Selected Highlights in American Soil Science History from the 1980s to the mid-2010s

Eric C. Brevik¹, Jeffrey A. Homburg^{2,3}, Bradley A. Miller^{4,5}, Thomas E. Fenton⁴, James A. Doolittle⁶, and Samuel J. Indorante⁷

1 – Department of Natural Sciences, Dickinson State University, Dickinson, ND, USA;

Eric.Brevik@dickinsonstate.edu

2 – Statistical Research, Inc., Tucson, AZ, USA; jhomburg@srcrm.com

3 – School of Anthropology, University of Arizona, Tucson, AZ, USA

4 – Agronomy Department, Iowa State University, Ames, IA, USA; millerba@iastate.edu, tefenton@iastate.edu

5 – Leibniz Centre for Agricultural Landscape Research (ZALF) e.V., Institute of Soil Landscape Research, Eberswalder Straße 84, 15374 Müncheberg, Germany

6 – USDA-NRCS-NSSC, 11 Campus Boulevard, Suite 200, Newtown Square, PA, USA (retired)

7 – USDA-NRCS, Du Quoin, IL, USA (retired); sjindorante@siu.edu

*- corresponding author

Abstract

The beginning of the 20th century through the 1970s were good times for soil science in the USA, with relatively strong funding and overall growth in the profession. However, the soil science discipline in the USA hit hard times in the 1980s and 1990s. Federal funding for soil survey work began to decline as did student numbers in university programs and membership in the Soil Science Society of America (SSSA). Despite this, there were still many positive advances within soil science in the USA during these two decades. There was an increased use of geophysical instrumentation, remote sensing, geographic information systems (GIS), and global positioning systems (GPS), and research began in digital soil mapping, all of which lead to better understanding of the spatial distribution and variability of soils. Many NRCS soil products were put online, making them widely available to the general public, and the use of soil knowledge was expanded into new areas such as archaeology and environmental work, and historic connections to geology were re-established. While expansion into new areas required soil science to evolve as a field, separating the discipline to an extent from its agricultural roots, it also helped reinvigorate the discipline. As we move through the early parts of the 21st century, student numbers are increasing in university soil science programs and membership in SSSA is at an all-time high. Digital soil mapping is being incorporated into the National Cooperative Soil Survey, and the

impact of humans on the soil system is being fully recognized. The importance of soils is being recognized by events such as the United Nations declaration of 2015 as the “International Year of Soils”. The expansion of soils into new areas and widening recognition of the importance of soils gives the field hope for a bright future in the USA.

Keywords: soil science history; pedoarchaeology; digital soil mapping; soil and the environment; geophysical instrumentation; remote sensing

1. Introduction

Many papers, book chapters, and at least one book have been written that focus on aspects of soil science history within the USA. However, the recent history (last ~35 years) of soil science has received much less attention than the history of 50+ years ago, and there have not been any previous attempts to synthesize a major portion of this recent history into a single publication. This paper, the second in a two part series along with Brevik et al. (2015a), aims to synthesize information from a wide variety of scholarly communities, including archaeology, geography, geology, history, and pedology, to create a timeline of soil knowledge and advancements within the USA. This paper focuses primarily on soil landscapes, soil-human interactions, and several of the advances in technology that allowed study in these areas to expand at the end of the 20th and beginning of the 21st centuries. It should be noted that many advances in areas such as soil biology, soil chemistry, and soil physics were also made during this time. These aspects of soil science are covered indirectly as they are important to environmental, reclamation, and other interdisciplinary issues that are discussed in the paper, but this paper will not deal directly with those parts of the field.

With a few exceptions during periods such as the World Wars in the early and mid-1900s, soil science as a discipline saw steady growth in the USA from the end of the 1800s through the 1970s (Brevik et al., 2015a). However, the 1980s saw a general global economic downturn (Garrett, 1998), and budgets for soil work also saw declines during this period (Hartemink and McBratney, 2008) with the USA being no exception. Student numbers in college-level soil science programs declined within the USA, likely caused by declining farm income and a corresponding decline in rural population. This relationship was likely due to soil science programs most commonly being within agronomy departments in the USA, the bleak outlook in agricultural career fields at the time, and a desire on the part of students who might have gone into soil science to pursue careers in fields that they viewed as being more closely associated with the environment or with stronger economic prospects (Miller, 2011; Brevik et al., 2014).

Despite these challenges, access to new technologies and the application of soil knowledge to an expanding range of issues also led to many opportunities within soil science. In the USA, much like elsewhere, the digital revolution was highly influential by providing new sensing devices (e.g., remote sensing, geophysical instrumentation, and spectroscopy), improved geospatial technologies (e.g., geographic information systems (GIS) and global positioning systems (GPS)), and the Internet. At the same time, those seeking to address environmental issues or the sustainability of international food production have been increasingly recognizing the importance of soil science. In order to adapt to this shift in sources of funding and students, many soil science programs remarketed themselves or have completely reorganized. Academic departments that were traditionally heavily focused on the agronomy of local farm operations took steps to emphasize the natural connections of soil science to topics such as environmental science and global food security. Steps such as these have served to reverse declining student numbers (Miller, 2011; Brevik et al., 2014) and improve public perception of

soils in general (Brevik and Hartemink, 2010a). However, budgetary challenges still exist for those who wish to expand our knowledge of soils (Brevik and Sauer, 2015; Section 2.1).

2. Adapting to Losses in Traditional Support

On top of struggling farm markets, a sense of nearing the completion of soil survey may have contributed to a reduction of interest in soil science in the 1980s and 90s. By the mid-1990s it was estimated that modern soil surveys were available for 85 percent of the USA and Trust Territories (Indorante et al., 1996), providing detailed soil maps that varied in scale from 1:15,840 to 1:24,000. An indicator of the priority given to soil survey in the USA is the amount allocated in the NRCS (United States Department of Agriculture, Natural Resources Conservation Service) federal budget for soil survey. In 1980, that budget was \$43,463,000, which translates to \$124,544,175 in 2015\$. The high point for the budget in terms of 2015\$ equivalent over the last 35 years was in 1988, but by 1990 the budget amount, when adjusted for inflation (2015\$), was below the 1980 budget, and it has stayed below that 1980 value every year since. The years 2011-2015 represent the five lowest funded years for the NRCS soil survey budget over the past 35 years (Figure 1).

Faculty at universities across the USA noted decreases in undergraduate enrollment in soil science programs for several years through the 1980s and 1990s and into the early 2000s. This trend affected soil science as a profession, and also affected course offerings, the potential pool of graduate students, and the structure of departments. Collins (2008a) reported on the results of a survey of 33 universities (four 1890 Institutions and 29 Land Grants). The topic of the survey concerned trends in enrollment of undergraduates majoring in soil science over the previous 10 years. The study showed decreasing enrollment of students studying in traditional soil science majors. Reasons given for this decline included

the majors not being well known, students having more majors to choose from, and other majors having pre-professional choices (i.e. animal science leading to veterinary medicine).

There were several other studies in this time period investigating trends in soil science education in the USA and the possible future of the profession. Baveye et al. (2006) surveyed soil science departments in the USA and Canada and found that the number of Ph.D. degrees conferred had decreased by 63%. Of the 36 institutions responding, 30 had experienced decreased enrollments. However, there was an increase in the number of female students. Baveye et al. (2006) reported that between 1992 and 2004 total student numbers in soil science fell by at least 40% in more than 80% of the responding schools.

The need for change in American soil science had been recognized prior to 1994. That year the Soil Science Society of America (SSSA) addressed some of these problems with the publication of Special Publication No. 37: Science Education: Philosophy and Perspectives. Suggestions included making soil science more interdisciplinary with less emphasis on agronomic topics (Letey, 1994). Taskey (1994) reported on revisions made to the undergraduate program in the Soil Science Department at California Polytechnic State University (Cal Poly) in the 1990s that incorporated an interdisciplinary approach. These changes were followed by an enrollment change from a low of 46 undergraduates to 120 undergraduates just two years later (Taskey, 1994). Cal Poly Faculty contacted private industry, alumni, and governmental agencies to gather information on the problems that needed to be addressed and used these facts to establish new goals and to revise their curriculum. By the early 2000s the teaching of soil science as part of interdisciplinary programs such as environmental science and restructured soil science programs that emphasized applications beyond agriculture had become common at USA universities (Brevik, 2009). However, the teaching of soil science by affiliated fields has sometimes

created problems as well, such as the incorrect presentation of soil information by non-specialists (Brevik, 2002).

Although updating curriculums to reflect modern knowledge and societal needs is always critical, the improved marketing approach has also been fruitful. For example, at Iowa State University – where soil science has long been supported within the agronomy program – new marketing approaches about the applicability of the curriculum to the environment, sustainability, and global food systems have coincided with tremendous enrollment growth (Miller, 2011). From 2005 to 2015, enrollment increased from 106 to 324 undergraduate students. That increase included a change in the demographics within the major from 18% to 33% female.

Another way to view the standing of soil science within the USA over time is to look at indicators of the health of SSSA, the largest national soil science professional society in the country. From the founding of SSSA in 1937 membership grew steadily, reaching a high at the time of 6,402 members in 1985. However, between 1985 and 2002 membership dropped to 5,319, a decline of 17% (Figure 2). The overall financial value of SSSA also suffered a 54% decline in the late 1990s (Brevik, 2011). Both of these indicators served as markers of difficulties facing the soil science profession within the USA.

3. Expanding interest in soil science

In the 1940s and 1950s soil scientists in the USA began to expand the use of soil knowledge beyond agriculture and into areas such as land use planning, geomorphology, and the role of soil in human health (Brevik et al., 2016). In the 1980s and 1990s there was a rapid expansion of non-agricultural applications of soil science into new areas, including archaeology, environmental work, and geologic mapping. American soil scientists even expanded the definition of soil to subaqueous environments

(Demas et al., 1996). This was a response to the fact that many of the problems facing the world today require a full systems approach, of which soil is nearly always a part (Bouma, 2015; Brevik and Burgess, 2013; Brevik et al., 2015b; Ibáñez et al., 2015).

3.1 Archaeology

Soil science and geology are playing an increasingly important role in archaeological research. This interdisciplinary work focuses on defining and understanding the environmental context of archaeological sites. In particular, this research considers site formation processes for interpreting the sedimentary history, alteration, and preservation of the archaeological record. Archaeological research then evaluates how this information advances our understanding of human activities and adaptations on landscapes of the past. Research that integrates these topics falls in the domain of two subdisciplines: pedoarchaeology and geoarchaeology, the application of soil science and the geosciences to archaeology, respectively.

With a few exceptions, soil science methods were rarely applied to archaeology in the Americas prior to the 1980s. There are two noteworthy exceptions: (1) a soil chemistry study by Cook and Heizer (1965) of archaeological settlements in California that found that C, N, and Ca were concentrated in the center of sites relative to their peripheries, reflecting the relative intensity of ancient occupation, and (2) a soil fertility study by Arrhenius (1963) of ancient agricultural fields in the American Southwest that concluded that farming depleted P and other nutrients and caused fields to be abandoned. The explosion in the literature since the 1980s is a clear indication that pedoarchaeology is maturing as a subdiscipline as scientists are drawn to conduct this kind of research. For example, pedoarchaeology symposia are now being held at national and international archaeology and soil meetings (e.g., Holliday, 1992; Foss et al., 1994; Goodyear et al., 1994; Collins et al., 1995). One book deserves special mention, a

book entitled “Soils in Archaeological Research” by Vance Holliday (2004), geoarchaeology professor at the University of Arizona. This book synthesizes much of what was known about pedoarchaeology up to about ten years ago, demonstrating the increased sophistication of this type of research. Homburg (2005) provides a brief review of soil science applications to archaeology.

Many pedoarchaeological studies focus on interpreting the stratigraphy of cultural deposits such as middens (trash deposits) and earthen Indian mounds (e.g., Homburg, 1988). Soil science techniques have been used to address a variety of pedoarchaeological research topics. Examples of some of these other applications include: (1) pH analysis to assess bone preservation potential (Linse, 1992); (2) identification of ancient fields and soil productivity evaluations (Dart, 1986; Homburg and Sandor, 2011; Homburg et al., 2005; Huckleberry, 1992; Sandor, 1995; Sandor and Homburg, 2011; 2015; Sandor et al., 2007); (3) use of soil P analysis to identify intra-site activity areas on ancient occupation surfaces and to interpret soil stratigraphy (Homburg, 1988); (4) soil micromorphology analysis of archaeological deposits and ancient agricultural fields (Courty et al., 1989; Purdue et al., 2010; Figure 3); (5) analysis of cores for the purpose of landscape reconstruction (Ciolek-Torrello et al., 2013; Homburg et al., 2014a); (6) use of soil survey maps to predict the potential for buried archaeological sites and the agricultural productivity of ancient agricultural systems (Green et al., 2012; Heilen et al., 2013; Homburg et al., 2014b); and (7) analysis of strength of adobe material used in ancient single- and multi-story adobe architecture, based on soil properties such as bulk density, carbonate content, and penetration resistance (Howell and Homburg, 2013).

Just as soils have been useful to archeological studies, archeological sites and features have been useful in the study of soil genesis, with much, but not all, of this work also being done in the 1980s or later. For example, Parsons et al. (1962) used soils formed in dated archaeological features to estimate rates of

soil formation. Archaeological sites (Webb et al., 1986; Sandor and Eash, 1991; Homburg et al., 2004) and features (Sharratt et al., 1998; Dixon-Coppage et al., 2005; Brevik and Fenton, 2012) have been used to investigate long-term effects of human activity on soil processes and properties. In these ways, the growing relationship between soils and archeology has proven to be beneficial to both fields.

3.2 Sustainability of ancient farming systems

Archaeologists and soil scientists began studying soil quality in ancient farming systems of the semiarid American Southwest in the early 1960s, and this type of research has accelerated since the 1980s. Ancient agricultural soils in the Southwest are especially well suited for evaluating soil quality and agricultural sustainability because: (1) soil-formation processes (e.g., weathering, leaching, and illuviation) proceed much more slowly in deserts than in more humid climates, so soil changes caused by cultivation practices tend to persist and be detectable for long periods after fields are abandoned (e.g., millennial time scales up to 3,000 years or more); (2) canals, earthen field borders, terraces, rock alignments and piles provide important clues for discerning and sampling soils that were cultivated relative to uncultivated control areas (Figure 4); and (3) many ancient fields have not been cultivated since they were abandoned, so more recent plowing and artificial fertilizer additions have not masked properties caused by ancient farming practices.

A common outcome of long-term agriculture, especially in deserts, is soil degradation, whereby changes in soil properties reduce agricultural productivity (e.g., reduced N and P levels, compaction, accelerated erosion, decreased A-horizon thickness, and salinization). Soil studies conducted in the American Southwest, however, indicate that the consequences of cultivation are highly variable in terms of soil quality and possible degradation because of many interacting environmental and cultural factors, ranging from degradation to enhancement of soil fertility, as well as intermediate to no changes

between these two extremes (Homburg and Sandor, 2011; Sandor and Homburg, 2011). A few soil studies in the Southwest have found that ancient farming systems degraded the nutrient status of agricultural soils. For example, long-term cultivation significantly lowered the fertility of terraced fields in the Mimbres area of southwestern New Mexico (Sandor et al., 1986; 1990). Other studies in central Arizona, especially those associated with rock-mulch agricultural systems, have found that agricultural soils were not degraded (Homburg, 1994; Homburg and Sandor, 1997; Homburg et al., 2004). This lack of degradation is often due to replenishment of organic-rich sediments and nutrients in many runoff fields (Figure 5) or protection and conservation of organic matter in rock mulch systems.

In Sandor's study of the long-term effects of runoff agriculture in the Sapillo valley of southwestern New Mexico, Mimbres agricultural terrace soils associated with small rock alignments were compared to uncultivated control samples (Sandor and Gersper, 1988; Sandor et al., 1986; 1990). Agricultural terraces promoted water retention by reducing slope angle and length on the surface, and by creating a sediment wedge upslope of small terrace dams (Sandor et al., 1986; 1990). The sediment wedge became a thicker topsoil with a desirable loamy to sandy texture that increased water infiltration, rooting volume, and thus available water capacity. However, Sandor's results indicated that the primary anthropogenic soil changes were degradational, and that the effects of cultivation could be detected about 800 years after the fields were abandoned. Compared to uncultivated control soils, Sandor found that cultivated soils were lighter in color, more compacted, and had thicker A horizons with more blocky and less granular structural aggregates. In addition, he found that cultivated soils had lower organic C, N, total and available P and Cu levels, and higher Mn and pH values. Rock alignments primarily functioned as dams to reduce the velocity of runoff, increase infiltration, and thicken naturally thin A horizons by impounding sediments.

The findings of Sandor's Mimbres study contrasts strongly with that of other soil studies in central Arizona in the Tonto Basin (Homburg, 1994), Horseshoe Basin of the Lower Verde valley (Homburg and Sandor, 1997), Safford Basin (Homburg et al., 2004) and Queen Creek Valley (Homburg et al., 2011). The Tonto Basin, Horseshoe Basin, and Queen Creek Valley studies focused on measuring the effects of cultivation on soil fertility by comparing rock mulch and terraced soils with adjacent uncultivated soils. Compared to uncultivated control soils, agricultural soils in all of these study areas generally had similar or elevated levels of N, P, and organic C, often at differences that were statistically significant. The lack of soil degradation in these cases may be due to the combined effects of multiple factors, including short-term use of fields, replenishment of nutrients in organic debris deposited naturally in runoff, use of rock mulch to reduce organic matter oxidation, or cultivation of drought-adapted crops that have low nutrient requirements. Soil studies have shown that rock mulch has a number of favorable effects for dryland agriculture, including: (1) reduced evaporation and moisture conservation in the root zone; (2) increased water infiltration into the root zone; (3) increased soil fertility and agricultural productivity; (4) increased heat retention to protect against frost damage and accelerated seed germination and crop growth; and (5) reduced soil erosion.

The biggest gap in knowledge of ancient agricultural soils is for ancient irrigation systems. A soil quality study conducted at the Las Capas site in the Tucson Basin of Arizona has helped to fill this gap. Homburg (2015) documented and evaluated the soil productivity and hydraulic properties of this ancient agricultural irrigation complex. Long-term indicators of agricultural soil quality, such as organic C, nutrient content (N and available P), and hydraulic soil properties, indicated that anthropogenic changes were favorable for agricultural production and that the Las Capas irrigation system was sustainable. Sodium adsorption ratios, though elevated in the Las Capas fields, are far below levels detrimental to crop production. Irrigation water reduced salinity through leaching. Canals regularly supplied water to

the fields, but they also supplied nutrient-rich silt and clay that renewed soil fertility, countering nutrient losses caused by crop uptake, volatilization, leaching, and oxidation. Another study of the soil quality of irrigated soils (anthrosols formed as a result of prolonged deposition of silty to loamy sediments from irrigation water that overlies a natural argillic horizon) was recently completed next to Snaketown, an ancient Hohokam village located near the Gila River in central Arizona that was occupied from ~A.D. 450 to 1450. (Woodson et al., 2015). The Snaketown study corroborates some of the findings at the Las Capas site. The Snaketown soils have a number of favorable soil conditions, most notably a reduction in salts, Na, and pH relative to uncultivated control soils.

3.3 Environmental work

The application of soil knowledge to environmental issues was probably the fastest growing non-agricultural area of soil science in the late 20th century (Brevik and Hartemink, 2010b). This has included problems such as contamination, reclamation, water quality, and climate change. The early 21st century also saw the development of hydropedology. With its attempts to bridge pedology with soil physics and hydrology to improve our understanding of soil-water processes at multiple scales, hydropedology provides critical information to a number of environmental applications of soil knowledge (Lin, 2003; Lin et al., 2006).

Contamination studies covered a wide range of contaminants and sources of contamination. Heavy metal contamination by fertilizers (Mortvedt et al., 1981), manure applications (Jaja et al., 2013), smelters (Roy and McDonald, 2015), mining operations (Mbila and Thompson, 2004), and landfills (Nixon, 1995) were included in the studies conducted during this time, and the ability of soils to purify wastes through means such as septic systems was investigated (Bouma, 1979). Organic chemicals in soil have also received considerable attention, including those introduced as pesticides (Jury et al., 1983),

through industrial wastes (Travis, 2002), and landfills (Nixon, 1995). While many studies have separated different types of contaminants in their research, there are a number of situations where heavy metals and organic chemicals are found in combination and represent a threat to the soil resource. This is true of electronic wastes (e-wastes), something that has become an increasing concern in the modern world beginning with the proliferation of home computers and other electronics in the 1980s (Kang and Schoenung, 2005). In many cases these contamination studies were combined with investigations of the potential impacts of contamination on human health (Burgess, 2013; Brevik and Sauer, 2015). Beyond documenting contamination, remediation of contaminated soils also became a topic of considerable interest (Van Der Lelie et al., 2001).

USA Public Law 95-87, known as the Surface Mine Control and Reclamation Act, was passed and signed into law in 1977. This law required that disturbed land be returned to approximately its original condition, including the reconstruction of soil profiles, the return of land to its approximate original contours, and the establishment of grass and legume cover except on land returned immediately to agricultural production (Plass, 2000). Soil science became an important part of the reclamation of degraded land, and several soil studies were undertaken to investigate how well soils recovered given various reclamation treatments (Gardiner, 1983; Doll et al., 1984; Elkins et al., 1984; Potter et al., 1988; Roberts et al., 1988) and to investigate spatial distribution of soil properties in disturbed environments (Indorante and Jansen, 1981; Indorante and Jansen, 1984). Reclamation studies have remained important to the present day, including work on carbon sequestration (Dixon-Coppage et al., 2005; Shukla and Lal, 2005; Ussiri et al., 2006), soil formation in mined lands (Bronick and Mokma, 2005), and the recovery of soil quality indicators following reclamation (Seybold et al., 2004; Dangi et al., 2012; Thomas et al., 2015).

Studies into soil erosion and its connection with water issues continued from the 1980s into the early part of the 21st century. Many of the efforts at this time focused on improving modeling of soil erosion and related processes. The Revised Universal Soil Loss Equation (RUSLE) was released in 1992, making the model applicable to regions beyond the eastern USA (Troeh et al., 2004). RUSLE became one of the most widely used soil erosion models in the world (Pal and Al-Tabbaa, 2009; Boni et al., 2015). In 1985, USDA began development of the Water Erosion Prediction Project (WEPP) model, created to simulate physical processes that influence water erosion such as infiltration, runoff, raindrop and flow detachment, sediment transport and deposition, plant growth, and residue decomposition to replace empirically based erosion prediction models, with initial release in 1995 (Flanagan et al., 2007). At the end of the 20th century the USA was the only country in the world that had long-term soil erosion data collected using standardized methods (Cerdan et al., 2010) and eroded sediment and nutrients were recognized as major water pollutants (Troeh et al., 2004). Pimentel et al. (1995) estimated that soil erosion cost the USA a total of \$44 billion annually, or about \$100 annually ha⁻¹ of cropland and pasture. In response to these erosion-related costs, a number of federal programs were developed that provided farmers and ranchers with incentives to conserve soil and improve water quality (Brevik et al., in press). However, farmers did not always perceive the erosion problem the same way that the federal government did. In a study by Osterman and Hicks (1988), farmers tended to disagree with government assessment of what constituted highly erodible land, did not accurately perceive the severity of erosion occurring in their fields, and were concerned about potential economic losses through reduced crop yields but did not see erosion as a problem in and of itself.

The interactions between climate change and soils have received considerable attention since the 1990s (Brevik, 2012). For soil scientists in the USA, this has often meant studies into carbon sequestration by soil. Research into soil carbon sequestration became common in the USA in the early 1990s and surged

in the 2000s; some of the early works in this area included studies conducted by Hansen (1993), Kern and Johnson (1993), and Chadwick et al. (1994). Agricultural management has long been recognized as a factor that influences the organic carbon content of soils (Fenton et al., 1999), and several studies indicated that no-till management was a good way to sequester carbon (Franzluebbers et al., 1994; Karlen et al., 1994; Post et al., 2012). However, most of these studies were based on sampling the top 20-30 cm of soil. In recent years this methodology has come into question, with indications that no-till may concentrate carbon accumulations in upper soil layers with reductions of soil carbon at depth, giving no net difference in carbon versus clean-till techniques when the entire soil profile is considered (Baker et al., 2007; Blanco-Canqui and Lal, 2008; Christopher et al., 2009). That being said, results have been mixed, with some studies indicating that no-till does lead to higher soil carbon content than clean-till even when sampling is done to depths of about 1 m or deeper (Omonode et al., 2006; Varvel and Wilhelm, 2011; Carr et al., 2015). It now appears that whether or not no-till sequesters soil carbon at depths greater than 20-30 cm may depend on climate (VandenBygaart et al., 2003). Other topics that revolve around soils as carbon reserves have included the influence of specific natural environments such as wetlands, forests, permafrost, or floodplains (Rabenhorst, 1995; Grossman et al., 1998; Brevik and Homburg, 2004; Birdsey et al., 2006; Ping et al., 2015), the effects of soil compaction in agricultural environments (Brevik et al., 2002), urban soils (Kaye et al., 2005), the influence of soil aggregates (Six et al., 2000) and the need for policy makers to recognize the issue (Lal et al., 2003).

Potential changes in soil processes and properties due to climate change have also received a considerable amount of study. Early in the investigation of links between soils and climate, it was widely expected that increased atmospheric CO₂ would lead to increased soil organic carbon content through the CO₂ fertilization effect (Coughenour and Chen, 1997). However, more recent studies have questioned this (Hungate et al., 2003; Zavaleta et al., 2003; Long et al., 2005; Grace et al., 2006). Soil

water dynamics under changing climates have been studied (Nowak et al., 2004; Hatfield, 2011), as has the potential impact of climate change on soil erosion (Zhang et al., 2004) and soil ecosystems (Drennan and Nobel, 1996; Kardol et al., 2011). Techniques to simulate soil climate change have also been proposed and studied (Rasmussen et al., 2015).

3.4 Geology

During the early 20th century there was a move to distance soil science from geology within the USA, but that trend began to reverse as soil geomorphology was emphasized in the 1950s through 1970s (Brevik et al., 2015a; Landa and Brevik, 2015). Another way that geology and soil science has reconnected has been in the use of soil survey information to address geologic mapping issues (Brevik and Miller, 2015). This began with Lindholm (1993; 1994a), who used maps from the USA's National Cooperative Soil Survey (NCSS) to aid his geologic work in the Culpeper Basin of northern Virginia because detailed geologic maps were not available. When detailed geologic maps became available, Lindholm (1993; 1994a) found that his soil-based geologic maps were accurate. NCSS soil maps have also been used to improve geomorphologic mapping (Lindholm, 1994b; Brevik and Fenton, 1999), determine ice-edge positions in glaciated areas (Schaetzl, 2001; Millar, 2004), study loess deposits (Schaetzl and Weisenborn, 2004; Scull and Schaetzl, 2011; Luehmann et al., 2013), and map glacial deposits (Miller et al., 2008; Oehlke and Dolliver, 2011). Recently there have been some studies that attempted to quantify the relationships between NCSS soil maps and geology maps (Evans, 2002; Oehlke and Dolliver, 2011; Miller and Burras, 2015). However, there is a need for additional studies that quantitatively compare the match between soil and geology maps for additional landscape types (Brevik and Miller, 2015).

4. New technologies

Many of the technologies that have been revolutionizing American soil science over the past few decades are methods that increase the efficiency with which soil properties and their covariates can be detected. One of the most notable ways that these new technologies are creating research opportunities in soil science is that they increase the ability to better extend observations from the pedon to the landscape scale. Soil sampling only provides detailed information about the soil at the specific sampling locations. In order to make predictions about the soil in unsampled locations between sampling points, soil scientists have to utilize observable features on the surface that they know are associated with the soil properties of interest. From the 1930s through today, American soil scientists have depended on aerial photographs to identify areas of similar tonal patterns based on vegetation and topography to associate delineated areas on the map with map units (Bushnell, 1929). Today, with improving proximal and remote sensing technologies, the number of possibilities for quantitatively assessing relationships between soil and more readily measurable covariates is increasing exponentially.

4.1 Growing use of geophysical sensors and proximal soil sensing

Traditional methods for soil observation, sampling and analyses provide detailed information on the soil at specific locations, but are limited in number, volume, and spatial coverage. In the mid to late 1970s, soil scientists, realizing the limitations of traditional point-sampling methods to characterize soils and soil properties at field and landscape scales, began to use several geophysical sensors in soil research and surveys. Geophysical sensors measure changes in a physical property (i.e., density, dielectric permittivity, electrical conductivity, electrical resistivity, magnetic susceptibility, seismic velocity) of the subsurface without direct access to the sampled volume (Allred et al., 2008; Daniels et al., 2003). By the early to mid-1980s, electromagnetic induction (EMI), electrical resistivity, and ground-penetrating radar (GPR) had become the most commonly used geophysical tools in soil research and surveys (Allred et al., 2010 and 2008). Electrical resistivity methods had first been used for soil moisture monitoring (Edlefsen

and Anderson, 1941) and soil salinity assessment (Rhoades and Ingvalson, 1971). The development and use of EMI and GPR in soils and agriculture were summarized by Collins (2008b) and Corwin (2008), respectively.

4.1.1 Electromagnetic induction (EMI)

Electromagnetic induction (EMI) sensors (Figure 6A and 6C) measure the "bulk" or apparent conductivity (EC_a) of earthen materials. Apparent conductivity is a complex measurement resulting from the interaction of several soil properties (i.e. bulk density, cation exchange capacity, mineralogy, temperature, texture and clay mineralogy, water and soluble salt contents). Apparent conductivity measured with EMI methods is used as a quantitative proxy for a soil property such as for salinity, clay content, or water content.

Electromagnetic induction was initially used to assess soil salinity in the late 1970s and early 1980s (Rhoades et al., 1976; de Jong et al., 1979; Rhoades and Corwin, 1981). Presently, EC_a mapping is recognized as one of the most valuable methods in agriculture for measuring the spatial variability of soil properties at field and landscape scales (Corwin, 2008; Lück et al., 2009). Electromagnetic induction has been used to map variations in soil types; characterize soil water content and flow patterns; assess variations in soil texture, compaction and organic matter content; and determine the depth to subsurface horizons, stratigraphic layers or bedrock surfaces (Doolittle and Brevik, 2014).

Electromagnetic induction has also been used to assess difference in lithology and mineralogy, pH, field-scale leaching rates of solutes, herbicide partition coefficients, CEC, available N, and exchangeable Ca, Mg, and $CaCO_3$ contents (Doolittle and Brevik, 2014).

Though used in some high-intensity surveys, EMI has principally remained a research and investigatory tool in soils (Corwin, 2008). The future should witness a greater use of multiple-frequency and multiple-coil EMI sensors and integration with other sensors to assess the spatial variability of soil properties (Triantafilis et al., 2013; Brevik et al., 2016). Data analysis will also be improved with advanced processing and presentation systems. In addition, more sophisticated geostatistical modeling algorithms will be developed and used to interpolate EMI data, improve the resolution of subsurface features, and assess soil properties (Meerschman et al. 2013; Triantafilis et al., 2013; Triantafilis and Santos, 2013).

4.1.2 Electrical resistivity (ER)

Soil electrical resistivity (ER) represents the capacity of soil materials to resist the flow of electrical current. Typically, ER methods measure the apparent resistivity, and then convert this measurement into its inverse, the apparent electrical conductivity of the soil. Electrical resistivity methods can be divided into those that inject currents into the ground through direct coupling and those that function through capacitively-induced coupling. Presently, the direct coupling method is more commonly used in soils.

Highly mobile, continuous recording, direct coupling ER systems that are integrated with GPS receivers have been developed to expedite fieldwork and facilitate the collection of spatially dense data sets at field scales (Figure 6B). These direct coupling sensors measure the potential gradient resulting from the injection of electrical currents into the soil through coulter-electrodes. As towed-electrode arrays are invasive, their field use is restricted by plant growth and cover and soil wetness. Towed-electrode array systems have been extensively used to indirectly measure and characterize variations in soil structure and physico-chemical properties, detect preferential flow paths, and monitor temporal changes in soil water distributions (Adamchuk et al., 2014; Corwin and Lesch, 2005).

4.1.3 Ground-penetrating radar (GPR)

The first study on the use of GPR for soil surveys was conducted on the sandy soils of Florida (Benson and Glaccum, 1979; Johnson et al., 1979). By the mid-1980s, GPR was being routinely used in Florida as a quality control to estimate the taxonomic composition and to assess the variability of soils and soil properties within map delineations (Schellentrager et al., 1988; Collins, 2008b). Later, as a research and investigatory tool, GPR was used by soil scientists to identify and chart soil horizons, pans, water tables, and bedrock and stratigraphic surfaces; assess soil compaction and plow pan development; and infer variations in soil texture, organic matter content, humification, and cementation (Figure 7).

Many soils were found to have unfavorable properties (e.g., high soluble salt, clay and water contents) that limited the penetration depth, resolution, and effectiveness of GPR. By the early 1990s, the reality that many soils have unfavorable properties (e.g., high soluble salt, clay and water contents) for effective GPR use began to temper the initial excitement and expectation for this technology (Annan, 2002). By the late 1990s, knowledge of soil properties and conditions under which GPR is most effective had been achieved. Based on this knowledge the *Ground-Penetrating Radar Soil Suitability Map of the Conterminous United States* was developed in 2002 (Doolittle et al., 2002). This thematic map of the conterminous USA shows the relative suitability of soils for GPR applications and is based on field experience and soil attribute data contained in the State Soil Geographic (STATSGO) database developed by the Natural Resources Conservation Service (Figure 8). In 2008, larger-scale GPR soil suitability maps were prepared on a state basis using the Soil Survey Geographic (SSURGO) database (Doolittle et al., 2009). By 2014, detailed soil maps with GPR soil suitability interpretations were available online for more than 95 percent of the counties in the USA thru the Web Soil Survey.

Ground-penetrating radar has been mainly used as a quality control tool to document the presence, depth, lateral extent, and variability of diagnostic subsurface horizons used to classify soils (Doolittle and Collins, 2004; Collins, 2008b; Doolittle and Butnor, 2008). In the early 2000s, GPR played an expanded role in several new frontiers of soil surveys such as subaqueous (Libohova et al., 2014) and urban (Van De Vijver et al., 2014) soils, biomonitoring (Doolittle and Butnor, 2008), and hydropedology (Doolittle et al., 2012). Continued advances in instrumentation, computational capabilities, data processing, interpretative and display systems, and integration with other technologies (e.g., field computers, global positioning systems (GPS)) have increased the effectiveness of GPR in soils.

4.1.4. Other proximal soil sensing methods

Other geophysical methods, such as magnetic, magnetic susceptibility, self-potential, and time domain reflectometry are being used in soil research and investigations (Adamchuk et al., 2014). These methods have been most commonly used to characterize and map anthropogenic and hydric soils, industrial pollutants, and to assess different metals and soil water contents.

In the mid to late 1990s, the growth of precision agriculture stimulated interest in a large and diverse range of field-based sensors that can be used to measure soil properties at field scales. These sensors are referred to as proximal soil sensors (PSS). They include all field-based sensors that are operated either in close (within 2 m) or in direct contact with and obtain signals from the soil (Viscarra Rossel et al., 2011). Proximal soil sensors include most geophysical methods and others such as ion-selective potentiometry, nuclear magnetic resonance, optical reflectance (ultraviolet, visible-near infrared, and mid-infrared reflectance spectroscopy), gamma ray spectroscopy, X-ray fluorescence and mechanical impedance (Adamchuk et al., 2014; 2005; 2004; Viscarra Rossel et al., 2011). These sensors have been used to identify and measure the concentrations of soil fertility indicators, different metals, carbon,

carbonates, clay minerals, and iron oxides. Presently, with the exception of EMI, GPR and electrical resistivity, most PSS have had limited application in soils. Many PSS are currently in a developmental phase and are used primarily in research, while others are available commercially. The future should witness improved sensor designs, signal processing and data analysis techniques, increased sensor fusion, and an expanded use of PSS in soil science.

4.2 Remote sensing

The continuing development of remote sensing technologies have greatly expanded the amount of potential soil covariates available for study by soil scientists. Although American soil scientists have been using remote sensing - in the form of aerial photographs - to manually delineate map units since the 1930s (Bushnell, 1929), digital remote sensing products were not widely available until the 1970s. For example, the first satellite from the USA's Landsat program – a popular source of data for digital soil mapping – was launched in 1972.

Production of another popular input variable for soil mapping, digital elevation models (DEM), began in the USA in the mid-1970s (Osborn et al., 2001). However, a complete coverage of the conterminous USA was not available until 1999. For the most part, these data products have been built from existing topographic maps, not remote sensing. Nonetheless, they are increasingly being improved by remote sensing technologies, in particular by LiDAR, which is a technology typically implemented from an airplane that uses the same principles as radar, except that it uses lasers, to collect high resolution elevation data.

4.3. Geospatial technologies

4.3.1 Global Positioning Systems (GPS)

The first GPS network available to civilian users was launched by the USA military in the 1970s. By triangulating radio signals from satellites, a GPS receiver can calculate its position anywhere on Earth where it can receive signals from at least three satellites. However, the accuracy of the signal was initially degraded such that inaccuracies of up to 500m would occur to provide an advantage to the USA military over possible adversaries (Hannay, 2009), making GPS of limited use to soil scientists. In 1983 the degradation of the civilian signal was reduced to no more than 100m, and in 2000 the civilian degradation was removed (Hannay, 2009). Each reduction in the signal degradation improved the accuracy and applicability of GPS for use in soil science studies.

The implementation of GPS in soil science has been revolutionary for spatial research. All data collected can now have its precise location recorded in an efficient and repeatable manner. That additional information greatly improves the ability for soil research to revisit sampling sites and to intersect soil data with related covariates (e.g., proximal and remote sensing data).

4.3.2 Geographic Information Systems (GIS)

The synergy among computer technology, mapping, and natural resources is undeniable. For this reason, it is not surprising that the first GIS was assembled for the purpose of land inventory (Aguirre, 2014). However, in order to reach the soil information systems we know today, several additional threads needed to interact and develop. These additional developments were quantitative spatial analysis and digital geographic information, which has been largely facilitated by remote sensing.

In the 1960s, geographers and statisticians were keenly motivated to devise quantitative techniques for analyzing spatial phenomena. Even without the use of computers, many new measures of spatial characteristics were developed during this time (e.g., Bunge, 1962). Hole and Campbell (1985) later

integrated developments in soil geomorphology and quantitative spatial analysis, demonstrating the important partnership between the soil and geographic sciences.

Part of what motivated Tomlinson (1962) to propose the first GIS was the desire to analyze more spatial variables together. He observed that, “when you put six things on your desk and overlay them, even when they’re Mylar sheets, when you start to look down at them you get an awful mess of lines” (Aguirre, 2014). This concept of using GIS to spatially analyze multiple variables at the same time fit and enhanced the spatial association approach described by Hudson (1992) as the soil-landscape paradigm. Since the early days of the NCSS, soil scientists would overlay different maps on each other in an attempt to understand the spatial relationships (e.g., Marbut, 1951). The advent of a digital, geographic information system removed the limitation for the number of spatial variables that could be analyzed together, which opened the door to a whole new way of studying soil formation and improved methods for soil mapping. In a GIS, the more quantitative equivalent of overlaying different maps essentially equates to what is broadly called map algebra (Tomlin, 1990). Although map algebra didn’t address the problem of identifying useful spatial prediction models, it created tremendous opportunity to automate the quantified processing of spatial variables. However, the quantitative nature of this analysis placed new demands on the base maps (spatial covariates) and the models used to synthesize them. In contrast to traditional soil mapping, every aspect of the spatial model needed to be explicitly defined and the input variables for the model had to be available in a spatially comprehensive, digital format.

5. Expanding and communicating knowledge

5.1 Digital soil mapping (DSM) and spatial statistics

Advancements in DSM largely occurred outside the USA from the late 1970s through the 1990s. Centers of activity in DSM research tended to be in the United Kingdom, Australia, Hungary, and France. For

example, Richard Webster and his students were among the pioneers to put soil information into a GIS and began to emphasize the use of geostatistics in soil mapping (Minasny and McBratney, 2016).

Geostatistics emphasize the geographic principle of spatial autocorrelation, which relies on similarity by proximity. The statistical framework of geostatistics was developed by Kolmogorov (1941). Krige (1951) built on those concepts and first used 'kriging' to make predictions about geologic formations for the purpose of mining. The efficiency of computers later made it more practical to perform the complex calculations on the large datasets needed for geostatistics. To create a map with geostatistics, one needs to statistically quantify the strength and range of the observed spatial autocorrelation, i.e. calculate a semivariogram, and then use that information to interpolate values at unobserved locations between sample points. Recognizing the usefulness of spatial association used in traditional mapping (more specifically environmental correlation for soil mapping), geostatistics has evolved to incorporate information from covariates in increasingly sophisticated ways (Goovaerts, 1999). Most of the studies in the USA experimenting with these techniques for DSM have focused on the field or local scale (e.g., Cambardella et al., 1994; Pozdnyakova and Zhang, 1999; Mueller and Pierce, 2003; Kravchenko and Robertson, 2007; Holleran et al., 2015). However, geostatistics have been used to identify and map spatial patterns for larger areas (e.g., White et al., 1997; Mishra et al., 2009; Ross et al., 2013; Levi and Rasmussen, 2014).

5.1.1 Predicting the spatial distribution of soil properties

As new technologies presented potential covariates, soil scientists tested their relationships with specific soil properties. Horvath et al. (1984) were one of the first in the USA to use remotely sensed variables to predict soil properties. In 1992, Bell et al. combined digital terrain analysis (DTA) of a DEM with the digitization of relevant existing maps (e.g., streams and geology) to refine the spatial prediction of drainage class. The following year, Moore et al. (1993) published the landmark paper relating several

DTA covariates with both physical and chemical soil properties. Over the years, the most popular soil properties to attempt prediction on have been various forms of soil carbon and soil texture fractions. Predicting the spatial distribution of A horizon thickness as well as various forms of phosphorus and nitrogen have also been popular target variables.

As the USDA-NRCS moves to provide better data for environmental modeling and to contribute to the global soil map project (Sanchez et al., 2009), the most efficient strategy has been to convert existing data from the polygon to the raster data model and to fill gaps in the attribute database (Figure 9). Part of this initiative has been to harmonize differences between soil mapping areas, which finds inconsistencies between map boundaries and improves the quality of the overall map now providing continuous coverage across the USA (Thompson et al., 2012). For filling gaps in the attribute tables of the USA's soil geodatabase, researchers have been applying pedotransfer functions and interpolating soil properties in the vertical profiles using spline functions (Odgers et al., 2012; Libohova et al., 2014). In some ways, the focus on the soil attributes for existing map delineations has limited the production of better maps based on truly DSM methods, but these digitized soil maps are still the envy of the world. For many parts of the world, DSM is producing the first detailed soil maps, yet they cannot match the intensity of field surveying for large extents that the NCSS has done.

5.1.2 In support of the soil map unit paradigm

Although research on DSM technologies has been developing since the mid-1980s, using these new technologies to improve the delineation of map units within the NCSS has been more complex. Map units were and continue to be important entities for communicating with many end users because a map unit conveys concepts about a variety of soil conditions with short terminology. By simply naming a map unit, the user can relate a large amount of information from past experiences without needing to

know specifics about each of several soil properties. This framework also serves the mission of the NCSS to map for identifying differences in best use and management practices. Research has also shown the advantages of transferring traditional soil map unit information into forms that can be accommodated by modern modeling methods (Bonfante and Bouma, 2015).

Map units are also important to the NCSS because of the soil-landscape paradigm employed to make soil landscape predictions. Soil scientists producing maps for the Soil Survey had accumulated a large amount of knowledge from their fieldwork. Therefore, to enhance and build upon the large library of existing Soil Survey maps in the USA, it has been desirable to leverage expert knowledge for building DSM models. Zhu and Band (1994) first addressed the issue of extracting expert knowledge, which was used to create fuzzy membership functions to deal with the uncertainty and gradients in the soil landscape. Covariates used in that study included a locally produced DEM, some derivatives from that DEM, canopy coverage derived from the Landsat Thematic Mapper, and a traditionally produced geology map that had been digitized. Later work on this approach experimented with different levels of interaction with the field experienced soil scientists, ranging from conducting zonal statistics on existing map delineations to interviews for refining the quantitative models. Applications of this approach continue to be explored and have been implemented in the production of a published NCSS map (Shi et al., 2009).

The expert knowledge approach has generally produced soil maps that improve upon the legacy maps. However, much of this improvement comes from the use of better base maps and digital processing for delineations (Miller and Schaetzl, 2014). The delineations in the legacy soil maps of the NCSS are primarily based on what could be observed by the human eye on a 1930s-1980s vintage aerial photograph. Digital base maps are more accurate spatially, provide more information, and have a higher

resolution. Also, in contrast to the human limitations for minimum delineation size for traditional soil maps, the minimum delineation size for digital mapping models is a single pixel. For these reasons, it is not surprising that any reasonable digital mapping model would exhibit finer detail and greater accuracy than a traditional soil map because those properties reflect the spatial characteristics of the digital base maps. Despite the clear increase in map quality generated from this approach to soil mapping, it should be noted that it is not a strategy designed to expand our knowledge about the distribution of soil properties and their relationships with more readily observed covariates.

5.2 Soil information systems

5.2.1 Geospatial databases

The development of the State Soil Geographic (STATSGO) database started in 1984 using United States Geological Survey (USGS) 1:250,000 topographic quadrangles as base maps and generalizing the data depicted on more detailed soil survey maps. STATSGO provides a summary inventory of larger zones that contain repeating patterns of certain soils across the landscape, which is more suitable for display cartographically at the 1:250,000 map scale. The data were made available in digital form for use in GIS in 1994, with coverage that included the continental USA and Hawaii. Alaska was added in 1996 and is covered by this aggregated data set at a scale of 1:1,000,000. The Digital General Soil Map of the United States (STATSGO2) was developed to update the tabular data to correspond to the SSURGO database structure (Soil Survey Staff, 2015a). Released in 2006, STATSGO2 expanded coverage to Puerto Rico and the Virgin Islands (Sharon Waltman, personal communication, 31 May 2016).

The National Soil Survey Geographic (SSURGO) database first appeared in the mid-1980s (Reybold and TeSelle, 1989). Existing soil surveys were updated, which primarily involved recompiling and recorrelating older work to fit modern soil taxonomy and soil survey standards. However, some

remapping was also undertaken where necessary. The updated legacy maps were then digitized on a county by county or regional basis. The original digital products were available on a county by county basis on CD-ROM. In 2005 a national initiative to digitize soil surveys began (NCSS-GA, 2014).

Gridded SSURGO (gSSURGO) is derived from the SSURGO database but is a raster stored in a geodatabase. In this form, the rasterized SSURGO has the capacity to store data more efficiently and thus represent greater spatial extents than the traditional SSURGO database (Soil Survey Staff, 2015c). Transforming traditional NCSS information into a DSM format also puts the information into forms that are more user-friendly for incorporation into modeling applications in support of interdisciplinary and transdisciplinary studies, something that represents a significant future need (Brevik et al., 2016).

5.2.2 Online products

Web Soil Survey was developed in the early 2000s to allow access to SSURGO data using an online GIS program. The website was created to make soil survey information that was once only available as hard copy published reports widely and easily available via the internet. The map data can be viewed within the Web Soil Survey website or downloaded as shapefiles. Microsoft Access® can be used to download and manipulate attribute data (Soil Survey Staff, 2015b). Another recent development is SoilWeb, which allows access to NCSS data for most locations in the USA using a smart phone (Beaudette and O'Geen, 2010).

In addition to their mapping products, the NRCS has several other online resources. These have been expanded over the years, but many go back to the 1990s. These resources include the official soil series descriptions (OSD) found at soilseries.sc.egov.usda.gov. This online database allows a user to look up any of the now over 20,000 soil series in the NRCS database (Figure 10), and obtain information

including the current taxonomic classification, series description, and a geographic extent map. The NCSS Lab Data Mart (ncsslabdatamart.sc.egov.usda.gov) allows a user to access soil characterization data generated by the NCSS program. A pdf copy of Soil Taxonomy (Soil Survey Staff, 1999) can be accessed at www.nrcs.usda.gov/wps/portal/nrcs/main/soils/survey/class/taxonomy and both English and Spanish versions of the latest *Keys to Soil Taxonomy* (Soil Survey Staff, 2014c) can be accessed at www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/class/taxonomy/?cid=nrcs142p2_053580. Several other technical references are available online as well from links at www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/ref/?cid=stelprdb1247805, including the Soil Survey Manual (Soil Survey Staff, 1993), Land Capability Classification guide (Klingebiel and Montgomery, 1961), the Soil Survey Laboratory Methods Manual (Soil Survey Staff, 2014d), the Field Book for Describing and Sampling Soils (Schoeneberger et al., 2012), and Field Indicators of Hydric Soils in the United States (Vasilas et al., 2010). The ability to access documents such as these online has been a major asset in attempting to standardize soil science practices within the USA, and also likely contributes to the widespread use of Soil Taxonomy (Brevik et al., 2016; Hartemink, 2015) and American soil science standards and techniques even in studies conducted outside of the USA by scientists who are not Americans (see for example Vacca et al., 2012; Rivest et al., 2013; Millán et al., 2014; Vacca et al., 2014; Certini et al., 2015; Madruga et al., 2015; Novara et al., 2015; Terrón et al., 2015; Reidy et al., 2016).

In 2015 NRCS released a guide to pronouncing taxonomic terms (Soil Survey Staff, 2015d). This guide includes information on the origin of each term, the phonetic spelling for each term, and an audio file with a recording of each term being pronounced. Products such as these continue to expand the NRCS offerings, making them more useful to researchers and other end users alike.

5.3 Additions to Soil Taxonomy

Two additional soil orders, Andisols and Gelisols, were added to Soil Taxonomy after the original publication of the “final” classification system (Soil Survey Staff, 1975). Andisols were added following the work of the International Committee on Andisols (ICOMAND), which was established in 1978 and finished its work in 1988 (Leamy et al., 1990). In the late 1980s Moore and Ping (1989) noted that Soil Taxonomy did not adequately address soils in permafrost regions, and proposed that a new order was needed. To address this category of soils, Gelisols were added following the work of the International Committee on Permafrost-Affected Soils (ICOMPAS), which produced its first proposal for Gelisol classification in 1994 (Bockheim, 1994) and produced its final proposal in 1996 (Bockheim, 1996). Andisols and Gelisols have strong links to geology and climate, respectively, common themes within Soil Taxonomy (Bockheim et al., 2014). These orders appeared for the first time in the updated *Keys to Soil Taxonomy* released in 1990 and 1998 for Andisols and Gelisols, respectively, and in the updated version of Soil Taxonomy (Soil Survey Staff, 1999).

In addition to new soil orders, Soil Taxonomy undergoes regular updates to introduce new terms and remove outdated terms at all levels within the system. To this end, 12 *Keys to Soil Taxonomy* were produced between 1983 and 2014 (Table 1), meaning Soil Taxonomy has been updated roughly once every two years from 1983 to the present. Proposals for changes to Soil Taxonomy criteria at the time this paper was written included changes to carbonate-rich Histosols, freshwater subaqueous soils, Aquic Hapludults, and a proposal to define episaturation over densic materials. One of the primary goals of Soil Taxonomy was to provide a dynamic classification system that was relatively easy to modify as our knowledge of soils grew (Smith, 1986). The ability to add new soil orders and the publication of the *Keys to Soil Taxonomy* to regularly provide updates at all taxonomic levels are prime examples that demonstrate the flexibility of the taxonomic system.

6. Reinvigoration of soil science (2000s)

In many ways soil science in the USA has undergone a resurgence in the first 15 years of the 21st century. Although soil science student numbers declined through the 1990s and early 2000s (Baveye et al., 2006; Collins, 2008a), there is now evidence that student numbers are on the rise in most university soil science programs within the USA (Brevik et al., 2014). After hitting a recent low in 2002, membership in SSSA recovered to mid-1980s levels by 2011 and the years 2011-2015 represent the five highest membership levels in the history of SSSA (Figure 2). Evidence such as this indicates that in many ways soil science in the USA has recovered from the relatively tough times of the 1980s and 1990s.

To accomplish this recovery, soil science has had to evolve as a profession so that the soil scientists of today are not exactly the same as the soil scientists of a few decades ago. Most of the original soil science departments at USA universities have been combined with other departments to create hybrid departments such as “Agricultural and Environmental Management”, “Earth and Soil Sciences”, “Forest Resources”, “Environmental Sciences”, “Natural Resources”, “Plant and Earth Science”, “Soil, Water, and Environmental Sciences”, and “Renewable Resources”, with only five “Soil Science” departments left in the entire country (Brevik et al., 2014). Degrees that include a background in soil science can be found in departments with all of these names and more. In addition, several allied fields such as agronomy, environmental science, geography, and geology continue to offer soil science coursework within their curricula at universities across the USA (Brevik, 2009). While most soil science courses and degree programs are still offered at Land Grant institutions (Brevik, 2009; Brevik et al., 2014), which have traditional ties to agriculture, the new hybrid departments and the common offering of soil science coursework by allied fields indicates the much broader scope, beyond agriculture, that soil science encompasses in the modern day USA (Landa and Brevik, 2015). However, in many ways this can be seen as a return of soil science to its roots. It should not be forgotten that the first proposal for a soil survey

in the USA was for it to be established within the USGS (Amundson and Yaalon, 1995). Curtis Fletcher Marbut, one of the most influential figures in the early forming of the modern Soil Survey in the USA, was trained by the renowned physical geographer, William Morris Davis (Miller and Schaetzl, 2016), and other influential American figures such as Mark Baldwin, Hugh Hammond Bennett, George Nelson Coffey, Williamson E. Hearn, Francis Hole, Ralph McCracken, Thomas D. Rice and James Thorp were trained as geologists (Brevik, 2010).

6.1 Integration of digital soil mapping into the National Cooperative Soil Survey

Despite the growing DSM activity within academia, the implementation of DSM in the NCSS has only occurred recently. Possible reasons for this include the tremendous momentum of a very successful manual mapping paradigm and dwindling federal investment in the NCSS (Figure 1). Part of the political disinterest in soil mapping is related to that fact that most of the USA has been mapped (Indorante et al., 1996). In many respects this situation leaves the argument for renewed investment in soil mapping resting on the benefits of updating and improving existing maps rather than the usefulness of soil maps in general (Miller, 2012). Nonetheless, the NRCS with its partners in the NCSS has been working to integrate DSM methods into existing Soil Survey procedures. The momentum towards DSM was given a boost in 2007 by the formation of a formal working group within SSSA.

As NCSS staff have become more familiar with the tools, GIS and digital data layers have been increasingly utilized in the soil mapping process over the past two decades. Although the use of GIS and digital data layers within conventional compilation techniques do not constitute DSM, the increasing comfort and reliance upon these resources represents a trend towards a more digital Soil Survey. For the most part, these geospatial technologies have been used to support and improve the traditional paradigm of manual delineation of map units based on human-determined groupings of environmental

conditions. For example, in updating the Soil Survey map for the East Shore Area of the Great Salt Lake, Utah, a supervised classification of Landsat 7 imagery was used to help identify areas of differing wetness, salinity, calcium carbonate concentration, and vegetation cover type. The classified imagery was then used as a base map to guide improved delineations of the soil map units (Kienast-Brown and Boettinger, 2007).

The few areas in the USA that have not yet been mapped by the Soil Survey lend themselves as opportunities to experiment with DSM techniques for establishing initial delineations. To extend soil map coverage into areas difficult to access in Washington, USA, Frazier et al. (2009) sampled the most accessible locations to gain understanding of soil relationships with environmental covariates. They then developed a set of classification rules that were implemented in a GIS to produce digital delineations of their soil map units. Additional work attempting to implement more DSM techniques in the NCSS has also been done in select areas of California, Minnesota, Utah, Texas, and Wyoming. The only NCSS product considered to be fully DSM-based thus far is in Essex County, Vermont. The latest soil map produced for that area utilized the ArcSIE software package to automate creation of the digital classification rules and estimations of uncertainty (Shi et al., 2009). ArcSIE uses the expert-knowledge approach described above and allows for interaction with the soil scientists in the classification process. The multiple opportunities for the soil scientists to shape the quantified model to their understanding of the landscape helps to more fully utilize their mental model.

Despite a continued heavy reliance on mental models, the NCSS is experimenting with greater integration of statistical models to support the improvement of the SSURGO database and to produce new maps of soil properties. The strength of the NCSS has been and continues to be the high degree of fieldwork involved in creating soil maps. Integrating new DSM and spatial analysis techniques are clearly

beneficial, but it is appropriate to be cautious not to lose aspects that have made the NCSS maps such high quality products in the past.

6.2 Recognition of soils as human-natural bodies and urban soils

While the two subjects in this section are not synonymous, there are links between them, as urban locations tend to have soils that have been highly altered by human activities (Brevik and Arnold, 2015). While anthropogenic effects on soil may be most noticeable in urban environments, such impacts extend into rural areas as well through the impact of management on agricultural soils. The idea of soils as human-natural bodies was first proposed by Yaalon and Yaron (1966), but it was several decades before the idea caught on (Itkin, 2014; Brevik et al., 2015c). In recent years the idea of soils as human-natural bodies has been well documented (Richter, 2007; Richter et al., 2011; Richter and Yaalon, 2012), and is in line with the recognition by geologists that humans are now the primary geomorphic agent shaping the Earth's surface (Hooke, 2000; Wilkinson, 2005). In recognition of the importance of humans on soil processes and properties, the USDA-NRCS formed the International Committee on Anthropogenic Soils (ICOMANTH) with the charge to define appropriate classes in Soil Taxonomy for soils that have their major properties derived from human activities. The first ICOMANTH Circular was sent in 1995 (Ahrens, 1995) and the most recent Circular was produced in 2010 (Galbraith, 2010). Many of the recommendations made by Galbraith (2010) were incorporated into the 12th Edition of *Keys to Soil Taxonomy* (Soil Survey Staff, 2014c).

The NCSS began to make soil survey interpretations for urban development in the 1950s and 1960s (Pettry and Coleman, 1974; Zayach, 1974). However, urban soils received limited attention within the USA outside of contamination and human health issues (i.e., Menzie et al., 1992; Mielke et al., 1999) or studies into horticultural issues such as urban soils and tree growth (Ware, 1990) prior to the 2000s. In

the 2000s interest in urban soil issues expanded, with studies into topics such as carbon sequestration in urban soils (Kaye et al., 2005; Pouyat et al., 2006), soils as part of the urban ecosystem (Pickett et al., 2008), and urban soil pedogenesis (Howard and Olszewska, 2011) and soil survey (Howard and Shuster, 2015). Another indication of the increased interest in urban soils was the creation of an Urban and Anthropogenic Soils Division by SSSA during their 2013 restructuring. This increased interest in urban soils has developed as urban populations in the USA have grown along with a more than doubling in the area of land that is urbanized (Vesterby et al., 1994; Alig et al., 2004).

6.3 Increased recognition of the need for soils knowledge

As we have moved into the 2000s, there has been an increasing recognition of the importance of soil knowledge from people beyond the core of soil science specialists and to address issues beyond traditional soil science topics (Hartemink, 2008; Hartemink and McBratney, 2008; Brevik et al., 2015b). A positive impact for soils was the publication of a special issue in the journal *Science* in 2004 entitled *Soils-The Final Frontier*. There has been renewed interest in the scientific study of soil in recent years as it has been recognized that biogeochemical processes that occur at the Earth's surface influence global climate change, land degradation and remediation, the fate and transport of nutrients and contaminants, soil and water conservation, soil and water quality, food sufficiency and safety, global carrying capacity, wetland function, and many other issues pertinent to the stewardship and conservation of land and water resources (Science 304, 11 June 2004). Soils are now recognized as the most complex ecosystem on the planet (Young and Crawford, 2004).

Another example of the recognition of the interdisciplinary importance of soil within the USA is given in the preface to a soil workshop run by the National Research Council, a group within the National Academies of Sciences, Engineering, and Medicine of the USA. That preface says “Soil provides support

for both natural and human systems. While basic research provides an understanding of fundamental soil processes, increasing trends in land transformation, environmental challenges, and policy issues require interdisciplinary approaches. To successfully address major research needs, soil scientists must collaborate with each other and with scientists in other disciplines" (National Research Council, 2009).

Soils have gained importance in transdisciplinary research as well, such as socio-economic work. Soils have been shown to be an important consideration when evaluating the economics of introducing new cropping systems (Yi et al., 2014), when developing new policies to address environmental impacts (Mérel et al., 2014), or when linking biophysical and economic modeling to consider changes in agricultural management for mitigation of climate change (Howitt et al., 2009). There has also been recent work in the USA linking soils to art, such as realism in American landscape painting (Feller et al., 2015) and the depiction of soils in the film industry (Landa, 2010). The power of applying transdisciplinary principles to real-world problems has been verified by several studies such as those reviewed in Bouma et al. (2011).

Therefore, as the first 15 years of the 2000s came to a close there was promise for soil science in the USA. While it is an international event, there is probably nothing that indicates this promise more than the recognition of the importance of soil as a resource to the world through the naming of 2015 as the International Year of Soils (IYS) by the 68th General Assembly of the United Nations. The objectives of the IYS were:

- To create full awareness of civil society and decision makers about the fundamental roles of soils for human life;
- To achieve full recognition of the prominent contributions of soils to food security, climate change adaptations and mitigation and sustainable development;

- To promote effective policies and actions for the sustainable management and protection of soil resources;
- To sensitize decision makers about the need for robust investment in sustainable soil management activities aiming at healthy soils for different land users and population groups;
- To catalyze initiatives in connection with the Sustainable Development Goals and post 2015 agenda; and
- To advocate rapid enhancement of capacities and systems for soil information collection and monitoring at all levels (global, regional and national).

As part of meeting these goals, SSSA has developed several materials in support of the IYS that can be accessed at www.soils.org/iys.

7. Conclusions

The 1980s and 1990s were challenging times for soil science in the USA. Federal budgets, particularly in the late 1980s through the 1990s, were on the decline as were student numbers in university soil science programs and membership in SSSA. Because soil science had been supported for the better part of a century as a primarily agricultural activity, declines in support from that sector has meant that soil science has needed to reevaluate its identity. Fortunately, soil science has many applications and when properly considered, is an important piece to a great number of Earth systems and ecosystem services.

Despite the challenges, there were many exciting developments happening as well. The advent of GPS, GIS, and exploration of remote and proximal sensing capabilities revolutionized our ability to collect, analyze, and display spatial data. Soil information was put online, and the use of soil information expanded into new, less traditional areas such as environmental applications, human health, archaeology, and returned to its early geological roots. The 2000s became a period of reinvigoration for soil science in the USA, not

necessarily due to increased funding, but because of a greater recognition across disciplines of the critical role that soil has in many systems. Expansion into nontraditional areas brought about a renewed appreciation for the importance of soil, accompanied by increased enrollment in academic programs and membership in soil science professional societies. However, movement into these new areas has also changed the field. Striking an appropriate balance between agricultural interests and all the other interests that now utilize soil information represents a significant challenge that faces the discipline.

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Table 1. Soil Taxonomy and its modifications since official adoption in 1965. Although the NCSS began using Soil Taxonomy in 1965 following the guidelines of the 7th Approximation, the “final” version of Soil Taxonomy wasn’t published until 1975 and it has been modified several times since.

Publication	Date
Soil Classification, A Comprehensive System, 7 th Approximation	1960
Supplement to Soil Classification System (7 th Approximation)	1967
Soil Taxonomy, A Basic System of Soil Classification for Making and Interpreting Soil Surveys	1975
Keys to Soil Taxonomy	1983
Keys to Soil Taxonomy, Second Printing	1985
Keys to Soil Taxonomy, Third Printing	1987
Keys to Soil Taxonomy, Fourth Edition	1990
Keys to Soil Taxonomy, Fifth Edition	1992
Keys to Soil Taxonomy, Sixth Edition	1994
Keys to Soil Taxonomy, Seventh Edition	1996
Keys to Soil Taxonomy, Eighth Edition	1998
Soil Taxonomy, A Basic System of Soil Classification for Making and Interpreting Soil Surveys, Second Edition	1999
Keys to Soil Taxonomy, Ninth Edition	2003
Keys to Soil Taxonomy, Tenth Edition	2006
Keys to Soil Taxonomy, Eleventh Edition	2010
Keys to Soil Taxonomy, Twelfth Edition	2014

Figure 1. The NRCS Federal budget for the Soil Survey in 2015 dollars from 1980 to 2015. Data courtesy of USDA-NRCS.

Figure 2. Membership in the Soil Science Society of America (SSSA). Note the steady growth from the founding of SSSA through the mid-1980s, followed by a sharp decline in membership from the early 1990s through 2002 before membership recovered in the 2000s.

Figure 3. A – A soil profile near Los Angeles, CA, being prepared for sampling to create soil thin-sections for micromorphological analysis. Thin-section samples will come from the areas with rectangular cut-outs, and soil thin-sections have proven useful in the study of archeological artifacts. B – Burned shell as seen in a soil thin-section. C – Burned eggshell as seen in a soil thin-section. D – Unburned bone as seen in a soil thin-section. Photos courtesy of Jeffrey Homburg.

Figure 4. Ancient gridded fields in southeast Arizona. The rock alignments along the edges of fields delineate areas where ancient agriculture was practiced. Grid cells range from about 3 to 5 m in size. Photo courtesy of Jeffrey Homburg.

Figure 5. Left – Runoff into a Zuni wheat field following a 12 mm rainfall. Right – Organic-rich runoff debris in a Zuni maize field. Photos courtesy of Jonathan Sandor.

Figure 6. Electromagnetic induction and electrical resistivity are two of the most commonly used geophysical methods in soils. Pedestrian soil survey being conducted with an EMI meter (A) and mobile surveys being conducted with a towed-array ER system (B) and an EMI meter (C). Photos courtesy of James Doolittle.

Figure 7. Modern GPR systems are light-weight, highly mobile, and integrated with GPS. A typical GPR system consists of a radar control unit (located beneath blue-colored visor on cart) with an antenna (orange-colored box beneath the cart) and GPS. Photo courtesy of James Doolittle.

Figure 8. GPR Soil Suitability Map of the Conterminous USA. Dark green colors have the highest suitability, with successively lower suitabilities progressing to purple (see key in lower left corner of figure). Figure courtesy of USDA-NRCS.

Figure 9. Conversion of legacy soil maps to a digital soil information system for an area of Hamilton County, Iowa. The (a) original Soil Survey map (Dideriksen 1986) was first (b) digitized to bring the spatial data into a polygon (vector) data model within a GIS (Soil Survey Staff, 2014a). In (c), these data were converted to a raster data model. The soil map units were then simplified to the associated soil organic carbon values to produce a single soil property map (d) (Soil Survey Staff, 2014b).

Figure 10. The growth of soil series mapped in the United States. Note the sudden increase in the number of soil series as Soil Taxonomy was adopted in the mid-1960s. Figure originally published in Brevik and Hartemink (2013), courtesy of Dylan Beaudette, USDA-NRCS, California Soil Resource Lab.