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History of soil geography in the context of scale

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ABSTRACT

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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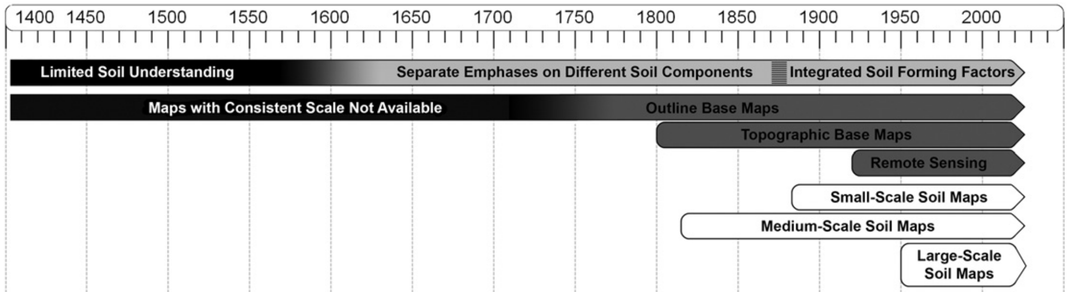

Fig. 1. Timeline of important developments in the scientific sphere of soil geography. In all instances, 'scale' refers to cartographic scale. Soil maps (white) are a product of both the scientific understanding of soil (light gray) and the geographic technologies available at the time (dark gray). Although 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