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Progress in soil geography I: Reinvigoration

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Abstract

The geography of soil is more important today than ever before. Models of environmental systems and myriad direct field applications depend on accurate information about soil properties and their spatial distribution. Many of these applications play a critical role in managing and preparing for issues of food security, water supply, and climate change. The capability to deliver soil maps with the accuracy and resolution needed by land use planning, precision agriculture, as well as hydrologic and meteorologic models is, fortunately, on the horizon due to advances in the geospatial revolution. Digital soil mapping, which utilizes spatial statistics and data provided by modern geospatial technologies, has now become an established area of study for soil scientists. Over 100 articles on digital soil mapping were published in 2018. The first and second generations of soil mapping thrived from collaborations between Earth scientists and geographers. As we enter the dawn of the third generation of soil maps, those collaborations remain essential. To that end, we review the historical connections between soil science and geography, examine the recent disconnect between those disciplines, and draw attention to opportunities for the reinvigoration of the long-standing field of soil geography. Finally, we emphasize the importance of this reinvigoration to geographers.

Keywords

Soil, critical zone, soil mapping, geology, spatial science, ecosystem services, geospatial revolution

I Introduction

Geography and soil science have much in common. One of those commonalities is a connected origin in natural resource inventory, which today makes both disciplines essential to address key environmental issues. The two disciplines also share a highly interdisciplinary nature. Being naturally interdisciplinary is a strength in that it allows both soil science and geography to bridge gaps between other, complementary disciplines (Brevik and Hartemink, 2010). On the other hand, it can become a

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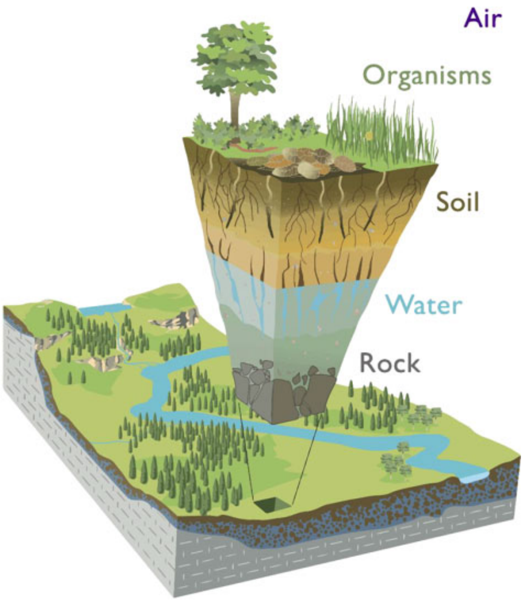

Figure 1. Conceptual diagram illustrating the critical zone. Although difficult to illustrate in a single diagram, soil is the subsurface environment shaped over time by geological, chemical, physical, and biological processes. All of these phenomena are spatially heterogeneous. After Chorover et al. (2007).

weakness when allied fields seek to absorb portions of soil science or geography into their own spheres of academic influence (Brevik, 2009; Harvey, 1984); this concern seems to have been shared by both fields at various times in their histories.

Soil forms at the interface between the atmosphere, lithosphere, hydrosphere, and biosphere. Traditionally, this interface has been called the pedosphere (Targulian et al., 2018). However, more recently the concept of the pedosphere has been extended to include the top of the vegetative canopy to form the concept of Earth's critical zone (Figure 1). Critical zone research has generated new excitement in interdisciplinary fields, as it focuses on the processes occurring within this interface, from micro- to global scales (Brantley et al., 2007). Regardless of the terminology or scientific approach, two concepts about soil are clear: 1) soil and the processes occurring within it are essential to life on Earth, and 2) to understand soil, one must consider the interacting processes from the respective spheres, including their positive and negative feedback loops.

The terminology used in the preceding description of soil should resonate with geographers, as the concept of feedback loops is central in modern geography, including soil geography (Chadwick and Chorover, 2001; Muhs, 1984; Phillips, 1993; Torrent and Nettleton, 1978). Similarly, a goal of physical geography is to "explain the spatial characteristics of the various natural phenomena associated with the Earth's hydrosphere, biosphere, atmosphere, and lithosphere" (Pidwirny and Jones, 2017). The overlap between soil science and geography is self-evident; soil science and geography have evolved as interdependent fields (Rodrigo-Comino et al., 2018). However, in various parts of the world, different academic structures and funding sources have led to some academic disconnects, despite their apparent commonalities.

Traditionally, soil science and geography have intersected in subfields such as soil geomorphology (Holliday et al., 2002), pedology (Schaetzl and Thompson, 2015), and soil geography (Arnold, 1994). Although soil geomorphology research has been active in geography, geology, Earth science, and soil science/agronomy departments, soil geography research has not been as active for a better part of the 20th century. If a reinvigoration in soil geography is occurring, it is time for a reconnection between the two disciplines to be recognized and implemented to build upon the strengths of both fields.

The concept of soil, in general, has received increased attention recently due to rising concerns about sustainability, especially in the context of the ecosystem services that soil system provides. One of the key services that soil provides in sustaining human life is mediated through agriculture. Since the emergence of farming, human impacts on the soil system have become an important aspect of soil dynamics (Grieve, 2001; McLauchlan, 2006; Veenstra and Burras, 2015). The change from a nomadic to a sedentary lifestyle changed the relationship between soil and humans, beginning an era of increasing impacts that people have on soil functions (Pereira and Martinez-Murillo, 2018). The recent exponential growth of the human population has intensified demand for food and resources, resulting in anthropogenic impacts on soil to a level that has never before been experienced (Ferreira et al., 2018). However, it should be noted that human manipulation of soil has a long history and does not necessarily lead to negative impacts. For example, there is archeological evidence that humans have influenced soil formation to increase productivity, such as the *terra preta de Indio* (McMichael et al., 2014). With the expansion of human activities, we humans have become an important soil-forming factor (Bajard et al., 2017; Bidwell and Hole, 1965; Bockheim et al., 2014). Concerns about environmental issues have resulted in increasing interest in both soil science and geography (e.g. Jónsson and Davíðsdóttir, 2016; Pereira et al., 2018). For the same reasons that both disciplines were born in an era of investment in the management of natural resources, they are once again in demand.

Surges in these disciplines appear to occur at the convergence of new technologies and pressing issues facing society. When these two ingredients come together, doors into areas of new exploration are opened, new approaches are tested, and investment becomes a greater priority for government leaders. By the 19th century, surveying technology had reached a point that facilitated the unprecedented, quantitative study of spatial relationships, at the same time that nations recognized the critical role that natural resources played in the accumulation of wealth (Miller and Schaetzl, 2016). Today, as we begin the 21st century, geospatial technologies such as global positioning systems (GPS), remote sensing, and geographic information systems (GIS), coupled with vastly improved spatial datasets such as LiDAR elevation and frequently updated aerial imagery archives are revolutionizing the capabilities and opportunities of both geography and soil science. The second ingredient – societal demand – is at our doorstep. The great concerns about environmental issues, including global climate change, ecosystem services, water quality and quantity, soil degradation, loss of biodiversity, food security and quality, are all well known to geographers and soil scientists. As recognition of these issues progresses around the world, the need for geography and soil science expertise can only grow.

In this paper, we review (1) the historical connections between soil science and geography, and (2) how recent technological advancements have provided an impetus to reinvigorate each of these two respective disciplines' interest in the other. Future papers in this three-paper series will explore the opportunities for future collaboration between geography and soil science in greater depth.

II Historical origins of soil science and geography

Soil science and geography have similar historical roots as academic disciplines. Although some aspects of geography have been important to human societies for thousands of years (Harvey, 1984) and geographical concepts have been taught in universities for a few centuries (Johnston, 2003), geography was only established as a formal academic discipline in the latter part of the 19th century (Harvey, 1984; Johnston, 2003; Sack, 2002; Shaw and Oldfield, 2007) and was not taught in some countries as a formal university subject until much later (Barnes, 2007). Similarly, although soil and soil science concepts have been societally important for thousands of years, soil science per se was only organized as an independent field of scientific study in the late 19th century (Brevik and Hartemink, 2010; Krupenikov, 1993). In the late 19th and early 20th centuries, both soil science and geography received strong, foundational contributions from scientists trained as geologists; in fact, with a lack of formally trained geographers it was common for the first geography scholars to come from fields such as biology, geology, history, journalism, and mathematics (Johnston, 2008). The beginnings of soil science were largely the same, with early concepts of soil being driven by many of the same respective base disciplines. For example, in the 19th century, chemists favored an emphasis on the humic content of soil while geologists emphasized the mineral content. It is noteworthy that the motivating purpose to study soil at the time was for agriculture, leading to terms such as agrochemists and agrogeologists (Krupenikov, 1993).

Both soil science and geography benefited from the scientific advancements stemming from the Age of Exploration and the associated motivations of national governments. Enough scientific advancement occurred in the 15th century for the European empires to realize the benefit of, and to invest in, the accurate mapping of national borders and resource inventory. In part, these developments were based on improved survey methods, but that effort in turn gave rise to more scientific study of spatial patterns for better spatial prediction and understanding of processes.

The confluence of these two disciplines and the rise of scientifically based "spatial thinking" is exemplified by one of the founders of geography, Alexander von Humboldt (1769–1859) (Figure 2) (Bouma, 2017; Hartshorne, 1958). Humboldt published a treatise on the basalt formations along the Rhine River early in his career (von Humboldt, 1790), but he was mostly known for his botanical work while on expeditions to explore the western hemisphere. What made Humboldt remarkable was his use of quantitative methods, including the careful recording of latitude and longitude, and attention to the covariation of phenomena over space, later termed "spatial association" in geography. Prime examples of this were Humboldt's identification of relationships between vegetation and elevation (von Humboldt and Bonpland, 1807/2009), and with global climate zones (von Humboldt, 1817). His scientific achievements made Humboldt an academic superstar. For this reason, Russia repeatedly invited Humboldt to conduct expeditions into Asia, an offer that was finally realized in 1829 (Wulf, 2015).

Figure 2. Alexander von Humboldt (pictured here in 1814) implemented more quantitative methods during the Age of Exploration to advance understanding of spatial patterns in the physical environment. His work inspired a new generation of geographers and approaches to studying the Earth.

Like Humboldt, the naturalist Charles Robert Darwin (1809–1882) (Figure 3) became famous from his studies during his exploration of the western hemisphere. Besides his well-known work on evolution, Darwin also made contributions to understanding soil processes, particularly mixing by soil fauna (bioturbation) (Darwin, 1869, 1881). Darwin's work laid the

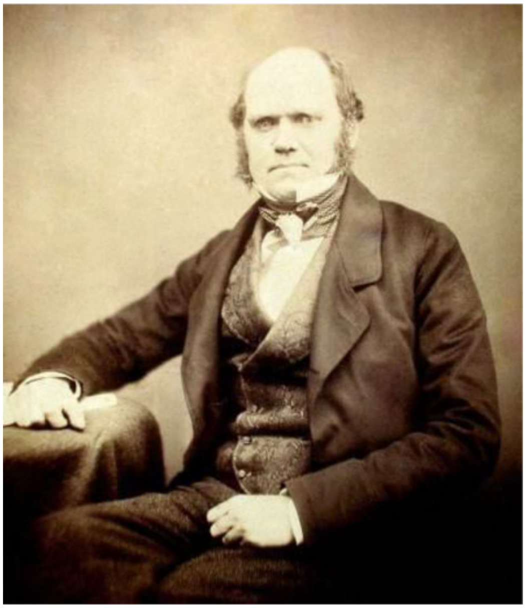

Figure 3. Charles Darwin (pictured here in 1855), best known for his work as a naturalist, contributed to soil science with his observations of the effect of bioturbation on the soil.

foundation for an array of multidisciplinary studies on pedogenic processes during the ensuing decades, even though this approach to soil science remained in the shadow cast by Dokuchaev's more geographic approach to the study of soil (Johnson and Schaetzl, 2014). In 1975, Darwin's ideas reappeared in Soil Taxonomy (Soil Survey Staff, 1975), if only minimally, as a part of the then-emerging "biomantle" concept (Johnson et al., 2005). Recently, however, the bioturbation concepts first espoused by Darwin have gained considerable traction (e.g. Balek, 2002; Fey, 2010; Humphreys et al., 1996).

The founder of modern soil science was born into this academic environment. The Russian Vasily Vasilyevich Dokuchaev (1846–1903) (Figure 4) was trained as a geologist and early in his career worked on mapping the geology and soils of Russia (Dokuchaev, 1877, 1879). Expanding on Humboldt's approach of spatial association between organic life and environmental conditions, Dokuchaev recognized that soil spatially co-varied with both biota and other environmental conditions (Brown, 2006). Specifically, Dokuchaev identified soil as resulting from the combined factors of climate, vegetation, parent material, relief, and time (Dokuchaev, 1883/1967).

Figure 4. Vasily Vasilyevich Dokuchaev (pictured here in 1888) had profound impacts on the inception of soil geography as a science. Dokuchaev did not associate with geography, but his work and the work of his students laid the groundwork for most of the soil maps in use today.

The interactions between geology, geography, and soil science in the late 19th to early 20th century were numerous and complex, frequently making it difficult to place individuals into one of these disciplinary categories. As an example, the geologist Arthur E. Trueman (1894–1956), who had originally joined University College, Swansea as the first head of the Department of Geology, expanded the department to include geography, which later

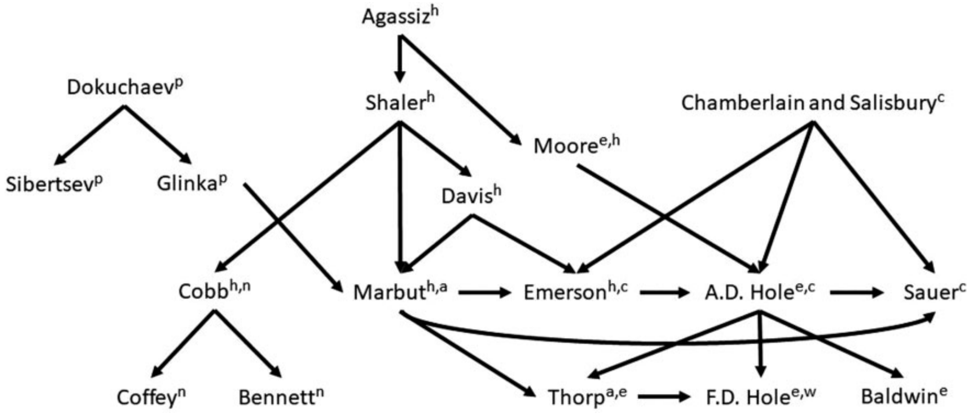

Figure 5. Academic tree of key influencers in American soil geography. Many of the names in this chart will be recognized by geographers, geologists, and soil scientists as members of their own discipline. (a – Graduate School of the USDA, c – University of Chicago, e – Earlham College, h – Harvard University, n – North Carolina State University, p – Imperial University of St Petersburg, w – University of Wisconsin at Madison) (Extended from Tandarich et al., 1988a)

separated into two successful departments (Pugh, 1958).

In the late 9th century, geologists at Harvard University generated the foundations of geography and soil science in the USA (Figure 5). Nathaniel S. Shaler (1841–1906) authored a classic work on "The Origin and Nature of Soils" (1891), which extended Darwin's work on bioturbation. Shaler's student and later colleague, William Morris Davis (1850–1935), is recognized today as the father of American academic geography (Sack, 2002). Collier Cobb (1862–1934), a student of both Shaler and Davis, later became the head of the Geology Department at the University of North Carolina where he conducted research on human geography, coastal processes, and aeolian processes. In addition, while at the University of North Carolina, Cobb established a Bachelor of Science program in Soil Investigation, which supplied many of the mappers for the early soil survey program in the USA (Brevik, 2010). Another of Davis' students, Curtis F. Marbut (1863–1935), served as the director of the USA's Soil Survey Division from 1913 to 1935, a critical time in forming the procedures that produced the soil maps used in the USA today. Davis was the first and fifth president and Marbut was the twentieth president of the Association of American Geographers.

In central Europe, Dokuchaev laid the groundwork that would establish soil science as an independent scientific field (Johnson and Schaetzl, 2014; Tandarich and Sprecher, 1994). Although modern soil scientists celebrate Dokuchaev's recognition of soil as an independent body of study, the core of his work laid the foundations of soil geography, not pedology (Buol et al., 2011). Before World War I, American geographers regularly studied and corresponded with German geographers (Martin, 2015). Among them was Marbut, who translated "The Great Soil Groups of the World and their Development" from German to English. The author of that text was Konstantin Dmitrievich Glinka (1867–1927), the first director of the Dokuchaev Soil Science Institute. Between Marbut's study of the Russian philosophies on soil science and the work of American geologist Eugene W. Hilgard (1833–1916), the notion that soil was more than the product of only geologic processes were being adopted in the USA.

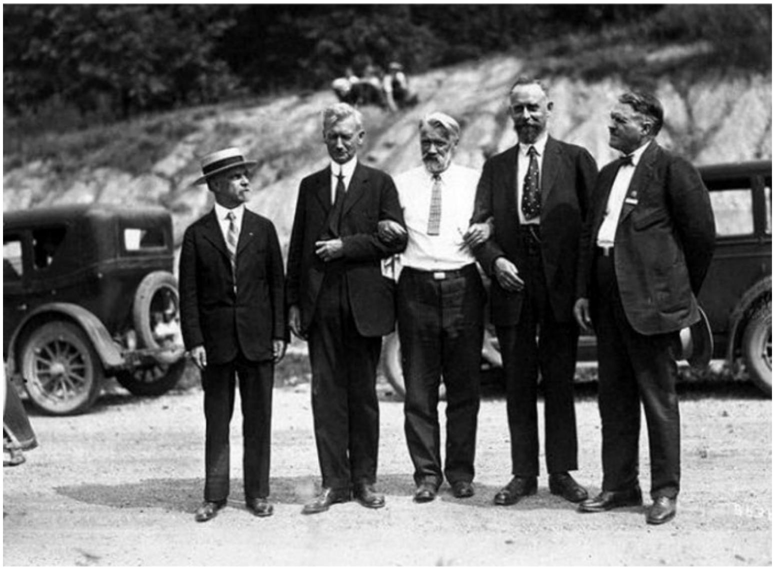

Figure 6. Curtis Marbut (second from left) and Konstantin Glinka (middle). These were the leaders of the two most active soil survey programs in the world, during the most critical time of soil mapping methods development. Marbut was a proponent of the concepts that Glinka had written about. Photograph taken at the first re-organized Congress of the International Association of Soil Science, hosted by the USA in 1927.

In 1927, the USA hosted the first meeting of the re-organized Congress of the International Association of Soil Science. That conference was monumental in its gathering of influential leaders for soil mapping at the time when soil survey programs were gaining major momentum (Figure 6). The list of congress attendees was filled with notable scientists that geographers and soil scientists of the respective countries will recognize, such as J.H. Ellis (Canada), E.J. Russell (England), A. Penck (Germany), H. Stremme (Germany), L. Kreybig (Hungary), P. Treitz (Hungary), H. Jenny (Switzerland), M. Baldwin (USA), T.M. Bushnell (USA), C.F. Marbut (USA), K.D. Glinka (USSR Russia), S. Neustruev (USSR Russia), and L. Prasolov (USSR Russia). These connections and commonalities between the founders of modern geography and soil science, with geology frequently a common link, illustrate the natural and historical ties between these disciplines.

I The connections

Soil geography is, in its most fundamental sense, the study of the spatial distribution of soil. Inherent in that study are the patterns of soils, soil properties, and the processes that produced those patterns. There is evidence of interest in soil geography per se, starting well before the time that soil science and geography had become established as academic fields of study. Archeologists have found evidence of farming according to soil fertility patterns dating back to 3000–2000 BCE, information on the spatial distribution of soil properties was recorded in China as early as 300 CE (Miller and Schaetzl, 2014), and maps of soil attributes were made in Europe by the early 1700s (Brevik and Hartemink, 2010). In North America, native peoples recognized that soil in floodplain areas were fertile places for crop production before European settlers arrived (Brevik et al., 2016b). Also, in the modern American Southwest, farming was concentrated in locations where soil water was preferentially retained in the root zone due to restrictive layers such as shallow bedrock, petrocalcic, or argillic horizons (Homburg et al., 2005; Sandor et al., 1986). Although these examples do not indicate the existence of a formal academic field, they do show that the fundamental recognition of spatial variation in soil properties has had a long history.

In Europe, early mapping of soil tended to be by boundaries of land ownership due to the connection with land valuation and taxation. Although largely a geology map, William Smith (1769–1839) mapped the variation of soils in his landmark map of England, Wales, and Scotland (1815). In Germany, unique soil classification systems were being proposed by the mid-1850s (Krupenikov, 1993). For example, Friedrich Fallou (1794–1877) published books on the soil types of Saxony and Prussia (Fallou 1853, 1868, 1875). With advancements in understanding soil fertility, soil mapping endeavors in Germany shifted from cadastral to the ability of soil to respond to different management practices. In general, the soils of Europe were first mapped by geologists, as they were the most familiar with surveying and mapping techniques. Approaching soil from this perspective, the scientists working in this area advocated for the study of soil to be defined as agrogeology, a subdiscipline of geology (Berendt, 1877; Ehwald, 1964). József Szabó (1822–1894) published soil maps of this style for Hungary in 1861, adding considerations of groundwater (Szabó, 1861). In 1867, A. Orth's map entitled "Geologic-Agronomic Mapping" won a competition for "agricultural geognosy," sponsored by the Agricultural Union of Potsdam (Mückenhausen, 1997). German unification occurred in 1871 and coincidently the reputation of German geography, as well as German soil mapping, rose in the world. Indicative of the influence of German soil geography, M. Fresca was invited to map the soil of Japan from 1885 to 1887 (Krupenikov, 1993).

The recognition and mapping of soil spatial properties were central to the establishment of soil science as an independent field of study (Brevik et al., 2016a). The foremost individual in this undertaking was Dokuchaev, who although trained as a geologist specializing in mineralogy (Tandarich and Sprecher, 1994), became noted for his studies of soils and their distributions. As with all major scientific advances, the contributions that elevated soil science were made by a number of individuals, but because Dokuchaev's contributions led to definite changes in the way soil science was viewed and conducted, he is widely recognized as the father of soil science (Jenny, 1961; Johnson and Schaetzl, 2014; Krupenikov, 1993; Landa and Brevik, 2015; Schaetzl and Thompson, 2015). A major piece of that contribution was Dokuchaev's publication on the Russian Chernozem (1883/1967), which espoused the interdisciplinary view that soil was a product of more than only geologic processes. Ironically, Dokuchaev expressly refused to associate himself with the field of geography and did not feel that the fledgling science he was helping to create coincided with geography (Shaw and Oldfield, 2007). Nonetheless, his student, Glinka, produced the first soil map of the world in 1908 (Hartemink et al., 2013). In 1909, several followers of Dokuchaev, all wrestling with how to better map soil, attended the first International Agro-Geological Conference hosted by the Royal Hungarian Geological Institute in Budapest. That conference marked a turning point for soil science in that it addressed the "confusion [that is] for a time inevitable in a borderland subject like the present, that joins up with geology, botany, and chemistry, and is closely connected with agriculture; indeed, even its very name has not yet been settled, for we find the subject of the conference referred to as agrogeology, agricultural geology, pedology, or simply 'the science of soil'" (Russell, 1910, p. 157).

Figure 7. Milton Whitney (pictured here in the 1910s) was the first chief of the American Bureau of Soils, which was charged with the first nationally coordinated soil survey, including uniform standards and practices for the staff producing the soil maps.

Similar to the experience in Europe, early soil mapping efforts in North America were generally performed by trained geologists, largely because academic programs in soil science did not yet exist (Brevik, 2010; Coffey 1911; Lapham 1949). The USA established the first nationally coordinated soil survey effort in 1899 (Marbut, 1928). This undertaking was significant for soil geography in that it represented the first attempt to spatially catalog the soil of a country using uniform standards and practices. Under the direction of Milton Whitney (1860–1927) (Figure 7), the first generation of these maps were produced using the agrogeology approach. In the 1930s, Marbut's integration of Dokuchaev's multi-factor approach and the wider availability of aerial photography came together to facilitate a second generation of soil maps, using the concept of the soil-landscape paradigm. Essentially, the soil-landscape paradigm established that soil map units should occur together in a regular, repeatable pattern, based on the spatial patterns of the soil-forming factors. Those areas with similar factors, especially topography, were predicted to have similar soil properties (Hudson, 1992). The soil map units so-mapped tended to be based on the factors of soil formation identifiable in stereo-orthophotographs (Simonson, 1989). A set of soil map units occurring together was called a soil association in the USA's Soil Survey system; this term was parallel to Milne's catena

Figure 8. Hugh Hammond Bennett (center) in the field calling attention to the severity and impacts of soil erosion. Image courtesy of the USDA-NRCS.

concept established for soil mapping in Africa (Bushnell, 1943; Milne, 1935).

Other examples of pioneering soil work done by geographers are easily found. The first soil fertility map of Britain was prepared in the 1930s by the geographer Sir Dudley Stamp (1898–1966), with help from other geographers such as E.C. Willatts (1908–2000) (Willatts, 1987). Stamp, whose academic training was as a geologist but who made his career as a geographer, became one of the most influential geographers in Britain (Johnston, 2008). Willatts was also widely known and became the organizing secretary of the Land Utilisation Survey of Great Britain (Wise, 2000).

Hugh Hammond Bennett (1881–1960) (Figure 8), trained as a geologist by Cobb at the University of North Carolina, began his career as a soil surveyor, which took him across the USA and other countries conducting soil research. As a result of those experiences and an address given by Chamberlain, Bennett became concerned about the problem of soil erosion in the 1920s. In 1928, he co-authored "Soil Erosion: A National Menace," which would be influential in the development of the USA's Soil Conservation Service (SCS). Bennett became the director of the Soil Erosion Service when it was established within the USA's Department of Interior in 1933 and then became head of the SCS when it was established within the Department of Agriculture in 1935. Bennett's advocacy for protecting soil resources was pioneering, strengthened by increased public awareness during the Dust Bowl which occurred between 1934 and 1940 (Helms, 2010; Lee and Gill, 2015). Hugh Hammond Bennett served as president of the Association of American Geographers from 1943 to 1944.

Carl O. Sauer (1889–1975) was a highly influential American geographer (Kenzer, 1985) who served as president of the Association of American Geographers from 1940 to 1941. He influenced soil geography largely through his role on President Franklin D. Roosevelt's (1882–1945) Presidential Science Advisory Board in the 1930s. Sauer suggested that the SCS should integrate pedology, geology, and climatology in their land research (Holliday et al., 2002). This recommendation was in line with Sauer's background, for even though he made his reputation as a cultural geographer, he began his graduate studies in geology, with a specialization in petrography (Kenzer, 1985). Sauer was an advocate for broad academic training and for including individuals from related fields with geographic interests in the study of geography (Sauer, 1956). The SCS accepted his advice and started a research program under the geographer/climatologist Charles W. Thornthwaite (1899–1963), who studied under Sauer at the University of California at Berkeley (Mather, 2005). This research began to form the foundation of soil geomorphology, work that was interrupted by World War II (Holliday et al., 2002).

Perhaps the academic crown jewel of geology-soil academic linkages was the soil geomorphology program, established by the USA's National Cooperative Soil Survey (NCSS) in the 1930s. The NCSS is a special partnership between the American federal government, state and local governments, and universities to improve soil maps. Using many of the ideals espoused by Sauer, the NCSS led the development of the soil geomorphology program, which was to be focused on "surface and soil," and to have pedologists, geologists, as well as climatologists work together and focus on the interactions and co-development of soil and landscapes (Effland and Effland, 1992). Under the leadership of Charles Kellogg (1902–1980) and assisted by Guy Smith (1907–1981), the program had a stated research mission to understand soil-landform relationships in support of soil mapping (Grossman, 2004). Smith and the NCSS established several research locales where soil geomorphology was to be studied in detail, including subhumid Iowa (led by Robert Ruhe (1918–1993), a geologist), a desert site in New Mexico (led by Leland Gile (1920–2009), a soil scientist), a humid site in the Pacific Northwest of Oregon (led by Robert Parsons, a soil scientist), and one in North Carolina (led by Ray Daniels (1925–2009), a soil scientist). Theories and data that poured out of these four sites spurred considerably more work of this kind within the university community, had profound effects on theories of soil and landscape evolution, and greatly influenced the way soil was classified (Effland and Effland, 1992). Much of this effort culminated in the first textbook devoted to soil geomorphology, written by geologist Peter Birkeland (Birkeland, 1974).

Although this brief discussion is by no means exhaustive, and there are many additional individuals and advances that could be discussed, it does serve to demonstrate that there are strong historical ties between soil science and geography, and that significant advances were being made in both soil science and geography in the late 19th and early 20th centuries (Figure 9). It also demonstrates that advances in soil geography were driven by individuals trained in a number of fields, including chemistry (e.g. Whitney), geography (e.g. Sauer, Thornthwaite), geology (e.g. Dokuchaev, Marbut), natural science (e.g. Darwin), and others (Helms, 2002; Johnson and Schaetzl, 2014; Johnston, 2008; Landa and Brevik, 2015).

2 The disconnect

Soil science and geography share some historical background; they are both highly interdisciplinary, and in fact, overlap with one another. They share many "founding fathers." And yet, despite the connections and commonalities, in many ways it seems that there has been a disconnect between the fields for much of their recent histories. This is particularly true in the USA. Although geographers have made numerous contributions to soil science in Europe, where an academic association between soil science and geography is common (Brandt, 1999; Freeman, 1987; Willatts, 1987), soil science work in the USA has largely been conducted in colleges of agriculture at the land grant universities, particularly in departments of agronomy, plant and soil science, soil science, etc. (Brevik et al, 2016c; Landa, 2004). Brevik (2009) estimated that there were only about 50

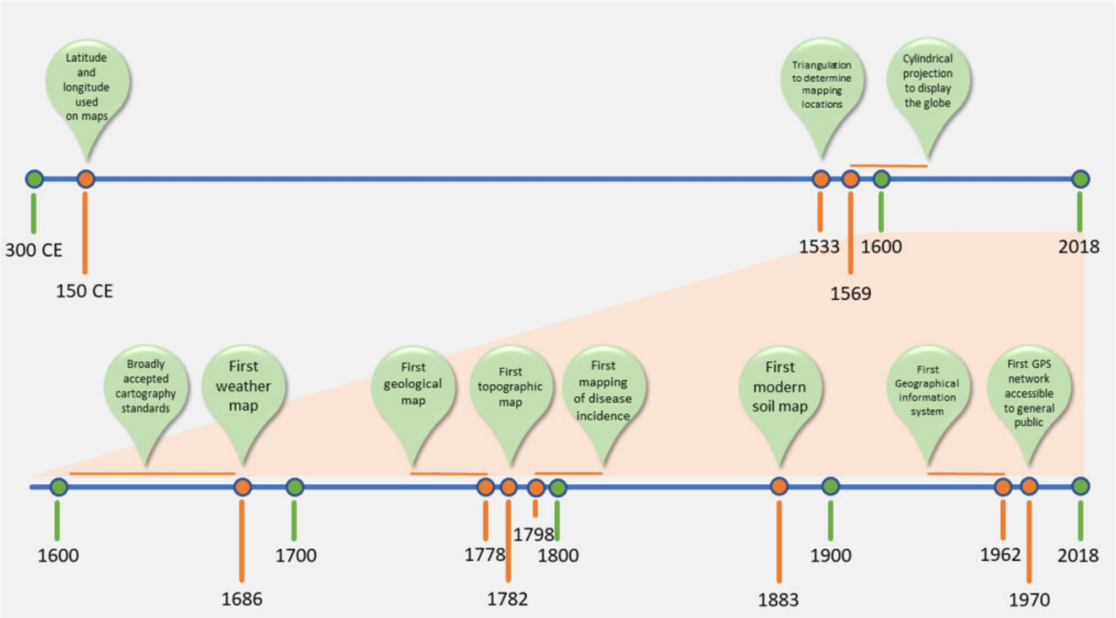

Figure 9. Milestones in the development of map-making technologies, leading to important advancements for both geography and soil science.

soil specialists (as compared to approximately 2,500 total geographers) employed in the geography departments of USA colleges and universities in 2005. Only about one in five geography programs had a stated soil specialist. This contrasted with approximately 640 soil specialists employed in agricultural-based soil programs, even though geography programs were offered at >260 universities in the USA while agricultural-based soil programs were offered at only about 76 universities (Brevik, 2009). Landa and Brevik (2015) found that 76% of the soil science programs in the USA were offered by land grant universities, only 5% were offered by Earth science departments, whereas the remaining 20% were offered by non-land grant universities that had agriculture programs.

In addition to soil research and teaching being primarily within agriculture departments at American universities, federal soil mapping and research programs have traditionally been housed within the USA's Department of Agriculture (USDA). This organization occurred despite early attempts by Eugene W. Hilgard (1833–1916) and John Wesley Powell (1834–1902), two prominent American scientists, to create a division of agricultural geology within the USA's Geological Survey (Amundson and Yaalon, 1995). Within the USA, the largest professional soil science society, the Soil Science Society of America (SSSA), evolved from the American Society of Agronomy (ASA) and routinely holds their annual meetings in association with ASA and the Crop Science Society of America. Only one annual meeting of SSSA to date has been in association with an Earth science society, that being a meeting with the Geological Society of America in 2008 (Brevik, 2011). Because of its association with agriculture at both the academic and federal government levels, soil science has typically not been viewed as a geoscience in the USA (Landa, 2004), likely weakening potential ties between soil science and geography.

The evolution of geography as a discipline has likely had its own effect on the drift of geography away from soil studies. At the beginning of the 20th century, what we would today call physical geography dominated geography departments, and soil was often studied by geomorphologists. For example, geographers may consider Davis the "father of American geography," but geologists also consider him as one of their own. At least in the USA, physical geography became a smaller component of geography as the rise of human geography proceeded. Today, physical geographers sometimes wrestle with distinguishing themselves from their colleagues in geology or biology departments, disciplines that also share connections with soil science. In many ways, this is a natural situation for interdisciplinary topics, but in general, soil research has been largely overlooked by non-agricultural disciplines over the past century.

In recent decades, the field of soil science has moved away from the science of mapping. Soil science was born out of the recognition of multiple factors affecting the processes and thus the spatial distribution of different soil properties. However, by the early 20th century the scientific study of mapping soil, *sensu stricto*, was fading. In 1929, Thomas Bushnell complained that the meetings of the organization once called the "American Association of Soil Survey Workers" was no longer balanced between the study of soil and the study of surveying or mapping. That organization evolved into the SSSA, which today comprises 14 divisions of interest. Soil mapping is a subset of the pedology division, which also includes soil formation, classification, physical and chemical properties, interpretation of soil behavior, human land-use decisions, and ecosystem evolution. To be fair, there are also separate divisions for soil chemistry, mineralogy, biology, physics, as well as for different ecosystems. In addition, soil formation and interpretation of soil behavior are natural pairings with soil mapping. Nonetheless, investment and research activity on the geographic nature of soil studies has been decreasing. For example, other than a brief spurt of interest between 2009 and 2011, presentations on soil mapping at national SSSA meetings have been sparse (Figure 10) and the USA's federal budget for soil mapping has declined from an all-time high in the late 1980s to a long-time low in 2013–2015 (Brevik et al., 2016c). Soil scientists today need to answer questions such as: Why should more investment be made in soil mapping? Weren't the strategies for mapping soil worked out by the 1940s? Why should areas that have already been mapped be revisited (e.g. >85% of the USA has already been mapped (Indorante et al., 1996))?

A symptom of the disconnect between soil science and geography is the lack of recognition of core geographic concepts as the basis for the soil mapping paradigm. Geographical context is crucial to understand soil formation and disturbances. Ask a soil scientist how they map soil, they will likely cite or describe the soil-landscape paradigm (Hudson, 1992). If pressed to explain why that works as a means of spatial prediction, they would likely describe the five factors of soil formation that broadly describe processes influencing soil properties. What many do not think about is that this concept of spatial covariation has a long history in the geographic study of many topics. When Bushnell (1929, p. 23) was complaining about the lack of attention to mapping concepts by soil scientists, he observed that "once we enter the map making game, there are rules to be obeyed and standards, which must be met." Because of the relatively small change in soil mapping methods over the past century, the old rules are largely adhered to, with minimal thought about methodological improvement. Meanwhile, geography has evolved, and new datasets have emerged; there now exist new methods of analysis, awareness of spatial complications (e.g. modifiable

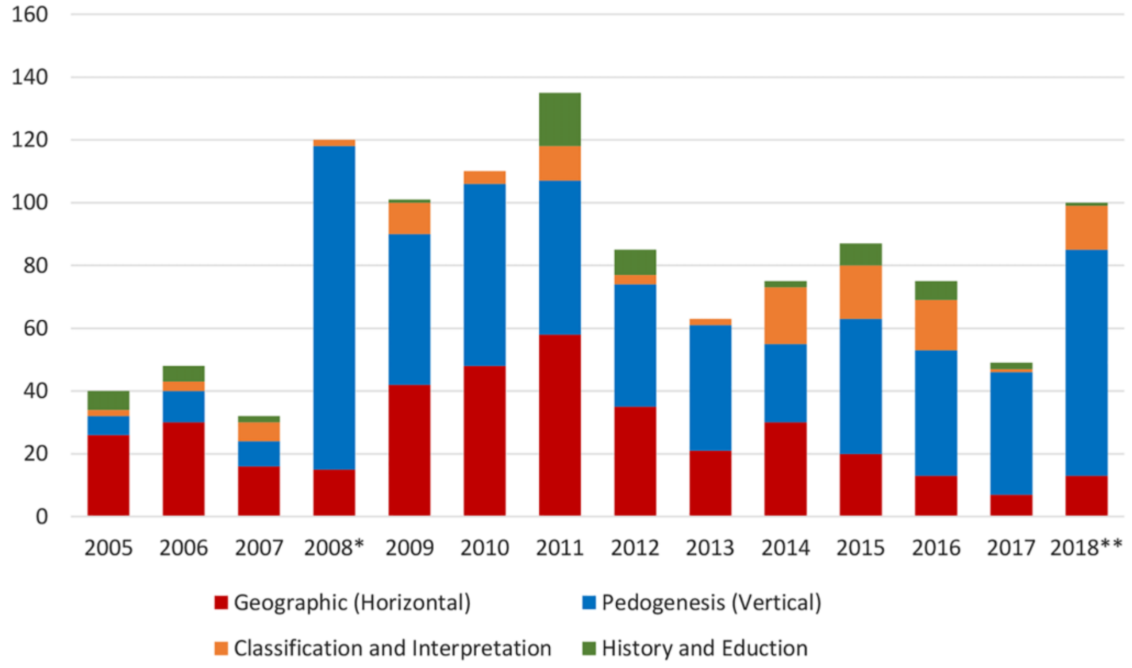

Figure 10. Topical trends for presentations given in the pedology division of the Soil Science Society of America (SSSA). After reaching a peak in 2011, which corresponds with a surge of interest by Americans in digital soil mapping, the quantity of presentations on the spatial prediction or geographic distribution of soil has been declining. *2008 was a joint meeting with the Geological Society of America. **2018 was held in January of 2019, independently of the usual association with the Crop Science Society of America and the American Society of Agronomy.

areal unit problem), and higher standards for quality map production.

There are, of course, exceptions to these broad generalizations. Vladimir M. Fridland's (1972/1976) work on analyzing soil cover patterns is one example. In 1985, Francis D. Hole and James B. Campbell wrote *Soil Landscape Analysis*, which uses the term "spatial association" to describe the traditional method of soil mapping. In many ways, the analyses presented in that book (Hole and Campbell, 1985) echo the style of thinking advanced by geographer William W. Bunge (1928–2013) in his seminal text for geography's quantitative revolution, *Theoretical Geography* (Bunge, 1962). It is also worth noting that the eminent Francis D. Hole (1913–2002), who was trained in geology and soil survey, held a joint appointment at the University of Wisconsin in both the Departments of Soil Science and Geography (Brevik, 2010; Devitt, 1988; Tandarich et al., 1988b).

III Soil science's renewed interest in soil mapping

1 The geospatial revolution's effect on soil mapping

The tools made available by the geospatial revolution of the past 20 years have undoubtedly had major impacts on many avenues of scientific investigation (Longley et al., 2015). This impact is especially true for mapping applications in soil science. Similar to the stimulation that the first and second waves of soil mapping provided to soil science, the current third wave

Figure 11. Global position systems (GPS) have changed soil sampling by improving pre-planning, re-use of sample data, and the accuracy of relating soil properties with covariates. The researchers in this photo created a sampling design using digital terrain analysis and are now locating those sample points using a GPS receiver.

is setting the stage for discovering spatial patterns that will prompt further research into the processes producing those patterns.

Not long ago, the locations of representative soil samples were commonly described in writing as distances and directions from an available landmark. Today, GPS units are commonplace, making it simpler and more accurate to record sample locations using geographic coordinates (Figure 11). In addition to improving the ability to return to those sampling sites, the association of the observed soil data with accurate geographic coordinates has opened a completely new realm of spatial analysis and mapping. Sampling designs can now be planned in a GIS and the soil data collected can be intersected with multiple layers of environmental covariates.

This same geospatial revolution produced a tremendous number of new base maps and related data sources, all of which could contribute to the new mapping effort. Satellite images can span the electromagnetic spectrum and cover large extents, providing indicators of vegetation, natural hazards, and other physical landscape properties (Joyce et al., 2009; Mulder et al., 2011; Xie et al., 2008). LiDAR-based elevation data are highly accurate and detailed and are becoming increasingly common (Hodgson and Bresnahan, 2004). Adding value to elevation alone, digital terrain derivatives provide important information related to surface topography and wetness (Gessler et al., 2000; Moore et al., 1993; O'Loughlin, 1986). Although usually for smaller extents, proximal sensing systems such as ground-penetrating radar, electromagnetic induction, and electrical conductivity penetrate the surface to provide detailed data about stratigraphy within and below the soil profile (Doolittle and Brevik, 2014; Hedley et al., 2004; Huisman et al., 2003; Molin and Faulin, 2013; Rhoades and Corwin, 1990). Some of these data products can be incorporated into the manual process of delineating map units, but the quantity of data set layers quickly becomes more than can be utilized by visual inspection. By quantifying the relationships between these covariates and soil properties with tools such as machine learning, the mapping process can be made more automated and more repeatable.

In the pre-digital soil mapping paradigm, experience from surveying the soil landscape helped the mapper develop a mental model for predicting the expected spatial distribution of soil types and their associated soil properties (Hudson, 1992). Mappers would seek to establish relationships among soil types and, in particular, landscape position and vegetation cover (e.g. Barrett et al., 1995; Parsons et al., 1970). That mental model was then applied to the best available base map, often a stereopair of aerial photographs, to delineate soil map units (Miller and Schaetzl, 2014). In the case of a stereopair, the soil mapper would use cues from changes in topography and vegetation to hand-draw map unit boundaries in the office and field-check them later. Although difficult to directly overlay, the soil mapper would also make use of any existing maps – such as geology maps – to better predict where different soil types occurred. GIS software changed that system by making it easier to overlay different base maps and to edit map unit delineations (Chrisman, 1987; MacDougall, 1975). Of course, GIS has the power to do much more, but for traditional soil mappers, GPS-logged field observations, access to better base maps, and easier overlays best describe the first step into the geospatial revolution.

A major asset of the traditional soil mapping approach was the human mind's ability to synthesize years of field experience and add a degree of intuitive knowledge to the field mapping effort. However, that mental model approach has two major limitations: 1) it is based on human judgement, making it largely not repeatable, and thus, 2) much of the knowledge is lost when the soil mapper retires. This latter problem has been a major issue for the current mapping effort within the USA's Soil Survey, where most mappers from the 1970s and 1980s have since retired; the brain drain is real and there may be no solution. The number of soil scientists employed by the US federal government declined by 39% from 1998 to 2017 (Vaughan et al., 2019). If the time has run out for documenting localized expert knowledge, the best approach for the next generation of soil maps may be to "start over," using the enhanced data sets and powerful mapping and modeling software that have recently emerged. Again, GIS offers the tools to quantify the spatial relationships between soil properties and covariates, making the spatial models more efficient and repeatable. Regardless, the original base soil maps and their underlying data remain, from which new and better mapping efforts can be built. At the minimum, the previous generation of soil data provides the opportunity to study soil change (e.g. Veenstra and Burras, 2015).

Early work connecting geospatial technologies with soil mapping began simply with storing and representing soil information in a GIS (Legros and Hensel, 1978; Tomlinson, 1978; Webster and Burrough, 1972; Webster et al., 1979). Although digital cartography is an achievement in itself, the visualization of soil maps using a computer did not utilize the potential to improve the maps with the spatial analysis components of the geospatial revolution. Soil scientists took note of the effects of spatial autocorrelation and instituted spatial sampling designs to avoid this type of bias in the early 20th century (Fisher, 1925; Mercer and Hall, 1911; Youden and Mehlich, 1937). The availability of general use computers reignited the application of computationally intensive statistics again later in that century (e.g. Hole and Hironaka, 1960; Rayner, 1966; Webster and Burrough, 1972). With the addition of Matheron's concepts for geostatistics (Matheron, 1965, 1969), these combined elements spurred enthusiasm for spatial models to predict the distribution of soil properties (e.g. Burgess and Webster, 1980; McBratney and Webster, 1983; Vauclin et al., 1983). By 1994, the study of soil science with statistical and probability approaches afforded by computers came to be known as pedometrics (Webster, 1994). Early approaches to digital soil mapping emphasized geostatistics, but over time methods for digital soil mapping relying on the covariation of soil properties with variables measured by remote or proximal sensing have become more dominant (Figure 12).

2 The era of digital soil mapping

Two papers were coincidently published in 2003 that explored new trends in geospatial technologies and their increasing utilization in soil mapping research. One was published in the journal *Progress in Physical Geography* (Scull et al., 2003), the other in *Geoderma* (McBratney et al., 2003). Both papers were exemplary reviews of the state of the art for utilizing geospatial technologies to model the spatial distribution of soil. The publication of these papers marked the widespread recognition that

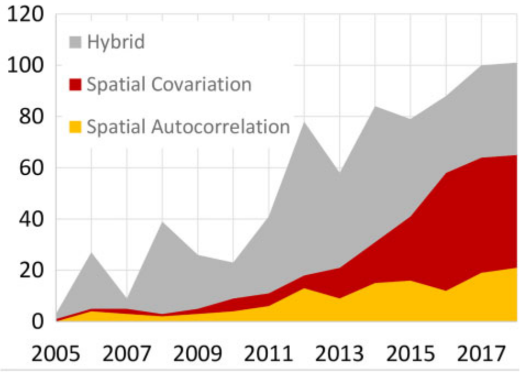

Figure 12. Trends in spatial prediction methods used in digital soil mapping. Geostatistics (spatial autocorrelation) was an early favorite for digital approaches to soil mapping. However, more recently spatial regression (spatial covariation) approaches have gained in popularity. Data obtained from a search of Scopus (2019) using the search term "digital soil mapping."

geospatial technologies were providing new ways of thinking about soil mapping. The article by McBratney et al. (2003) – targeted to soil scientists – had 2120 citations as of February 9, 2019 (Google Scholar). Although the article by Scull et al. (2003) – targeted to geographers – has not exactly been ignored, it nonetheless had 431 citations on the same date. This disparity may be an important indicator of the respective disciplines' interest in soil mapping; soil scientists may be more interested in digital soil mapping, even though many are self-made geographers. Those that work on digital soil mapping are more likely to have soil science as their home discipline and then to indirectly adopt geospatial technologies as tools. While this is a natural situation for interdisciplinary topics, it is not the same as directly interacting with researchers who have the scientific study of spatial analysis and prediction as part of their academic heritage. Although our paper argues for greater collaboration between geographers and soil scientists, there is no doubt that great strides have already occurred in the realm of digital soil mapping. The annual number of papers that Google Scholar has indexed using the words "digital soil mapping" increased from 22 to 557 in the decade following the landmark review papers in 2003 (Figure 13).

In response to demands for a global data set to assist decision making addressing issues of food security, climate change, and environmental degradation, the Digital Soil Mapping Working Group of the International Union of Soil Science established the Global Soil Map initiative in 2008. This project is coordinating national soil mapping agencies to produce a standardized digital product of soil information (Sanchez et al., 2009). Although several countries were already reinvigorating their soil mapping programs with digital soil maps, the Global Soil Map project has created a target for map quality and important soil properties to be included. For example, one of the major objectives of the project is to include estimates of spatial uncertainty. The ambitions of this project have attracted funding to assist areas with the greatest need for this information, particularly sub-Sahara Africa.

Beyond the obvious use of digital tools to represent the spatial distribution of soil, digital soil mapping aims to incorporate other improvements to soil maps. Digital soil mapping is careful to distinguish digitized soil maps from digital soil maps. The former does not leverage the benefits of spatial analysis in a GIS. Although legacy soil maps still hold a lot of value, simply digitizing them into a GIS fails to advance the science of soil mapping. In the process of transitioning to digital soil mapping, three goals have been added as benchmarks: 1) addition of soil observations using statistical sampling techniques, 2) production of soil maps by quantitative spatial models, and 3) inclusion of uncertainty associated with predictions (Lagacherie et al., 2006).

In the earlier section describing the geospatial revolution's effect on soil mapping,

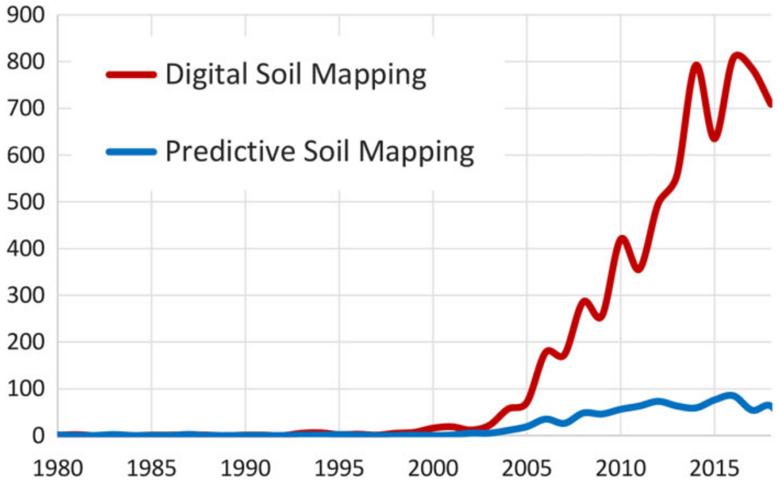

Figure 13. Trend in digital soil mapping activity as indicated by Google Scholar results for the terms "digital soil mapping" and "predictive soil mapping" by year. Although the term "predictive soil mapping" at times gains in popularity as an alternative term for the current revolution in soil mapping methods, it should be noted that soil mapping is inherently an exercise in spatial prediction.

geospatial technologies were described as tools for digital soil mapping. Soil is a quintessential geographic entity. Soil is the product of complex interactions of phenomena occurring at different scales. This characteristic makes soil and its spatial distribution a highly suitable subject for geographers and geographic information scientists. Researchers of digital soil mapping regularly debate the most appropriate data structures and computational techniques to capture, represent, process, and analyze soil information. When attempting to produce better digital soil maps, uncertainties that arise from overlaying multiple data layers, identifying spatial patterns, and making predictions based on those patterns must be evaluated. Further, questions on how to best communicate the resulting map and represent the associated uncertainty are omnipresent. Complications of scale, such as the modifiable areal unit problem, continue to cause confusion on how to best analyze patterns of soil and covariates. In short, soil is an excellent test subject for the systematic study of issues of scale, accuracy, and spatial analysis.

3 Modern issues creating new demands for soil maps

Soil is intimately intertwined with the topical alignments of both human and physical geography (Figure 14) (Arbogast, 2017; Kuby et al., 2013). Soil is a physical feature of the Earth. Soil is affected by human activity and influences populations, as it is an essential natural resource.

The original motivation for soil mapping was resource inventory for the purpose of land valuation, then later, for guiding landowners to optimize agricultural production (Miller and Schaetzl, 2014). Following awareness of soil erosion as an issue, soil maps became important for identifying areas of high erosion risk and planning conservation practices. Subsequently, soil maps have been used for many applications of land suitability including identifying limitations for water management, building development, and wildlife habitat. In response to these recognized uses of soil maps, the attribute tables for soil map units have adapted and expanded. For the most part, this continues to be the case

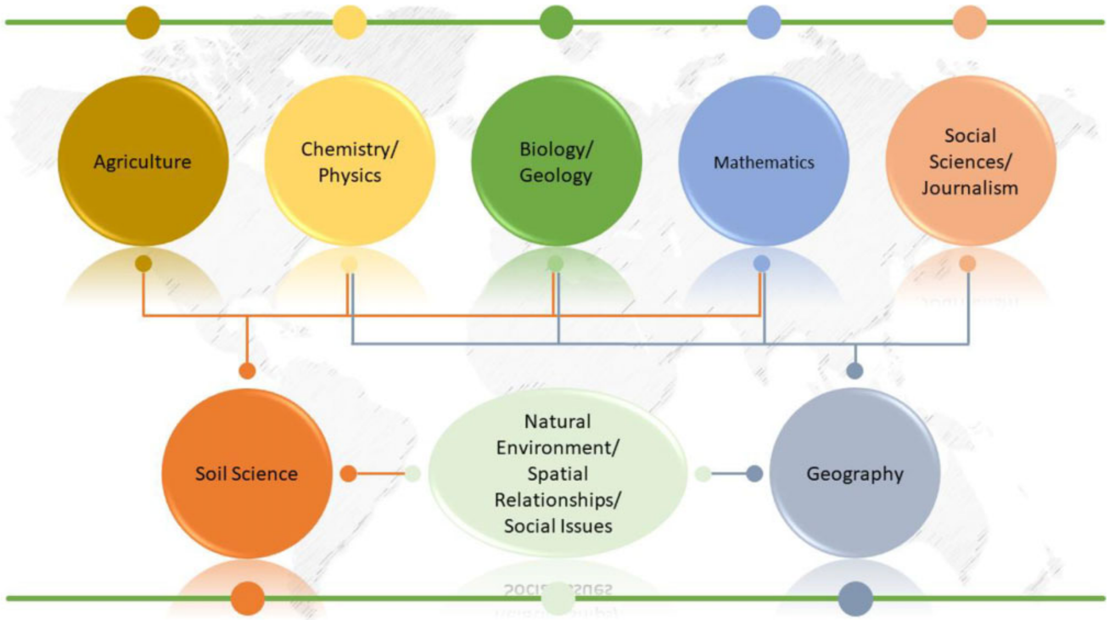

Figure 14. Interdisciplinary overlaps between soil science and geography.

for issues of newly increased concern, but some new issues will require new kinds of soil maps. Interpreting legacy soil maps for the new demands has been useful. However, the spatial accuracy and precision of those maps may not be sufficient for some of the new uses of soil maps (Miller, 2012).

Environmental issues are one of the primary areas putting new demands on soil maps (Hartemink and McBratney, 2008). Because soil plays a key role in all of the spheres of the Earth, most models of the environment benefit from spatially explicit soil data. Prediction of flooding, for example, depends on the interaction between rainfall and the spatially variable ability of soil to absorb that water. Water quality models need to account for biological, physical, and chemical interactions of water with the soil across watersheds. Many of the models for these kinds of issues aggregate soil information at the watershed level, which means that much of the spatial information is discarded in the interest of model efficiency. With increasing computing power, however, there exists an opportunity to improve these models with better soil maps and better consideration of spatial connectivity.

Soil and water connectivity is an emerging topic, and mapping soil and water flows is fundamental to understand the impact of different land uses on overland flow and erosion. Under natural conditions, connectivity depends on the parent material type, soil texture and structure, topography (e.g. slope, aspect), climate patterns, and vegetation distribution (e.g. patchy or continuous). Connectivity can be affected by natural phenomena such as fire, or other human-induced impacts (e.g. mining, grazing, or agriculture). Normally, these disturbances increase connectivity, as compared to the natural condition. The spatial distribution of connectivity can be complex, and mapping provides an important contribution to a better understanding of where soil and water fluxes are high. Several indexes have been developed to measure connectivity; these have been applied at different spatial and temporal scales (Heckmann et al., 2018). Soil and water connectivity maps have been produced in several environments, such as mountain catchments (Cavalli et al., 2013; Zuecco et al., 2019), abandoned and afforested mountainous areas (Lopez-Vicente et al. 2017), mountainous areas with heterogeneous land use (Lopez-Vicente and Ben-Salem, 2019), agricultural lowland basins (Casamiglia et al., 2018), places affected by landslides (Persichillo et al., 2018), and urban environments (Kalantari et al., 2017). Despite the recent progress in this area, further work should be focused on the validation of these models.

The soil-atmosphere interface is another aspect of how spatially variable soil affects the human quality of life. The interactions of soil with the atmosphere are important processes to consider for improving the accuracy of weather forecasting (Fennessy and Shukla, 1999; Koster et al., 2004). Similarly, soil stores a large stock of carbon, which makes it a major potential carbon source or sink (Lal, 2004). Soil's role in the carbon cycle makes it an important factor in the positive and negative feedback loops of global climate change.

The early interests in soil maps to improve food production and protect soil as a resource have not gone away. The global population is expected to reach 8.5 billion by 2030 (United Nations, 2017), and 30–60 Mha of cropland is expected to be lost to infrastructure (e.g. housing, industry, roads) over the same period (Döös, 2002). Soil degradation works against goals to increase agricultural crop productivity. Although soil erosion has been recognized as a problem for a century and great effort has been made to address the issue, large losses of valuable soil resources continue (Brevik et al., 2017).

Innumerable works have focused on mapping soil erosion at local, regional and global scales (e.g. Bahadur, 2009; Gelder et al., 2017; Nachtergaele et al., 2010; Panagos et al., 2015). The first attempt to map soil degradation (including erosion) at the global level occurred with the Global Assessment of Land Degradation and Improvement (GLASOD), but this work did not use soil data (Pereira et al., 2017). The accuracy of soil erosion maps increased appreciably with the availability of covariate maps with more types of information and higher resolution, primarily developed in concert with the recent revolution in geospatial technologies. Included among those covariate maps are continuous maps made possible by spatial interpolation methods (Borrelli et al., 2018).

The majority of the soil erosion maps produced today focus on erosion risk (Farhan and Nawaiseh, 2015; Haregeweyn et al., 2017; Mancino et al., 2016; Ochoa-Cueva et al., 2013) and the estimations are often carried out using the Revised Universal Soil Loss Equation (RUSLE) (Brevik et al., 2017). RUSLE calculates soil loss rates (E) by rill and sheet erosion based on the rainfall (R), erodibility factor (K), cover management factor (C), slope length and slope steepness factor (LS), and support practices factor (P) (Panagos et al., 2015). Fewer studies have been carried out to map wind erosion, despite widespread recognition that wind erosion increases soil degradation (Borrelli et al., 2016). Wind erosion is much more complex to model than water erosion. Nevertheless, some attempts have been made at the local (Harper et al., 2010; Sterk and Stein, 1997; Zobeck et al., 2000) and regional (Borrelli et al., 2014, 2016) levels. Other works have mapped sediment sources and deposition areas (Cavalli et al., 2017; Petropoulos et al., 2015).

The assessment of soil ecosystems and their services has increased rapidly in the last decade, and mapping is crucial to identify the distribution of these services (regulating, provisioning, cultural, and supporting ecosystem services). Maps can represent the synergies and trade-offs between ecosystem services (ES), trends, costs and benefits, monetary value, and aid in estimating costs and benefits (Burkhard et al., 2018; Maes et al., 2012). An extensive body of literature exists on mapping ES; this effort uses soil variables to assess regulating and provisioning services (e.g. Burkhard et al., 2012; Syrbe and Walz, 2012). The relationship between the quality and quantity of ES with the services provided directly or indirectly by soil is clear (Adhikari and Hartemink, 2016; Brevik et al. 2019; Pereira et al., 2018). Soil functions are crucial for ecosystem vitality and healthy ES; thus, they are normally integrated into ES estimations in well-known ES assessment models such as InVEST (Sharp et al., 2018) and Aires (e.g. Bagstad et al., 2014) (e.g. carbon storage, sediment delivery ratio). These models produce maps of ES distribution and valuation.

Several works that link soil functions with ES (e.g. Barrios, 2007; De Vries et al., 2013; Lavelle et al., 2006; Pulleman et al., 2012) and that quantify soil ES (Dominati et al., 2010; Robinson et al., 2013). However, more effort should be made to map soil ES individually to understand the real value of soil in ES assessment, and more research is needed to optimize the mapping of soil ES. Also, soil ESs are overlooked and not considered in some ES classifications such as "The Economics of Ecosystems and Biodiversity" (TEEB) (Pereira et al., 2018).

IV Conclusions

A reinvigoration is occurring in soil geography. This renewed interest in improving soil maps is stimulated by the confluence of improving capabilities for producing maps, and the increasing need for spatial soils data. Innovations from the geospatial revolution, coupled with the increasing power of computing and machine learning, have added many new and useful opportunities available to the soil mapper's toolkit and theoretical base. To address modern issues facing society, including supporting a growing population and other impacts on ecosystem services, more frequent improvements of soil maps, often manifested as "updates," will be required. Even though other disciplines continue to have a strong vested interest in the study of soil, there is a clear need for the spatial sciences in the future of this field. Mapping the environment, discovering processes, and understanding interactions between these processes across space work cyclically with each other, which makes the new wave of soil mapping exciting both for soil science and for geography.

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