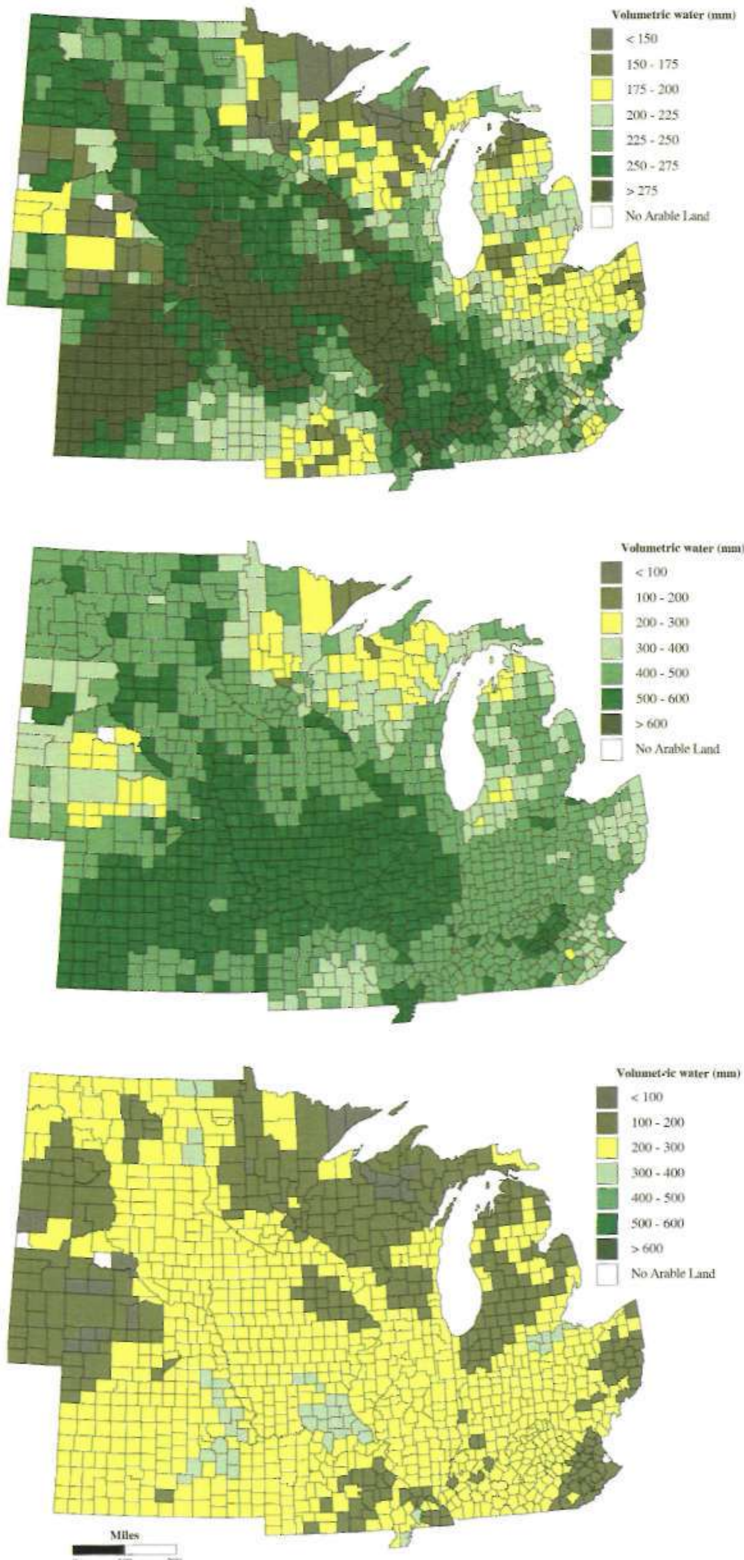
Note: The soil surface is the top of all soil layers and the bottom of the soil layers are at depths of 10. 25. 50, 100. 150. and 200 cm, respectively.

Table 17. Cumulative Volumetric Water Content in Each Soil Layer with Soil Moisture at the Lower Limit of Plant Available Water (Wilting Point) across the 13-State Region

	Weighted Average (cm)						*Standard Deviation (cm)*					
State	*10*	*25*	*50*	*100*	*150*	*200*	*10*	*25*	*50*	*100*	*150*	*200*
IL	1.6	4.1	8.3	16.9	24.5	31.9	0.2	0.4	0.8	1.5	2.3	3.2
IN	1.3	3.2	7.1	14.5	21.1	27.2	0.1	0.3	0.9	1.7	2.6	3.7
IA	1.8	4.4	8.7	17.3	25.0	32.5	0.2	0.4	0.9	2.2	3.6	4.9
KS	1.6	4.0	8.7	17.8	25.9	33.7	0.2	0.5	1.0	2.2	3.1	4.0
KY	1.3	3.3	7.0	14.6	22.1	28.4	0.2	0.4	1.0	2.8	4.4	5.9
MI	1.0	2.5	5.6	12.2	18.1	24.1	0.2	0.5	1.2	2.7	4.3	6.0
MN	1.4	3.4	7.0	13.8	20.2	26.4	0.4	0.9	1.8	3.4	5.0	6.7
MO	1.5	3.9	8.4	17.2	25.5	33.7	1.3	0.7	1.4	3.2	4.4	5.5
NE	1.4	3.7	7.5	14.7	21.0	27.2	0.3	0.9	1.9	3.9	5.8	7.8
ND	1.4	3.6	7.3	14.6	21.8	28.8	0.3	0.6	1.1	2.1	3.4	4.8
OH	1.4	3.5	7.7	15.7	22.6	28.9	0.2	0.6	1.3	2.6	4.0	5.9
SD	1.4	3.5	7.2	14.2	20.5	26.7	0.3	0.8	1.7	3.5	5.2	6.9
WI	1.1	2.9	6.2	12.5	17.6	22.4	0.3	0.7	1.6	3.7	5.7	7.8
Region	1.4	3.6	7.5	15.3	22.3	29.0	0.3	0.8	1.6	3.3	4.9	6.7

	Range (cm)											
	Minimum						*Maximum*					
State	*10*	*25*	*50*	*100*	*150*	*200*	*10*	*25*	*50*	*100*	*150*	200
IL	1.1	2.8	5.8	12.2	18.0	23.6	1.9	4.8	9.5	19.5	28.6	37.6
IN	0.8	2.0	4.2	8.3	11.8	15.1	1.6	4.1	9.3	18.7	27.5	36.1
IA	1.2	3.1	6.3	12.5	17.9	22.6	2.1	5.1	10.3	20.3	30.7	39.7
KS	1.2	2.9	6.2	13.2	18.3	23.2	2.0	5.1	10.6	21.7	32.0	42.2
KY	0.9	2.4	4.5	8.5	10.9	12.8	1.5	3.8	8.5	18.3	27.9	37.8
MI	0.7	1.6	3.3	6.6	9.9	12.0	1.6	4.1	8.9	18.4	27.7	37.5
MN	0.9	2.2	4.9	10.7	16.2	21.5	2.4	6.0	12.3	25.1	38.1	51.1
MO	1.1	2.8	5.8	11.9	17.9	23.9	2.1	5.3	11.7	24.3	35.0	44.9
NE	0.7	1.7	3.4	6.4	9.2	12.0	2.0	5.2	10.8	21.5	30.6	39.2
ND	1.2	3.0	5.9	11.0	15.9	20.8	2.2	5.5	10.6	21.1	31.8	42.7
OH	1.1	2.7	5.8	11.6	16.1	18.4	2.1	5.4	11.3	23.1	33.9	44.7
SD	0.6	1.4	2.6	5.1	7.6	10.1	1.8	4.5	8.9	18.8	27.2	35.6
WI	0.5	1.3	2.5	5.1	7.5	10.0	1.9	4.6	9.7	20.5	29.3	38.0
Region	0.5	1.3	2.5	5.1	7.5	10.0	2.4	6.0	12.3	25.1	38.1	51.1

Note: The soil surface is the top of all soil layers and the bottom of the soil layers are at depths of 10. 25, 50, 100, 150, and 200 cm. respectively.



a. Plant-available water

b. Drained upper limit

c. Drained lower limit

Figure 12. Weighted average of the a) volumetric plant-available water, b) drained upper limit (field capacity), and c) drained lower limit (wilting point)

Permeability

Soil texture and bulk density determine permeability or the rate at which water will pass through a soil layer. Sandy soils have faster permeability rates, while soils with high bulk densities have slower rates. Highly permeable soils tend to be more drought-prone because water moves through them faster than through less permeable soils. The variation of permeability within the 0- to 25-cm layer across the region is shown in figure 13. The most permeable soils occur in the sandhills of Nebraska, in western South Dakota, on the high organic soils in Minnesota, in northwestern Indiana, and in Michigan. Soils in eastern Kansas are the least permeable soils in the region (table 18).

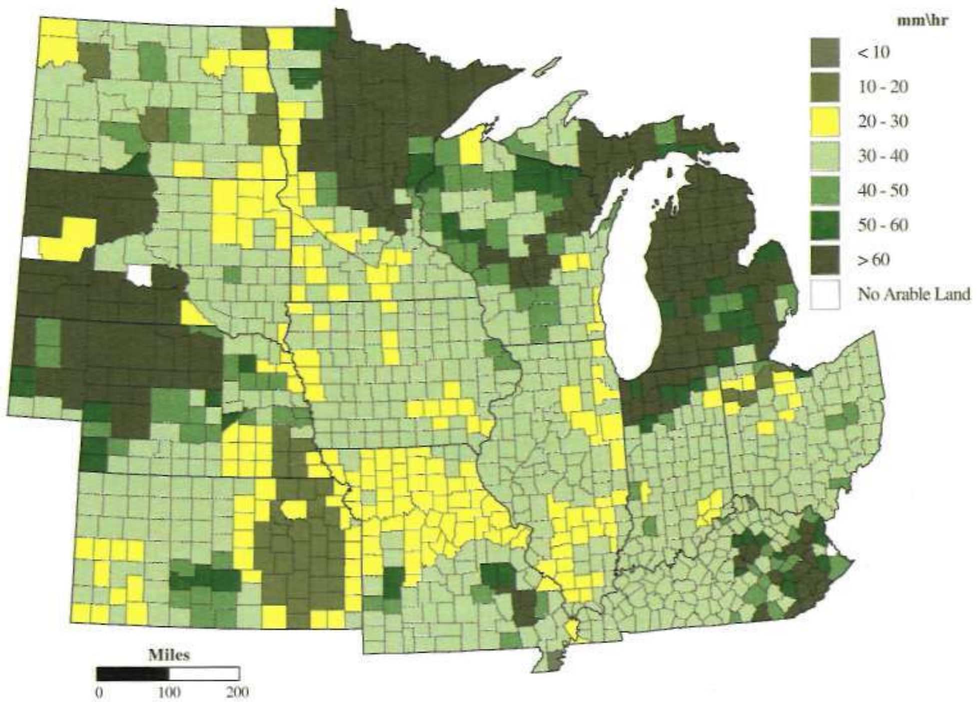


Figure 13. Weighted average of permeability rate for the 0- to 25-cm soil layer

Table 18. Permeability Rate of Each Soil Layer across the 13-State Region

	Weighted Average (cm/hr)						*Standard Deviation (cm/hr)*					
State	*10*	*25*	*50*	*100*	*150*	*200*	*10*	*25*	*50*	*100*	*150*	*200*
IL	3.2	3.2	2.9	2.8	3.0	3.1	0.2	0.2	0.4	0.7	1.2	1.5
IN	4.1	4.1	3.8	3.6	3.9	4.4	2.1	2.1	2.1	2.4	2.9	3.4
IA	3.2	3.2	3.1	3.6	4.4	4.8	0.3	0.3	0.3	1.2	2.2	2.7
KS	2.9	2.8	2.5	2.3	2.4	2.5	1.0	1.0	0.9	1.0	1.1	1.2
KY	4.4	4.3	4.2	3.9	3.7	3.8	1.5	1.5	1.5	1.5	1.6	1.7
MI	8.8	8.4	7.2	5.9	5.7	5.9	3.6	3.3	3.1	2.8	3.1	3.9
MN	5.1	5.1	4.9	5.1	5.6	5.8	3.5	3.4	3.2	3.3	3.6	3.8
MO	3.3	3.2	2.9	2.4	2.5	2.7	0.8	0.8	0.9	0.9	0.9	1.1
NE	6.4	6.3	6.2	6.6	7.6	8.2	6.4	6.5	6.5	6.8	**7.7**	8.2
ND	3.1	3.2	3.1	2.8	2.7	2.7	0.7	0.7	0.7	0.7	0.8	1.0
OH	6.3	3.2	2.9	2.7	2.9	3.3	0.5	0.5	0.7	0.9	1.1	1.5
SD	7.0	7.0	6.8	6.9	7.1	7.2	8.1	8.1	8.1	8.0	7.9	7.9
WI	4.4	**4.4**	4.3	5.0	6.9	8.1	1.5	1.5	1.7	2.3	3.5	4.4
Region	4.5	**4.1**	4.1	4.0	4.4	4.6	3.5	3.5	3.4	3.5	3.9	4.3

	Range (cm/hr)											
	Minimum						*Maximum*					
IL	2.6	2.6	1.9	1.3	1.0	0.8	3.6	3.6	3.6	4.6	7.8	9.7
IN	2.5	2.5	2.0	1.4	1.2	1.1	18.1	18.1	18.1	19.6	21.5	22.9
IA	2.4	2.4	2.4	2.0	1.8	1.7	4.2	4.2	4.3	7.5	11.9	14.0
KS	1.4	1.3	1.0	0.7	0.7	0.6	5.9	5.9	5.3	4.6	5.0	5.5
KY	3.0	2.9	2.9	2.4	2.1	1.9	8.4	8.4	8.4	8.4	8.7	9.1
MI	3.4	3.3	2.8	2.4	1.8	1.5	21.5	17.7	17.1	16.7	18.2	20.0
MN	3.1	3.1	3.1	3.3	3.4	3.4	23.4	23.3	23.5	24.5	25.0	25.2
MO	1.1	1.0	1.2	1.0	0.7	0.6	7.0	7.0	6.9	5.9	5.6	5.5
NE	1.9	1.8	1.5	1.5	1.5	1.6	29.6	29.6	29.6	29.6	30.7	31.4
ND	1.1	1.2	1.3	1.2	1.1	1.1	5.2	5.2	5.2	5.2	5.4	5.8
OH	1.4	1.4	1.2	1.1	1.1	1.1	5.3	5.2	4.5	5.5	5.6	8.0
SD	2.2	2.2	2.2	1.7	1.5	1.4	33.0	33.0	33.0	33.0	33.0	33.0
WI	2.7	2.6	1.9	1.7	1.8	1.7	10.5	11.2	11.9	13.2	16.9	19.1
Region	1.1	1.0	1.0	0.7	0.7	0.6	33.0	33.0	33.0	33.0	33.0	33.0

Note: The soil surface is the top of all soil layers and the bottom of the soil layers are at depths of 10, 25. 50, 100, 150, and 200 cm, respectively.

DISCUSSION

Detailed soils data are required for more accurate simulation of soil moisture and crop yields throughout the North Central region. The soils database presented here for average prime farmland soil located in each county provides details at a resolution never before available. Average soil characteristics were determined by a weighted average. Ideally, the actual soils data should be geographically referenced at the individual field level, but such data are not available at this time. Additionally, the weather data are available only at resolutions greater than field levels. Therefore, the errors introduced by using an "average" soil for a county are no greater than those introduced by the procedures used to estimate rainfall.

The variation of soils data and the soil factors limiting crop growth and yields throughout the region can be discerned from figures 1-12. The factors that most limit crop growth are the water-table depth, rooting depth, soil bulk density, and the water-holding capacity of the soil. The maps in the figures show that the best soils for crops are located in Illinois, Iowa, southern and western Minnesota, northern Missouri, Kansas, Nebraska, eastern North Dakota, and eastern South Dakota. If the entire region experienced the same weather, crop yields in these states would be about the same. However, geographic location of the soils complicates crop growth because of large variations in weather across the region in a given year and among years.

Coupled with current and historical weather data, the personnel at the Midwestern Climate Center will be able to develop products that will give an earlier warning of potential agricultural production problems. For example, earlier detection and forecasting of droughts should allow the positioning of agricultural resources in regions where these resources are not normally required, and therefore not normally available to producers in those regions. County-level yield estimates simulated using the soils data and actual weather conditions will assist grain dealers in more accurately marketing and transporting crops. These same yield data will allow government policy-makers and insurance adjusters to more accurately assess crop problems and disasters.

The MCC will eventually incorporate 4-kilometer (km) doppler weather radar rainfall estimates and more detailed soils data. Within the next ten years, field-level geographically referenced soils data should be available. These data along with geographically referenced rainfall and weather data will make it possible to more accurately estimate yield and variation of yields within counties. Such data will be useful to producers and agri-businesses that must distribute materials for agricultural production and move agricultural products from the farmer to the consumer.

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