Geoderma 226–227 (2014) 231–237

Contents lists available at ScienceDirect

Geoderma

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

Soil-forming factors and *Soil Taxonomy*

J.G. Bockheim [a,*], A.N. Gennadiyev [b], A.E. Hartemink [a], E.C. Brevik [c]

[a] University of Wisconsin, Department of Soil Science, 1525 Observatory Drive, Madison, WI 53706, USA
[b] Faculty of Geography, Moscow State University, Moscow, Russia
[c] Department of Natural Sciences, Dickinson State University, Dickinson, ND 58601, USA

ARTICLE INFO

Article history:
Received 4 November 2013
Received in revised form 18 February 2014
Accepted 23 February 2014
Available online 15 March 2014

Keywords:
Soil classification
Soil processes
Pedogenesis
Soil history

ABSTRACT

Here we analyze the past and present roles of the five soil-forming factors in USDA *Soil Taxonomy*. As opposed to the 7th Approximation of 1960, the factorial and genetic approach is clearly present in *Soil Taxonomy*. Soil climate is the most important factor in *Soil Taxonomy*. It is used at the highest level to define two of the 12 soil orders: Aridisols, the soils of the dry regions, and Gelisols, the permafrost-affected soils. Climate is also used to differentiate suborders in eight of the remaining orders. Parent material is used to fully define two orders: Histosols and Andisols, and partially to define the suborders in the Entisol order (Fluvents, Psamments). Only one group of organisms, the worms (Verm-), is used at the great-group and subgroup levels in several orders. Relief and time are not used in defining taxa in *Soil Taxonomy*. Three of the eight epipedons are defined on the basis of parent material (folistic, histic, melanic), two from human activities (anthropic and plaggen), and two from the interaction of climate and vegetation (mollic and umbric). Of the 19 subsurface horizons, 11 originate from the interaction of climate and parent material. There is an imbalance in the utilization of the soil-forming factors in *Soil Taxonomy*.

1. Introduction

Dokuchaev postulated in 1886 that the soil is always and everywhere a function of parent rock, the climate, the vegetation, the age of the terrain, and the terrain topography Dokuchaev, 1883. This was widely discussed between 1927 and 1935 at the first and third International Congresses of Soil Science (e.g., Crowther, 1930; Joel, 1927; Mitchell and Muir, 1935; Nikiforoff, 1935; Rice, 1927). These relationships seemed to get particular attention at the second International Congress of Soil Science held in Leningrad, Russia in 1930, with a section consisting of 22 papers focusing on soil genesis and the influence of the various soil forming factors (Prassolov and Vfleruky, 1930; Shaw, 1930). The factors were recognized as interacting and changing over time.

Jenny (1941) formalized the factors and did not see the factors as formers, creators or forces, but as state factors that define the state of the soil system (Hoosbeek and Bryant, 1994). It became clear that the soil-forming formula was not easily solved from a mathematical perspective (Kline, 1973; Phillips, 1998; Stephens, 1947), but the soil-forming factors have provided a strong framework for our thinking and approaches and have dominated soil genesis research since they were postulated. Overall, the soil-forming factor equation has become a popular concept in pedology (Bockheim et al., 2005).

The soil-forming factors have also influenced the development of soil classification systems, although differently in various countries. Krasilnikov et al. (2009) provided an excellent overview of over 25 national soil classification systems. Some of the systems rely on processes, but most systems use soil properties, morphology and features to group different soils. The diagnostics are mostly quantitative and based on a combination of horizons, soil properties and materials. Most soil classification systems group according to genesis of the soil.

Early soil classification systems in the USA by Marbut (1935) and Baldwin et al. (1938) took into account the factors of soil formation. However, there was widespread concern about their usefulness, and in 1949 the initial work on the development of *Soil Taxonomy* started. There were seven approximations before the first edition of *Soil Taxonomy* was launched in 1975 (Soil Survey Staff, 1975); the second edition was published in 1999 (Soil Survey Staff, 1999). *Soil Taxonomy* is a detailed categorical system that has defined quantitative boundary values for each unit at each level. The system was designed to be of assistance to the preparation of soil surveys which includes both the mapping and the interpretation of map units. The rationale for the system has been well explained (Forbes, 1986) but also criticized (e.g. Sombroek, 1985; Webster, 1960). *Soil Taxonomy* is a mature system that is widely used in the USA and dozens of other countries (Krasilnikov and Arnold, 2009). The soil-forming factors are largely hidden in *Soil Taxonomy*.

The objectives of this paper are to: (i) analyze how the soil-forming factors were used in USA soil classification systems and (ii) to unravel the presence and importance of soil-forming factors in *Soil Taxonomy*, and (iii) to suggest some implications for future classification systems. There is renewed interest in soil classification systems (Hempel et al.,

* Corresponding author.
E-mail address: bockheim@wisc.edu (J.G. Bockheim).

http://dx.doi.org/10.1016/j.geoderma.2014.02.016
0016-7061/

2013) and this paper aims to contribute to advance ideas and concepts for existing and new soil classification systems.

2. History of soil-forming factors in the USA soil classification systems (1900–1975)

The first attempts at soil classification in the USA were made in the late 19th and early 20th centuries. Detailed study of glacial and periglacial deposits and the progress in agronomy and technology played an essential role in the development of the first USA soil-classification systems. Buol et al. (2011) identified this first period as the "technical" period, which was a time of collecting data on physiography, geomorphology, and composition of sedimentary deposits.

The main goal of the first USA soil classification was to support soil surveys. These were started at the national level in 1899 and were based on Whitney's (1909) three-tiered system. The upper tier was geomorphological provinces (major soil provinces); soil series represented the second level, and soil types were the lower level. Weathering as part of soil formation was taken into account to distinguish different soils. Soil types were divided on the basis of particle-size distribution and were "characterized by unity from standpoint of agricultural production, adaptation to the same crops and requiring the same treatment" (Whitney, 1909). The criteria for distinguishing soil series were chiefly their textural properties and lithological features. One of the first soil series, the Miami, which appeared on USA maps in 1900, described soils as "representing sandy, or gravelly, or clay loams, having a surface horizon from light yellowish-cinnamon brown to black in color, well, moderately, or poorly drained and forming on morainal or alluvial deposits." Whitney (1909) recognized 260 soil series. In the course of new soil surveys, these broad combinations of different soils (similar to the Miami series) were converted into many independent series. At present there are approximately 23,000 soil series in the USA.

The necessity of systematizing the growing number of soil series was one of the reasons why Marbut (1928) and Baldwin et al. (1938) decided to use the Russian approach to soil classification. This approach was founded by V.V. Dokuchaev and further developed by Glinka (1927), Prassolov (1931), Ivanova (1956), and Gerasimov and Glazovskaya (1960). The Russian concepts of soil classification were transferred to the USA in the 1920–30s (Paton and Humphreys, 2007; Simonson, 1989). The USA soil classification systems of the 1930s and 1940s were derived from factor-genetic principles and concepts of zonality (zonal, intrazonal, and azonal soils were distinguished at higher levels). The Russian approach was used including landscape features, color, and folk names in naming soils at the second and third levels (Podzols, Chernozems, etc.) and introducing taxonomic units, such as great soil groups (comparable Russian genetic soil types).

The development of zonal or factorial ideology of soil classification reached its maximum in Russia in the 1940s to 1950s. Zonal genetic soil types were central to the system. World groups of classes of soil formation were distinguished according to the geographic belts, and soils were divided into automorphic, hydromorphic and semihydromorphic groups (Ivanova, 1956). The Russian soil-factorial concept was used in USA pedology through the 1950s. However, it was found that the USA soil series were incompatible with the system of great soil groups introduced from Russia. For example, Marbut (1928) found that it was not possible to distribute all of the soil series among the great-soil groups which had a definite conceptual factorial framework. There were no clear quantitative criteria for the great-soil groups. Therefore, as Cline (1963) and Smith (Forbes, 1986) acknowledged, there were two conceptually independent soil-classification systems in the USA during the 1920s to 1950s. One was based on the quantitative soil properties of soil series, while other relied on conceptual descriptions at higher taxonomic groups distinguished on the basis of genesis and factors of soil formation (Gennadiyev et al., 1995).

In the mid-1940s, C. Kellogg, director of the USDA Soil Conservation Service, set about to improve the definition of the great-soil groups and develop a set of quantitative criteria. Several working committees on great-soil groups were established. However, this was not successful because they did not find formal substantive parameters for distinguishing zonal soils from azonal and intrazonal soils. Gradually, these activities resulted in a fundamental revision of the basic principles for distinguishing taxa at higher taxonomic levels. An entirely new approach to soil classification began.

The "7th Approximation," which appeared in 1960 (Soil Survey Staff, 1960), was essentially a conceptual change to the factorial-genetic concepts that dominated USA soil classification during the 1920s to 1950s. The primary goal of the system was to quantify the requirements for orders, suborders, great soil groups, and subgroups and to allocate the many thousands of soil series and families among the higher taxa. The differentiae used among the orders were developed by generalizing soil properties that seemed to differ little in the type and effect of processes that tend to develop soil horizons (Soil Survey Staff, 1960). However, it was also recognized that the criteria for the orders tended to give a broad climatic grouping of soils.

The 7th Approximation was modified and published in 1975 as *Soil Taxonomy: a Basic System of Soil Classification for Making and Interpreting Soil Surveys*. There are distinct differences between *Soil Taxonomy* and the 7th Approximation in terms of the use of the factorial and genetic characteristics of soils (Gennadiyev and Gerasimova, 1980). There was a subtle return to the factorial-genetic approach of soil classification. In both the 7th Approximation and *Soil Taxonomy*, soil orders are distinguished mainly on the presence or absence of one or more diagnostic horizons in the soil profile. Whereas soil properties are emphasized in the systematic description of soil orders, their genetic nature is revealed only indirectly via the diagnostic horizons. Differences between the 7th Approximation and *Soil Taxonomy* are reflected in the sections that precede chapters with a detailed description of each soil order. Table 1 compares the views on soil orders in the 7th Approximation and *Soil Taxonomy* at the beginning of each of the ten soil orders. It suggests a return of *Soil Taxonomy* to the genetic approach, which contrasts with the approach in the 7th Approximation. The use of concepts associated with soil processes and factors was limited in the 7th Approximation, and soil genesis was on a "thoroughly hidden basis of order in the system" (Cline, 1963).

This trend becomes more obvious when we compare the suborders of soils in the two versions of the classification (Table 2). The number of soil-climatic (factorial) formative elements in the names of *Soil Taxonomy* suborders is greater than in the 7th Approximation. The proportion of "factorial" suborders also increases. All the suborders within the Alfisols are distinguished exclusively according to the soil climate. They include Alfisols with signs of gleying (Aqualfs), Alfisols with a low-temperature regime (Cryalfs), and Alfisols with moist (Udalfs), intermittently dry (Ustalfs), and dry summer/moist winter (Xeralfs) soil climates. This trend is even more distinct at the great soil group level. Whereas only 11 out of 105 great-soil groups (10%) had a soil-climatic formative element in their names in the 7th Approximation (cry-, therm-, ust-), 61 out of 230 great-soil groups (27%) had this feature in *Soil Taxonomy* (cry-, med-, torr-, trop-, ud-, ust-, xer-).

Soil temperature and moisture regimes in the 7th Approximation were only partially discussed and occupied less space in the chapter on "Horizons and properties of diagnostics significance" than the description of any of the diagnostic horizons. It can be concluded that a third-level role was ascribed to factorial criteria in the 7th Approximation.

In *Soil Taxonomy* more emphasis is given to soil temperature and moisture regimes and their role in soil-forming processes than in the 7th Approximation. In the 1975 section of *Soil Taxonomy* dealing with temperature and moisture regimes, it is mentioned that, owing to the absence of direct and reliable data on the regimes, use was made of some general climatic information over a 30-year period of standard observations, such as mean air temperature, annual precipitation, and evapotranspiration. The relation between the curves and subtending areas of graphic representations of the soil-moisture regimes made it

Table 1
Description of soil orders in the 7th Approximation, *Soil Taxonomy* and approximate equivalent in the Revised Classification of Baldwin et al. (1938).

Order	Approximate equivalent in Baldwin et al (1938)	7th Approximation (1960)	Soil Taxonomy (1975)
Spodosols	Podzols, Brown podzolic soils, and groundwater Podzolc	Spodic horizon	Appearance of process of humus-transport with amorphous R_2O_3-accumulation in the spodic horizon and frequently in the albic horizon
Entisols	Azonal soils, and some low humic gley soils	Plaggen horizon, possibly ochric, anthropic, albic, histic, agric, buried horizons	Lack of manifestation of complexes of soil processes. Predominance of mineral material and absence of distinct soil-genetic horizons
Oxisols	Laterite soils, Latosols	Oxic horizon, possible umbric, ochric, histic epipedons. Possibly argillic and plinthic horizons near the surface	Extremely severe weathering of all minerals, except quartz, to kaolinite and R_2O_3. Very weak activity of clay, loamy or clayey texture
Alfisols	Gray–brown podzolic soils, gray wooded soils, noncalcic brown soils, degraded chernozems, and associated Planosols and Half-bog soils	Usually complex soils. No mollic, oxic, spodic horizons. There are argillic and nitric horizons. Saturation of lower horizons exceeding 35%.	Appearance of clay transport processes without strong leaching of bases and without formation of a mollic horizon. Ordinary combination of ochric or umbric horizons with an argillic horizon.
Ultisols	Red–yellow podzolic soils, Reddish–brown lateritic soils of the US, and associated Planosols and Half-bog soils	No oxic and nitric horizons. Argillic horizon saturated less than 35%. Possible various epipedons, fragipans or plinthite.	Signs of clay movement accompanied by strong removal of bases/Argillic horizon, unsaturation, and mean annual soil temperature above 8u °C.
Mollisols	Chestnut, Chernozem, Brunizem (prairie), Rendzinas, some Brown, Brown forest, and associated Solonetz and Humic Gley soils	Mollic horizon, soils with an oxic horizon and several other properties are excluded	Mollic horizon, predominance of Ca in the soil adsorption complex, predominance of clay minerals with medium and high exchange capacity
Inceptisols	Ando, Sol Brun Acide, some Brown Forest, Low-Humic Gley and Humic Gley soils	Cambic horizon	Soils of humid regions that have altered horizons that have lost bases or Fe & Al but retain some weatherable minerals; they do not have an illuvial horizon enriched with silicate clays or Fe–Al–SOC complexes
Gelisols	Tundra soils	[not recognized]	Included in Pergelic subgroups of Entisols, Histosols, & Inceptisols; have mean annual soil temperature lower than 0 °C
Vertisols	Grumusols	Slickensides, self-mulching	Clayey soils with deep wide cracks and high bulk densities
Aridisols	Desert, Reddish Desert, Sierozem, Solonchack, some Brown & Reddish Brown soils, & associated Solonetz	Argillic, calcic, cambic, duric, natric, or salic horizon	Soils with low soil water availability; soil horizons reflect relict or current soil-forming processes; pedogenic horizons are enriched in silicate clays, carbonates, or Si
Andisols	Ando soils	Included in Inceptisols	Included in Andepts suborder; more or less freely drained; have low bulk density & appreciable amounts of allophane
Histosols	Bog soils	Histic epipedon	Dominantly organic soil materials; generally saturated or nearly saturated for most of the year; classification provisional

possible to estimate a soil moisture regime. The temperature of the soils and the factors determining them were discussed in detail and it was stated that "…… The results of observations of the soil-temperature regime in various geographic locations and in genetically and texturally different soils showed that…….. The temperature variations with latitude, with snow cover, etc., were discussed and it was found that…… Ten soil-temperature regime-classes were distinguished, which were used mainly at a low (family) taxonomic level" (Soil Survey Staff, 1975).

3. Soil-forming factors in *Soil Taxonomy* (1975–present)

During the period 1975 to 1999, two orders, the Gelisols and the Andisols, were added to *Soil Taxonomy*. The number of suborders was increased from 47 to 64, the number of great groups from 185 to 325, the number of subgroups from 970 to >2,400, and the number of soil series from ~10,500 to >19,000 (Table 3).

During this period, the folistic and melanic epipedons were added in response to refining the Histosol and Andisol orders. Three subsurface horizons (glossic, kandic, and ortstein) were added, as well as additional soil characteristics and materials, e.g., gelic (Gelisols = new order), andic (Andisols = new order).

3.1. Climate

Climate is the primary factor used to key out two orders in *Soil Taxonomy*: Aridisols (dry soils) and Gelisols (very cold soils). It is also used to differentiate suborders in eight other orders: Alfisols, Andisols, Inceptisols, Mollisols, Oxisols, Spodosols, Ultisols, and Vertisols. All of these suborders have an Aqu- (aquic) subgroup for soils with hydric conditions (Table 4). A single suborder, the Aquents, is climate-based in the Entisol order. Six of the eight orders (except Oxisols and Spodosols) have Ud- (udic), Ust- (ustic), and Xer- (xeric) suborders reflecting the cumulative days of dryness and in the case of Xer- suborders seasonal distribution of moisture, i.e., soil climate. A Cry- (cryic) suborder is present in six of the eight orders (except Ultisols and Oxisols), and a Gel- (gelic) suborder is present in Andisols, Inceptisols, Mollisols, and Spodosols. Torr- (torric) suborders representing hot and dry conditions are used in Vertisols, Andisols, and Oxisols. A Per- (peric) suborder representing continually moist conditions occurs in the Oxisol order. Soil temperature is recognized at the great-group level in Entisols (Cry-, Gel-) and at the family level in all soil orders.

Several of the eight orders listed in Table 4 recognize properties other than climate at the suborder level, including Hum- (humic) for illuvial humus (Ultisols and Spodosols), Vitr- (vitric) for vitreous materials (Andisols), Anthr- (anthric) for soils affected markedly by humans (Inceptisols), Alb- (albic) for a bright E horizon, Rend- (rendzina) for soils derived from calcareous materials (Mollisols), and Orth- (orthic) for other soils in the Spodosols.

The use of climate, or more precisely soil climate, to differentiate soils at the high levels of order and suborder in *Soil Taxonomy* contrasts with Dokuchaev's ideas that all of the soil-forming factors are of equal importance in soil formation. In support of climate as a key criterion in

Table 2
The soil-climatic (factorial) formative elements in the suborder names of the 7th Approximation and Soil Taxonomy.

7th Approximation	Soil Taxonomy (1975)
Aqu—excessive wetting	Aqu-
Alt—high-mountain climate	Ud-
Ud—humid climate	Ust—intermediate between udic and aridic
Ust—dry climate	Bor—boreal
	Torr—dry with heavy showers
	Trop—tropical
	Xer—moist cool winters, dry hot summers

Table 3
Changes in taxonomic categories and diagnostic horizon from 1960 to 2010.

Category	1960	1975	1999	2010
Orders	10	10	12	12
Suborders	33	47	64	65
Great groups	99	185	325	344
Subgroups	246	970	>2400	~1800
Series	?	10,500	>19,000	~23,000
Epipedons	0	6	8	8
Subsurface horizons	0	17	19	19
Properties/characteristics of mineral soils	0	17	19	20

Soil Taxonomy, Wilding (1994) interprets Jenny's work as indicating that climate is the primary driver acting over time, with parent material, organisms, and topography as secondary controls. The use of climate at the highest levels may be a relic of the zonal approach used prior to 1975, where zonal soils were controlled primarily by climate whereas intrazonal and azonal soils were controlled by local factors such as parent material and relief. According to Guy Smith, the ideas of Baldwin et al. (1938) were influential in the development of *Soil Taxonomy* (Forbes, 1986).

A second example of the emphasis of soil climate in *Soil Taxonomy* is the importance given to soil-temperature regimes which are linked to geographic crop adaption. The mean annual soil temperature (MAST) is used to determine where specific agricultural crops or forest species are best adapted in the USA. Citrus crops are grown in warmer parts of the thermic regime (MAST 15–22 °C and in a hyperthermic temperature regime (MAST >22 °C; cotton will grow in a hyperthermic soil temperature regime but generally not in a mesic (MAST <7 °C) or colder regime; and grain corn grows well in a thermic soil temperature regime but not as well is in a frigid regime. (However, genetics are moving the boundaries.) This could be viewed as linking of the organisms and climate factors of soil formation.

3.2. Parent material

The second most important factor in distinguishing among taxa in *Soil Taxonomy* is parent material, and it is used to identify three soil orders: Histosols (derived from organic materials), Andisols (soils derived from glass, pumice, and short-range minerals), and partially for Entisol suborders derived from fluvial or sandy materials (e.g., Fluvents and Psamments). Parent material is also important for Vertisols in that the cracking, wedge-shaped peds, and slickensides required for this order generally require materials with 30% or more shrink-swell clays. There is a common belief that most soils with a spodic horizon are in sandy or sandy-skeletal particle-size classes. However, data contained in the NRCS SSURGO database suggest that 41% of the soils are sandy and 40% are in loamy classes (includes coarse-loamy, fine-loamy, loamy, and loamy-skeletal).

Parent material is also used at the subgroup level, e.g., Andic, Arenic, Grossarenic, Lamellic, Lithic, Paralithic, and Vitrandic, for most of the soil orders. For example, Shaw et al. (2004) showed the importance of parent material and subsequent illuviation on distribution and genesis of Ultisol subgroups (Psammentic, Grossarenic, Arenic, and Typic) in the southeastern USA. Soils with argillic horizons developed in thick loamy or clayey sediments often classify in Pale- great groups. However, as discussed below, time is also an important factor influencing these soils. Properties of the parent material are recognized at the family level for mineral soils as particle-size and mineralogy classes. However, these classes may change also as a result of soil formation.

3.3. Other factors

Relief is recognized in *Soil Taxonomy* at the finest level, the soil phase, primarily for mapping purposes. However, relief plays a key role in soil pedogenesis via solute movement, changes in moisture regime (climate) and parent materials.

Organisms are recognized in *Soil Taxonomy* on the basis of only one group of organisms, the worms, i.e., Verm- (vermic) at the great-group (e.g., Vermaqualfs, Vermaquepts, Vermudolls, and Vermustolls) and at the subgroup level (e.g., Vermic Hapludolls). Human activities have been recognized for a long time as a soil-forming factor (Yaalon and Yaron, 1966). *Soil Taxonomy* has been considering a new soil order, the Anthrosols, for more than three decades (Capra et al., 2013). Currently, the human effect is recognized in Inceptisols at the suborder level (Anthrepts), at the great-group level in Inceptisols and Aridisols (Plagganthrepts, Anthracambids), and at the subgroup level (Anthraquic in Alfisol, Andisol, Entisol, Inceptisol, Mollisol, and Ultisol great groups; Anthropic in Entisol and Ultisol great groups; and Plagganthropic in Entisol and Spodosol great groups). No soil series in these taxa have been identified to date.

Finally, time is not recognized directly in *Soil Taxonomy* but it plays a key role in soil genesis. The Pale- great group in Alfisols, Aridisols, Mollisols, and Ultisols is in recognition of thick argillic horizons partly due to the age of the soil and partly to climate.

3.4. Soil-forming factors and diagnostic horizons

In Table 5 we review the relative importance of the soil-forming factors in the development of diagnostic horizons and diagnostic soil characteristics, particularly in the USA. The rankings are supported by key references. We recognize that pedologists working in the USA or other areas of the world may rank the factors differently.

Of the eight epipedons, parent material is important for the folistic and histic (organic materials), and melanic (andic soil properties) epipedons (Table 5). Humans play a dominant role in the anthropic and plaggen epipedons; a combination of climate and organisms (vegetation) is important for the mollic and umbric epipedons; and climate and relief are important for the development of umbric horizons. All of these surface horizons, with the exception of the ochric epipedon, require ca. 10^1–10^2 yr to form (Brevik, 2013).

A combination of factors that always includes climate and parent material are important in the formation of 11 of the 19 diagnostic subsurface horizons (Table 5). Parent material plays the major role in defining 19 of the 39 diagnostic soil characteristics. Climate is predominant in two, and a combination of factors is important for the remaining soil characteristics.

3.5. Relative importance of soil-forming factors in Soil Taxonomy

When expressed on a percent basis, climate, parent material, and time each are employed in distinguishing 17% of the soil orders (Fig. 1). Climate accounts for 63% of the suborders, parent material 19%, and organisms (humans) 1%. Parent material, organisms, and humans each account for 25% of the epipedons. Parent material is used to the greatest

Table 4
Prefixes used in suborders of eight orders in Soil Taxonomy.

Suborder prefix[a]							
Alfisols	Andisols	Inceptisols	Mollisols	Oxisols	Spodosols	Ultisols	Vertisols
Aqu- Cry- Ust- Xer- Ud-	Aqu- Gel- Cry- Torr- Xer- **Vitr-** Ust- Ud-	Aqu- **Anthr-** Gel- Cry- Ust- Xer- Ud-	**Alb-** Aqu- **Rend-** Gel- Cry- Xer- Ust- Ud-	Aqu- Torr- Ust- Per- Ud-	Aqu- Gel- Cry- **Hum-** **Orth-**	Aqu- **Hum-** Ud- Ust- Xer-	Aqu- Cry- Xer- Torr- Ust- Ud-

[a] Bold-face prefixes are not climatically related.

Table 5
Role of soil-forming factors in diagnostic horizons.[a]

Horizon	Climate	Organisms	Relief	Parent material	Time	Humans	Reference
Epipedons							
Anthropic						X	Soil Survey Staff (2010)
Folistic		X	x				Fox and Tarnocai (2011)
Histic		x	x	X			Kroetsch et al. (2011)
Melanic				X			Takahashi et al. (1994)
Mollic	x	X		x			Liu et al. (2012)
Ochric					X		Bravo et al. (2007)
Plaggen						X	Soil Survey Staff (2010)
Umbric	X		x	x			Senesi and Certini (2005)
Subsurface							
Agric						X	Soil Survey Staff (2010)
Albic			x	X			Sauer et al. (2009)
Argillic	x		x	X	x		Bockheim and Hartemink (2013a)
Calcic	x			X	x		Shanker and Achyuthan (2007)
Cambic					X		Ciolkosz and Waltman (1995)
Duripan	x			X	x		Chadwick et al. (1987)
Fragipan	x	x		X			Bockheim and Hartemink (2013b)
Glossic	x	x		X			Bockheim (2012a)
Gypsic	x		x	X			Cantón et al. (2003)
Kandic	x			X	x		Bockheim and Hartemink (2013a)
Natric	x		x	X			Bockheim and Hartemink (2013a)
Ortstein	x		x	X			Bockheim (2011)
Oxic	x	x			x		Ferreira et al. (2010)
Petrocalcic	x			x	x		Brock and Buck (2009)
Petrogypsic	x			X	x		Herrero (2004)
Placic	x		x	x			Bockheim (2011)
Salic	x		X	x			Bockheim and Hartemink (2013c)
Sombric	X	x					Bockheim (2012b)
Spodic	X	x	x				Schaetzl and Isard (1996)
Diagnostic soil characteristics							
Mineral soils							
Abrupt textural change				X			Pazos (1989)
Albic materials			x	X			Sauer et al. (2009)
Andic soil properties				X			Parfitt and Kimble (1989)
Anhydrous conditions	X						Soil Survey Staff (2010)
Coeff. of linear extensibility				X			Soil Survey Staff (2010)
Durinodes	x			X	x		Chadwick et al. (1987)
Fragic soil properties	x	x		X			Bockheim and Hartemink (2013b)
Free carbonates	x			X			Soil Survey Staff (2010)
Identifiable secondary carbonates	X			x			Soil Survey Staff (2010)
Interfingering of albic materials	x	x		x			Pazos (1989)
Lamellae			x	X			Bockheim and Hartemink (2013d)
Linear extensibility				X			Soil Survey Staff (2010)
Lithologic discontinuity				X			Soil Survey Staff (2010)
n value				X			Soil Survey Staff (2010)
Petroferric contact	x			X	x		Soil Survey Staff (2010)
Plinthite	x		x	X			Aide et al. (2004)
Resistant minerals	x			X	x		Soil Survey Staff (2010)
Slickensides	x			X			Khitrov (2012)
Spodic materials	x	x			x		Schaetzl and Isard (1996)
Volcanic glass				X			Parfitt and Kimble (1989)
Weatherable minerals	x			X	x		Soil Survey Staff (2010)
Organic soils							
Fibric soil materials			x	X			Kroetsch et al. (2011)
Hemic soil materials			x	X			Kroetsch et al. (2011)
Sapric soil materials			x	X			Kroetsch et al. (2011)
Humilluvic materials			x	X			Kroetsch et al. (2011)
Limnic materials			x	X			Kroetsch et al. (2011)
Mineral and organic soils							
Aquic conditions			X	x			Soil Survey Staff (2010)
Cryoturbation	X						Soil Survey Staff (2010)
Densic contact				X			Soil Survey Staff (2010)
Gelic materials	X						Soil Survey Staff (2010)
Glacic layer	X						Soil Survey Staff (2010)
Lithic contact				X			Soil Survey Staff (2010)
Paralithic contact				X			Soil Survey Staff (2010)
Paralithic materials				X			Soil Survey Staff (2010)
Permafrost	X						Soil Survey Staff (2010)
Soil moisture regime	X						Soil Survey Staff (2010)
Soil temperature regime	X						Soil Survey Staff (2010)
Sulfidic materials			x	X			Soil Survey Staff (2010)
Sulfuric materials			x	X			Soil Survey Staff (2010)

[a] Large-case X = most important; small-case x = less important.

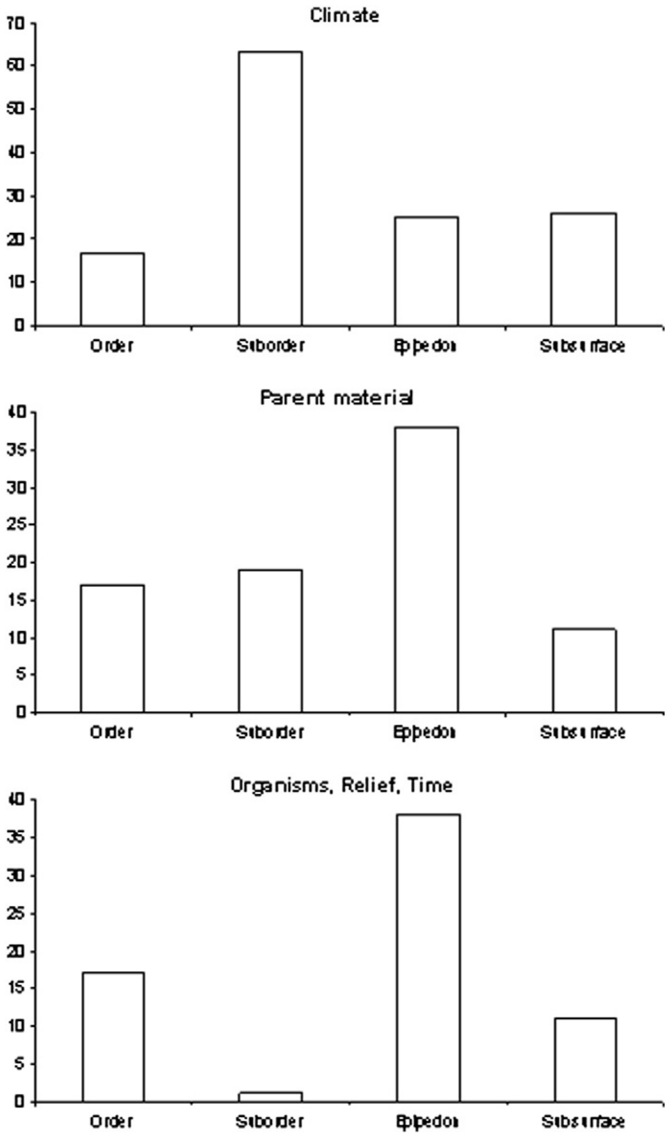

Fig. 1. Proportion (percent) of orders, suborders, epipedons, and diagnostic subsurface horizons affected primarily by climate, parent material, or the other soil-forming factors.

extent in defining diagnostic subsurface horizons (58%), followed by a mixture of soil-forming factors (21%). Parent material accounted for 85% of the diagnostic soil characteristics.

4. Implications for current and future classification systems

In *Soil Taxonomy* parent material appears to have the greatest importance in the definition of soil taxa and the diagnostic horizons and materials upon which they are based. Climate and organisms (macro-vegetation) play important roles. Time plays a subsidiary role in the identified of early stages of soil formation (Entisols and Inceptisol orders, ochric epipedon, and cambic subsurface horizon). Relief plays a minimal role but is employed in distinguishing among soil phases, i.e., soil catenas. In our opinion, these factors and their impact do not constitute a bias in ST. Numerical approaches as have proposed for the Universal Soil Classification System can further unravel the relationships between the soil forming factors and ST. According to Powell et al. (1992), numerical approaches have the advantage of dealing with a large number of soil properties simultaneously and would not require a ranking of properties to be identified at different levels in the taxonomic scheme. In any event, it seems that a more even treatment of the soil-forming factors within any new classification system would be an improvement over the current situation where a subset of the factors dominates *Soil Taxonomy*.

5. Conclusions

Here we have analysed how the soil-forming factors were used in US soil classification systems and in particular in *Soil Taxonomy* (1975, 1999). From this analysis the following can be concluded:

- The soil-forming factors were used in the first soil classification systems in the US following the genetic approach developed in Russia. It was soon discovered that a new approach was needed to allocate the many thousands of soil series and families among the higher taxa. This led to the development of the 7th Approximation (1960) and *Soil Taxonomy* (1975, 1999).
- The 7th Approximation was developed to break-away from the soil-forming factors.
- In the 1975 *Soil Taxonomy* system it appears that the soil forming factors resurfaced. Here we have shown that in the current system, parent material and climate are used as distinguishing criteria in 47 and 34 (out of 67) epipedons, subsurface horizons, diagnostic soil materials, and organic and mineral soils.

In conclusion, *Soil Taxonomy* uses the soil forming factors at all levels, including at high levels in the system.

Acknowledgments

The authors appreciate the constructive comments of the two reviewers of this manuscript.

References

Aide, M., Pavich, Z., Lilly, M.E., Thornton, R., Kingery, W., 2004. Plinthite formation in the coastal plain region of Mississippi. Soil Sci. 169, 613–623.

Baldwin, M., Kellogg, C.E., Thorp, J., 1938. Soil classification. Soils and Men. U.S. Dep. Agric. Yearbook. U.S. Govt. Print. Office, Washington, DC, pp. 979–1001.

Bockheim, J.G., 2011. Distribution and genesis of ortstein and placic horizons in soils of the USA: a review. Soil Sci. Soc. Am. J. 75, 994–1005.

Bockheim, J.G., 2012a. Origin of glossic horizons in Cryalfs of the eastern Rocky Mountains, USA. Geoderma 187–188, 1–7.

Bockheim, J.G., 2012b. Revisiting the definitions of the sombric horizon in Soil Taxonomy and the World Reference Base for Soil Resources. Geoderma 170, 127–135.

Bockheim, J.G., Hartemink, A.E., 2013a. Distribution and classification of soils with clay-enriched horizons in the USA. Geoderma 209–210, 153–160.

Bockheim, J.G., Hartemink, A.E., 2013b. Soils with fragipans in the USA. Catena 104, 233–242.

Bockheim, J.G., Hartemink, A.E., 2013c. Salic horizons in soils of the USA. Pedosphere 23 (5), 600–608.

Bockheim, J.G., Hartemink, A.E., 2013d. Classification and distribution of soils with lamellae in the USA. Geoderma 206, 92–100.

Bockheim, J.G., Gennadiyev, A.N., Hammer, R.D., Tandarich, J.P., 2005. Historical development of key concepts in pedology. Geoderma 124, 23–36.

Bravo, O., Blanco, M.C., Amiotti, N., 2007. Control factors in the segregation of Mollisols and Aridisols of the semiarid–arid transition of Argentina. Catena 70, 220–228.

Brevik, E.C., 2013. Forty years of soil formation in a south Georgia, USA borrow pit. Soil Horiz. 54 (1). http://dx.doi.org/10.2136/sh12-08-0025.

Brock, A.L., Buck, B.J., 2009. Polygenetic development of the Mormon Mesa, NV petrocalcic horizons: geomorphic and paleoenvironmental interpretations. Catena 77, 65–75.

Buol, S.W., Southard, R.J., Graham, R.J., McDaniel, P.A., 2011. Soil Genesis and Classification, 6th ed. Wiley-Blackwell, NY.

Cantón, Y., Solé-Benet, A., Lázaro, R., 2003. Soil–geomorphology relations in gypsiferous materials of the Tabernas Desert (Almeri´a, SE Spain). Geoderma 115, 193–222.

Capra, G.F., Vacca, S., Cabula, E., Grilli, E., Buondonno, A., 2013. Through the decades: taxonomic proposals for human-altered and human-transported soil classification. Soil Horiz. 54. http://dx.doi.org/10.2136/sh12-12-0033.

Chadwick, O.A., Hendricks, D.M., Nettleton, W.D., 1987. Silica in duric soils: I. A depositional model. Soil Sci. Soc. Am. J. 51, 975–982.

Ciolkosz, E.J., Waltman, W.J., 1995. Cambic horizons in Pennsylvania soils. Agron. Ser. 133, 1–26.

Cline, M.G., 1963. Logic of new system of the soil classification. Soil Sci. 96, 17–22.

Crowther, E.M., 1930. The relationship of climatic and geological factors to the composition of soil clay and the distribution of soil types. Proc. R. Soc. B 107, 1–30.

Dokuchaev, V.V., 1883. Russian Chernozem. Selected works of V.V. Dokuchaev, vol. I. Israel Program for Scientific Translations, Jerusalem (translated in 1967).

Ferreira, C.A., Silva, A.C., Torrado, P.V., Rocha, W.W., 2010. Genesis and classification of Oxisols in a highland toposequence of the upper Jequituinhonha valley (MG). Rev. Bras. Ciênc. Solo 34, 195–209.
Forbes, T.R. (Ed.), 1986. The Guy Smith interviews: rationale for concepts in Soil Taxonomy. SMSS Technical Monograph no. 11. USDA Soil Conservation Service, Washington DC.
Fox, C.A., Tarnocai, C., 2011. Organic soils of Canada: Part 2. Upland Organic soils. Can. J. Soil Sci. 91, 823–842.
Gennadiyev, A.N., Gerasimova, M.I., 1980. Some present soil classification trends in the United States. Soviet Soil Sci. 12 (5), 559–566.
Gennadiyev, A.N., Gerasimova, M.I., Arnold, R.W., 1995. Evolving approaches to soil classification in Russia and the United States of America. Soil Surv. Horiz. 36, 104–111.
Gerasimov, I.P., Glazovskaya, M.A., 1960. Fundamentals of Soil Science and Soil Geography, Moscow (490 pp._In Russian).
Glinka, K.D., 1927. The Great Soil Groups of the World and Their Development. Transl. from German by C.F. Marbut Edwards, Ann Arbor, MI.
Hempel, J., Micheli, E., Owens, P., McBratney, A., 2013. Universal Soil Classification System Report from the International Union of Soil Sciences Working Group. Soil Horiz. http://dx.doi.org/10.2136/sh12-12-0035.
Herrero, J., 2004. Revisiting the definitions of gypsic and petrogypsic horizons in Soil Taxonomy and World Reference Base for Soil Resources. Geoderma 120, 1–5.
Hoosbeek, M.R., Bryant, R.B., 1994. Towards the quantitative modeling of pedogenesis—a review. Geoderma 55, 183–210.
Ivanova, Y.N., 1956. An attempt at a general classification of soils. Pochvovedenie 6, 82–103.
Jenny, H., 1941. Factors of soil formation. A System of Quantitative PedologyMcGraw-Hill, New York.
Joel, A.H., 1927. Predominant Saskatchewan soil profiles correlated with soil development factors in northern latitudes. Proceedings and Papers of the First International Congress of Soil Science, Washington, DC, USA, June 13-22, 1927, vol. V, pp. 200–222.
Khitrov, N.B., 2012. Vertigenesis in soils of the central chernozem region of Russia. Eurasian Soil Sci. 9, 834–842.
Kline, J.R., 1973. Mathematical simulation of soil-plant relationships and soil genesis. Soil Sci. 115, 240–249.
Krasilnikov, P., Arnold, R., 2009. The United States Soil Taxonomy. In: Krasilnikov, P., Ibanez, J. J., Arnold, R.W., Shoba, S. (Eds.), Soil Terminology, Correlation and Classification. Earthscan, London.
Krasilnikov, P., Ibanez, J.J., Arnold, R.W., Shoba, S., 2009. Soil Terminology, Correlation and Classification. Earthscan, London.
Kroetsch, D.J., Geng, X., Chang, S.X., Saurette, D.D., 2011. Organic soils of Canada: Part 1. Wetland organic soils. Can. J. Soil Sci. 91, 807–822.
Liu, X., Burras, C.L., Kravchenko, Y.S., Duran, A., Huffman, T., Morras, H., Studdert, G., Zhang, X., Cruse, R.M., Yuan, X., 2012. Overview of Mollisols in the world: distribution, land use and management. Can. J. Soil Sci. 92, 383–402.
Marbut, C.F., 1928. A scheme for soil classification. 1st Int. Congr. Soil. Sci. Com. 5. Proc. and Papers, 4, pp. 1–31.
Marbut, C.F., 1935. Soils of the United States. In: Baker, O.E. (Ed.), Atlas of American Agriculture. USDA Bureau of Chemistry and Soils, U.S. Gov. Print. Office, Washington DC, pp. 1–98.
Mitchell, R.L., Muir, A., 1935. The brown earth in Scotland: Its relation to continental types. Transactions of the Third International Congress of Soil Science, Oxford, England, July 30-August 7, 1935, pp. 322–323.
Nikiforoff, C.C., 1935. Weathering and soil-formation. Transactions of the Third International Congress of Soil Science, Oxford, England, July 30-August 7, 1935, pp. 324–326.
Parfitt, R.L., Kimble, J.M., 1989. Conditions for formation of allophane in soils. Soil Sci. Soc. Am. J. 53, 971–977.
Paton, T.R., Humphreys, G.S., 2007. A critical evaluation of the zonalistic foundations of soil science in the United States. Part I: The beginning of soil classification. Geoderma 139 (3–4), 257–267.
Pazos, M.S., 1989. Génesis y clasificación de los Argiudoles con horizonte A2 incipente de la región pampeana. Cien. Suelo 7 (1–2), 87–95.
Phillips, J.D., 1998. On the relations between complex systems and the factorial model of soil formation (with discussion). Geoderma 86, 1–21.
Powell, B., McBratney, A.B., MacLeod, D.A., 1992. Fuzzy classification of soil profiles and horizons from the Lockyer Valley, Queensland, Australia. Geoderma 52, 173–197.
Prassolov, L.I., 1931. A unified nomenclature and the fundamentals of genetical soil classification. Pochvovedenie 8 (in Russian).
Prassolov, L.J., Vfleruky, D.G. (Eds.), 1930. Commission V: classification, geography and cartography of soils. Proceedings and Papers of the Second International Congress of Soil Science, Leningrad—Moscow, USSR July 20-31, 1930.
Rice, T.D., 1927. Should the various categories in a scheme of soil classification be based on soil characteristics or on the forces and conditions which have produced them? Proceedings and Papers of the First International Congress of Soil Science, Washington, DC, USA, June 13-22, 1927, vol. V, pp. 108–112.
Sauer, D., Schűlli-Maurer, I., Sperstad, R., Sørensen, R., Stahr, K., 2009. Albeluvisol development with time in loamy marine sediments of southern Norway. Quat. Int. 209, 31–43.
Schaetzl, R.J., Isard, S.A., 1996. Regional-scale relationships between climate and strength of podzolization in the Great Lakes region, North America. Catena 28, 47–60.
Senesi, G., Certini, G., 2005. The umbric epipedon in the N Appenines, Italy—an example from the Vallombrosa Forest. J. Plant Nutr. Soil Sci. 168, 392–398.
Shanker, N., Achyuthan, H., 2007. Genesis of calcic and petrocalcic horizons from Coimbatore, Tamil Nadu: micromorphology and geochemical studies. Quat. Int. 175, 140–154.
Shaw, C.F., 1930. A soil formation formula. Proceedings of the Second International Congress of Soil Science. USSR, Leningrad, pp. 7–14.
Shaw, J.N., West, L.T., Bosch, D.D., Truman, C.C., Leigh, D.S., 2004. Parent material influence on soil distribution and genesis in a Paleudult and Kandiudult complex, southeastern USA. Catena 57, 157–174.
Simonson, R.W., 1889. Historical highlights of soil survey and soil classification with emphasis on the United States, 1899–1970. International Soil Reference and Information Centre Technical Paper 18. (ISRIC, Wageningen, The Netherlands. 83 pp.).
Soil Survey Staff, 1960. Soil Classification, a Comprehensive System, 7th Approximation. U.S. Govt. Print. Office, Washington, DC.
Soil Survey Staff, 1975. Soil Taxonomy. A Basic System of Soil Classification for Making and Interpreting Soil Surveys. Agricultural Handbook, 436 (Washington DC).
Soil Survey Staff, 1999. Soil Taxonomy, 2nd edition. USDA National Resources Conservation Services, Washington DC.
Soil Survey Staff, 2010. Keys to Soil Taxonomy, 11th ed. USDA, National Resources Conservation Service, National Soil Survey Center, Lincoln, NE.
Sombroek, W.G., 1985. Towards an international reference base for soil classification. ISRIC Working Paper. ISRIC, Wageningen.
Stephens, C.G., 1947. Functional synthesis in pedogenesis. Trans. R. Soc. S. Aust. 7, 168–181.
Takahashi, T., Dahlgren, R.A., Sase, T., 1994. Formation of melanic epipedons under forest vegetation in the xeric moisture regime of northern California. Soil Sci. Plant Nutr. 40, 617–628.
Webster, R., 1960. Fundamental objections to the 7th Approximation. J. Soil Sci. 19, 354–366.
Whitney, M., 1909. Soils of the United States. USDA Bur. of Soils Bull., 55. U.S. Gov. Print. Office, Washington, DC.
Wilding, L.P., 1994. Factors of soil formation: contributions to pedology. Factors of soil formation: a fiftieth anniversary retrospective. SSSA Special Publication No. 33. SSSA, Madison, WI, pp. 15–30.
Yaalon, D.H., Yaron, B., 1966. Framework for man-made soil changes—an outline of metapedogenesis. Soil Sci. 102, 272–277.