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History of soil geography in the context of scale

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A R T I C L E I N F O

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A B S T R A C T

We review historical soil maps from a geographical perspective, in contrast to the more traditional temporal–historical perspective. Our geographical approach examines and compares soil maps based on their scale and classification system. To analyze the connection between scale in historical soil maps and their associated classification systems, we place soil maps into three categories of cartographic scale. We then examine how categories of cartographic scale correspond to the selection of environmental soil predictors used to initially create the maps, as reflected by the maps' legend. Previous analyses of soil mapping from the temporal perspective have concluded that soil classification systems have co-evolved with gains in soil knowledge. We conclude that paradigm shifts in soil mapping and classification can be better explained by not only their correlation to historical improvements in scientific understanding, but also by differences in purpose for mapping, and due to advancements in geographic technology. We observe that, throughout history, small cartographic scale maps have tended to emphasize climate–vegetation zonation. Medium cartographic scale maps have put more emphasis on parent material as a variable to explain soil distributions. And finally, soil maps at large cartographic scales have relied more on topography as a predictive factor. Importantly, a key characteristic of modern soil classification systems is their multi-scale approach, which incorporates these phenomena scales within their classification hierarchies. Although most modern soil classification systems are based on soil properties, the soil map remains a model, the purpose of which is to predict the spatial distributions of those properties. Hence, multi-scale classification systems still tend to be organized, at least in part, by this observed spatial hierarchy. Although the hierarchy observed in this study is generally known in pedology today, it also represents a new view on the evolution of soil science. Increased recognition of this hierarchy may also help to more holistically combine soil formation factors with soil geography and pattern, particularly in the context of digital soil mapping.

1. Introduction

1.1. Influence of Scale on Soil Knowledge

This paper examines the co-evolving relationship between soil knowledge and soil maps. Specifically, we evaluate changes in soil knowledge that coincide with changes in map *scale*. To analyze this relationship, we first examine the nature of soil maps.

Soil maps, like all maps, are products of the mapper's understanding of the phenomena being mapped, the geographic technologies available at the time, and the map's purpose (Brown, 1979; Thrower, 2007). Reviews on the history of soil science have tended to focus on the evolving scientific understanding of soil phenomena. This focus has led to the conclusion that soil knowledge and soil classification systems have co-evolved over time (Cline, 1949; Simonson, 1962; Brevik and Hartemink, 2010). However, such an analysis should also consider the interactions between soil classification systems and the maps for which they are designed. We suggest that shifts in dominant theories may be as much a product of changes in geographic technology and purpose (i.e., scale), as actual improvements in soil knowledge.

To separate the influences of soil knowledge and geographic technology on soil mapping, it must be recognized that maps at certain cartographic scales were more common at different times in the past, due to technological constraints (Fig. 1). Base maps are a prerequisite for the production of thematic maps, such as soil maps. Therefore, soil maps through time have been constrained by the cartographic scales (and hence, level of detail) of the available base maps (Miller and Schaetzl, 2014). It then follows that the development of geographic soil principles should be considered in the context of map scale. This paper identifies the scale dependency of soil science concepts that at times in history have been viewed as contradictory or of debated importance.

Soil science made a major advancement in 1883 when Vasily Dokuchaev (1846–1903) integrated several theories of soil formation by describing soil as the product of the interactions between climate, parent material, organisms, relief, and time (Dokuchaev, 1883/1967). The identification of these multiple factors began a revolution in how soil is conceptualized, studied, and mapped (Huggett, 1975; Hudson,

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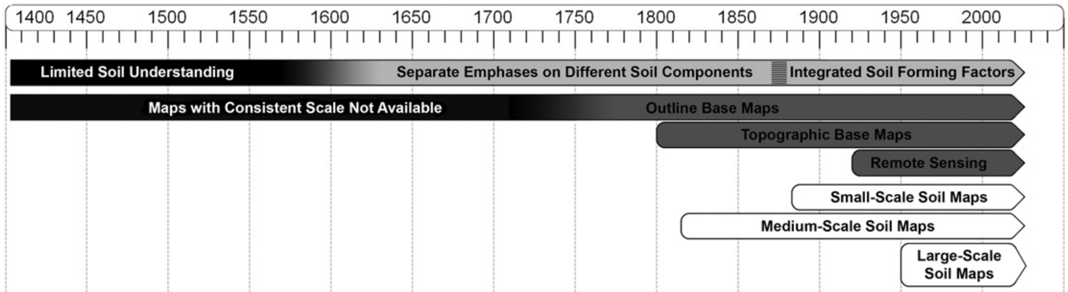

Fig. 1. Timeline of important developments in the scientific sphere of soil geography. In all instances, 'scale' refers to cartographic scale. Soil maps (white) are a product of both the scientific understanding of soil (light gray) and the geographic technologies available at the time (dark gray). Although soil geography has been valued since early civilizations, actual soil maps could not be produced until the appropriate base maps were available. Topographic maps at a medium cartographic scale were available before small scale because of the time required to cover larger extents. Soil mapping with more detail (large cartographic scale) was generally not practical until aerial photographs provided easier spatial referencing and spatially exhaustive predictor variables (e.g., vegetation).

1992; Bockheim et al., 2005). However, an emphasis of one or more of these factors is typical, as reflected in the design of early soil classification systems (e.g., Whitney, 1909; Marbut, 1928). These ostensible conflicts in soil science appear less contradictory in the context of scale.

The purpose of this paper is to examine the predictor variables chosen by soil geographers throughout the history of soil science. However, instead of analyzing events by time alone, we take a geographical approach and analyze the events in terms of map scale. Because certain map scales have dominated during different times in history, we also review the context of evolving geographic technologies and map purposes that determined the focus on certain map scales at different times. We have organized our analysis by grouping soil maps according to ranges in cartographic scale, with minimal regard for when they were produced. This approach allows for the comparison of emphasized predictor variables by the respective maps' cartographic scale, as opposed to simply a discussion of scientific perspectives when the maps were made. Soil knowledge is always advancing, but soil spatial knowledge has also been focused through the lens of the map scale used to depict the soil landscape. Therefore, progress in soil geographic knowledge will be better understood in the context of map scale.

2. Methods for Analyzing Map Characteristics

2.1. Scale in Soil Geography

Our comparison of historical soil maps and classification systems requires, first, an explicit definition of map characteristics. The term *scale* has had various meanings in scientific literature. We apply the definitions of different types of scale as used in modern geography (Montello, 2001). Cartographic scale is the relationship between distance on the map and distance on the Earth. In contrast, analysis scale refers to the areal size of the map units, which reflects the level of detail or generalization that the map displays. Natural phenomena commonly display geographic structure, which makes a particular phenomenon more detectable or discernible at certain analysis scales. Therefore, adjusting analysis scale to detect phenomenon scale has been a tool for identifying process scale.

When the primary mode of analyzing spatial patterns was paper maps, cartographic and analysis scales were essentially linked (Miller and Schaetzl, 2014). Smaller cartographic scales necessitated larger analysis scales. Use of broad extent maps, i.e., those with small cartographic and large analysis scales, revealed only processes operating at large phenomenon scales, and vice versa. Although other factors influence the cartographer's choice in map unit size, cartographic scale constrains that choice. For a given cartographic scale, map units that are too large would be pointless, because too little geographic pattern would be displayed. For the same cartographic scale, map units that are too small become excessively tedious for the cartographer and less likely to be adequately supported by data available to the cartographer. An example of this point is given by the U.S. Soil Survey, which sets minimum sizes for map units, for soil maps of different cartographic scales (Soil Survey Staff, 1951, 1993; Schoeneberger et al., 2012). Although this connection is no longer valid for digital maps (Goodchild and Proctor, 1997), it does justify the use of cartographic scale as a proxy for analysis scale on paper maps. Because geographic information systems (GIS) have decoupled cartographic scale from analysis scale, lessons learned during the era of paper maps in terms of cartographic scale should now be applied in terms of analysis scale.

2.2. Detecting Phenomena Scale

When modeling soil, it is important to select the most appropriate predictor variables (covariates) for the scale of interest because phenomena governing soil formation and distribution operate at different scales (Schoorl and Veldkamp, 2006). Patterns observed at one analysis scale are often not observed at other analysis scales. This behavior is known as the scale effect of the modifiable area unit problem (MAUP) (Armhein, 1995; Jelinski and Wu, 1996). Therefore, higher levels of generalization can, in some cases, provide more explanation of a spatial variable than higher resolution maps (Moellering and Tobler, 1972; Hupy et al., 2004). After scientific understanding reached the point where soil geographers became aware of the major soil formation factors, they were free to choose the environmental covariates that best explained soil variability at their respective cartographic scale. Therefore, emphasis on different covariates as predictors at different cartographic scales reflects soil geographers' mental model of phenomenon scale for factors influencing the spatial soil distribution.

Although Curtis Marbut (1863–1935), director of the U.S. Soil Survey from 1913 until his death in 1935, may not have recognized the scale effect of MAUP per se, he described his encounter with this problem in 1928, stating, "When we superpose over a soil map, maps of various kinds of climatic forces, and the various kinds of natural vegetation, we find certain definite relationships. When, however, we superpose a soil map of *mature* soils, a geological map, we find no relationship between the general broad, predominant characteristics of the soils and the characteristics of the geologic formations. In the same way when we superpose a topographic map over a map of mature soils we do not find a relationship. When, however, we superpose a topographic map or a geological map over a soil map on which all soils, both mature and immature, have been mapped, we find a clear relationship between both" (Marbut, 1951, p. 19). Because "immature" soils were considered to be exceptions to the "mature" or normal soils that were spatially predominant, Marbut's observations illustrate how different analysis scales show greater correlation with different soil formation factors.

The current U.S. Soil Survey Manual recognizes different phenomena scales for soil formation factors by describing the distribution of soils as "the result of climate and living organisms acting on parent material, with topography or local relief exerting a modifying influence and with time required for soil forming processes to act" (Soil Survey Staff, 1993, p. 8). However, the respective phenomenon scales for each soil formation factor have not been formally determined. To better understand the development of soil geographers' mental models of soil phenomena, we review the progress of soil maps in the context of the geographic technology (i.e., base maps) available. We then examine the resulting strategies for creating soil maps, in three major categories of cartographic scale. By utilizing Keates' (1989) principle that the cartographic art of generalization reflects the knowledge of the map maker, we attempt to identify the phenomenon scale of the various soil forming factors as they have been utilized throughout history.

3. Review of Soil Maps at Different Cartographic Scales

3.1. Small Cartographic Scale Maps (< 1:1 million)

3.1.1. Geographic Technology

One of the key services that geographic technology provides is positional reference. For this reason, thematic maps (i.e., soil maps) created by traditional methods were commonly drawn onto existing maps (Brown, 1979). The existing map served as a base for the mapper to plot their observations and convey their understanding of the theme's distribution (Thrower, 2007). This reliance on the base map was caused by the time-consuming work of determining accurate locations. Until the widespread availability of global positioning systems (GPS), soil mappers have greatly depended upon base maps for positional reference (Miller and Schaetzl, 2014). As technology for accurately determining location improved, and the availability of spatial information increased, the quality of base maps available to soil mappers also improved.

The technology to geographically plot observations on accurate base maps, and to examine generalized spatial patterns on these maps, was available by the beginning of the 18th century (Bennett, 1987). However, producing these scientific maps was very time consuming. The earliest base maps with a reasonable amount of accuracy were outlines of land masses (i.e., continents and islands). Later, national boundaries were mapped and then additional information was added within the outlines. Eventually these base maps evolved into what we know as topographic maps (Harvey, 1980).

The first accurate outline map of a France, the first of its kind, took 70 years to complete (Konvitz, 1987). Many countries followed France's lead, by first accurately surveying national borders, then by adding additional detail within those outlines. A scientific survey of France proceeded to fill in the first outline map with locations of cities, rivers, forests, etc., and indications of areas with major relief. This work resulted in a crude, but important, topographic map that was fully published in 1815 (Brown, 1979; Konvitz, 1987). This map is known as the Cassini map; it required four generations of that family to supervise its progress. It was maps like these that soil geographers had available to them in the 19th century to spatially record their observations (Fig. 2). Therefore, many of the soil maps of the 19th century were drawn on basic topographic maps, at small cartographic scales and included only national boundaries, major cities, roads, rivers, and little or no elevation information.

3.1.2. Purpose and Strategies of Soil Mapping

Alexander von Humboldt (1769–1859), considered to be one of the founders of geography (Hartshorne, 1958), popularized thematic maps of the world. He chose to use small cartographic scales and the corresponding generalization of details to identify the broad laws relating to the spatial distribution of climate (Robinson and Wallis, 1967). This approach is equivalent to using large analysis scales. He first introduced isothermal lines when he read his essay on the distribution of heat over the globe before the Académie Royale des Sciences in 1817. Humboldt based his isotherms on quantitative observations of temperature in the Americas and purposefully ignored small, local differences (Fig. 3). He then examined the geographic trends of climate and vegetative forms to delineate climate–vegetation zones (Brown, 2006). Wladimir Köppen (1846–1940) later defined climate classifications by extending

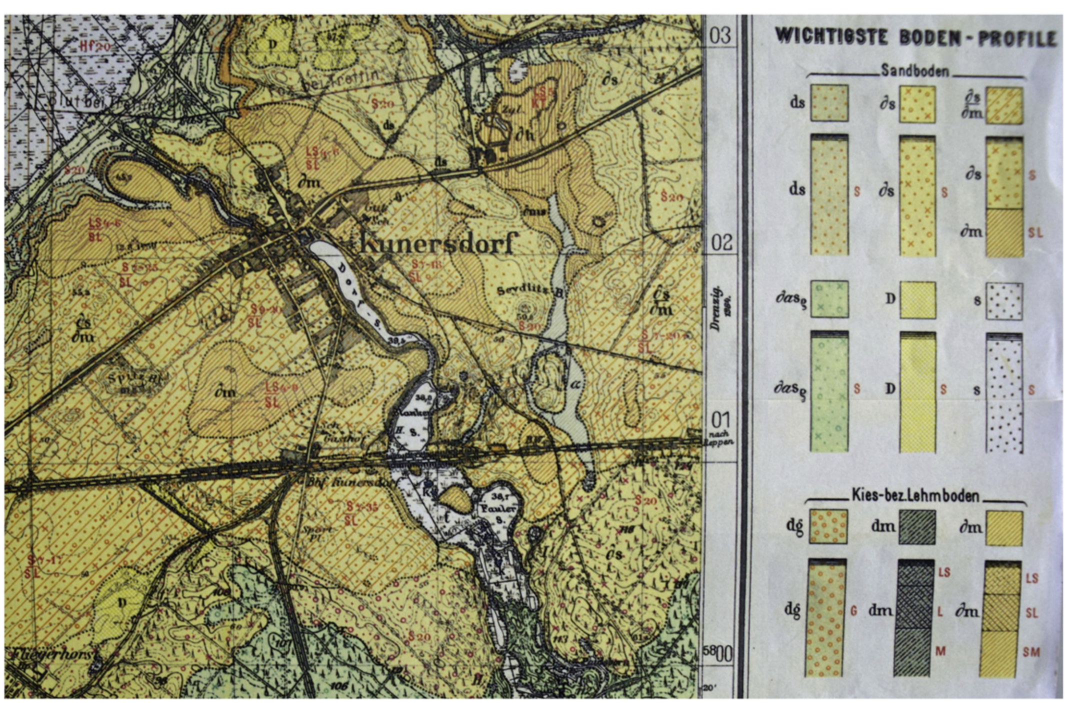

Fig. 2. An excerpt from a soil map of an area near the modern day city of Frankfurt an der Oder, Germany, produced by the Prussian Land Survey at a scale of 1:25,000. The base map, which consists of the black lines showing locations of vegetation types, waterways, elevation contour lines, and man-made structures, was produced at least by 1894 and was exceptionally detailed for its time. The geologic and agronomic properties shown in color were added later, for which this is the third update (Linstow, 1928). This map is an example of how early soil maps generally depended upon the available topographic map as a base map. The mapper needed to relate what they observed in the field with the information on the topographic map for spatial reference.

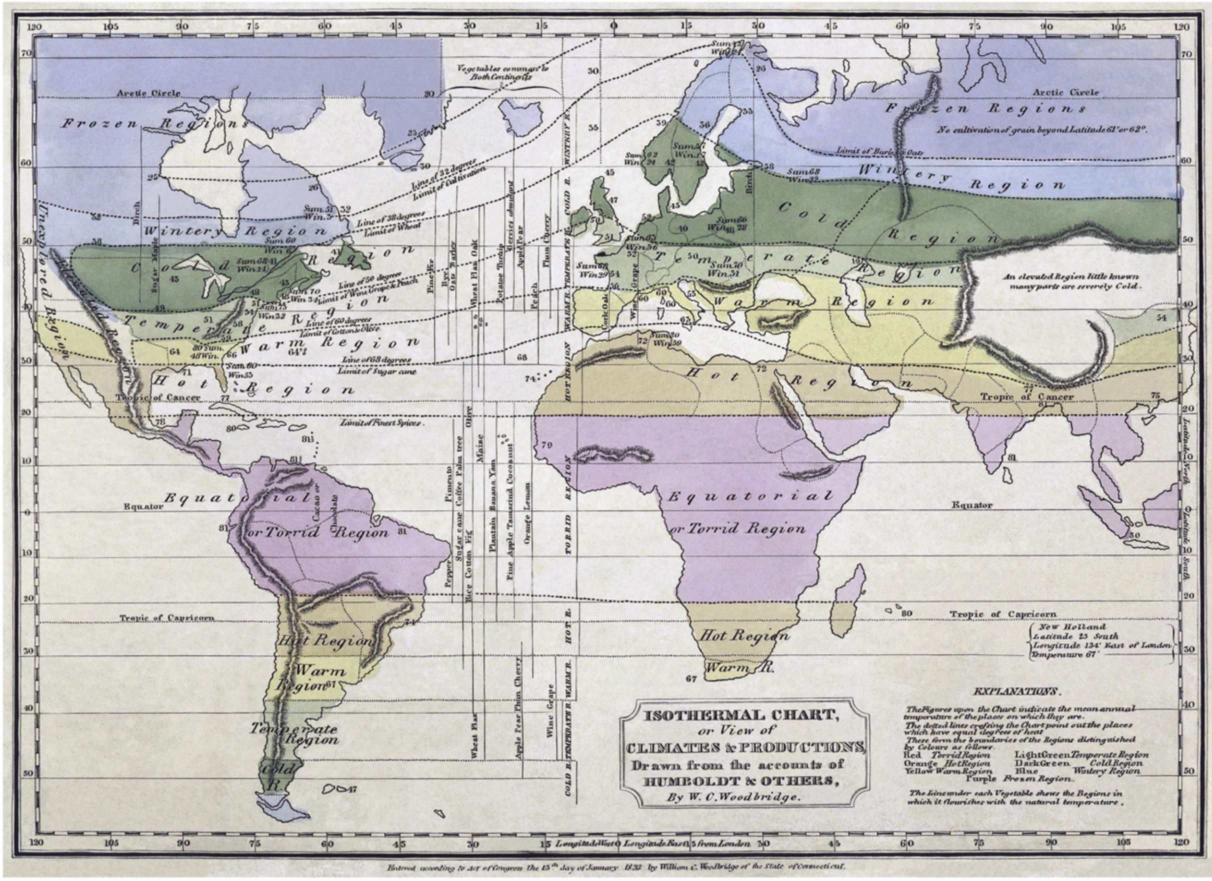

Fig. 3. Isotherm map of the world, based on the work of Humboldt (Woodbridge, 1823). Cartographic scale not provided.

the work of Humboldt on climate–vegetation relationships (Köppen, 1884).

It is in this context that Vasily Dokuchaev published his landmark work on the Russian Chernozem (Kovda and Dobrovolsky, 1974; Hartemink et al., 2013). A geologist by training, Dokuchaev had initially focused on geologic properties to explain the origin and distribution of Chernozem soils. When that approach proved unfruitful, he turned to soil humus data that had also been collected (Krupenikov, 1993). It is useful to note that the humus data collected were at sites deemed typical for the area. Selectively sampling 'typical' sites follows in the logic of Humboldt for ignoring local variation for the purpose of finding the processes operating across broad extents. Dokuchaev categorized his data points cartographically to derive "isohumus belts" for a map covering European Russia (Fig. 4). In this map, he observed a clear geographic pattern, with the highest humus content of the soils in a central southwest to northeast belt, with belts of decreasing humus content to the north and south (Brown, 2006).

Dokuchaev later developed a soil classification system based on his understanding that Chernozem zones corresponded to climatic belts. With an interest in developing explanatory generalizations, classifying soils in a similar fashion as the Köppen-Geiger climate classification was a logical strategy. In that spirit, Dokuchaev divided soils by normal, transitional, and abnormal (Krupenikov, 1993). Then his classification system subdivided soils by "mode of origin," ranging from vegetative-normal to transported. The vegetative-normal category was split according to climate zones and humus content. The first level of the classification system was a mechanism for dealing with scale. Normal soils were comprised of predominant soils in a bioclimate zone. Abnormal soils were considered exceptions to the generalized patterns.

Several versions of zonal soil classification systems have been used since Dokuchaev, each adapting to local conditions and experimenting with appropriate subdivisions (Krupenikov, 1993). However, all zonal classification systems have focused on climate–vegetation relationships, and then have used the classification of intrazonal and azonal soils to accommodate the exceptions to the broader soil regions (Baldwin et al., 1938; Duchaufour, 1982). Zonal classification systems identify the corresponding pattern of climate–vegetation zones as the optimal predictor for the general character of soils at large analysis scales. However, recognizing that local hydrologic and geologic phenomena can result in exceptions to zonal generalizations, intrazonal soils became the inclusions that generally could not be drawn on maps of small cartographic scale. Similarly, the exceptions of where the climate and vegetation processes have not had time to alter the parent material are also allowed as exceptions, i.e., azonal soils.

Utilizing the concepts of zonal soil classification, geographers began regularly producing soil maps of countries and continents based on climate–vegetation zones. One of the early adopters was Marbut, a student of the famous Harvard physical geographer William Morris Davis (1850–1934) (Davis, 1909; Holmes, 1955; Friend, 2000). While head of the U.S. Soil Survey, but before becoming chief of the Bureau of Soils (Helms, 2002), Marbut produced a generalized soil map of Africa (Fig. 5), based on soil samples collected by botanist G.L. Shantz. The 1:10 million scale map contained 16 classes of zonal soils (Shantz and Marbut, 1923). Marbut (1928) presented a soil classification system to the International Congress of Soil Science in 1927 that included zonal soils (Bockheim et al., 2014). Marbut focused his classification system on what he considered to be mature or normal soils. Classification of soils with imperfectly developed profiles or those deemed abnormal due to topography were weakly defined. In other words, undeveloped or abnormal soils were treated as exceptions to the more important, generalized trends of normal soils. Even though Marbut used soil

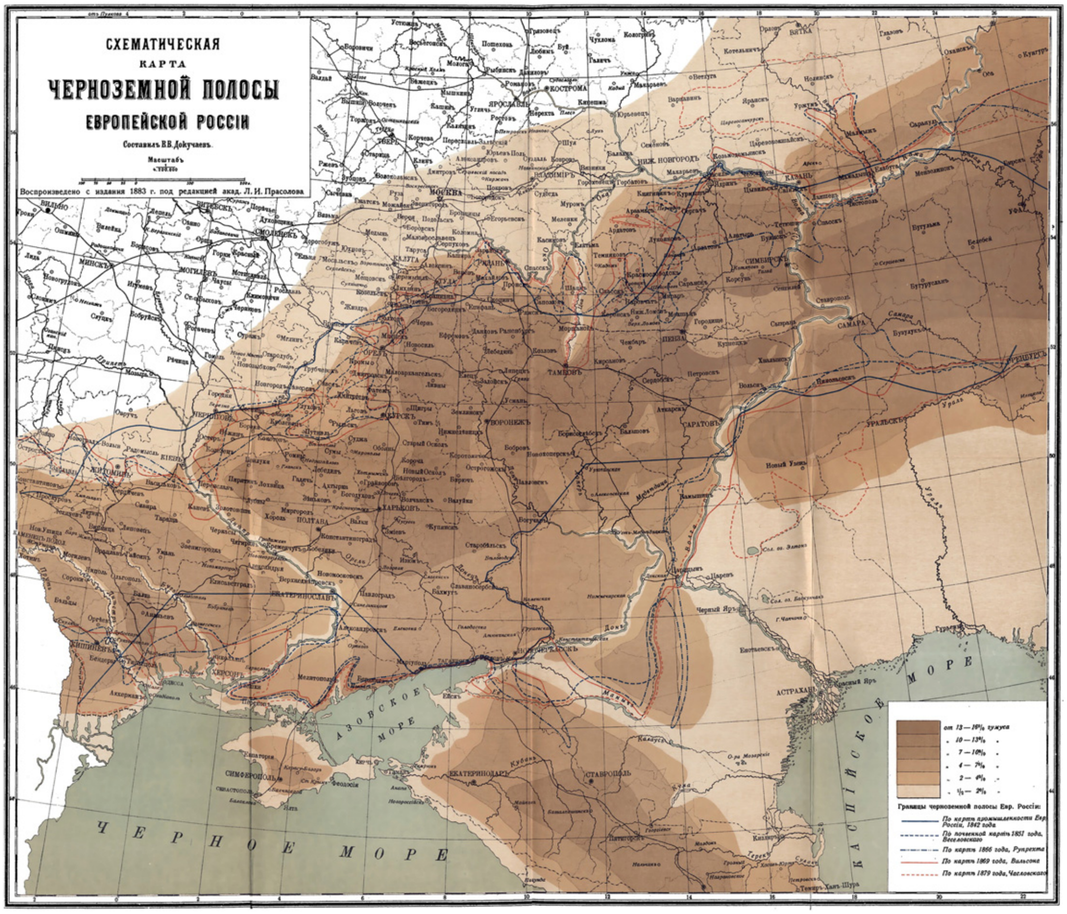

Fig. 4. Isohumus belts identified by Dokuchaev based on quantitative point observations (Dokuchaev, 1883a, 1883b). Cartographic scale was 1:4.2 million. This map is another example of thematic soil attributes drawn onto a pre-existing base map.

series as examples of different normal soils, the undefined immature and abnormal soils left the generalized classification system disconnected from the classification used for detailed soil maps (Baldwin et al., 1938).

The first two International Congresses of Soil Science (1927 and 1930) facilitated the widespread use of bioclimatic–soil relationships for creating smaller cartographic scale soil maps. In the years following these meetings, many countries established soil surveying agencies and began mapping soils at such small cartographic scales, in the Dokuchaevan zonal style. Among those, Prescott (1933) produced a map of Australia. In 1936, the Russian V. Agafonoff published a soil map of France at 1:2.5 million (Legros, 2006). At China's invitation, the American James Thorp, with a team of young Chinese pedologists, mapped the soil zones of China at 1:7.5 million (Thorp, 1936; Gong et al., 2010). In 1937, a soil map of Europe was produced at a scale of 1:2.5 million (Stremme, 1997). The *Great Soviet World Atlas* is noteworthy from this time period because of the combination of maps presented (Gorkin and Schmidt, 1938). In addition to a 1:50 million soil map of the world, the atlas also included geologic, climate, and botanical maps at the same scale, for comparison.

The early 20th century explosion in the production of small cartographic scale soil maps can be considered an extension of the Age of Exploration. Of course, an underlying motivator of this movement was the discovery, inventory, and planned exploitation of natural resources. However, it was also mixed with the Humboldtian tradition of scientific interest in identifying generalized laws that enhanced understanding of our world. Small cartographic scale maps using the zonal soil classifications satisfied the purpose for both of these motivations, at least until greater spatial detail (resolution) was needed.

3.2. Medium Cartographic Scale Maps (1:1 million to 1:25,000)

3.2.1. Geographic Technology

Early soil mapping in the agrogeology tradition, with its emphasis on parent material, was generally focused on producing more detailed maps than the deductive approach commonly used with small cartographic scale maps. However, the limitation of available base maps on cartographic and analysis scales remained. Although basic topographic maps – based on astronomic triangulation – began to appear for Europe in the 18th century, most areas were not surveyed until the 19th century. Even when early topographic maps became available, by today's standards they were relatively small in cartographic scale and contained little detail. For example, the Cassini map, described above, had a cartographic scale of 1:86,400. Therefore, soil geographers who wanted to create more localized maps could use larger cartographic scales than those mapping continental or national extents. However, the available base maps still limited them to relatively small cartographic scales.

Although the U.S. Soil Survey has always been interested in producing maps specific enough to provide guidance for agriculture (Whitney, 1900, 1909), the coarse resolution of available base maps prevented early detailed soil maps from using large cartographic scales (Simonson, 1952). When the U.S. Soil Survey began in 1899, the U.S. Geological Survey had produced topographic maps for only a small percentage of the USA, and they were usually not in areas for agricultural production (Brown, 1979). Where a topographic map was not available, soil boundaries would be sketched on a blank plat book (Lapham, 1949). Relying on property boundaries as spatial references, soil mappers in the early U.S. Soil Survey used compasses, protractors and scales, as well as alidades and

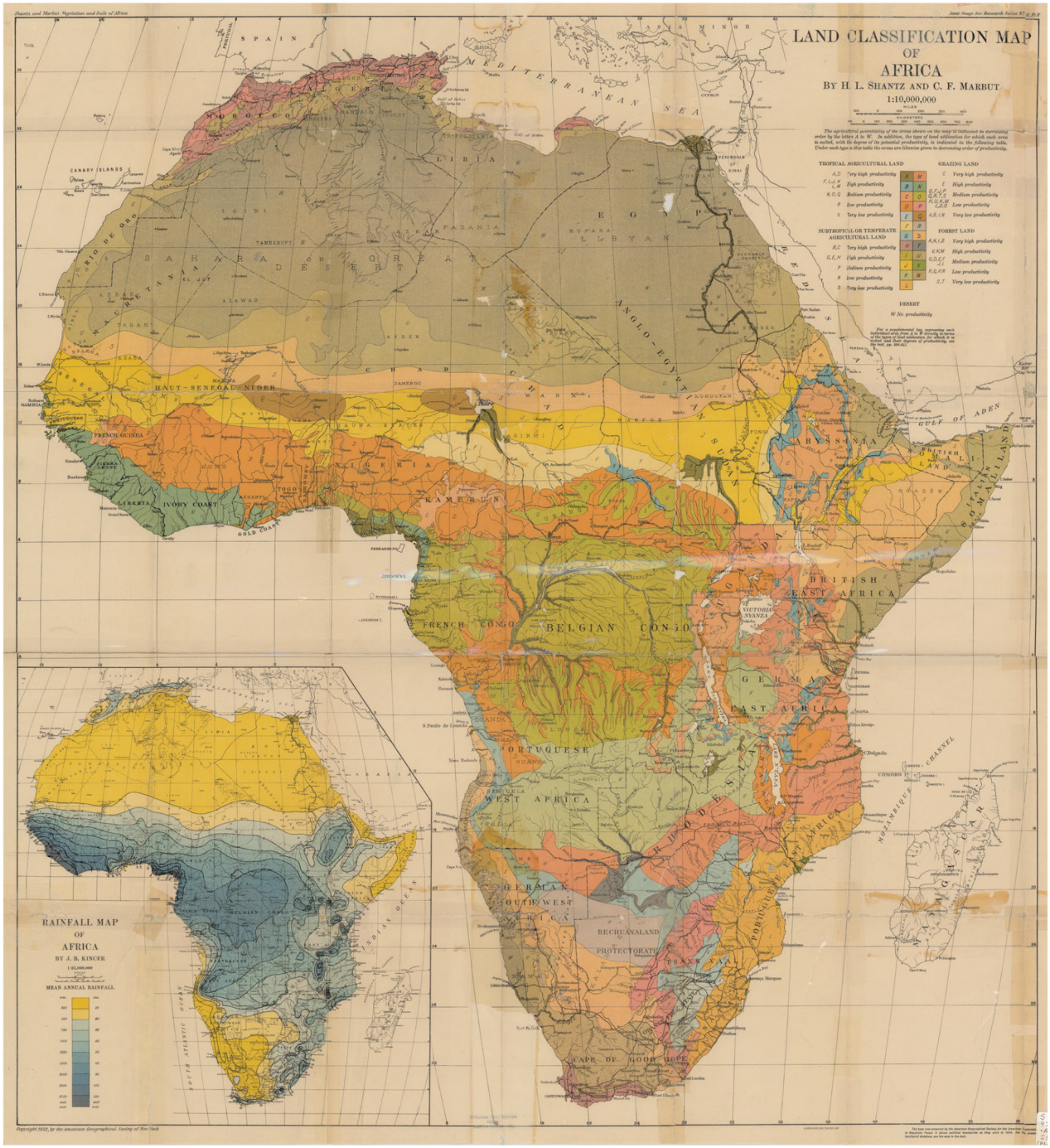

Fig. 5. Soil map of Africa based on zonal classification system (Shantz and Marbut, 1923). Cartographic scale was 1:10 million.

plane tables, to place their observations within the spaces of the base map (Kellogg, 1937). Under the pressure to survey large amounts of area in a short period of time, soil maps were limited by geographic technology for the level of detail that could be included. Although these soil maps were considered to be detailed at the time, they were drawn at what we have categorized as medium cartographic scales.

3.2.2. Purpose and Strategies for Soil Mapping

By the turn of the 20th century, countries like the USA and Britain had begun to map soils in greater detail. Sir Edward Russell (1872–1965) and Sir A.D. Hall (1864–1942) acknowledged the Russian climatic approach for describing soil variability at the continental scale by citing N. Tulaikoff's, 1909 paper. However, they considered the climate of England to be relatively uniform and believed the long cropping history had obliterated native vegetation influences (Krupenikov, 1993). They considered that at the scale of the soil map they were creating, “it was a matter of experience that within the district there was a general correlation between soils and geological outcrop” (Hall and Russell, 1912, p. 186). Recognizing that generalizations were still needed, Hall and Russell avoided sampling exceptions to general trends such as soils on steep slopes, in hallows, and near stream beds. Also, they noted that their map should be interpreted “in the light of local conditions, such as climate, water supply, and drainage” (Hall and Russell, 1912, p. 185).

In the USA, the earliest known effort to map soil was in 1820, when the agricultural society of Albany County, New York, sponsored a geological survey (Coffey, 1911). The classification system on the resulting map divided soils into transported (alluvion) and untransported (geest) categories. Untransported soils were then subdivided into five categories based on texture and relative landscape position.

In 1882, Thomas Chamberlain (1843–1928) produced the first map in the USA with ‘soil’ explicitly in the title. Chamberlain's *General Map of the Soils of Wisconsin* shows a strong influence from his geology training (Fig. 6), with landscape cross-sections and eight soil classes, predominantly based on texture (Tandarich, 2001; Hartemink et al., 2012). Although cartographic scales were not provided for these maps, they covered smaller extents than the small cartographic scale soil maps of the time.

Milton Whitney (1861–1928) was a strong advocate of agrogeology in the USA (Cline, 1977). During his tenure as chief of the U.S. Bureau of Soils (1894–1913), he conducted extensive surveys at cartographic scales of approximately 1:63,000 (Fig. 7). These maps were done in the agrogeology style of classifying soils by parent material, using data on soil physics and chemistry (Kellogg, 1974; Brevik, 2002). Whitney implemented a system of grouping soils of similar geologic material, but with different textures, into soil series. The series concept was modeled after geologists' use of the term for grouping a succession of beds in a sedimentary deposit with varying textures (Simonson, 1997). This early series concept was analogous to soil associations in the U.S. Soil Survey today. Today's statewide maps of soil associations, or more generalized soil regions, resemble updated versions of early agrogeology soil maps, and are popular tools for surface geology

Fig. 6. General soil map of Wisconsin produced in the agrogeology style by T.C. Chamberlain, 1882. Cartographic scale not provided.

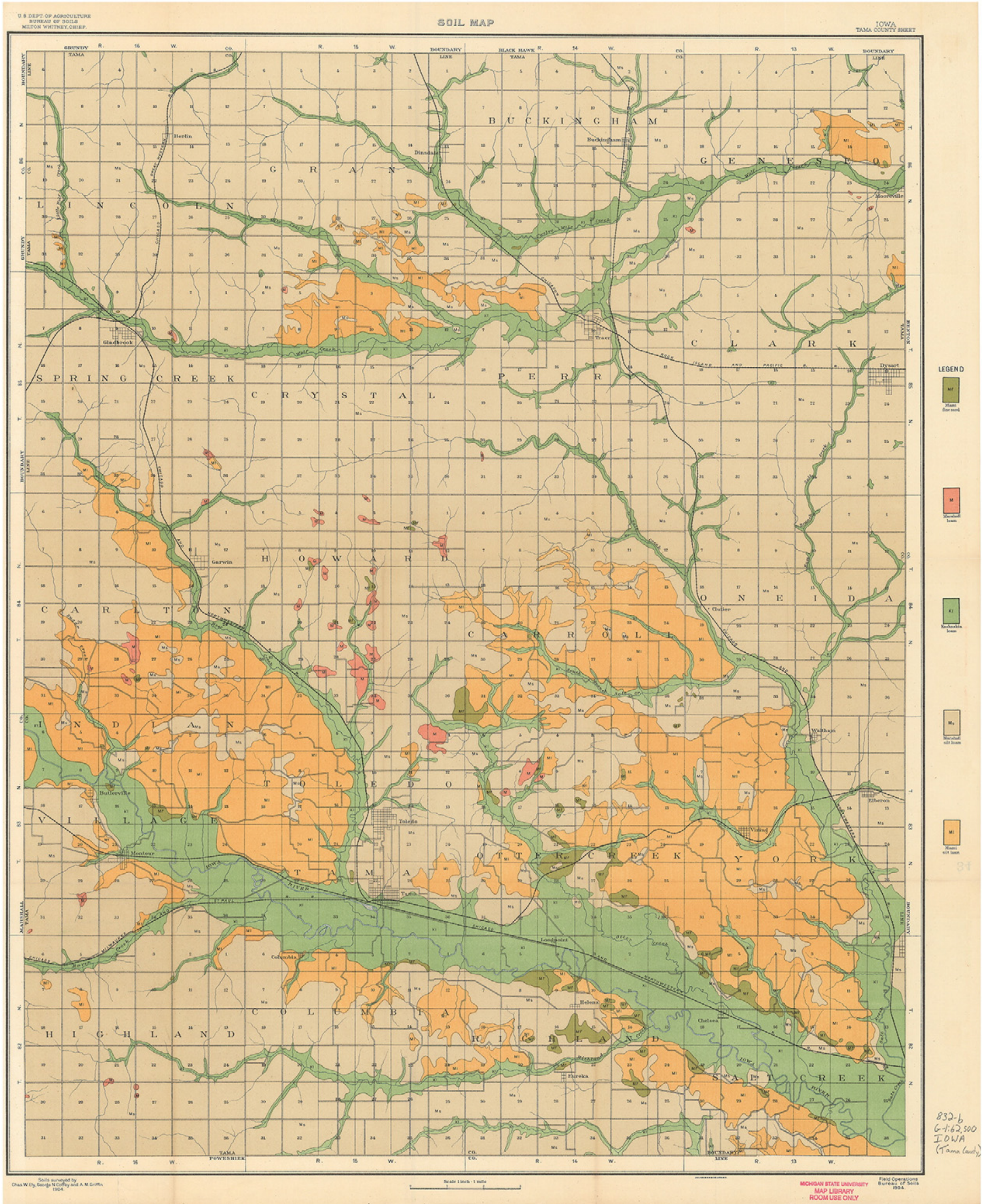

Fig. 7. Soil map of Tama County, Iowa produced at a cartographic scale of 1:63,360 (Ely et al., 1904). Only five map units are delineated, each of which primarily differ in parent material. Variation of soils due to climate or relief is not included.

(Figs. 8 and 9) (Lindholm, 1993, 1994; Brevik and Fenton, 1999; Miller et al., 2008; Oehlke and Dolliver, 2011). Chamberlain's soil map of Wisconsin (Fig. 6) primarily differs from the modern soil regions map of Wisconsin due to more accurate spatial information in the modern soil regions map. Both maps display similar patterns related to the spatial distribution of geologic/parent materials.

In the late 19th century, several countries began their soil mapping efforts using medium cartographic scales and agrogeology style classifications (Krupenikov, 1993). For example, between 1870 and 1890, maps of parts of Prussia were produced at scales up to 1:25,000. In these Prussian soil maps, "diluvium" (moraine soils) were commonly divided into 14 categories and alluvial soils into 32 geologic formations (e.g., valley alluvial sand). The map units indicated color, texture, structure, and physical condition of the soils. Similarly, the Netherlands produced national soil maps at 1:200,000 during this time with legends connected to geologic formations (Hartemink and Sonneveld, 2013).

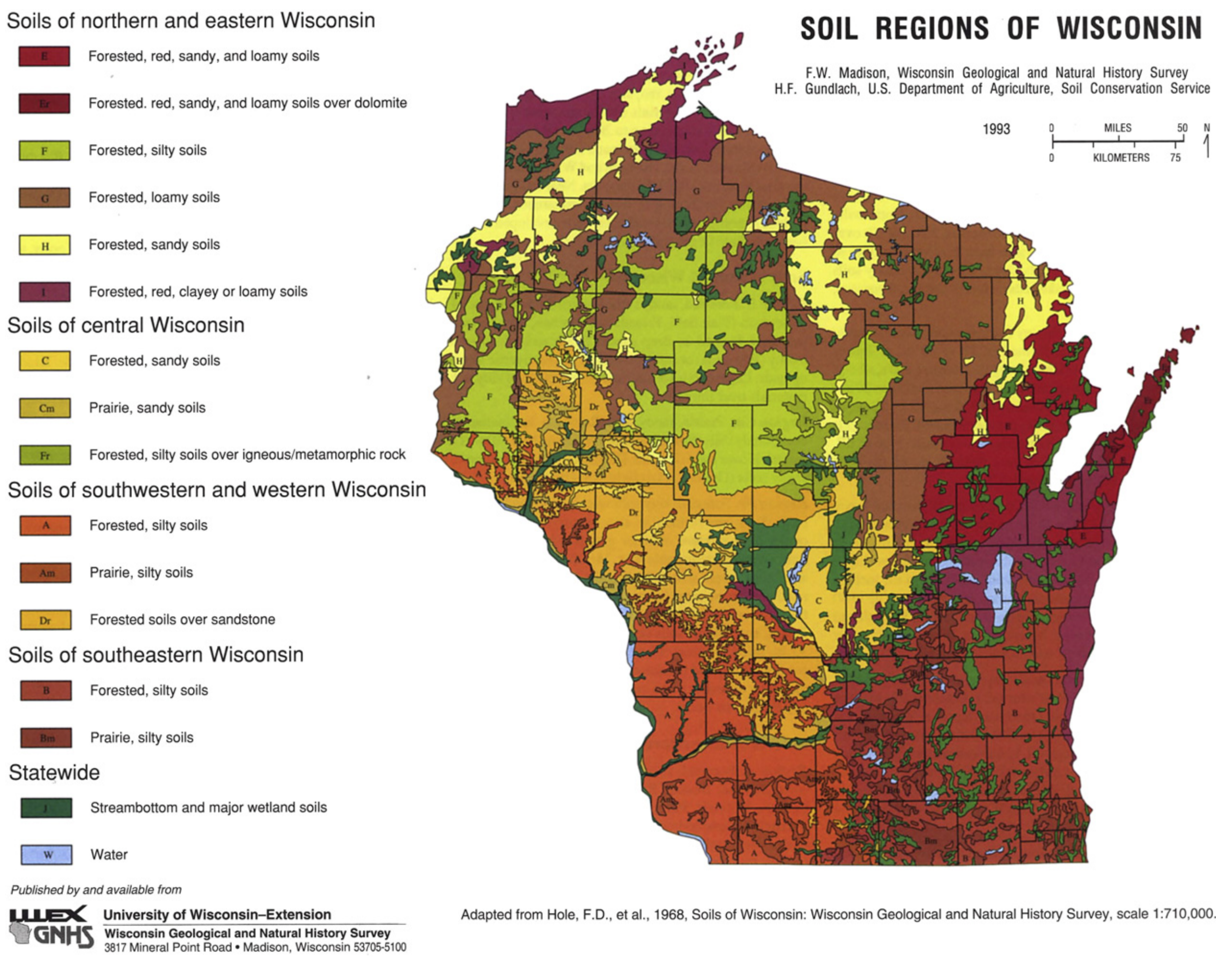

Fig. 8. Soil regions of Wisconsin map published by the Wisconsin Geological and Natural History Survey. Cartographic scale was 1:710,000 (Madison and Gundlach, 1993). The spatial patterns in this map are very similar to the patterns in the earlier, agrogeology style soil map of Wisconsin. The two maps primarily differ due to more accurate spatial information being available for the modern soil map.

Nonetheless, schools of soil science that had begun at smaller cartographic scales did not remain static. After the establishment of climate–vegetation based, small cartographic scale soil maps, Russian soil scientists began to experiment with using other factors for differentiating soil groups for higher resolution soil maps. For example, Prasolov (1922) subdivided previous soil zones of European Russia into 35 regions based on the criteria of parent material and landscape relief.

3.2.3. Gradient Between Phenomena Scales

The choice of emphasizing parent material or climate–vegetation relationships has been a contentious debate within the history of soil science (Cline, 1977; Krupenikov, 1993). For the most part, the two perspectives correspond to respective cartographic scales, which was also a function of map purpose. However, the divide between maps emphasizing parent material and those emphasizing climate–vegetation relationships is blurry. Although soil maps at medium cartographic scales have mostly focused on parent material, vegetation influences are sometimes included. For example, in the recent 1:710,000 scale, *Soil Regions of Wisconsin* map, a few map units are subdivided between soils formed under forest vs. prairie (Fig. 8). This map is at the smaller end of the medium cartographic scale spectrum, covering an area large enough for part of the geographic structure of the bioclimatic phenomenon to be observed. Therefore, while certain environmental factors may dominate the spatial variation at respective scales, there is a gradient between phenomena scales where there can be a blend between useful predictors.

3.3. Large Map Scales (> 1:25,000)

3.3.1. Geographic Technology

The ability to accurately and efficiently map soils at cartographic scales larger than 1:25,000 was enabled by the advent of georectified aerial photography, which became available after World War I (Smith, 1985). Aerial photography improved the U.S. Soil Survey products by facilitating greater detail, precision, and accuracy in the maps (Bushnell, 1932). Although detailed Soil Survey work had already begun to progress towards this finer resolution of soil mapping, the availability of these base maps expedited the process (Miller and Schaetzl, 2014). Aerial photography was gradually integrated into the mapping process of the U.S. Soil Survey in the 1930s. As a result, maps published by the U.S. Soil Survey shifted from a cartographic scale of 1:63,360 to between 1:24,000 and 1:15,840, which changed the analysis scale from about 15.8 ha to about 1 ha (Soil Survey Staff, 1993).

Simonson (1952) illustrated the progress of increasing soil map detail, using Tama County, Iowa, USA as an example. Between 1904 and 1938, the number of map units for the 1800 km^2 county increased from five to fifty. In 1904, a soil surveyor could map 13 km^2/day. By the 1950s, a soil surveyor would only map between 1 and 3 km^2/day, but in much more detail. With the more detailed soil maps, the rate of

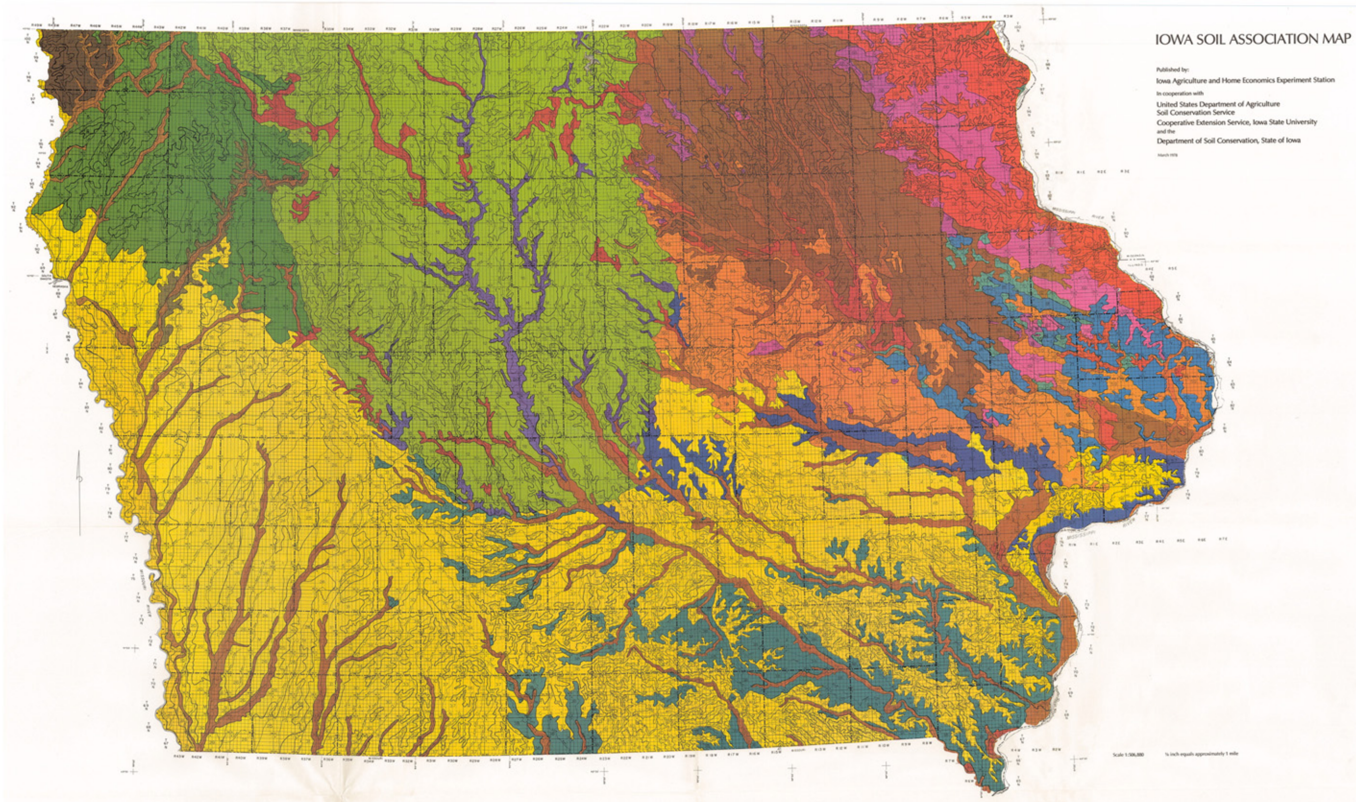

Fig. 9. Soil associations of Iowa map published by the Iowa Agriculture and Home Economics Station (National Cooperative Soil Survey, 1978). Cartographic scale was 1:506,880. This soil map has a level of detail similar to the contemporary soil map of Wisconsin (Fig. 7); both primarily represent the spatial distribution of geologic/parent materials.

mapping depended on the complexity of the soil pattern and readily observable features in the aerial photograph (e.g., topography).

3.3.2. Purpose and Strategies

Almost immediately after Dokuchaev published his small cartographic scale map of Chernozems, Russian soil scientists began producing larger scale maps in select locations, to improve land assessment and address local agricultural problems (Krupenikov, 1993). One of Dokuchaev's students, Nikolai Sibirtsev (1860–1900), conducted detailed soil surveys and discovered the need to subdivide landscape components at finer scales, using topographic features to draw soil boundaries (Sibirtsev, 1966). Since that time, Russian scientists have continued to study the spatial patterns of soil with respect to elements of relief, culminating in the concept of the *elementary soil areal* (Fridland, 1974). Vladimir Fridland (1919–1983) observed that the repeating, geographic structure of elementary soil areals is only seen on large cartographic scale maps.

Soil surveyors in the USA had a similar experience to the Russians, as they began to create maps with increasing detail. Even before aerial photography was widely available, U.S. soil surveyors worked to increase the level of detail in soil maps to provide support for land use and management. As early as 1902, U.S. soil scientists began observing topography-related soil patterns within parent material-based map units (Marean, 1902; Bushnell, 1943). As the level of soil map detail increased, U.S. soil surveyors began having problems with emphasizing parent material for explaining soil spatial variability (Simonson, 1991). Encountering and solving these problems instigated a reevaluation of soil science concepts.

A landmark in recognizing topographic differentia in soil survey was the establishment of the catena concept. The term “catena” was introduced by Geoffrey Milne (1898–1942), who implemented it while assigned the task of constructing two soil maps of east Africa, each for separate purposes: 1) a detailed (large cartographic scale) map for agricultural management, and 2) a regional (small cartographic scale) map for inclusion in a world soil map. To aid in production of the former map, Milne devised a way to represent repeating patterns of soils on similar hillslope positions. Seeing the general benefits to utilizing topographic soil cover patterns, Milne defined the concept of a catena as “a unit of mapping convenience…, a grouping of soils which while they fall wide apart in a natural system of classification on account of fundamental and morphological differences, are yet linked in their occurrence by conditions of topography and are repeated in the same relationship to each other wherever the same conditions are met with” (Milne, 1935a, p. 197). Milne's original proposal of a catena was for mapping soil complexes with repeating internal patterns. The limitation of mapping soil complexes, instead of individual soils within the pattern, was probably due to the limitation in base maps of sufficient resolution. When Milne learned of soil surveyors in the USA mapping the component soils of a repeating pattern based on the catena concept, he thought it an appropriate extension of his original proposal (Bushnell, 1943).

Early in the development of large cartographic scale soil maps, soil scientists began to focus on pedogenic processes influenced by topography. Milne identified the process of erosion — deposition (Milne, 1936) and changes in parent material at the surface corresponding with topography (Milne, 1935b). In Canada, John Ellis (1890–1973) then described the influence of topography on hydrologic flow pathways, resulting in differences in drainage and corresponding soil properties (Ellis, 1938). These early studies on topographic relationships to pedogenesis and resulting soil properties have since been expanded upon and utilized by many researchers (e.g., Ruhe and Walker, 1968; Walker and Ruhe, 1968; Kleiss, 1970; Furley, 1971; Malo et al., 1974; Hall, 1983; Gregorich and Anderson, 1985; Donald et al., 1993; Stolt et al., 1993; Schaetzl, 2013).

Taking advantage of improving aerial photographs as base maps, some countries have been producing maps at larger cartographic scales.

However, few countries have mapped soils at the level of detail that the U.S. Soil Survey has, with field verification, and for such large extents. With the exception of several countries in southeastern Europe, most European countries have only mapped select areas with particular land use management needs at large cartographic scales (Bullock et al., 2005). Countries that have mapped soil at cartographic scales greater than 1:65,000 have done so with soil series being the lowest category of classification. That concept of soil series, like the USA concept, has evolved from grouping soils with similar parent materials to subdividing by differences in profile characteristics caused by relief or other external features (Hollis and Avery, 1997).

Hudson (1992) packaged together the concepts of soil mapping that had been developing and put into practice during the 20th century. The name he gave to this collection of mapping strategies was the soil-landscape paradigm. Building on the catena concept introduced by Milne (1935a) and expanded upon by Bushnell (1943), one of the key points of this paradigm was the predictability of soil properties for areas where the factors of soil formation were similar. This relationship corresponds to the term 'spatial association' in geography, which more broadly describes the degree to which things co-vary across space. Hole and Campbell (1985) used the term 'spatial association' when describing the prediction method used when producing soil survey maps with limited samples. Nonetheless, the defining of the soil-landscape paradigm was a milestone for soil geography because it explicitly called on the use of all five factors of soil formation for the prediction and delineation of similar soil map units.

3.3.3. Local Modification of Larger Scale Phenomenon

Larger scale phenomena, such as seen in climate–vegetation zones and physiographic regions, are obviously greatly modified locally by topography. Topography modifies local climate and vegetation communities by directing hydrologic flow (Ellis, 1938) and by influencing microclimate (Hunckler and Schaetzl, 1997; Beaudette and O'Geen, 2009). Topography also influences the spatial pattern of surficial geology by exposing different stratigraphic layers across hillslopes (Milne, 1935b; Ruhe et al., 1967) and sorting of transported sediments (Milne, 1936; Paton et al., 1995; Schaetzl, 2013). Although variability of soil properties influenced by topography can be greater than the variability found between bioclimate regions, the range of variability related to topography is still constrained by the conditions provided by the larger scale phenomena of parent material and climate.

Therefore, local exceptions do not invalidate generalizations. Rather, the purpose of generalization is to provide the map user with the most important information that can be represented at the given cartographic scale (Keates, 1989). In this context, it is important to distinguish the summarizing of attribute variability (range) from summarizing a spatial analysis unit. The range of soil attributes in a defined area may be large due to topographic effects, but when summarized by a single number (e.g., the mean), the local variation is ignored and the pattern observed focuses on the differences between the larger map units. This is the effect of increasing analysis scale. Generalization is also a tool in the deductive approach of science, which identifies exceptions to broadly applicable theories as areas requiring additional inquiry. Therefore, considering levels of generalization – corresponding to phenomenon scale – help conceptualize complex spatial interactions and to discover additional factors that can increase the spatial accuracy of our understanding about natural phenomena.

3.3.4. Untapped Potential

Under the theory that soil classification – and by association, soil maps – have evolved with improved understanding of soils in general, the identification of topographic-soil relationships was in itself an advancement of soil science. However, this advancement also coincided with increases in cartographic scale and the availability of more accurate and precise base maps (Miller and Schaetzl, 2014). By the 1950s, the transition to aerial photographs as base maps allowed much of the USA to have soil maps at a cartographic scale of 1:24,000 (Simonson, 1952). Today, many of the U.S. Soil Survey maps are available at a cartographic scale of 1:15,840, but the corresponding minimum delineation size of one hectare leaves many delineations as soil complexes (Soil Survey Staff, 1993). Complexes are areas where there is known variation in important soil properties, but it is not practical to delineate them separately.

Geomorphic studies of landscapes have demonstrated the predictable patterning of soil distributions that exists due to the influence of topography on surficial and pedogenic processes (Milne, 1936; Ellis, 1938; Ruhe and Walker, 1968; Walker et al., 1968; Walker and Ruhe, 1968; Daniels et al., 1971; Dixon, 1986; McFadden and Knuepfer, 1990; Gerrard, 1992; Steinwand and Fenton, 1995). For this reason, dividing the landscape into toposequences or geomorphic components has become standard practice in soil science research (cf., Sommer et al., 2000; Young and Hammer, 2000; Zebarth et al., 2002; Martin and Timmer, 2006; Vanwalleghem et al., 2010). Although not perfectly suited for all landscapes, the most commonly used descriptors of topographic process zones are the five hillslope profile elements described in the *Handbook of Soil Science* (Wysocki et al., 2000) and the *Field Book for Describing and Sampling Soils* (Schoeneberger et al., 2012).

Although the benefits of considering hillslope geomorphology for improving soil maps have long been recognized (Swanson, 1990; Effland and Effland, 1992; Holliday, 2006), the resources for delineating five hillslope profile elements on large cartographic scale maps (i.e., adequate base maps and time) have not always been available. Instead, it is not uncommon to find delineations in the U.S. Soil Survey maps that encompass entire hillslopes or at most divide them into only three parts. In closed system landscapes, the light–dark patterns visible in aerial photographs are commonly used to delineate topographic soil cover patterns, analogous to high ground – low ground landscape elements (Bushnell, 1943). In open system landscapes, entire slopes are often delineated as one map unit, particularly where use and management needs are consistent across the area (Fig. 10). However, for modern environmental modeling requirements, the standards of differentiating use and management needs are no longer sufficient. Topography, whether categorized – as supported by soil geomorphology research – or applied as a continuous field, offers the next level of increasing resolution for modeling soil variability.

This opportunity has already been identified by the experience of soil surveyors working at larger and larger cartographic scales (Coffey, 1911; Bushnell, 1943). However, with respect to traditional soil mapping, another limit has been reached for the level of detail that can be included in the map using current methods. Soil surveyors are often aware of additional soil landscape features related to topography or hydrology, but sometimes these known details need to be ignored due to the time demands of surveying and delineating greater map complexity (Fig. 11).

Although remote sensing technology has continued to improve the detail and availability of high-quality base maps, the resources to manually enhance soil delineations are unlikely to be forthcoming. The recent advent of high resolution digital elevation data combined with digital terrain analysis provides an opportunity to complete the progression of applying observed process patterns to improve soil maps (Moore et al., 1993; Florinsky et al., 2002; Libohova et al., 2010; Ziadat, 2010; Miller and Schaetzl, 2015). The soil landscape can now be efficiently analyzed cell by cell or classified by the necessary criteria. However, in terms of soil classification, definitions of soil series may need to be updated to accommodate the higher spatial resolution. Therefore, soil classification systems may once again need to adapt to the spatial variability observed at newly mapped scales.

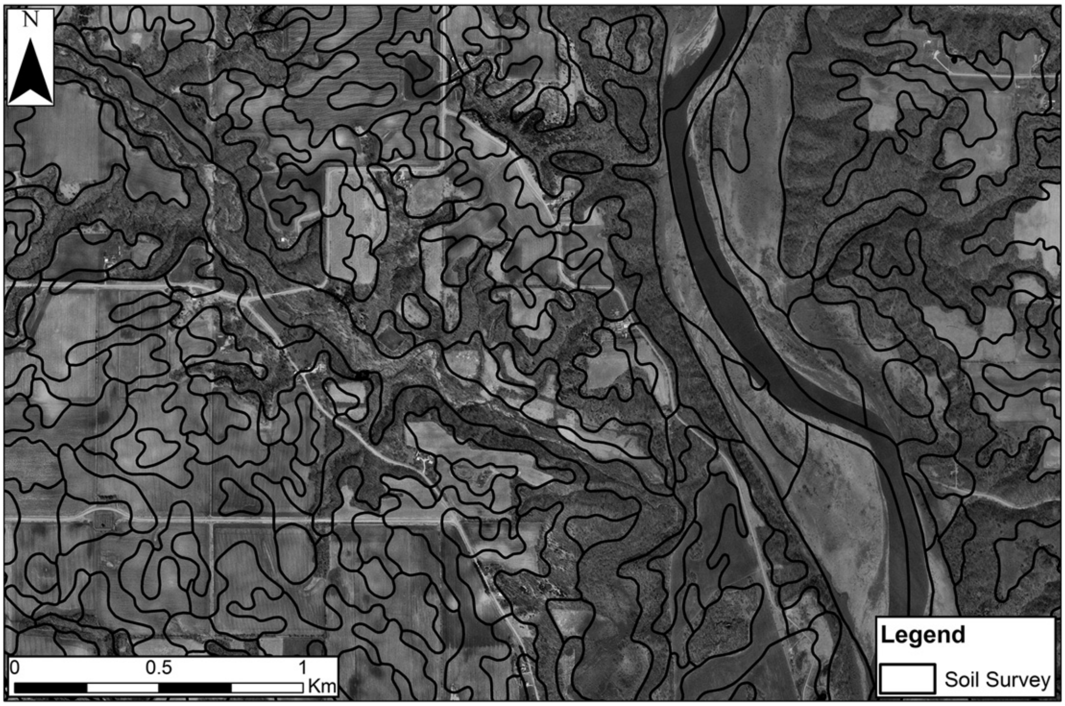

Fig. 10. Portion of soil map for Boone County, Iowa, U.S., constructed at the commonly used cartographic scale of 1:15,840 (Andrews and Dideriksen, 1981). Note that although topographic features are being delineated, topographic sequences are not distinguishable in the aerial photograph base map. For the closed systems in the southwestern area of the map, an attempt was made to map the high-low soil pattern. For the open systems in the northeastern area, large areas are delineated together due to their similarity for use and management criteria.

4. Joining Scales with Classification Systems

4.1. Early Struggles

Prior to the acceptance of the multi-factor approach to soil science, numerous soil classification systems were proposed, each based on a favored theory of soil formation or the soil property believed to be the most critical for plant growth (Krupenikov, 1993). The emphasis of particular soil properties deemed important by the soil expert has remained a common theme for soil classification systems (Krasilnikov and Arnold, 2009). When Dokuchaev's zonal classification gained acceptance, most soil geographers were using agrogeology style classification systems as a guide for creating their medium cartographic scale soil maps. The climate–vegetation emphasis of Dokuchaev's classification system was welcomed by agronomists at the time, who had observed the important role of humus for plant growth (Krupenikov, 1993). Conversely, many agrogeologists remained loyal to their observations of the mineral component, particularly mineral weathering as it is related to nutrient supply, and soil texture as it affects plant available water (Fallou, 1862; Whitney, 1892; Tisdale et al., 1993). These different views created a dichotomy of soil science perspectives, which has often been described as a transition in soil science understanding (e.g., Simonson, 1991; Brevik and Hartemink, 2010). However, the divide not only was a contrast in different properties emphasized by different experts, but also represented a duality between classification systems designed for small versus medium cartographic scale soil maps.

The reality of phenomena operating at different scales was a major reason for the difficulties in deriving a universal soil classification system in the first half of the 20th century (Helms, 2002). Soil classification systems designed for small cartographic scales seemed inadequate at larger cartographic scales. Conversely, classification systems designed for larger cartographic scales contained too many divisions to be represented on maps of large extent. Leading up to the development of the U.S. Soil Taxonomy, the debate over fundamental theories of soil science and how to create a unified soil classification system were regular discussion topics for soil scientists in the USA (Kellogg, 1974; Helms, 2002).

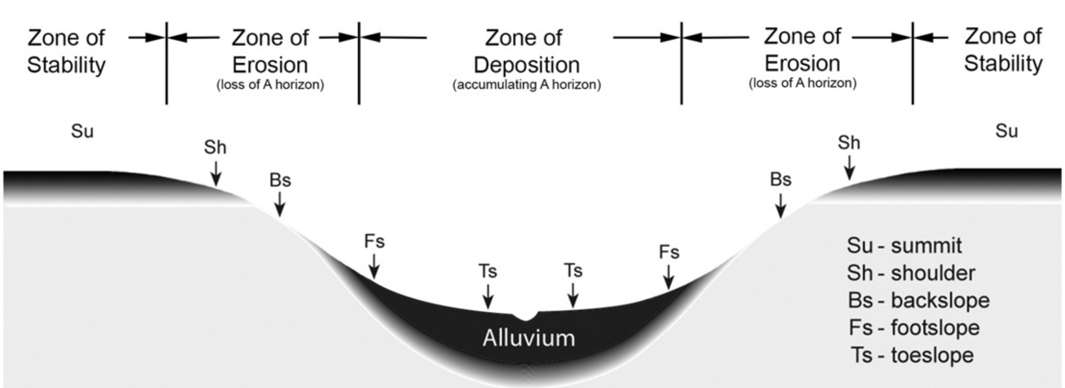

Fig. 11. Illustration demonstrating the difference in detail between delineating light–dark soil cover patterns (corresponding to stable-erosion-deposition zones) and the five hillslope positions commonly used in toposequences research.

With the goal of creating a classification system that distinguished unique soils of uniform agricultural value, Elmer Fippin (1879–1949) proposed a classification hierarchy that mirrors the phenomena scale hierarchy observed in soil maps (Fippin, 1911). In his scheme, the emphasis was first on the definition of series by properties, with further refinement of series to types by texture and structure. After these soil individuals with uniform properties of agricultural interest were identified, they were grouped by parent material and then by climate characteristics (Fig. 12). This strategy was an inductive ('bottom-up') approach, using observed properties to define the lowest order of the classification scheme. A hierarchal system, based on the observed phenomena scales, was then used to organize the identified individuals. Although not officially adopted, this proposed classification scheme illustrates the early underpinning philosophy that would later shape the U.S. Soil Taxonomy (Soil Survey Staff, 1975).

4.2. Adoption of a Multi-scale Classification System

In 1951, the task of a creating a new classification system for the USA was assigned to Guy Smith (1907–1981) (Helms, 2002). Smith used a community review process to develop quantitative definitions for grouping soils hierarchally (Simonson, 1991). These efforts resulted in the 7th approximation of the U.S. Soil Taxonomy (Soil Survey Staff, 1960). Central to the differentia was the soil anatomy, which later became termed diagnostic horizons. These horizons are layers that are quantitatively defined and distinguishable from other layers by a set of properties, and formed by pedogenic processes (Soil Survey Staff, 1993). Although Soil Taxonomy is often heralded for its use of quantified classification rules (Cline, 1977; Mermut and Eswaran, 2001), it also accomplished a great feat in joining classifications based on small and large scale phenomena.

Although the quantification that permeates Soil Taxonomy had several benefits for the utilization and management of soils, it was a step away from the traditional use of geographic attributes. As Dick Arnold noted, "When soil series were redefined to be in compliance with the class limits imposed by the hierarchy of Soil Taxonomy, they no longer were landscape map units. They assumed the role of providing identity only to pedons" (Arnold, 2006, p. 56). However, that disconnect does not mean that the system was constructed without the lessons learned from soil geography. Because of the recognized importance of soil forming factors for producing the diagnostic horizons and in predictive landscape models for soil mapping, the Soil Taxonomy hierarchy does, in many ways, reflect soil formation factors (Smeck et al., 1983; Ahrens et al., 2002; Bockheim et al., 2014). In Smith's words, "Genesis does not appear in the definitions of the taxa but lies behind them" (Smith, 1983, p. 43). For example, several of the soil orders correspond with broad vegetation communities, and most of the suborders correspond with soil climate. Although no longer defined by environmental correlation, the principles of scale that allowed zonal classification systems to be delineated on small cartographic scale maps remained in Soil Taxonomy. For this reason, in theory, soil map units in large cartographic scale maps can be classified using the lowest order of the hierarchy, while higher orders can be represented on small cartographic scale maps (Fig. 13).

Guy Smith did not use spatial variability as a constraining rationale for organizing Soil Taxonomy, which allows for some classification differentia to be raised in the hierarchy level due to properties considered to be of high importance. For example, in the controlling factors for the 12 Soil Taxonomy orders, as summarized by Brevik (2002), seven are based on bioclimatic–soil relationships and two are differentiated by the lack of time for bioclimatic processes to modify the parent material. The remaining three orders are based on hydrologic or geologic phenomena, which result in soil properties important to land management and still have large extents (see also Schaetzl and Thompson, 2015). Like zonal classification systems, soil order concepts in Soil Taxonomy place greater emphasis on bioclimatic differentia, with a few additional categories to allow for exceptions (Table 1). Therefore, even though soil classification systems have no obligation to be organized in a hierarchy of phenomena scales, as a matter of mapping practicality, Soil Taxonomy still reflects soil geographers' experience of shifting to different soil forming factors at different analysis scales.

Although the main purpose of Soil Taxonomy was to be based on observable properties considered important to use and management, the multi-level taxonomic hierarchy of the system was organized to

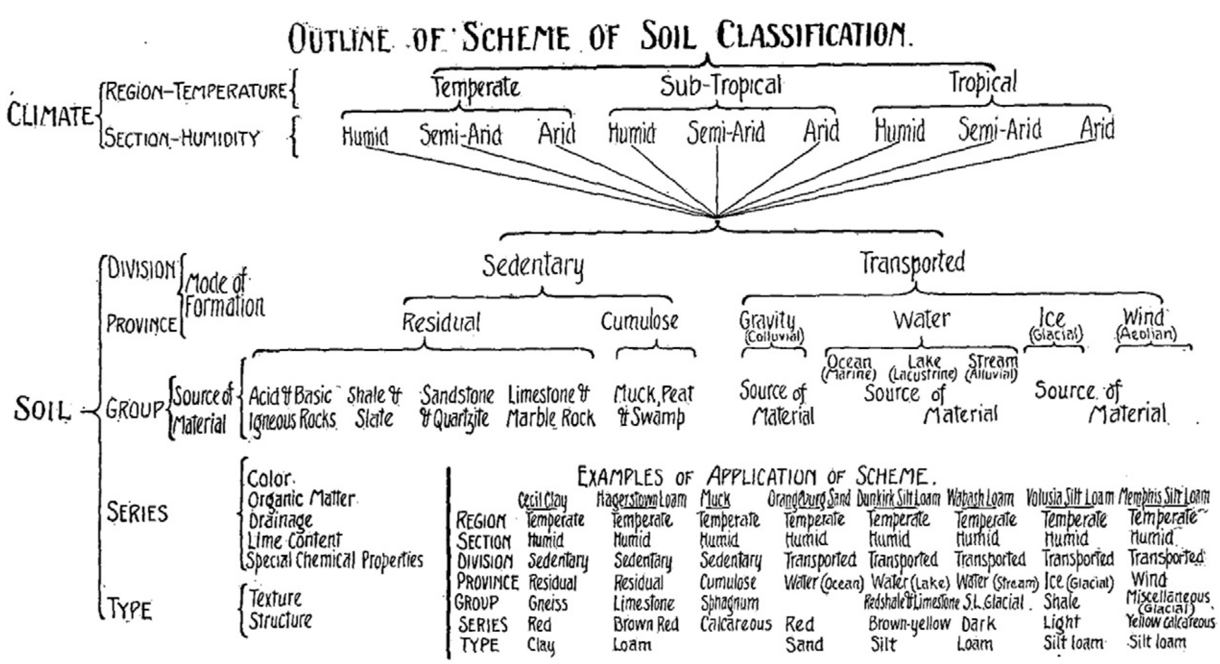

Fig. 12. Schematic of Fippin's proposed soil classification system (Fippin, 1911). Note the hierarchy of climate at the highest level followed by characteristics of parent material at the levels of division, province, and group. At the series and type level, multiple, specific soil properties are listed, several of which have direct connections to hydrology/topography.

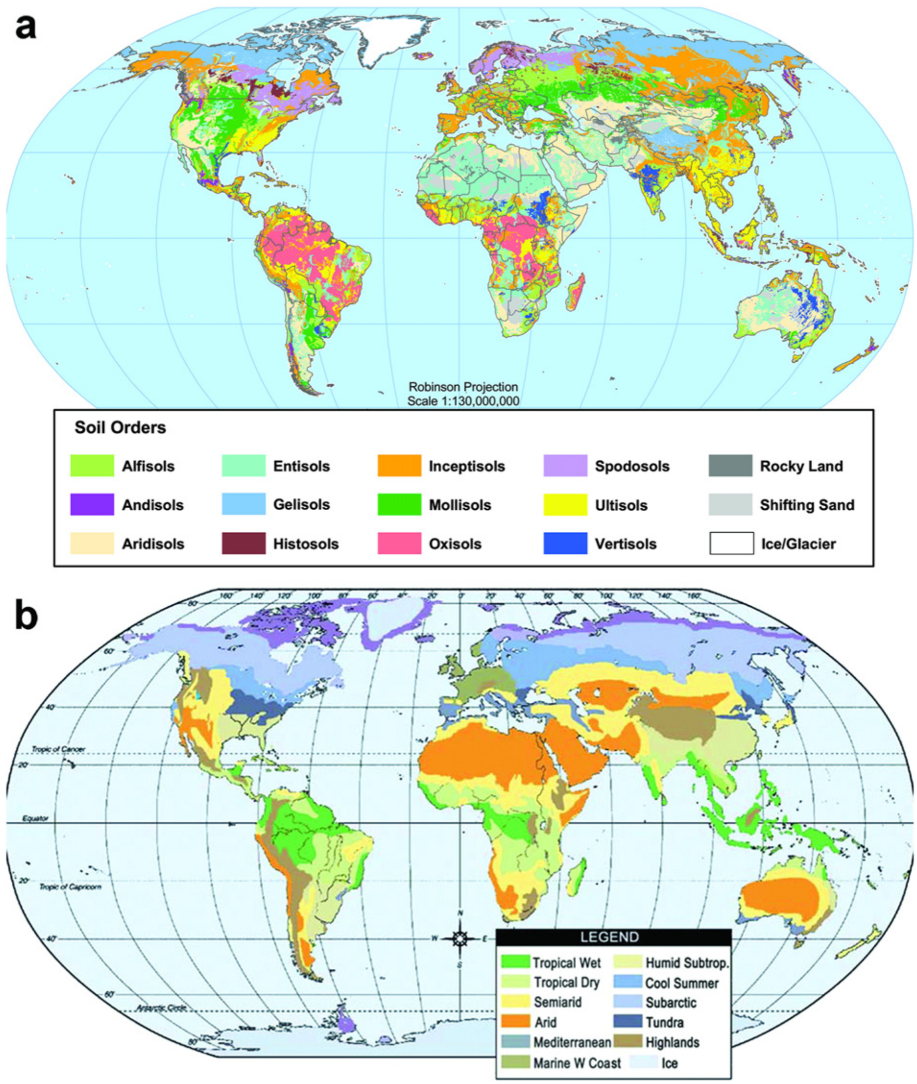

Fig. 13. a) World map of soil orders as classified by U.S. Soil Taxonomy at a cartographic scale of 1:130 million (USDA-NRCS, 2005). b) Köppen-Geiger climate zones presented for comparison with U.S. Soil Taxonomy soil orders (climate zone map courtesy of www.theodora.com/maps, used with permission).

accommodate both small and large cartographic scale maps (Smith, 1986). Despite criticisms that Soil Taxonomy is disconnected from pedogenesis (Bockheim and Gennadiyev, 2000), the mirroring of phenomenon scale in the classification hierarchy is one of the threads that link classification definitions back to processes.

Table 1
Relationship between the top levels of zonal classification and the current version of Soil Taxonomy.

Zonal	Intrazonal	Azonal
Climate–vegetation	Exceptions based on geology or hydrology	Exceptions based on time
Alfisols Aridisols Gelisols Mollisols Oxisols Spodosols Ultisols Vertisols (some) Inceptisols (some)	Histosols Andisols Vertisols (some)	Entisols Inceptisols (some)

5. Conclusions

Soil maps have evolved through and alongside advancements of soil knowledge and geographic technology. Soil maps at different cartographic scales – and by association, different analysis scales – have utilized the environmental predictor found best suited for explaining spatial variability at their respective scales. After such time as soil knowledge was able to recognize the influence of multiple environmental factors on resulting soil properties, ca. 1860–1880, soil scientists' selection of environmental predictors came to reflect the conceptual model best adapted to the respective map scale. Comparisons of historical soil maps of varying cartographic scales reveal three distinct groups: 1) small cartographic scale maps emphasizing bioclimatic relationships, 2) medium cartographic scale maps emphasizing parent material relationships, and 3) large cartographic scale maps emphasizing topographic and hydrologic relationships.

The correspondence between cartographic scale and soil scientists' selection of a respective environmental factor for predicting soil variability suggests that the process phenomena embodied in Dokuchaev's factors of soil formation are certainly operative, but are best expressed at different scales. Over time, the experiences of soil geographers have been tuned to the environmental factor that best explains the spatial variability of the soil at the operative or explanative scale of the map they are producing. At times, this association has led to debates over which factor provides the best prediction of geographic soil patterns. In some cases, not recognizing the scale effect of MAUP has led to outright rejection of valid, large scale phenomena when local exceptions are found (e.g., Beadle, 1951). However, debates over the most important soil forming factor are often moot, because the optimal predictor of soil spatial variability is usually a function of analysis scale.

The potential for mapping soils at small analysis scales (large cartographic scales) has not yet been fully utilized. Until recently, limitations in quality base maps (i.e., detailed representations of topography) have made extending modern soil geomorphology principles across large extents impractical. Technological advancements provide the opportunity to create better base maps and automate their analysis, which in turn offers the ability to bring soil maps to the levels of process scale studied in detailed soil geomorphic research.

The introduction of geographic information systems and digital mapping products to soil mapping has largely decoupled cartographic scale from analysis scale (Goodchild and Proctor, 1997; Miller and Schaetzl, 2014). To learn from the experience of past soil geographers, and to avoid repeating mistakes, it is important to apply lessons learned by cartographic scale with paper maps to analysis scales of digital maps. In this paper we have filtered out the influence of technological development over time to provide a more clear comparison of traditional soil maps produced at different scales. This evaluation demonstrated that past soil mapping approaches were based on conceptual models calibrated to the cartographic/analysis scale of the map. The conceptual models were tuned to the phenomena governing the spatial distribution of soils, which differed by map scale. Like traditional soil modelers, it is important for digital soil modelers to select the appropriate environmental predictors for the analysis scale of interest. Alternatively, digital soil modelers can use more multiscale approaches to integrate phenomena scales. An approach to integrating phenomena scales to conceptualize soil geography is to subdivide large scale phenomena by smaller scale phenomena, as is commonly done in modern soil classification systems. This framework of layering soil formation factors by a hierarchy of scale utilizes the experience of past soil geographers to form a holistic understanding of soil geography and pattern.

Acknowledgments

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