Catena 83 (2010) 23–33

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

Early soil knowledge and the birth and development of soil science

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ARTICLE INFO

Article history:
Received 9 February 2010
Received in revised form 7 June 2010
Accepted 28 June 2010

Keywords:
Soil science
History
Renaissance
Science history
Early civilizations
Soil erosion

ABSTRACT

Soils knowledge dates to the earliest known practice of agriculture about 11,000 BP. Civilizations all around the world showed various levels of soil knowledge by the 4th century AD, including irrigation, the use of terraces to control erosion, various ways of improving soil fertility, and ways to create productive artificial soils. Early soils knowledge was largely based on observations of nature; experiments to test theories were not conducted. Many famous scientists, for example, Francis Bacon, Robert Boyle, Charles Darwin, and Leonardo da Vinci worked on soils issues. Soil science did not become a true science, however, until the 19th century with the development of genetic soil science, led by Vasilii V. Dokuchaev. In the 20th century, soil science moved beyond its agricultural roots and soil information is now used in residential development, the planning of highways, building foundations, septic systems, wildlife management, environmental management, and many other applications in addition to agriculture.

1. Introduction

Humans have always had an intimate relation with the soil. Before sedentary agriculture started, soils were recognized as important sources for the growing of food, fiber, and fuel. When cultivation of crops started differences in soil properties and soil types were found which greatly affected the way people cultivated the soil and the crops they cultivated. It is from these differences in perception and the development in scientific thinking that soil science as a scientific discipline emerged. Initially, it followed the basic sciences like geology, biology, physics, and chemistry, but in the last part of the 19th century it became a solid science on its own.

The history of soil science has been fairly well documented in several books and monographs (Boulaine, 1989; Krupenikov, 1992; Yaalon and Berkowicz, 1997; Warkentin, 2006). These books have documented important progress in the development of the soil science discipline. They do not document how soil science evolved from the first human–soil interaction to the establishment of the soil science discipline along with changes and challenges up to the present day. Given the current upsurge of soil science (Hartemink, 2008; Hartemink and McBratney, 2008) and the need to advance the discipline, it is important to document the past thinking and roads that have led to our current thinking in soil science. In this paper, we succinctly summarise 11 millennia of human–soil interactions focusing on the first sedentary agriculture and soil traditions in Egyptian, Greek, Roman, and other cultures across the globe. This is followed by the changes brought about in the renaissance and the birth and development of soil science.

Due to the limitations of a journal length paper, the discussion of soil science history in this paper is necessarily brief and leaves out significant details. Much (although not all) of what is discussed in the section that covers 11,000 BP to 1900 AD is covered in greater detail in Krupenikov (1992), and the reader is referred to Krupenikov's work for a more in-depth discussion of soil science history in this time period. Within this paper, the historical discussion is also built upon works from many additional authors. The reader is also referred to these works for expanded discussions in the areas they address.

2. Early soils knowledge (11,000 BP to 1500 AD)

The move to sedentary agriculture likely represented one of the first times that humans considered soil properties, be it directly or indirectly, in decisions on land use. The earliest known evidence of agricultural practices comes from a site near the modern village of Jarmo in Iraq, where implements for harvesting and tilling were found dating back to 11,000 BP (Troeh et al., 2004). Early humans likely used a trial and error approach to determine where to farm. Agricultural settlements were established in places where the soils were suitable and conditions favorable for crop growth. Evidence of irrigation has been found in southern Iraq dating back to 9,500 BP (Troeh et al., 2004), showing efforts to manage and adapt soils for human needs.

2.1. The Middle East

The area between the Tigris and Euphrates Rivers in Iraq became home to the civilizations of Mesopotamia. The people of Mesopotamia

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doi:10.1016/j.catena.2010.06.011

recognized differences in soils and adjusted their cropping patterns based on differences observed in soil fertility (Krupenikov, 1992). Mesopotamia had an advanced system of irrigation canals under both the Sumerians and the Babylonians. Irrigation was intimately linked to the demise of the Mesopotamian civilizations. Political power in Mesopotamia shifted from the Sumerians to the Babylonians when the soils of Sumer became too saline and waterlogged for crop growth because of salts in the irrigation water and rising groundwater levels caused by irrigation (Hillel, 1991). Babylonian rule failed as canals filled with silt eroded off the surrounding hills. The Babylonians had removed timber from the hills to build their cities and grazed their sheep and goats on the hills. Increased erosion rates led to the deposition of as much as four m of sediment in Babylonian fields (Troeh et al., 2004). The ard, an early plow, was probably developed in the Middle East around 6000 to 4000 BC (Hillel, 1991; Lal, 2007a) (Fig. 1), an invention that allowed more soil to be prepared for planting in a given time.

In approximately 1400 BC, the Bible depicted Moses as understanding that fertile soil was essential to the well-being of his people. Numbers 13:18–20 (New International Version) reports on the charge Moses gave to the men he sent to explore Canaan. Moses said to them "See what the land is like and whether the people who live there are strong or weak, few or many. What kind of land do they live in? Is it good or bad?… How is the soil? Is it fertile or poor? Are there trees on it or no? Do your best to bring back some of the fruit of the land". Moses specifically instructed his men to evaluate the fertility of the soil.

During the Middle Ages, Islamic-based societies had formed and spread from the Arabian Peninsula and were among the world's leaders in science, mathematics, and technology. This included the agricultural sciences. Earlier works from civilizations such as the Greeks, Romans, Chinese, and Indians were known to Muslim scientists, who studied, combined, and built upon these earlier works (Idrisi, 2005). A hallmark of Middle Ages Muslim governments was the development and support of extensive networks of irrigation canals. Mathematics contributed greatly to the engineering of these irrigation systems. Muslim agronomists were also adept at identifying soils suitable to the crops being grown. Libraries in major Muslim cities typically contained numerous agricultural works, and the Muslim scholar Cordoba developed an agricultural calendar in the 10th century that listed, among other items, monthly tasks related to the preparation of soil for agriculture. Soil fertility was maintained through the use of manure, and it was recognized that different crops had different soil fertility requirements (Idrisi, 2005).

2.2. Egypt, Greece, and the Roman Empire

The Egyptians developed a civilization around the Nile River that lasted from about 3300 BC to 332 BC. The Egyptian civilization was based on irrigation and the fertility of their agricultural soils was naturally maintained through frequent flooding of the Nile River, which led to deposition of organic-rich silt (Hillel, 1991; Troeh et al., 2004). A number of water-lifting devices were invented to irrigate fields alongside the Nile (Hillel, 1991). The Egyptians had a cultivated agriculture and they understood preparation of the soil before sowing. They also understood that the Nile floods watered and fertilized the soils (Krupenikov, 1992) and the floods removed accumulations of salts (Hillel, 1991). Animal-pulled seed drills were used in Egypt by 2,100 B.C. (Lal, 2007b).

The Phoenicians, who were at their height from about 1200 to 800 BC, were the first to construct bench terraces on steep slopes in Lebanon and Syria. They practiced a cultivated, irrigated agriculture on these terraces, which showed an understanding of soil management to prevent erosion and thus allow for successful cropping (Troeh et al., 2004).

Another early Mediterranean civilization was based out of the city of Carthage in Tunisia. Eventually conquered by the Romans, the Carthaginians were excellent farmers with advanced cultivation and irrigation systems. However, erosion by wind and water eventually removed the topsoil around Carthage, and today the region cannot support the populations it once did (Troeh et al., 2004).

Agriculture-based groups also existed in more northerly parts of Europe in the pre-Roman era. The Celts in Britain cultivated fields across the slope to slow erosion, bench terraces were used in modern day France that possibly date back to the Phoenicians, and cultivation began in Poland as early as 5,500 BC. In general, agricultural techniques were improved in Europe when the Romans arrived. Farther east, farming tribes lived along the Dniester River as early as the 4th century BC and a clay jug with an agricultural calendar that dates to the 4th century AD has been found (Krupenikov, 1992).

The Ancient Greek philosopher-scientists developed a clear understanding of soils, recognizing differences between soils by the second millennium BC. They have been credited with creating the first recorded works that show knowledge of soil properties (Krupenikov, 1992). The philosopher Xenophon recognized that life started and ended in the soil. Hesiod wrote of different types of plows that were developed to work different soils, and Aristotle and Plato linked soil to the giving of life by comparing it to a woman or mother. Greek philosophers also realized that the soil supplies nutrition to plants (Sparks, 2006) and developed a

Fig. 1. A schematic of an ard (left) and a farmer in Mexico plowing with an ard (right).

concept of the soil profile (Krupenikov, 1992). Theophrastus wrote what was probably the first agronomic work, including a classification for soils. The Greeks were quite successful at choosing crops suitable for soils found in their colonies around the Mediterranean and had literature devoted to soil management practices (Krupenikov, 1992). Plato wrote of the ability of soils to store water (Hillel, 1991).

The Greeks were excellent observers of nature, but they did not test theories or conduct experiments (Easterbrook, 1999). Therefore, their knowledge of soils fell short of being science. As with the Babylonians before them, soil erosion became a serious problem in ancient Greece and the Greek agriculturists never developed techniques to combat soil erosion (Hillel, 1991; Troeh et al., 2004).

The agricultural knowledge of the Romans was initially developed under the influence of the Greeks. Italy had been colonized by Greece and produced grains under the Greek system for several centuries before the rise of the Roman Empire (Krupenikov, 1992). Therefore, Roman knowledge of agriculture and soils can be seen as an extension of Greek knowledge. Krupenikov (1992) divides Roman soils knowledge into three periods. The first period was during the 3rd century BC and began with Cato, who advocated the use of manure and green manure as amendments to improve the soil (Winiwarter, 2006). In particular, the use of green manure was a step further than Greek ideas concerning soil fertility, and Cato made the first recorded reference to what we now know as compost (Krupenikov, 1992). The Romans also began terracing their fields to reduce soil erosion (Troeh et al., 2004).

The second period of Roman soils knowledge began with M.T. Varro, a noted Roman historian and philosopher, during the 1st century BC with the reintroduction of works from Phoenician and Greek authors to the Roman literature (Krupenikov, 1992; Winiwarter, 2006). Varro proclaimed that farming is a science. He considered soils as one of two important components of farming and developed a classification system for the soils of Italy. He also advocated methods for the improvement of soil fertility (Krupenikov, 1992). By the third period of Roman soil knowledge, scientists such as Pliny the Elder were arguing that soil fertility declined under cropping and that soil fertility could never be replenished. While L.J.M. Columella (a Roman farmer and writer) and Strabo (a Greek geographer) offered opposing views, Roman ideas of soils and soil fertility as a whole took a step back (Krupenikov, 1992). By the end of the third period, the Romans had a form of soil classification that included consideration of grain size, color, density and structure, and fertility and had some recommended tests for determining the properties and fertility of soils (Tisdale et al., 1993; Winiwarter, 2006).

By the 2nd century AD, Roman science began to decline and the biggest contribution made at that time was in the recording of soils knowledge gained to that point, allowing it to be passed on to future workers (Krupenikov, 1992). Given that the Roman Empire completely encircled the Mediterranean Sea, Roman ideas on soil science had a profound influence on soil science throughout the Mediterranean. Other Mediterranean civilizations were tied to the soil but did not develop the same level of understanding of the soil as the Greeks and Romans (Krupenikov, 1992).

Following the decline of Rome in 410AD, Roman culture shifted to Byzantium in Turkey. Many Roman manuscripts, including agricultural manuscripts, were moved to Byzantium and the scientific ideas developed by the Roman Empire were preserved and advanced over the next 1000 years by the Byzantines. A 10th century AD agricultural encyclopedia showed Byzantine soils knowledge. It included works by Roman soils specialists, but several new Byzantine authors were also represented. It included a description of the soils of the Byzantine Empire, discussions of which crops were most appropriate for different soils, and ways to evaluate the quality of the soil (Krupenikov, 1992).

Agriculture declined in Europe following the fall of the Roman Empire; the decline included both the area of land under cultivation and crop yields. Brief periods of renewed interest occurred in the 8th and 9th centuries AD (Krupenikov, 1992). A moldboard plow with an iron share was widely used in Europe by the 5th century AD (Lal, 2007a), but real agricultural improvement did not take place until the 11th century. Draining of marshlands, fertilization of the soil with manure and marl, and use of a plow that turned over the upper layer of the soil all helped to increase agricultural yields; manure was in fact a highly valued commodity. Cultivation of fields across the slope and other conservation measures were developed on the British Isles fairly early (Troeh et al., 2004), and cultivated lands on steep slopes were returned to forest in parts of Europe as early as the 10th century AD in an effort to reduce soil erosion (Krupenikov, 1992).

2.3. Asia

In present day Uzbekistan, farmers worked sand and manure into the soils of the Amu Darya delta, found along the south shores of the Aral Sea, to improve fertility and other soil properties as early as 4,000 years ago (Krupenikov, 1992). In India, Neolithic (3rd to 2nd centuries BC) farming communities were found in areas with fertile *black regur* soils (Vertisols) on the Deccan Plateau. Writings from the 4th century AD mention irrigation of fields and fines or penalties for those who allowed breaches in the irrigation system (Krupenikov, 1992). These farming communities expanded at an early date to include the fertile floodplains of major rivers like the Ganges. By the 14th century AD irrigation, fertilization through manure application, fallow periods to restore fertility and selection of crops based on soils were widely used in India (Krupenikov, 1992). Records in India refer to the plowing of soils as a common practice at least as far back as 5,000 years ago (Lal, 2007b).

Rice cultivation in China dates to around 9,000 BP, and millet and wheat farming date to around 6,000 BP (Gong et al., 2003). Chinese accounts tell of Count Hui dividing soils according to their quality and location in the 2nd century BC and Fan Sheng-chih wrote of soil properties and of optimal times for tillage in the 1st century BC (Krupenikov, 1992). Early agriculture in China centered on the fertile floodplain of the Huang He or Yellow River. Channels supplied water for irrigation as early as 770 BC (Gong et al., 2003).

The first Chinese soil classification system dates to around 4,000 BP and was based on characteristics such as soil fertility, color, texture, moisture, and vegetation (Li and Cao, 1990; Gong et al., 2003). Many additional ancient soil classification systems were developed following this (Krupenikov, 1992; Gong et al., 2003). The Chinese also recognized over 2,000 years ago that soil fertility was a dynamic property that could be improved or depleted depending on management (Gong et al., 2003). The decrees of Chinese emperors showed a strong appreciation for soils. Emperor Hinn included soil quality in the determination of land taxes in 1115. Emperor Ming ordered that all lands be divided based on their location and soils in 1387, and land surveys including soils information were made for large portions of the country (Krupenikov, 1992). Soil conservation measures began in China by 956 BC, consisting primarily of contour terraces (Troeh et al., 2004).

Japanese agriculture was influenced by the Chinese until the 9th century AD, after which the Japanese halted immigration and moved away from Chinese influence. The lack of good land led the Japanese to place a high value on fertile soil. Several forms of soil fertility maintenance including manure, green manure, the growth of legumes, and crop rotations were used. Terraces were used on steep slopes and land surveys were common. Artificial soils were created on terraces on steep land where natural soils were poor (Krupenikov, 1992). The Japanese developed a reverence for soil (Winiwarter and Blum, 2006), possibly because of their lack of good agricultural land.

2.4. The Americas

Farming in Mexico included terracing and irrigation techniques by the 5th century BC. The Aztecs and Maya farmed flat valley lands with readily available water and commonly used built-up areas of artificial soil made of aquatic plants, clay from lake or river bottoms, marl, and manure (Coe, 1964; Hillel, 1991)—a system that required knowledge of soil properties. The Maya and the Inca in Peru developed bench terraces on mountain slopes, filling the area behind the terraces with non-soil material to within about a meter, then filling the final meter with fertile soils carried up from bottomland areas (Hillel, 1991; Krupenikov, 1992). These early American civilizations were some of the most successful in history at minimizing soil erosion and creating sustainable agricultural systems (Troeh et al., 2004; Sandor, 2006; Gonzalez et al., in press). These various agricultural techniques succeeded in supporting some large cities such as Teotihuacan, which had approximately 125,000 inhabitants at its height (Juo and Wilding, 2001; Gomez-Pompa, 2003).

The Aztecs developed a soil classification based on soil properties (fertility, texture, moisture, and genesis), topographic location, vegetation, and farmers' practices. This soil classification, with up to 45 classes, was used for several purposes, including taxation, soil management, medicinal usage, and construction (Williams, 2006).

Terra preta (dark earth) soils are found throughout the Amazon River basin in South America. These soils have carbon levels that can be up to 70 times greater than in the surrounding soils (Sandor et al., 2006). While research into just how these soils formed is still ongoing, they are believed to be related to long-term human management by past indigenous people. They most likely formed when organic material was added to the soils though burning and mulching, and some of the terra preta may even become self-regenerating when biologic activity in them reaches a certain threshold (Sandor et al., 2006).

3. Soils in the Scientific Revolution (1500–1800)

In western societies, the Middle Ages (5th to 14th Centuries AD) represented a period of repression for science that included a neglect of soils knowledge that had been gained by the Greeks and Romans. This neglect was due to the strong dominance of religion in western life and the absence of a thriving science community. Of course, local soils knowledge existed in the Middle Ages, and in some parts of the world where religion had less influence it was expanded. It is only in the Renaissance and the subsequent development of the natural sciences that the scientific study of natural resources, including the soil, started in the western world.

The 16th century marked the beginning of the Renaissance in Europe, a period when science and scientific thinking began to develop and grow. There are a number of significant events that occurred in the study of soils during this period. Soil science was not a distinct scientific field but many of the phenomena that occur in the soil such as the supply of plant nutrients and changes in soil over time were being investigated. Some new scientific methods were being applied to the study of soils and Europe's scientists were also rediscovering earlier works by the Greeks and Romans.

3.1. Soils and plant nutrition

The first soils studies focused on plant nutrition. Several researchers contributed to these studies with varying degrees of success in determining what processes lead to the exchange of nutrients between the soil and plants. Some names in the early studies of plant nutrition include Bernard Palissy (1510–1589), Francis Bacon (1561–1626), J.B. Van Helmont (1579–1644), and Robert Boyle (1627–1691).

Palissy promoted a “salts theory” of plant nutrition which held that plant nutrients came from salts in the soil, although it is worth noting that Palissy's idea of what constitutes salts was different than the modern definition (Feller et al., 2003b). Palissy felt that the benefits derived from the ash of burned residues or from manures came from salts in the ash or manure. While this idea was closer to what actually happens in the soil than several that followed it, Palissy's salts theory found little support from other scientists at that time (Krupenikov, 1992).

The concept that plant nutrition came from water and that soil was nothing more than a storage and supply medium for water was advanced by Van Helmont and Boyle and became the prevailing hypothesis of plant nutrition for over 100 years (Tisdale et al., 1993). Later experiments by J.R. Glauber (a German chemist), J. Mayow (an English chemist and physiologist), and others on the impact of nitrogen on plant growth identified nitrogen as an important plant nutrient in the soil and laid the groundwork for the development of soil chemistry (Krupenikov, 1992). Despite the advances made, a solid grasp of the role of soil in plant nutrition was not achieved until the 19th century. Another important related concept studied during this time was that of nutrient cycling in soils, a phenomena studied by Leonardo da Vinci using pots of grass from 1504 to 1506 (Krupenikov, 1992). Da Vinci also realized that “We know more about the movement of celestial bodies than about the soil underfoot”.

Investigations into soils and plant nutrition continued under several researchers. Jethro Tull in the UK believed that soils needed to be in numerous small, loose clods for best plant growth while manure application was unnecessary because plant nutrition came from very small soil particles (Tisdale et al., 1993; Manlay et al., 2007). This formed the origin of the idea of soil structure. J.A. Külbel promoted the idea of soil “nutritive juice”, which correlates well to water-soluble humus. I.G. Wallerius was probably the first to establish the term “humus” in the scientific literature (Manlay et al., 2007).

These works were followed by Albrecht Thaer (1752–1828), who promoted the “humus theory of plant nutrition” and studied the cycling of organic materials in soil. One tenet of the “Humus Theory” was that plants obtained their carbon content from the soil, not from the air as claimed by researchers such as G. Fabbroni, J. Ingenhousz, and J. Senebier. The “Humus Theory” prevailed well into the 19th century (Feller et al., 2003b).

3.2. Soil evaluation for taxation

In 16th century Europe, the land was considered the most important factor in the economy and there was a direct relationship between the land (soils) and government, and the philosopher Niccolò Machiavelli (1469–1527) believed variations in population density were primarily a function of soil fertility (Krupenikov, 1992). Therefore, governments could address problems of population distribution through fertilization of deficient soils. Baron de Montesquieu (1689–1755) believed that soil determines the economic vitality, governance, and national character of a country (Krupenikov, 1992).

Governments themselves continued to be interested in the valuation of land for taxation purposes, an undertaking that includes evaluation and mapping of the soil. The 18th century saw the first soil mapping efforts. As early as 1716, maps of individual estates in Europe were prepared with notations such as fields for wheat, hemp, or grapes. *General Land Survey* maps made in Russia in the 1760s reported on the quality of soils in various locations (Krupenikov, 1992). Soil mapping for taxation purposes was also popular in Germany. One of the founders of modern soil science, F.A. Fallou (1794–1877), worked on soil taxation for most of his professional life.

3.3. Soil as an evolutionary body

An important contribution from this period is that of Mikhail Lomonosov, published in 1763. Lomonosov viewed soil as an evolutionary, geobiologic body that formed over long periods of time. He recognized the important role of weathering, living organisms, and time in soil formation and the layered nature of soil. He also introduced the term “chernozem” to the scientific literature. These accomplishments and others have led to Lomonosov being recognized by some as the first Russian soil scientist (Krupenikov, 1992). This work helped established the foundation that eventually allowed soil science to become established as an independent field of study.

4. Soil science in the 19th century

Soil science evolved from allied fields, including biology, chemistry, and physics. The field of geology also played a significant role and soil science was often referred to as agrogeology at this time (van Baren, 1921). In the early 19th century, the modern science of geology was coming into being. This began in 1788 when James Hutton, widely considered the father of modern geology, published "Theory of the Earth, with Proofs and Illustrations". However, Hutton's writing style was somewhat difficult, and the book was not widely read. Hutton's theories were much more widely read and appreciated when John Playfair, a friend of Hutton's and adherent of his ideas, published his own book "Illustrations of the Huttonian Theory of the Earth" in 1802 (Levin, 2006).

Soil science lagged decades behind geology in becoming its own independent field of scientific study. However, many major parts of the foundation required to build a modern soil science were laid down in the 19th century (Hartemink, 2009). By the end of the 19th century, soil science followed geology and other related fields such as chemistry, physics, and biology into the realm of the modern sciences.

4.1. Agrogeology

Some tension developed in the 19th century between agrogeology and agricultural chemistry. The agrogeologists were a group of geologically trained individuals who studied soils. In Europe, this group included V.M. Severgin, G. Berendt, and F.A. Fallou (Tandarich, 2002). The agrogeologists objected that agricultural chemists had claimed soils as their "territory" and restricted their studies to the cultivated layer. The agrogeologists considered soil science to be a branch of geology and sought to add an agricultural component to geology, in part to help secure funding and justify the existence of the geological field (Krupenikov, 1992).

Geologists in the United States were including soils within the scope of their work in the early 19th century. Only five U.S. states (Georgia, Massachusetts, Michigan, North Carolina, and South Carolina) specifically requested agricultural studies from their geological surveys, but most other state geological surveys also included agricultural studies in their annual reports to help justify the expense associated with maintaining a state survey (Aldrich, 1979). The earliest such work completed in the United States is probably a geological survey of Albany County, New York, published in 1820 (Aldrich, 1979). One of the contributions made by the work of the American geological surveys was the discovery that potassium was the nutrient responsible for the agricultural benefits derived from the use of glauconite (green sands) as a fertilizer. Another typical contribution included the mapping of marl beds with the recommendation that farmers use the marl to supplement manure fertilization (Aldrich, 1979).

Some of the early soils work done by American geological surveys has gained acclaim by soil science historians. This work includes E.W. Hilgard's report on the geology and agriculture of Mississippi in 1860 and T. Chamberlain's soil map of Wisconsin published by the Wisconsin Geological Survey in 1882 (Coffey, 1911; Meyer and Moldenhauer, 1985). In the 1880s and 1890s, E.W. Hilgard and J.W. Powell were nearly successful in establishing a joint national agricultural and geological survey in the United States, something that could have changed the direction of soil research in America (Jenny, 1961; Amundson and Yaalon, 1995).

4.2. Soils and plant nutrition

The "Humus Theory" of plant nutrition persisted into the 19th century and spawned a large number of experiments that gave rise to the field of soil humus chemistry and scientists such as H. Davy and J. Berzelius. By the late 1820s, C. Sprengel, a student of A. Thaer, had disproved the "Humus Theory" and proposed a theory on mineral nutrition of plants and the law of the minimum at least 12 years before J. von Liebig's more famous work (Feller et al., 2003b). Sprengel also published *Die Bodenkunde oder die Lehre vom Boden*, the first book devoted to soil science, in 1837 (Blume, 2002).

In 1840, the "Humus Theory" was officially replaced by the "Mineral Theory" of plant nutrition when J. von Liebig published *Chemistry as a Supplement to Farming and Plant Physiology* (von Liebig, 1840). Liebig could justifiably be called the father of modern soil chemistry (Sparks, 2006). Liebig's work greatly inspired J. Stoeckhardt, who in 1847 went on to hold what was essentially the first extension faculty position in the world at the Academy of Forestry and Agriculture at Tharandt in Germany (Boehm and van der Ploeg, 2004).

4.3. Soil mapping

Great strides were made in soil cartography and mapping in the 19th century. S. Staszic compiled a multi-sheet geology/geomorphology/soils map of Eastern Europe in 1806, and in 1856 A.I. Grossul-Tolstoi compiled a soils map that was later acknowledged to be influential by V.V. Dokuchaev. Soil cartography originated in Germany, France, Austria, the Netherlands, and Belgium in the 1850s and 1860s based on ideas and classification developed in agrogeology. Expanding on this, the German scientist M. Fesca led the publication of agrogeology and soils maps of Japan between 1885 and 1887. In Russia, the Military Department published many maps showing items of interest to military operations, including relevant soils information, starting in 1812, and the Ministry of Government Properties started mapping soils for taxation purposes in 1838 (Krupenikov, 1992).

The earliest soil maps in the United States were made by the state geological surveys; the first appears to have been a soil map of Massachusetts published in 1841 (Aldrich, 1979). These early maps were geologic maps with the assumption that soils formed depended upon the underlying geology. The 1882 soil map of Wisconsin was unique in that it recognized that a geological map and a soils map were not necessarily one and the same, and was probably the first soil map published in the United States based on the physical properties of the soil rather than on the underlying geology (Coffey, 1911).

In 1899, the national soil survey program began in the United States. In the words of Curtis Marbut: "The idea of Soil Survey, so far as it concerned the soils of the United States, originated with Milton Whitney. So far as it concerned differentiation of soils in any considerable detail… it originated with him for the world…" (Simonson, 1986) (Fig. 2).

4.4. The soil profile concept

A major soil science concept that developed during the 19th century was the soil profile (Yaalon and Yaron, 1966; Tandarich et al., 2002; Bockheim et al., 2005). In 1875, A. Orth promoted the soil profile as an essential basis for agrogeologic mapping in Germany, carrying the soil profile down to the parent material. Influenced by Orth's work, G. Müller used the letters a, b, and c to designate turf (a), bleached sand or reddish earth (b), and underground (c) in soil profile diagrams made in 1878 (Tandarich et al., 2002).

Darwin's 1881 book on earthworms and soil has a soil profile with A-B-C-D designations for the horizons, with A being sod, B the topsoil, C a stoneline, and D bedrock (Fig. 3) (Darwin, 1881). Dokuchaev acknowledged Darwin's work in his own 1883 work on Russian Chernozems (Dokuchaev, 1883) but did not endorse Darwin's central

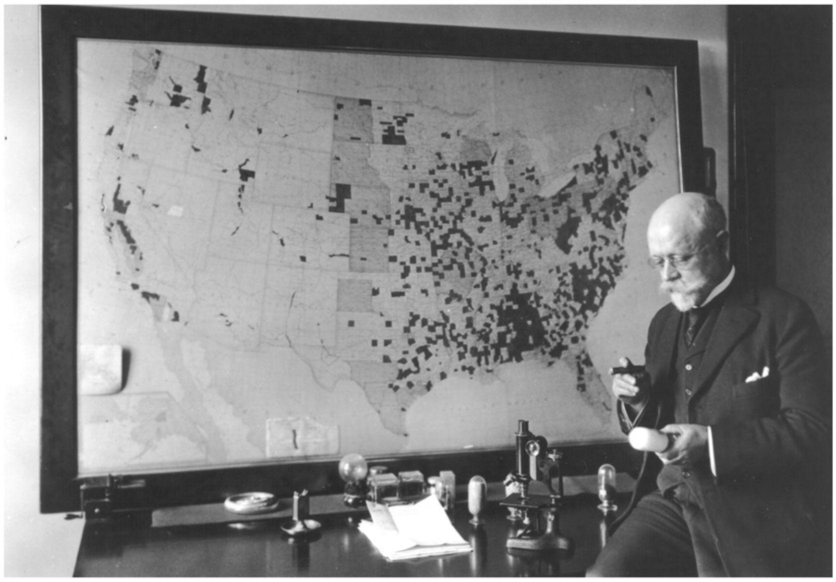


Fig. 2. Milton Whitney at work in his office, early 1900s. Photo courtesy of USDA NRCS.

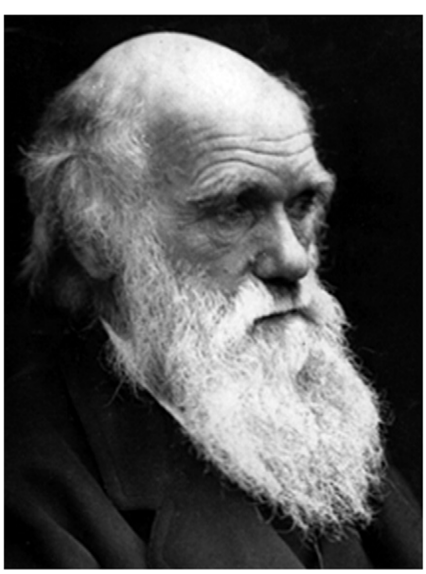
theme. Dokuchaev synthesized the soil profile concept in his works published from 1879 to 1893, crediting Fallou (1862) and Orth as being among those who had influenced him. In a broad sense, Dokuchaev introduced A, B, and C horizons as they are currently used in soil science, as he viewed A + B as constituting soil and C as root rock or subsoil, although these concepts have evolved over time and horizons have been added (Tandarich et al., 2002).

4.5. Darwin and soil biology

Although best known for his work on evolution, Darwin was also a leading figure in establishing soil biology as a separate discipline (Berthelin et al., 2006) (Fig. 3). In 1837, Darwin presented a paper explaining how earthworms form soil. Darwin would produce four additional papers on the same topic in 1840, 1844, 1869, and his famous book in 1881 (Feller et al., 2003a). In his works, Darwin demonstrated the importance of earthworms in affecting the rate of weathering of mineral materials in the soil, humus formation, and differentiation of the soil profile, accomplishments that make Darwin the first author of a scientific publication on the biological functions of soil (Feller et al., 2003a). He was the first to recognize the importance of animals in soil formation.

5. Soil science as an independent science

The Russian V.V. Dokuchaev was the primary figure in establishing the idea of genetic soil science at the end of the 19th century, issuing in the modern era of soil science. However, these new ideas did not immediately take hold outside of Russia (Joffe, 1936). In the United States, for example, a national soil survey had been established in



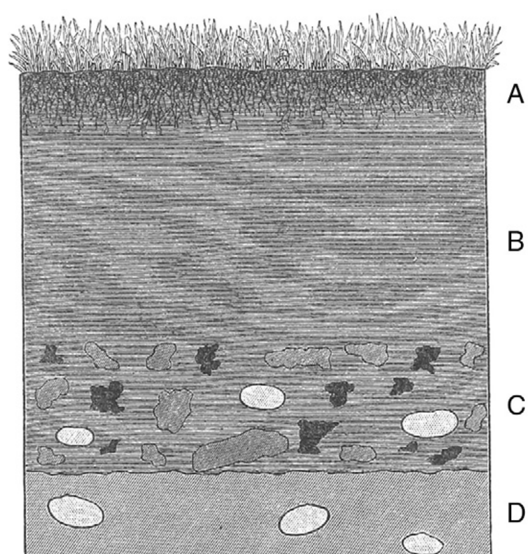


Fig. 3. Charles Darwin and a soil profile from his 1881 book *The Formation of Vegetable Mould through the Actions of Worms with Observations on their Habits*. The diagram shows an 18-cm thick topsoil of "…a waste swampy land that was enclosed, drained, ploughed, harrowed and thickly covered in the year 1822 with burnt marl and cinders". It was then sown with grass and used as pasture. Some 15 years after its reclamation, holes were dug in this field and the following was observed: the turf was about 1.2 cm thick (layer A); the topsoil (B, named vegetable mould by Darwin) was about 7 cm thick and contained no coarse fragments; the C layer was 4 cm thick and full of fragments of cinders and burnt marl that were red coloured; D was the subsoil consisting of black, peaty sand with quartz pebbles. It took 15 years for the cinders and marl to be covered; compared to other sites Darwin investigated the rate of coverage was interpreted to be slow because the land was poor and the worms were scanty (Darwin, 1881).

1899, but upon entering the 20th century this survey was headed by Milton Whitney. Whitney's ideas and classification of soils were based largely on geology, as were most of the world's systems outside of Russia at that time (Simonson, 1989). So while modern soil science began at the end of the 19th century, it did not take firm hold until the 20th century in many countries.

5.1. The birth of genetic soil science

Towards the end of the 19th century, there were several developments in soil science. All of the previous things learned about soils, particularly in the earlier part of the 19th century, laid the groundwork for the development of a new school of thought regarding soils: genetic soil science. Soil science became an independent scientific field through this new school of thought. The leading figure was Vasilii V. Dokuchaev who was trained as a geologist and taught mineralogy and crystallography at St. Petersburg University (Evtuhov, 2006). He had a varied academic background including botany and zoology and his initial area of research was geomorphology. Dokuchaev's introduction to soils came in 1875 when V.I. Chaslavskii invited him to assist on a compilation of a soil map of European Russia (Krupenikov, 1992).

During his work on Russia's chernozems, funded by the Free Economics Society, his field observations and laboratory analyses led him to dismiss the agrogeology definition of soil, the chemical approach to soil classification, and the agronomic view of soils (Krupenikov, 1992). By rejecting each of the views of soil held by the various fields that competed to include soils within their subject area and by recognizing soil as an independent natural body, Dokuchaev established the need to study soils as a separate, independent branch of the natural sciences. Furthermore, Dokuchaev established the five soil forming factors: climate, parent material, organisms, topography, and time; that were later put in an elegant but to this point unsolvable formula by H. Jenny (1941).

While Dokuchaev is the leading figure in the development of genetic soil science, others made significant contributions but have received less attention. P.A. Kostychev and N.M. Sibirtsev were Russian contemporaries of Dokuchaev (Sibirtsev, 1900). Kostychev was a soil microbiologist who was invited to undertake chemical studies of chernozems by the Free Economics Society. His work experimentally confirmed the validity of many of Dokuchaev's ideas and made him a co-founder of the field of soil microbiology along with Wöllny (Krupenikov, 1992) and Winogradsky (Berthelin et al., 2006). Sibertsev was a student of Dukochaev's who refined soil survey methods and established the relationship between the genetic approach to soil science and the assessment of soils using physical and chemical analysis. He became the first chair of genetic soil science in the world at the Novoaleksandrovsk Institute in 1894. He developed the first soil science curriculum and wrote the first soil science text book (Krupenikov, 1992).

Non-Russian scientists also played a role in genetic soil science. M.E. Wöllny was a German soil physicist and microbiologist who developed many standard techniques and equipment for determining soil properties and is also credited with some of the earliest studies of soil erosion by water (Meyer and Moldenhauer, 1985). E.W Hilgard was a German-born American geologist who, starting in 1860, independently developed many of the ideas and concepts that would later form the basis of the Russian school (Jenny, 1961; Amundson and Yaalon, 1995; Amundson 2006). However, Hilgard was unsuccessful in promoting these ideas in the United States. Dokuchaev called Hilgard's investigations into the laws of zonality excellent, and M.E. Wöllny, K.D. Glinka, and N.M. Sibertsev, among others, frequently citied Hilgard's work (Krupenikov, 1992).

Early attempts to introduce Russian ideas to American soil scientists failed (Brevik, 1999; Tandarich et al., 2002; Paton and Humphreys, 2007). P. Fireman published English translations of Dokuchaev's ideas in 1901 but they had little influence, neither did a work published in Great Britain in 1908 (Simonson, 1989). George N. Coffey, a Bureau of Soils employee who was in charge of soil classification and correlation for four years, attempted to introduce Russian ideas to American soil scientists. Coffey's first attempt was at the 1908 American Society of Agronomy (ASA) meeting. As the ASA President Coffey formed and chaired a committee on soil classification in 1909, but the committee was not able to agree on a classification system. Coffey's best-known effort to introduce genetic soil science to the United States came in 1912 with the publication of Bulletin 85 (Brevik, 1999).

Changes in American ideas in soil science did not come about until Curtis F. Marbut took up the cause at the Bureau of Soils in the 1920s. Marbut credited a publication by K.D. Glinka with converting him to the Russian school, but he must have known of Coffey's work as well (Brevik, 2001; Paton and Humphreys, 2007) as Coffey and Marbut served on the same ASA soil classification committee and were contemporaries at the Bureau of Soils for a time (Simonson, 1989; Brevik, 1999). Dokuchaev's ideas were taught in American schools for the first time in the late 1920s to early 1930s. One of the earliest to teach Dokuchaev's ideas at an American university was Charles Kellogg at North Dakota Agricultural College (now North Dakota State University) (Simonson, 1997). Kellogg led the U.S. soil survey following Marbut's retirement.

5.2. National soil mapping programs

The 20th century saw the development of detailed soil mapping programs in many countries. As previously mentioned, the national soil mapping program in the United States was established in 1899, and it grew rapidly in the first few years of the 20th century. Canada started a detailed soil survey program in 1914, Australia and Great Britain in the 1920s, China in 1931, The Netherlands in 1945, and Belgium in 1947 (Simonson, 1989). Russia began mapping at a scale of approximately 1:350,000 in 1908, with more detailed mapping (1:10,000 to 1:50,000) started in 1939 (Simonson, 1989).

National soil survey centers were established in many developing countries in the 1960s and 1970s with the technical and financial support of the Food and Agricultural Organization of the United Nations (FAO). Their mission was to support the many agricultural development projects that were initiated during that period. Only a limited number of these have survived and continue to provide laboratory and field survey services.

5.3. Soil erosion

Problems in soil erosion by water were investigated by Wöllny in Germany during the 19th century, but the problem of soil erosion by wind did not gain attention until the early part of the 20th century when it was studied by Edward E. Free (Free, 1911). A breakthrough in the work by Free is that it concentrates on the impact of windblown material on soil genesis as opposed to investigating wind and windblown material as a geomorphic process and deposit (Brevik, 2004). Free's observation that aeolian dust can introduce substances that are not present in local parent materials to the soil profile predated studies such as the New Mexico Desert Project soil-geomorphology study (Holliday et al., 2002) by over 50 years. Soil erosion was officially recognized as a significant problem in the United States with the formation of the Soil Conservation Service, headed by Hugh H. Bennett, in 1935 (Bennett, 1939; Helms, 2008). The use of reduced-till and no-till systems began in the United States in the 1900s in response to soil erosion problems and rapidly spread to other countries (Lal, 2007b; Berger et al., 2009).

5.4. Soil science moves beyond agriculture

Throughout much of its history, soil science has been concerned primarily with agriculture; emphasis was often placed on the study of soils related to crop production (Bouma and Hartemink, 2002). This was a complaint or criticism of the agrogeologists in the 19th century. In the mid 20th century, soil science moved beyond agriculture (Tinker, 1985; Simonson, 1989). This is evidenced in many ways. One is the development of soil geomorphology as a distinct field during the 20th century. As a field, soil geomorphology is "an assessment of the genetic relationships of soils and landforms" (Gerrard, 1992). In some respects, soil geomorphology is inherent in the Dokuchaev school given that topography is listed as one of the five soil forming factors. However, soil geomorphology did not come into its own as a field of study until the 1950s through 1970s. In this period, soil scientists and geomorphologists led by Robert V. Ruhe, Roger Morrison, Leland Gile, Robert Grossman, and John Hawley lead intensive research projects that formalized and provided direction to soil geomorphology (Holliday et al., 2002).

One of the earliest non-agricultural uses of U.S. soil surveys was in highway construction, a study that was undertaken in Michigan by C. Kellogg in the 1920s. By the 1950s, state highway departments had learned of Kellogg's work and put soil survey information to use for planning roadways. County governments started using soil surveys to plan residential developments. U.S. soil surveys were expanded to include information on the engineering properties of soil, suitability of given soils for uses including campgrounds, picnic areas, foundations, septic systems, wildlife management, and other uses in addition to the more traditional agricultural information (Simonson, 1989). These sorts of applications were not restricted to the United States. In Australia, for example, soil survey principles have been used in support of foundation engineering since the late 1940s (Aitchison, 1973).

Probably the fastest growing non-agricultural area of soil science in the 20th century was the application of soils to environmental problems like contamination and groundwater problems (Hartemink, 2002). Application of soils knowledge in areas such as waste disposal and water quality issues became common. Environmental consultants routinely use soils information as a part of site evaluations and carbon sequestration by soils gained widespread attention as a possible way to combat global warming. The most recent Division added to the Soil Science Society of America (SSSA) was Division S11—Soils and Environmental Quality, a reflection of this environmental movement.

The use of soils and paleosols in paleoenvironmental reconstructions gained attention in the second half of the 20th century (Schaetzl and Anderson, 2005). These reconstructions can involve complex interpretations of geologic, paleontological, and soils information done by multiple scientists working in interdisciplinary collaborations (Palacios-Fest et al., 2006). There has also been an increasing demand for soil information in archaeological studies. In investigating superimposed layers at an excavation site, it is often important to know whether this layering has a natural pedogenetic origin or is due to the accumulation of different sediments (Shelley et al., 2003).

Another issue that received increasing attention as the 20th century transitioned into the 21st is the relationship between soils and human health. It is now well recognized that healthy soils are necessary to provide the proper suite of nutrients in terrestrial food sources consumed by humans. Soils are also recognized as being able to transmit diseases, and a number of medicines have been isolated from soil organisms (Brevik, 2009a). Soils and human health is a topic that is likely to see increasing attention in coming years.

As the 20th century drew to a close, soil science had shown a remarkable transformation. What had started off as primarily an agricultural field had expanded considerably, and soils were being considered in evaluations of land use for virtually all functions. At the same time soil science had moved from largely qualitative and descriptive to more quantitative approaches including assessments of uncertainties.

5.5. The internationalization of soil science

Soil science became highly internationalized in the 20th century. This is represented by the exchange of scientists and ideas between countries and the FAO/UNESCO world soil map and classification system. One of the major ways to exchange ideas was through the International Society of Soil Science (ISSS) (van Baren et al., 2000). The ISSS was founded in 1924; its name changed to the International Union of Soil Sciences (IUSS) in 1998. At the time of its founding, the ISSS was primarily a group of European agro-pedologists interested in standardizing methods of soil analysis and classification (Krupenikov, 1992; van Baren et al., 2000).

The ISSS/IUSS has made several contributions to the internationalization and standardization of soil science, including the organization of 19 World Soil Congresses between 1924 and 2010, creation of committees and working groups to address soils related issues, creation of a Soil Map of the World, and numerous publications. The 1927 meeting in particular has been credited with ending the isolation of Russian soil ideas from the rest of the soil science world (Krupenikov, 1992) (Fig. 4).

Despite the exchanges, there is much work to do in terms of standardizing soil science worldwide. A prime example is soil classification, where Australia, Belgium, Brazil, Canada, China, France, Russia, the United Kingdom, and the United States, among others, all developed their own soil classification systems. Each was developed according to the needs of the user country, but the shear number of classification systems is confusing when trying to communicate information between countries. The number of soil scientists working on soil classification has decreased rapidly in the past two decades (Hartemink et al., 2001). As the current demand for soil property information exceeds demands on soil classification, the problems with different systems may become obsolete in the future.

Several countries were active in exchanges of scientists with other countries in the 20th century. Russian exchanges included work in South America and China (Li and Cao, 1990; Krupenikov, 1992), and various European countries conducted soils work in their colonies in Africa, Southeast Asia, the Caribbean, and other parts of the world (Warkentin, 2007; Young, 2007; Feller et al., 2008). In most British, French and Dutch colonies there were active groups of soil scientists mostly working on land development or soil fertility issues (Hartemink, 2002). On the U.S. side, G.N. Coffey assisted the Canadian survey when it started in 1914 (Brevik, 1999), W. Ogg of Great Britain visited the United States in 1920 to learn U.S soil survey techniques, R.L. Pendleton assisted with soil surveys in India in the mid 1920s, and C.F. Marbut studied the soils of the Amazon Basin (Simonson, 1989). W. Wenhao, head of the National Geological Survey of China, and D. Wenjuang, head of the Chinese Academy of Sciences, requested American assistance for soils mapping in China, leading to a succession of American soil scientists, including J. Thorp, going to China in the 1930s (Tandarich et al., 1985; Li and Cao, 1990). A number of international workshops on soil classification were held to improve U.S. soil taxonomy (Fig. 5).

Universities were also involved in international exchanges. Faculty members and graduate students from U.S. and Canadian universities were sent to other countries to study the soils, and in the reverse direction, many countries sent students to North American universities. European countries often enrolled foreign students in their universities as well, and it was common for students from communist countries to study in the Soviet Union. It was not uncommon for students from developing countries to get undergraduate degrees in their home country and then pursue MSc and PhD studies in Europe, Australia, Canada, or the United States. Faculty exchanges occurred as well, and in all these ways soil science ideas were discussed and circulated around the world.

6. Concluding remarks

The roots of soil science go deep into human history, but soil science as a distinct scientific discipline is quite young. The maturing of soil science as a distinct field first required scientific progress in related, supporting fields such as chemistry, physics, biology, geography, and

Fig. 4. Soil scientists participate in a field trip at the 1927 ISSS meeting, location unknown. Photo courtesy of USDA NRCS.

geology. This has lent both strengths and weaknesses to soil science as a discipline. Because it falls at the crossroads between many other disciplines, soil science is able to bridge some of the gaps between them. Soil scientists working in pedology may find they have more in common with geologists and geographers than with soil fertility and plant nutrition specialists, while many in soil fertility may relate more to crop scientists or botanists than to the pedologists. Other sub-disciplines in soil science have similar examples. This leads to divergent interests in what is supposed to be a single, united natural science field. In other words, the group of scientists that study soil is probably as diverse as the soil itself.

In many universities, soil science departments are being disbanded or combined with other academic departments and the number of soil science students is on the decline (Collins, 2008). When development projects require a soil investigation the studies are sometimes carried out rapidly by non-specialists using non-standard techniques and methods; an example of such development is the increasing use of remote sensing without field control and the overall decrease of field work in soil research (Hartemink et al., 2001).

At the academic level, soil science or agronomy departments at agricultural colleges have been the traditional place to teach soil science, but aspects of soils are now commonly taught in geology and geography departments at schools ranging from large public institutions to small liberal arts colleges (Hartemink et al., 2008; Brevik, 2009b), albeit not always well (Brevik, 2002). Division S05—Pedology of the SSSA voted at their 2003 business meeting to request a joint meeting with the Geological Society of America, a meeting that took place in November 2008. This was done because many of the soil scientists in S05 feel a closer connection with geology than with the plant scientists and agronomists they commonly meet with. Several symposia discussing the status and possible fate of soil science as a discipline have been held at recent meetings of SSSA and other soil science societies.

There are many hopeful signs as soil science heads into the future (Hartemink and McBratney, 2008). Renewed interest in sustainable food production, biofuels, erosion control, nutrient depletion issues, soils and human health, and environmental concerns have thrust soil science into the international spotlight again. At present, it is not

Fig. 5. Left to Right, Wim Sombroek (ISRIC), Frank Moorman (Utrecht University), The Netherlands, Marcello Camargo, Head of Soil Survey in Brazil, and Stan Buol, North Carolina State University, USA, in a soil pit during the Eighth International Soil Classification Workshop on Oxisols (ICOMOX) in Brazil, 1986. Photo courtesy of Stan Buol.

possible to staff all the soil science positions that various employers are trying to fill with qualified individuals. The future appears to have ample opportunities for individuals with strong soils training.

Acknowledgements

The authors thank Tom Sauer, USDA National Laboratory for Agriculture and the Environment, for discussion concerning soil history in the Bible.

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