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Soil maps of Wisconsin

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ABSTRACT

Legacy soil maps are an important input in digital soil mapping. This paper traces how reconnaissance soil maps in Wisconsin evolved between the 1880s and the present with some discussion on future directions. The first soil map in the USA was made in Wisconsin by the geologist T.C. Chamberlin in 1882. The second soil map of Wisconsin was made by A.R. Whitson in 1927, and the third by F.D. Hole in 1976. Soil texture and physiography were the major diagnostic mapping criteria. As more detailed county soil surveys were completed and knowledge of the soils increased, a higher level of detail can be observed on statewide soil maps. The detailed county soil maps were digitized in the 1990s and early 2000s and have been used in a wide range of studies and applications (e.g. agriculture, forestry, landscape architecture, and human health). In the 1990s, soil scientists transitioned from mapping on paper copy aerial photos to digital procedures. This change coincided with the development of digital soil mapping, and the introduction of several new observational techniques (GPR, EMI, and cone penetrometer). These modeling and observational tools continue to be used to evaluate small areas, but have not yet become widely used for current soil mapping activities.

1. Introduction

Mapping of soils has been one of the challenging and thought-provoking aspects of the soil science discipline. The process of developing a soil map forces one to understand the fundamentals of soils, how they were formed, occur across the landscape or the globe, and how they might respond to use and management. Soil mapping also aims to unravel deficiencies in our understanding of soil properties and processes—both in time and space. Globally, about two thirds of the countries have been mapped at a 1:1 million scale or larger, but more than two thirds of the total land area has yet to be mapped even at a 1:1 million scale (Nachtergaele and Van Ranst, 2003). Most of the existing maps were made during soil surveys conducted after the Second World War and up to the 1980s. There are great differences between countries in the status of mapped areas (extent, scale) but national coverage of exploratory soil maps (>1:250 000) is generally higher in the richer countries (Hartemink, 2008).

From the inception of the discipline, soil science in the USA differed from soil research conducted in Russia and Europe (Hartemink, 2002). In the older and long-settled areas of Western Europe farmers had learned much about their soils by trial and error (Kellogg, 1974). Possibilities for extending the farmed areas were limited as the population was relatively dense (Bouma and Hartemink, 2002). So, in Western Europe research interests focused on how to improve the soil conditions of existing fields. In the USA and the Russian Empire, there were large areas of soils that could be used for agricultural expansion. Here the questions centered on determining what soils were present, how to select those most responsive to management and how to develop farms to maximize soil potential (Kellogg, 1974). As a result, there was a need for detailed soil mapping and a better understanding of soil forming processes so that soil patterns and distribution could be predicted and mapped more accurately. Large contributions were made by the Russians V.V. Dokuchaev, P.A. Kostychev, N.M. Sibirtsev and by C.F. Marbut, E.W. Hilgard amongst others (Jenny, 1961; Krupenikov, 1992). That understanding formed an important base for the development of soil mapping, which was mostly developed in the USA and Russia, though along somewhat different lines (Simonson, 1989).

Agricultural and rural development in the USA was unevenly distributed, and related to the ease of settlement, abundance of natural resources and progress in development of roads and railways. The lands of the state of Wisconsin had been occupied by humans for thousands of years when the first French explorers arrived in 1634. Fur trade was the main interest of the French, and later the British colonists. Settlement was delayed by wars, but a large number of immigrants came in during the lead mining era (the "gray gold") in the southwestern part of the state in the 1820s and 1830s (Campbell, 1906; Schafer, 1922). By the 1850s both the fur trade and lead mining declined, railroads were opened and a large number of immigrants came from the Eastern United States (New England, New York), and from Ireland, Norway, and Germany. Wheat was the primary crop grown in addition to tobacco and cranberries. Diseases and low wheat prices forced the settlers into dairy farming and Wisconsin became the leading producer of dairy products in the USA in 1915 (Whitson, 1927). Scandinavians conducted extensive logging operations in the northern part of the state in the 1870s through the 1890s. Overall, agricultural development in Wisconsin was slower

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Fig. 1. Soil map of Wisconsin compiled by Chamberlin (1882). Legend in Table 2.

compared to states to the west that had less forest (Whitson, 1927). The University of Wisconsin was established in 1848 and the school of agriculture started the first agricultural research projects that were mainly focused on dairy farming. The interest in soils initially came from geologists and followed by F.H. King, who became the first professor of agricultural physics (Beatty, 1991).

In the 1820s government surveyors entered Wisconsin and they made the first detailed examination of the land (Schafer, 1922). They recorded

Fig. 2. Soil map of Wisconsin compiled by Whitson (1927). Legend in Table 2.

estimates of the land quality whether it was first class, second class, or third class, and described the surface as level, rolling, rough and broken, or swampy. They described the vegetation (trees, prairies) and this information could be procured by land seekers who could then select favorable locations for the opening of new farms (Schafer, 1922). No soil information *per se* was recorded by these government surveyors. The first soil map in Wisconsin was prepared as part of a statewide geologic survey conducted in the 1870s. Because agricultural development was relatively slow, the need for soil mapping was not emphasized until the early 1900s. Since then, all counties in the state have been mapped in

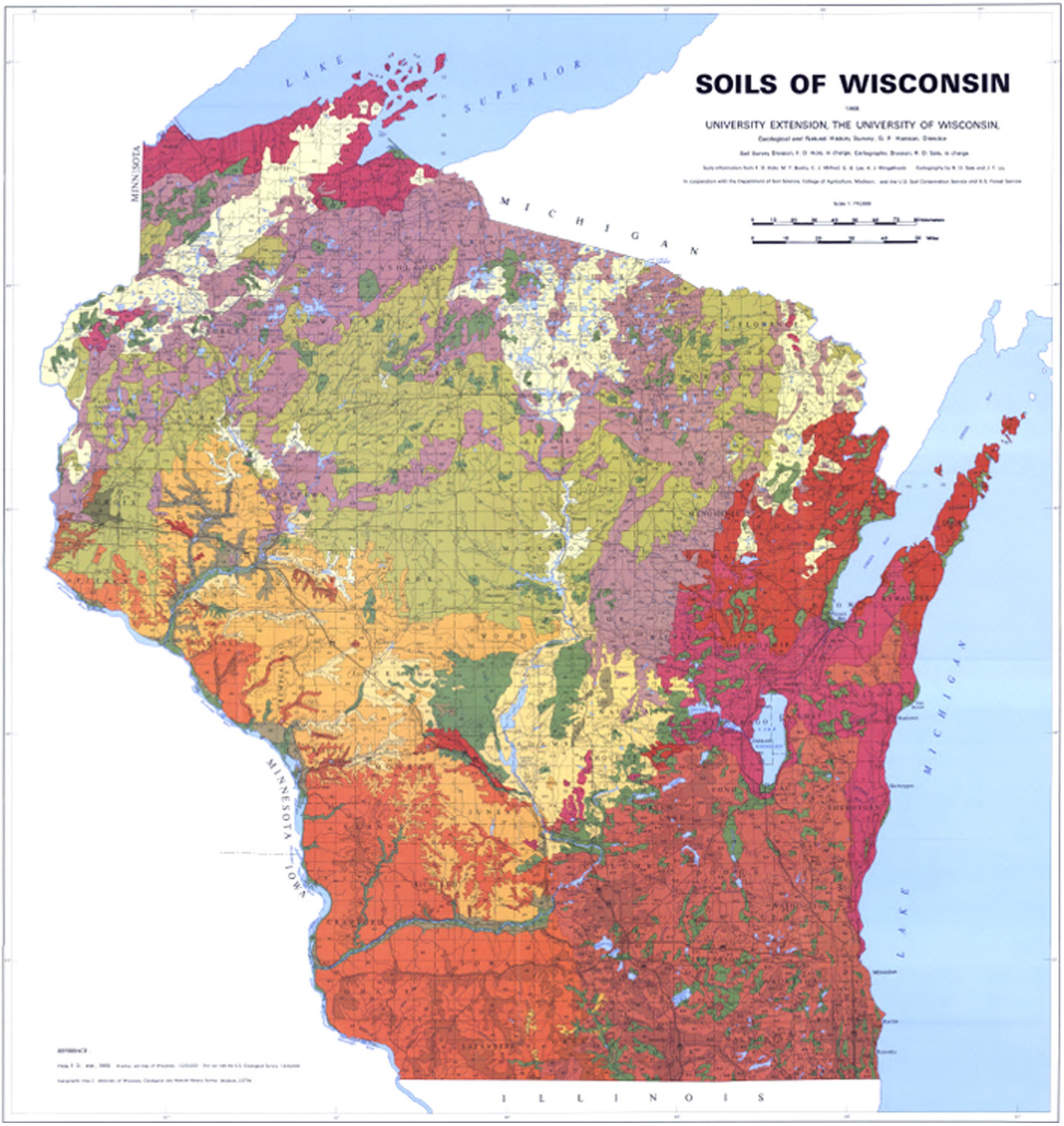

Fig. 3. Soil Map of Wisconsin compiled by Hole (1976). Legend in Table 2.

detail and several statewide soil maps have been produced. In this paper we trace the development of soil mapping in Wisconsin, including the development of reconnaissance maps between 1882 and 1993. We sketch a brief historic perspective of soil mapping, comment on the use of the soil maps, and review digital soil mapping and proximal soil sensing techniques that have been used in Wisconsin.

2. The first soil map 1882

The USA has a long tradition of research on soil genesis, mapping and classification. The first soil map in the USA was made in Wisconsin by T.C. Chamberlin (Brevik and Hartemink, 2010). There were maps prior to the map by Chamberlain, but these were largely based on surficial geology (Coffey, 1911). Chamberlin (1843 – 1928) was a prominent glacial geologist who, like many nineteen century scientists, had a wide range of interests. Before he became the President at University of Wisconsin-Madison (1887–1892), and joined the Geology Department at the University of Chicago (1892), Chamberlin was the chief geologist for Wisconsin (Fleming, 2000). Between 1873 and 1877 he published, with several co-authors, a four volume set of books totaling 3035 pages, titled "Geology of Wisconsin". The books include a chapter of 169 pages on the "Economic Relations of Wisconsin Birds" written by

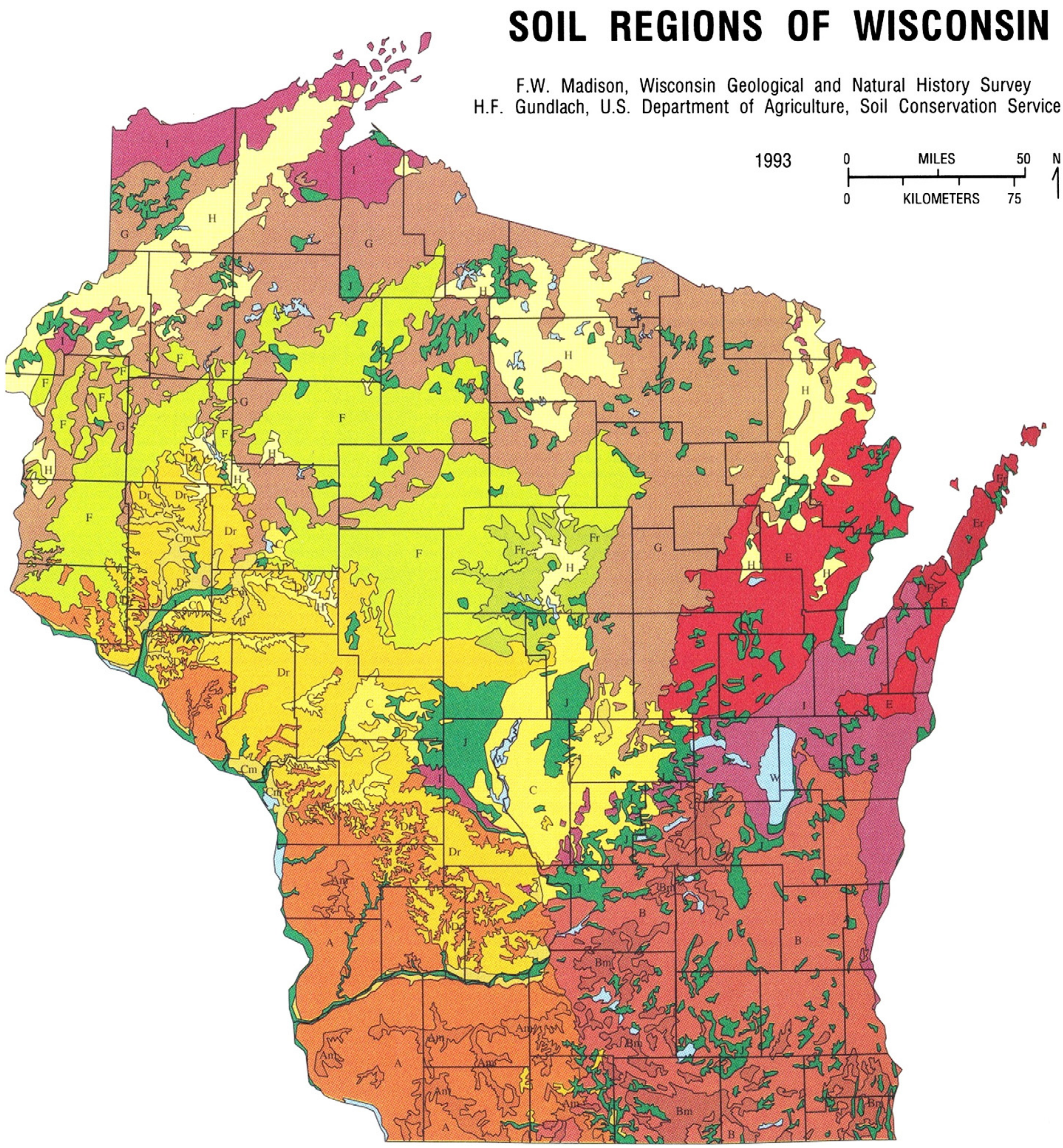

Fig. 4. Soil map of Wisconsin compiled by Madison and Gundlach (1993). Legend in Table 2.

F.H. King. Chamberlin introduced the concept of the glacial stages of North America, and produced an Atlas that includes the first soil map of Wisconsin (Figure 1).

Chamberlin's map shows eight soil textural groupings: sandy soils, sandy loams, calcareous sandy loams, prairie loams, clayey loams (3 types), and humus soils (Chamberlin, 1882). The central sands area of Wisconsin stands out, as do the red lacustrine clays in the eastern part of the state. The map contains three cross-sections from the Mississippi River to Lake Michigan that show bedrock geology, topographic features and end moraines. This map was printed in an atlas with a series of other maps (e.g. vegetation, topography of the quaternary regions, geology). A description of the soils of Wisconsin appears in Volume II of the Geology of Wisconsin (Chamberlin, 1877). Here Chamberlin starts the chapter on soils with: "*There are few subjects upon which it is more difficult to make an accurate, and at the same time an intelligible report, than upon soils. This difficulty arises partly from the nature of the subject, and partly from the vagueness of the terms used in speaking of soils*." His views on soil development were strongly influenced by geology ("*as the rock, so the soil*"), and he considered that the character of the soil depends upon the nature of the rock, the degree of weathering, and the amount and type of material lost by leaching and gained by vegetation or capillary action from beneath. Such views were common for most of the nineteenth century (Hartemink, 2009).

It is not clear how this first soil map of Wisconsin was made. It was most likely based on extensive travels through the state and Chamberlin's spatial knowledge of surficial geology. He evidently recognized the difficulties in mapping soils as he wrote: "*There are few natural formations more difficult to map than soils. There is an almost infinite gradation of varieties between which there are no hard-and-fast lines, and it is nearly or quite impossible to represent these gradations on a map*." It would take another 100 years before fuzzy logic and continuous soil class maps would enter the soil science domain (e.g. Burrough et al., 1992; De Gruijter et al., 1997; Odeh et al., 1992).

3. The Whitson soil map 1927

After the geologic survey of T.C. Chamberlin, the pioneering work in Wisconsin soil survey was begun at a meeting of the Wisconsin Academy of Sciences, Arts and Letters on 27th December 1893. A committee chaired by the geologist C.R. Van Hise (1857–1918) was appointed to secure legislation establishing a geological and natural history survey. This became a reality in 1897, when the Survey was created to study mineral resources, soils, plants, animals, physical geography, and natural history; and to do topographic mapping. Ever since, the soil mapping program of the Wisconsin Geological and Natural History Survey has moved forward in response to the legislative directive "*to cause a soil survey and a soil map of the State*" (F.D. Hole, unpublished letter). The federal soil survey began in 1899 (Helms et al., 2002) and thereafter soil survey in the nation became a cooperative effort between the United States Department of Agriculture (USDA) and other federal agencies, regional, state, and local agencies, tribal governments, universities, and private entities.

In Wisconsin, soil survey work was undertaken by the Geological and Natural History Survey, the Soils Department at the University of Wisconsin, the USDA Bureau of Soils, and the USDA Soil Conservation Service. Professor A.R. Whitson (1870–1945) was head of the Soils Department of University of Wisconsin-Madison (UW-Madison) from 1901 to 1939; he also was in charge of the Soil Survey Division of the Wisconsin Geological and Natural History Survey from 1909 to 1933. Under the field leadership of W.J. Geib, a number of general soil maps of the northern half of the state were published, as well as a reconnaissance map of the state (Figure 2).

On this reconnaissance soil map 12 units are distinguished, mainly based on topsoil textures, as follows: silt loams (2 classes), prairie soils, red clays, sandy soils, silt loams, sandy loams (2 classes), loams, rough land, wet land, and peat. The accompanying book provides fairly detailed descriptions of these classes including soil analytical data and soil management aspects (Whitson, 1927). It reflects the soil survey work that was conducted in the first decades of the twentieth century and the advances that were made in chemical analysis. The Whitson map shows that much more was known about the soils in the northern part of the state as compared to Chamberlin's map. Whitson was particularly interested in the soil fertility aspects of the soils in Wisconsin and wrote a soil fertility textbook that was widely used in that time (Whitson and Walster, 1918).

4. The last polygon soil map 1976

In the 1930s, state funds for soil survey lapsed, but the US Bureau of Soils, and later the US Bureau of Plant Industry and the Soil Conservation Service, carried on soil mapping. Their efforts were concentrated particularly in southwestern Wisconsin, where soil erosion control was most needed. The maps produced during this time period were not published (F.D. Hole, unpublished letter). In 1945, the Soil Survey Division of the Geological and Natural History Survey was reactivated, largely by the efforts of State Geologist E.F. Bean, and E. Troug and R.J. Muckenhirn of UW-Madison. Field work under the program was directed to detailed soil surveys for farm planning and soil conservation to assist the USDA Soil Conservation Service. In 1955, the Geological and Natural History Survey resumed publication of semi-detailed county soil maps to fill serious gaps in coverage of the state. Detailed soil survey reports accompany the maps to describe and scientifically characterize the soils, present research data, and indicate the limitations and potentials of the soils for a wide range of uses. In addition to the work by the Geological and Natural History Survey, the USDA Soil Conservation Service began publication of detailed soil maps for counties in Wisconsin in 1958. This was mostly done along with reports useful for farm planning and erosion control work.

As discussed in Section 2, Chamberlain made the first Wisconsin state soil map. He was also the major professor for Allen Hole, Francis Hole's father and undergraduate mentor, during Allen Hole's graduate studies (Brevik, 2010). Francis Hole returned to Wisconsin for graduate studies in 1938, joined the UW Madison Soils Department in 1946, and eventually took Chamberlain's place in Wisconsin when he became head of the Soil Survey division of the Geological and Natural History Survey (Hartemink, 2012). Under Francis Hole's supervision a seminal work on the soils of Wisconsin was published (Hole, 1976), that also contains a 1:710,000 soil map (Figure 3).

Prior to this 1:710,000 soil map a number of preliminary generalized soil maps were produced that cover the whole state of Wisconsin, these included leaflets with a generalized soil map published in 1946, 1957, 1964 and 1966 (Beatty et al., 1964; Hole and Beatty, 1957; Hole et al., 1966; Muckenhirn and Dahlstrand, 1947). These leaflets all highlight the broad groups or soil regions that that have some similarities with the earlier map by Whitson (1927). The soil regions were refined and detailed in the 1976 soil map (Hole, 1976). The 10 major soil regions are mainly characterized by differences in geography, soil texture, landform and land use (e.g. prairie) (Table 2). Within each region specific soil series are recognized. In total, 190 series can be distinguished on Hole's map (Hole, 1976) and these were also used to produce a photo-mosaic soil map of the whole state (Hole, 1977).

The 1976 soil map was recompiled by F.W. Madison and H.F Gundlach in 1993 (Figure 4). They regrouped the 10 soil regions into 5 broad geographic regions, with 15 subregions largely based on land use and soil texture (Madison and Gundlach, 1993).

A summary of the generations of soil maps (1882–1993) for Wisconsin is given in Table 1 and their legends are summarized in Table 2.

5. County soil maps

The first county in Wisconsin was mapped in 1906 (Table 3). About half of all the counties, mostly those in the south and southeast, were mapped in the 1970s or before that. Detailed mapping of all Wisconsin

Table 1
Overview of state wide soil maps for Wisconsin 1882–1993.

Year	Scale	Number of map units	Legend elements	Reference
1882	Not given	8	Soil texture (ranging from sandy soils to humus soils)	Chamberlin (1882)
1926	1:633,600 (1 inch to 10 miles)	12	Soil texture	Whitson (1927)
1976	1:710,000	190 soil series divided over 10 soil regions that are based on texture, geography and physiography	Soil texture, geography, landform, soil series	Hole (1976)
1993	Not given	5 broad geographic regions subdivided further into 15 map units	Soil texture, geography, land use, bedrock	Madison and Gundlach (1993)

Table 2
Legends of the Wisconsin state soil maps from Chamberlin (1882), Whitson (1927), Hole (1976) and Madison and Gundlach (1993).

1882	1926	1976	1993
T.C. Chamberlin	A.R. Whitson	F.D. Hole	F.W. Madison and H.F. Gundlach
Sandy Soils	Miami Silt Loam	**Soils of the Southwestern Ridges and Valleys**	**Soils of northern and eastern Wisconsin**
Sandy Loams	Knox Silt Loam	Forest and prairie soils; Alfisols, Mollisols, Entisols; Gray-Brown Podzolics, Brunizems, Lithosols, and Humic Gley soils	Forested, red, sandy, and loamy soils
Calcareous Sandy Loam	Prairie Soils	**Soils of the Southeastern Upland**	Forested, red, sandy, and loamy soils over dolomite
Prairie Loams (Including several sub-varieties)	Red Clays	Forest, prairie and wetland soils; Alfisols, Mollisols, Entisols, Inceptisols, Spodosols, Histosols; Gray-Brown Podzolics, Brunizems, Lithosols, Regosols, Humic Gleys, Podzols and Bog soils	Forested, silty soils
Clayey Loams, Lighter Varieties	Sandy Soils	**Soils of the Central Sandy Uplands and Plains**	Forested, loamy soils
Clayey Loams, Medium and Heavier Varieties	Colby Silt Loam	Forest, prairie and wetland soils; Alfisols, Entisols, Mollisols, Spodosols, Inceptisols, Histosols; Gray-Brown Podzolics, Regosols, Brunizems, Humic Gleys and Bog soils	Forested, sandy soils
Clayey Loams, derived from Red Lacustrine Clays	Boone Fine Sandy Loam	**Soils of the Western Sandstone Uplands, Valley Slopes and Plains**	**Soils of central Wisconsin**
Humus Soils (Embracing only those composed mainly of muck and peat)	Miami Fine Sandy Loam	Forest and wetland soils; Alfisols, Entisols, Inceptisols, Mollisols, Spodosols, Histosols; Gray-Brown Podzolics, Regosols, Lithosols, Humic Gleys, Podzols and Bog soils	Forested, sandy soils
Forested, silty soils	Kennan Loams	**Soils of the Northern and Eastern Sandy and Loamy Reddish Drift Uplands and Plains**	Prairie, sandy soils
Prairie, silty soils	Rough Land	Forest and wetland soils; Alfisols, Entisols, Inceptisols, Mollisols, Spodosols, Histosols; Gray-Brown Podzolics, Regosols, Lithosols, Brunizems, PHumic Gleys, Podzols and Bog soils	Forested, silty soils over igneous/metamorphic rock
Prairie, silty soils	Wet Land	**Soils of the Northern Silty Uplands and Plains**	**Soils of southwestern and western Wisconsin**
	Peat	Forest, prairie and wetland soils; Spodosols, Alfisols, Mollisols, Inceptisols, Histosols; Podzols, Gray-Brown Podzolics, Brunizems, Podzols, Humic Gleys and Bog soils	Forested soils over sandstone
		Soils of the Northern Loamy Uplands and Plains	**Soils of southeastern Wisconsin**
		Forest and wetland soils; Spodosols, Alfisols, Entisols, Inceptisols, Histosols; Podzols, Gray-Brown Podzolics, Regosols, Lithosols, Acid Brown Forest soils, Humic Gleys and Bog soils	Forested, silty soils
		Soils of the Northern Sandy Uplands and Plains	**Statewide**
		Forest and wetland soils; Spodosols, Entisols, Alfisols, Histosols; Podzols, Regosols, Gray-Brown Podzolics, Brown Podzolics and Bog soils	Streambottom and major wetland soils
		Soils of the Northern and Eastern Clayey and Loamy Reddish Drift Uplands and Plains	Water
		Forest and wetland soils; Alfisols, Mollisols, Spodosols, Inceptisols, Histosols; Gray-Brown Podzolics, Gray Wooded soils, Podzols, Humic Gleys and Bog soils	
		Soils of Stream Bottoms and Major Wetlands	
		Stream bottom, marsh and bog soils; Entisols, Histosols, Mollisols, Spodosols, Inceptisols, Alfisols; Alluvial soils, Bog soils, Regosols, Humic Gleys, Podzols, Brunizems, and Gray-Brown Podzolics	

Table 3
Counties in Wisconsin, year in which they were surveyed, number of series and map scale of the most recent survey; * only electronically available.

County	Area (km²)	First Soil Survey	Updated	Scale	Number of Soil Series
Adams	1779	1924	1984	1:20,000	31
Ashland	2739		2006*	1:12,000	106
Barron	2303	1948	1958, 2001	1:20,000	50
Bayfield	3917	1929	1961, 2006*	1:12,000	96
Brown	1360	1929	1974	1:20,000	45
Buffalo	1844	1917	1962	1:20,000	36
Burnett	2277	2006*		1:12,000	102
Calumet and Manitowoc	2549	1980		1:15,840	40
Chippewa	2697	1989		1:15,840	69
Clark	3156	2002		1:20,000	63
Columbia	2015	1916	1978	1:15,840	62
Crawford	1518	1930	1961	1:20,000	28
Dane	3104	1915; 1917	1978	1:15,840	63
Dodge	2357	1980		1:15,840	44
Door	1273	1918; 1919	1978	1:15,840	41
Douglas	3478	2006*		1:12,000	116
Dunn	2237	1975	2004	1:12,000	90
Eau Claire	1677	1977		1:15,840	57
Florence	1288	1962	2004	1:12,000	40
Fond du Lac	1875	1914	1973	1:15,840	57
Forest	2711	2005		1:12,000	39
Grant	3067	1956	1961	1:20,000	31
Green	1515	1928; 1930	1974	1:15,840	79
Green Lake	918	1928; 1929	1977	1:20,000	48
Iowa	1971	1912; 1914	1962	1:20,000	41
Iron	2081	2006		1:12,000	94
Jackson	2590	1922; 1923	1998	1:20,000	60
Jefferson	1461	1916; 1970	1979	1:15,840	50
Juneau	2083	1914	1991	1:15,840	36
Kenosha and Racine	1580	1922	1970	1:15,840	60
Kewaunee	854	1914	1980	1:15,840	43
La Crosse	1244	1914	1960; 2006*	1:12,000	63
Lafayette	1665	1966		1:15,840	41
Langlade	2300	1947	1986	1:20,000	29
Lincoln	2352	1996		1:20,000	39
Marathon	4082	1989	2003	1:20,000	41
Marinette	3707	1911	1991	1:20,000	50
Marquette	1178	1961	1975	1:20,000	34
Menominee	946	1967	2004	1:20,000	54
Milwaukee and Waukesha	2059	1918; 1919	1971	1:15,840	63
Monroe	2369	1929; 1931	1984	1:15,840	42
Oconto	2634	1988		1:15,840	35
Oneida	3202	1959	1993	1:20,000	27
Outagamie	1643	1921	1978	1:15,840	45
Ozaukee	609	1970		1:15,840	44
Pepin	643	1964	2001	1:12,000	59
Pierce	1533	1929; 1930	1968; 2006*	1:12,000	71
Polk	2507	1979		1:15,840	43
Portage	2088	1917; 1918	1978	1:20,000	38
Price	3313	2006*		1:12,000	64
Racine and Kenosha	1580	1923	1970	1:15,840	40
Richland	1529	1959	2006*	1:12,000	64
Rock	1867	1920; 1922	1974	1:20,000	59
Rusk	2410	2006*		1:12,000	78
Saint Croix	1901	1978		1:15,840	45
Sauk	2204	1925	1980	1:15,840	59
Sawyer	3496	2006*		1:12,000	96
Shawano	2416	1982		1:15,840	46
Sheboygan	1309	1929; 1931	1978	1:15,840	48
Taylor	2544	2005*		1:12,000	45
Trempealeau	1903	1927	1977	1:15,840	41
Vernon	2088	1928	1969	1:15,840	34
Vilas	2635	1915	1988	1:20,000	22
Walworth	1450	1924; 1924	1971	1:15,840	44
Washburn	2213	2006		1:12,000	81
Washington	1109	1971		1:15,840	50
Waukesha	1440	1914	1956	1:63,360	63
Waupaca	1971	1920; 1921	1984	1:15,840	35
Waushara	1652	1913	1989	1:20,000	32
Winnebago	1497	1927	1980	1:20,000	51
Wood	2090	1917; 1918	1977	1:20,000	48

counties was completed in 2006. In the past 20 years, five detailed soil surveys were remapped to provide more detailed and accurate information (Richland, Pierce, Pepin, Dunn, and La Crosse counties). In addition, parts of Marathon County have been remapped. The map scale of the available county maps ranges from 1:12,000 to 1:63,360 but most of the counties have been mapped at scales of 1:15,840 or 1:20,000.

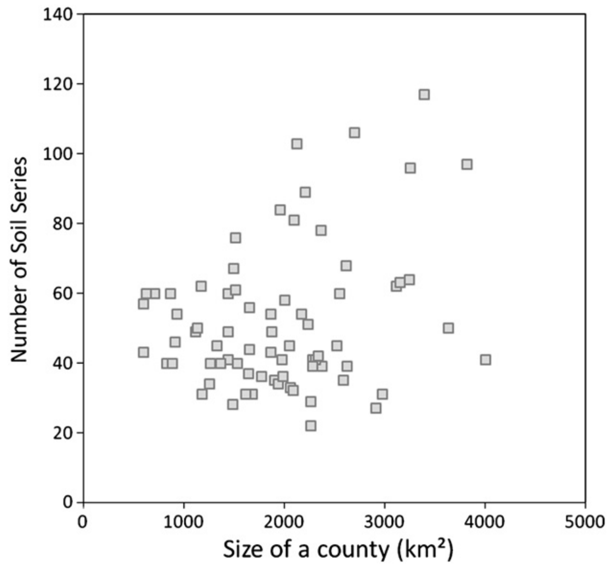

Fig. 5. Relation between the size of a county in Wisconsin and the number of established soil series.

Over 8000 soil map units naming more than 800 soil series have been mapped in Wisconsin. The number of soil series mapped in each individual county varies from about 22 to over 116. On average 52 series are recognized per county. The counties range in size from 601 to over 4000 km^2. The number of series mapped in each county is not related to the size of the county, although there is more variation in the number of series in larger counties (Figure 5).

All the county maps and data are available through the Soil Survey Geographic Database (SSURGO) of the Natural Resources Conservation Service (NRCS), available online through the Soil Data Mart (http://soildatamart.nrcs.usda.gov) and Web Soil Survey (http://websoilsurvey.nrcs.usda.gov). Besides the map, series descriptions and soil property data, a range of interpretations is available. Using the existing soil maps in SSURGO it is possible to retrieve individual soil orders or suborders maps (Figure 6). Smart phone applications also exist that allow for viewing soil maps, as well as soil series descriptions using global position systems (GPS) tracking at any location (Beaudette and O'Geen, 2010).

6. Digital Soil Mapping

Digital Soil Mapping or predictive soil mapping is the computer-assisted production of soil type and soil property maps. It involves the creation and population of soil information by the use of field and laboratory observational methods coupled with spatial and non-spatial soil inference systems (McBratney et al., 2006). A digital soil mapping system tested in several counties of Wisconsin is SoLIM (Soil Land Inference Model). SoLIM is a fuzzy inference scheme for estimating and representing the spatial distribution of soil types in a landscape (Zhu et al., 1997) and it has been used in various studies (Qi et al., 2006; Shi et al., 2004; Smith et al., 2006) across the state of Wisconsin. In the Central part of Wisconsin prototype category theory has been used in soil mapping (Qi et al., 2006). A prototype-based approach was developed to acquire and represent knowledge of soil-landscape relationships. This knowledge was applied in digital soil mapping using a fuzzy logic system. The created maps seem more accurate in terms of both soil series prediction and soil texture estimation than the case-based reasoning approach (Qi et al., 2006) although a detailed comparison between traditional survey methods and SoLIM has not been made. In addition, numerical classification methods have been used to delineate landscape units in a study area in southwestern Wisconsin (Irvin et al., 1997).

Besides digital soil mapping techniques, proximal sensors have been used to map soils at a fine scale resolution. Proximal sensors include the use of a human-informed mechanical-device (cone penetrometer) that allows for developing three-dimensional (3-D) soil maps (Arriaga and Lowery, 2005; Grunwald et al., 2000, 2001; Rooney and Lowery, 2000; Zhu et al., 2004). These maps are based on digital elevation models (DEM), thus they are largely physiographic based soil property maps. A

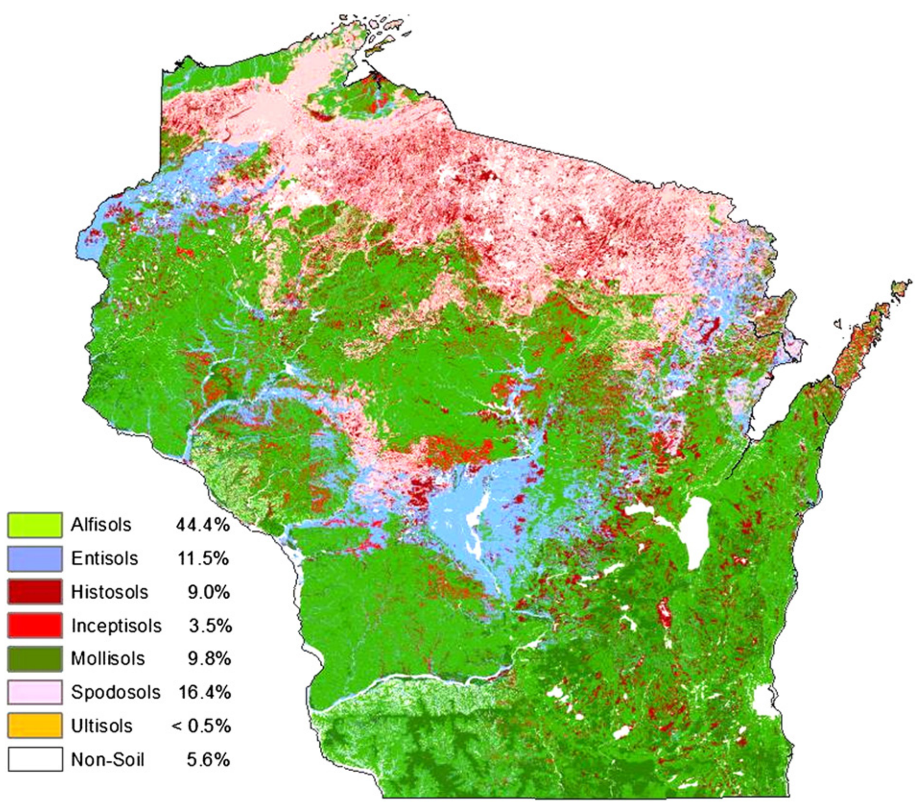

Fig. 6. SSURGO soil order map for Wisconsin.

cone penetrometer is calibrated for a given soil profile and mapping is completed using statistical applications to detect differences in soil properties with depth. Upon detection of a different soil profile, expert knowledge is introduced to recalibrate the new soil map unit. This process is continued to produce 3-D maps. These and other mechanically developed maps are being used for site-specific (precision) farming. Also, ground penetrating radar (Kung and Donohue, 1991; Lowry et al., 2009) and electromagnetic induction have been applied in mapping small areas of soils in Wisconsin (e.g. Morgan et al., 2000; Sudduth et al., 2005).

7. Discussion and conclusions

Soil science in the USA has made considerable advancements and there is a growing body of literature that has synthesized its progress and development (e.g. Brevik, 1999; Helms et al., 2002; Simonson, 1997; Tandarich et al., 2002; Viets, 1977). In Wisconsin systematic soil research was more or less started by F.H. King who wrote one of the first soil science text books for the USA (King, 1895). King, as an agricultural physicist, had little attention for soil mapping despite the fact that he worked under T.C. Chamberlin who made the first soil map of Wisconsin. King's successor at the Soils Department, A.R. Whitson, provided a large stimulus for soil mapping in Wisconsin and produced a soil map that was solely based on soil survey fieldwork and the chemical and physical analysis of a large number of soil samples across the state (Whitson, 1927). Hole's map (1976) shows a fine level of detail and summarizes the colossal progress that was made in the half-century since 1927. The physiographic and landscape approach to soil survey has been strongly developed in Wisconsin (Hole and Campbell, 1985; Schaetzl, 1986). In addition, one of the first examples of multidimensional soil classification using ordination was from Wisconsin (Hole and Hironaka, 1960).

Detailed soil mapping in Wisconsin required an intensive level of field investigation and sampling. Soil scientists mapping in the field were supported by laboratory and correlation staff in Wisconsin and in the National Soil Survey Center in Lincoln, Nebraska. Four soil scientists could map an average county in about four years. Including state, national, and partner support staff, approximately 1500 staff years were needed to complete the initial detailed soil survey of Wisconsin. In 2012 dollars the expense was over $150 million, making this one of the most valuable data sets for land use planning in existence. Most funding, leadership, and staff for the detailed soil survey of Wisconsin were provided by the USDA, NRCS. Significant funding and assistance was also provided by the University of Wisconsin; county, state and tribal governments, and other federal agencies.

The economic benefits of soil mapping in Wisconsin have not been well documented. One difficulty in assessing the cost-benefit ratio of soil mapping is that the cost of producing soil maps varies widely depending on the level of detail, accessibility, soil patterns, and other factors (Bie and Beckett, 1970). What is known is that the cost of soil survey (per unit area) rises sharply with the purity or uniformity to be achieved (Bie et al., 1973). Klingebiel (1966) reviewed a series of soil surveys and estimated that the benefit-cost ratios are larger than 50 for the USA. Although only a few studies have assessed the economic benefits of soil mapping and research, there are examples of projects that have failed because of a lack of soil information in all parts of the world (Bie and Beckett, 1970; Young, 1976).

The traditional published soil survey reports that accompany the county soil maps have extensive sections on the use and management of the soils. Usually included are general management practices applicable to all soils, management of the soils for crops and pasture, and capability groupings for most kinds of field crops based on the Land Capability Classification system (Klingebiel and Montgomery, 1961). The published reports include predicted average yields of principal crops under improved management. The semi-quantitative land evaluations also include (i) woodland suitability groupings (based on potential productivity, tree species, average site index, and annual growth), suitable species for reforestation, and management limitations or hazards (equipment limitations, erosion hazard, seedling mortality); (ii) tree species suitable for landscaping and windbreaks; (iii) wildlife habitat suitability ratings; (iv) engineering potentials and limitations of the soil including engineering soil classification systems (Unified and AASHTO), properties affecting engineering uses, and interpretations for common soil engineering practices; and (v) soil interpretations for town and country planning. This paper does not attempt to quantify how widely these land evaluations and soil interpretations have been used, but they have been systematically employed for land use planning by a wide variety of users in every county. In an early stage, soil survey information in Wisconsin was used in small scale waste management and the development of innovative soil disposal systems (Bouma, 1973). It has also been used in local land use ordinance control and farmland preservation legislation (Klingelhoets, 1972, 1978) and forestry (Cain, 1990).

In the past twenty years, SSURGO data have been used in a wide range of scientific studies, for example, the assessment of regional C stocks (Davidson and Lefebvre, 1993; Gelder et al., 2011; Rasmussen, 2006; Zhong and Xu, 2011), for modeling solute transport (Inskeep et al., 1996; Macur et al., 2000), nitrate removal from riparian zones (Gold et al., 2001), snowmelt simulation (Wang and Melesse, 2006), land use management (Wu et al., 2001; Yang et al., 2011), field identification of hydric soils (Galbraith et al., 2003) and many more. The soil maps of Wisconsin have been used for land evaluations for crop suitability (Ye et al., 1991), for predicting solute transport through the landscape (Macur et al., 2000), for assessing C stocks (Arriaga and Lowery, 2005), and in spatial studies on human health issues related to blastomycosis or lyme disease (Baumgardner et al., 2005; Guerra et al., 2002).

The era of reconnaissance polygon soil mapping is rapidly ending. Currently, the focus is shifting to raster-based soil property information (McBratney et al., 2003; Sanchez et al., 2009). This demand coincides with the emergence of a whole range of new observational techniques, digital soil mapping, and a renewed interest in the soil science discipline (Hartemink and McBratney, 2008). The long tradition and knowledge base of soil mapping in Wisconsin is extremely useful in developing raster-based soil information. Several new observational techniques have been tested and used in soil mapping but none of these methods are routinely used yet.

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