Soil Classification*

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Abstract: Soil classification is a long-debated issue. Despite the accumulation of empirical data and appearance of modern computer technologies, soil classification problems remain unresolved and relevant for discussion. The main problem is the creation of a universal soil classification system. The causes of soil classification problems are analyzed and a solution based on contemporary theories of classification and the general systems theory (open system) approach is presented. I discuss the purposes and the current state of soil classification, as well as unresolved issues such as: what definition of soils should be the basis for a universal soil classification system, should soil classification systems be genetic or morphological, how to make them evolutionary, and others. The common features of officially recognized national and international soil classification systems and some underdeveloped ones are reviewed, as well as those in which they differ from each other. It is shown that the shortcomings of soil classification systems are largely related to neglecting the essential character of soils, namely, its dual systemic nature to be not only an independent natural body (that is, a system), but also the result of interaction and interrelation of soil-forming factors (that is, an element of the system), ignoring the rules for logical division of concepts and replacing the differentiating criteria with diagnostic criteria. The theoretical basis and advantages of the "soil-landscape classification system" being developed by the author are outlined. To solve soil classification problems, an outside perspective is needed, that is, the use of classiology and the systems approach.

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1.0. Introduction

Soil classification is a long-debated issue. The first scientific version of the soil classification system developed by Vasily Dokuchaev was published in 1886. In 1962, Muir assessed the situation with regard to soil classification as follows: "soil classification is still in an elementary stage of development." Much time has passed since then, but one cannot say that the situation has changed fundamentally. Despite the fact that during this time a lot of empirical data accumulated and modern computer technologies appeared and were used, the transition to a qualitatively new stage in the development of soil classification did not happen. Soil classification problems remain the same; they are still unresolved and relevant for discussion. The main problem is the creation of a universal (that is, basic, unified, global, generally accepted) soil classification system (soil classification system hereinafter referred to as SCS). This was confirmed in 2010 at the 19th World Congress of Soil Science, where, by decision of the Council of the International Union of Soil Science (IUSS), a Working Group on Universal Soil Classification was officially established (https://www.iuss.org/index.php?article_id=525). However, a universal SCS has not yet been created.

In the present text I use contemporary theories of classification (classiology[1]) (Frické 2016; Hjørland 2017; Mill 1882; Parrochia 2017; Parrochia and Neuville 2013; Pokrovsky 2014; Rozhkov 2012; Rozova 1986; Subbotin 2001) and the general systems theory (open system) approach (or, if shortened, the systems approach[2]), developed by Bertalanffy (1968). Examples of attempts to apply the systems approach in natural science can be found in the works of Chorley and Kennedy (1971), Juma (1999), Karpachevsky (1981, 240-245), Phillips (1998), and Solntsev (1981). Such an interdisciplinary approach allowed us to see the shortcomings of the existing SCSs from an outside perspective and to propose the creation of a new, fundamentally different SCS, namely the "soil-landscape classification system" (hereinafter referred to as SLCS).

Officially recognized national and international and some so-called "underdeveloped" SCSs (or schemes) (Krasilnikov and Arnold 2009, 319) proposed by various soil scientists, which are interesting from a scientific point of view are discussed here. However, I do not cover the history of the development of these systems, since its detailed description can be found in many works, including the work of Krasilnikov and Arnold (45-335). At the same time, the following SCSs are not the subject of discussion: 1) narrow-focused, simple characterizations in which soils are divided using one criteria, for example, land use type, topography, age, parent materials, or color (Hartemink 2015, 131); 2) engineering (technical) used for practical purposes; 3) outdated and extinct; 4) folk; and, 5) numerical (quantitative) based on mathematical and statistical methods (pedometric approaches) (Hole and Hironaka 1960; Hughes et al. 2014; McBratney and Gruijter 1992; Parrochia 2017; Rayner 1966; Rozhkov 2011; Verheyen et al. 2001). Numerical SCSs are excluded from consideration for the following reasons. First, they relate to a large, specific, and independent section of soil classification and, therefore, require special attention. Secondly, the problem of scientific classification cannot be solved with the help of mathematical methods, since first of all the theory of classification should be developed (Rozova 1986, 196). Moreover, the development of a numerical soil classification is considered as an "auxiliary" and/or additional task in relation to the problem of developing a genetic soil classification (Sokolov 2004, 185). However, what purposes are set for soil classification?

2.0. Purposes of soil classification

There are scientific (theoretical, fundamental) and practical (applied) purposes of soil classification. For example, Arnold (2002) states: "Applied uses and scientific knowledge have both been major purposes of soil classification." The most frequently mentioned scientific purposes are:

- Providing a common scientific language to facilitate the comparison, exchange, and extrapolation of soil information, results, and experience on agricultural and environmental issues among scientists by correlating and harmonizing officially recognized SCSs and unification of soil nomenclature (Brevik et al. 2016; Cline 1949; De Bakker 1970; Hempel et al. 2013; IUSS Working Group WRB 2015, 5; Láng et al. 2013).
- Improving the scientific understanding of the genesis of soils by reflecting the relationship between soils and the environment (Beckmann 1984; Cline 1949; De Bakker 1970; Hartemink 2015; Kubiëna 1958; Muir 1962; Riecken 1963; Sokal 1974; Zonneveld 1959, quote according to De Bakker 1970).
- Identification and reflection of the main stages of soil formation and, on this basis, prediction of their behavior under different uses and management (Beckmann 1984; Kellogg 1963; Kovda 1973, 377-428).
- Discovery, display, and explanation of the basic laws of soil formation (Basinski 1959; Smith 1965; Sokolov 2004, 170).
- Defining the soil science paradigm to indicate the path to the future development and progress of soil science (Ibáñez and Boixadera 2002; Kiryushin 2011, 8).
- Providing the basis for developing soil map legends (De Bakker 1970; IUSS Working Group WRB 2015, 12-21; Rozova 1986, 67).
- Unification of diagnosic methods and development of a methodology for the identification of soils (Tyurin 1957, quote according to Basinski 1959).

Nevertheless, in spite of these scientific purposes, the overwhelming majority of officially recognized SCSs in development had mainly practical purposes, first of all, supporting soil surveys (mapping) (Arnold 2002; Baruck et al. 2016). For practical purposes, the already developed SCSs are used for inventory of soils and solving applied problems in agriculture, land use, engineering, and environmental surveys, construction, operation of roads, underground utilities, in the fields of geology, hydrology, forestry, etc. (De Bakker 1970; Riecken 1963; Sokolov 2004, 171). Before proceeding to the analysis of the unresolved issues of soil classification, discussed in soil science, let us dwell on the current state of soil classification.

3.0. The current state of soil classification

In 2001, Langohr characterized the state of soil classification as follows: it has a poor reputation and is often called useless because of too many classification systems changing too often, containing too many characteristics, requiring too complex data, having too complicated terminology, and not having common accurate soil names. In 2012, Rozhkov drew attention to the weak theoretical base of SCSs: "The existing soil classification systems do not completely satisfy the principles of classiology. The violation of logical basis, poor structuring, low integrity, and inadequate level of formalization make these systems verbal schemes rather than classification systems sensu stricto."

It can be said that little has changed since then. At the same time, it is encouraging that there is a growing desire to change the situation and make progress in soil classification (Brevik et al. 2016; Hempel et al. 2013; Ibáñez and Boixadera 2002; Nikiforova and Fleis 2018; Sokolov 2004, 170). The priority is to create a universal SCS, which is considered a challenge due to the continuous nature, extreme complexity and high spatial variability of soils, as well as due to the wide variety of soil-forming factors and incomplete soil data (Fridland 1986, 9; Heuvelink and Webster 2001; Ibáñez and Boixadera 2002).

The continuous nature and transitional forms of soils and the impossibility of unambiguously attributing them to a particular class (Rozova 1986, 97) create difficulties in soil classification. It should be said that this problem is acute not only in soil science, but also, for example, in geobotany and petrography (96). There are different points of view on how to solve this dilemma, but we will focus on the philosophical ones. To begin with, according to Rozova (95-96), "formal-logical criteria for good classification require a clear definition of the boundaries between classes of objects" and "if this condition cannot be met, the classification procedure cannot be implemented either." At the same time, philosophy does not give a definite answer how to establish these boundaries. On the one hand, in order to do this, it is proposed to get rid of intermediate classes in the process of building a classification system, thereby ignoring the transitional forms of objects (97). On the other hand, "in a situation when it is necessary to theoretically 'grasp' the development of an 'object,' the transitional forms should be separated into special independent classes." In general, philosophers conclude that the concept of a continuum of objects does not deny the possibility of their classification (see Rozova 1986, 156).

The situation is complicated by a misunderstanding of what classification is and what is the difference between the terms classification, classifying, and classification system (Ibáñez and Boixadera 2002; Rozova 1986, 194; Sokal 1974). For example, classification is often confused with classifying and is understood as the allocation of soils in accordance with a specific classification system (IUSS Working Group WRB 2015, 13). It can also be understood as the arranging of soils into classes for a specific (scientific, environmental, engineering, agronomic) purpose (Jones et al. 2005, 25) and as combining soils with similar properties into groups (Nagy et al. 2016). In this article, the term classification refers to the logical division of a set into subsets (disjoined classes and subclasses), whereas the term classifying to the identification of objects in accordance with the already developed classification systems. An example of such an understanding of classification and classifying in soil science is the statement by Sokolov (2004, 177). He stresses that there is a need of "a clear understanding of the differences between the development of classification and the identification of objects in accordance with the classification system already prepared." In addition, the terms classification and classification system, on the one hand, and mapping, zoning and map legend, on the other hand, are also often misunderstood and are used as synonyms (Krasilnikov, Martí, Arnold and Shoba 2009, 3; Narayanan et al. 1992), although the former are the basis for the latter (Avery 1973; Buol et al. 1980, 343; 345; De Bakker 1970; Rozova 1986, 67; Schelling 1970; Subbotin 2001, 59).

Soil classification problems are mainly associated with a lack of theoretical justification (Ibáñez and Boixadera 2002; Rozova 1986, 196; Sokolov 2004, 165). However, most current publications on soil classification are devoted to other topics, namely:

- History of creation and description of SCSs (Anderson and Smith 2011; Gennadiyev and Gerasimova 1996; Isbell 1992; Krasilnikov, Martí, Arnold and Shoba 2009; Paton and Humphreys 2007; Simonson 1989).
- Comparison and correlation (or harmonization) of SCSs (Hughes et al. 2017; 2018; Gerasimova and Khitrov 2012; Krasilnikov, Martí, Arnold and Shoba 2009; Lebedeva et al. 1999; Mazhitova et al. 1994; Michéli 2008; Murashkina et al. 2005; Shi et al. 2010; Shoba 2002; Zádorová and Penížek 2011).
- Diagnostics and classifying of soils (Deressa et al. 2018; Gobin et al. 2000; Lebedeva and Gerasimova 2012).
- Technological and mathematical (statistical) methods of classification and classifying of soils, as well as of revising, updating, and improving of the current SCSs (Da Silva et al. 2014; Hartemink and Minasny 2014; Hempel et al. 2013; Nagy et al. 2016; Ogen et al. 2017; Teng et al. 2018; Vasques et al. 2014).

4.0 Unresolved issues of soil classification

In this section, the following unresolved issues of soil classification, which are discussed in soil science, are covered: is a single universal SCS required, what definition of soils should be the basis for a universal SCS, what is the basic unit (minimal object with homogeneous properties) of soil classification (hereinafter referred to as BUSC), should SCSs be genetic or morphological, what is genetic soil classification, what type and method of constructing SCSs is more fruitful, and how to make SCSs evolutionary.

4.1 Is a single universal soilclassification system required?

There are two main points of view on the need for a single universal SCS. The first point of view is that there should be different SCSs for different purposes (Cline 1962; Ibáñez and Boixadera 2002), and the second point of view is that there should be one SCS, which serves as the basis for practical (applied) SCSs (Fridland 1986, 6; Sokolov 2004, 166). In defense of the second point of view, Fridland (1986, 6) emphasizes that a basic SCS should provide the basis for the integrity of soil science through a common language and the most effective use of results of soil science in other sciences and in practice. At the same time, Rozova (1986, 215), based on her philosophical position, believes that in the future, a unified system of a fundamental and applied nature may emerge.

4.2 What definition of soils should be the basis for their classification?

It is widely recognized that classification without a precise definition of its object is impossible. Dokuchaev, commonly regarded as the founder of soil science, gave the first scientific definition of soils. However, as evidenced by the constant appearance of old and new definitions, there is the need to improve Dokuchaev's definition or give another one. For example, in a recent study, Hartemink (2015) analyzes eighty-one definitions of soils and suggests another. However, these new definitions, in contrast to Dokuchaev's one, for the most part only list the diagnostic properties of soils, leaving their essential character without proper attention. Their essential nature lies in their duality—on the one hand, the soils are independent natural bodies (that is, systems), and on the other hand they are the result of the interaction and interrelationship of soil-forming factors (that is, elements of systems). As an example, we give the definitions of soils presented in the explanatory notes to the "world reference base for soil resources" (WRB), the U.S. soil taxonomy and Russian soil classification system:

- For WRB, soil is: any material within two meters of the Earth's surface that is in contact with the atmosphere, excluding living organisms, areas with continuous ice not covered by other material, and bodies of water deeper than two meters. The definition includes continuous rock, paved urban soils, soils of industrial areas, cave soils as well as subaqueous soils. Soils under continuous rock, except those that occur in caves, are generally not considered for classification. In special cases, the WRB may be used to classify soils under rock, for example for palaeopedological reconstruction of the environment. (IUSS Working Group WRB 2015, 4)
- For "U.S. Soil Taxonomy" (Soil Survey Staff 1999): "Soil … is a natural body comprised of solids (minerals and organic matter), liquid, and gases that occurs on the land surface, occupies space, and is characterized by one or both of the following: horizons, or layers, that are distinguishable from the initial material as a result of additions, losses, transfers, and transformations of energy and matter or the ability to support rooted plants in a natural environment."
- For the Russian soil classification system (Shishov et al. 2004): "The soil is a natural or natural-anthropogenic solid-phase body, exposed on the land surface, formed as a result of long-term interaction of the processes leading to the differentiation of the original mineral and organic material into horizons."

It should be recalled that there are two main versions of the definition of soils proposed by Dokuchaev, which have a similar first part (namely, the soil is an independent natural body) and are distinguished by their second part. These two parts of the definition reflect the dual nature of the soil. The second part of the well-known first version, which is commonly used every day: "Each soil is the product of the aggregate activity of parent material, climate, vegetation, and topography" (Dokuchaev 1879, 1). This second part of the first version varies in other works of Dokuchaev, since he returned to it many times over many years. Much more rarely is this second part used, namely: soils are "those daily or outward horizons of rocks … which are more or less changed naturally by the common effect of water, air and various kinds of living and dead organisms" (Dokuchaev 1886, 227). A comparison of these second parts of the two versions of the definition shows that, unlike the second part of the first version, the second part of the second version corresponds to the systems approach, despite the fact that it does not use its terminology (Nikiforova and Fleis 2018). However, at present, only the first part of Dokuchaev's definition is used as the basis for soil classification, while the second is either not used at all, or its use is only declared (see Buol et al. 1980, 17; 320; Florea 2012; Lebedeva and Gerasimova 2009). For example, Jenny (1941, 1-21) draws attention to the fact that most soil scientists deal only with the soil as such (that is, with the soil as an independent natural body), but not with the soil as a part of a wider system, namely the natural landscape or the environment," however, "often it is not sufficiently realized that the boundary between soil and environment is artificial." In turn, Karpachevsky (1981) expresses the following view: "An analysis of the soil definition given by V.V. Dokuchaev shows that although soil is a special natural body … it should always be considered as a subsystem of the other natural systems. There is no soil out of these systems. This provision, explicitly or implicitly, normally provides the foundation of all scientific researches of soils." Fridland (1986, 9) considers the relationship of soils with soil formation factors to be their main property. However, it is the second version of the definition of Dokuchaev, which is currently used to study the landscape in Russia. Moreover, mainly because of this version, Dokuchaev is considered to be the founder of Russian landscape science, despite the fact that he never used the term landscape in his works.

The definition of soils affects the set of objects that are proposed for inclusion in SCSs. For example, in addition to natural terrestrial soils, it is proposed to include in SCSs: 1) regolith and groundwater, which together with the soil form an integrated natural body that supports life on Earth (see Krasilnikov and Arnold 2009, 329); 2) superficial friable rocks, redeposited and artificially accumulated soils, as well as underwater bottom formations located at a shallow depth and serving as a substrate for green plants (Fridland 1986, 8-9); and, 3) all exogenous bodies characterized by fertility, since they are genetically related to soils by gradual transitions, perform biospheric ecological functions of soils, and are objects of economic activity, cartography, and accounting (Sokolov 1991).

4.3. What is the basic unit of soil classification?

The definition of soils and BUSCs are usuallly considered as different tasks. The following are often referred to as such BUSCs: prisms of a certain section, soil individuals, pedons, polypedons, soil profiles, solums, three-dimensional natural bodies, etc. Moreover, each of these BUSCs can have different content (AFES 1998; Avery 1973; Buol et al. 1980, 17; Ibáñez and Boixadera 2002; Krasilnikov, Martí and Arnold 2009, 16; Sokolov 1978; 2004, 175). Fridland (1986, 9) names the following requirements to BUSCs: they must: 1) not depend on any classification system; 2) be sufficiently homogeneous, indivisible within classification (this should be controlled by the disappearance of their connection with the soil-forming factors); and, 3) be three-dimensional bodies. At the same time, according to Sokolov (2004, 176), the declared BUSCs should not affect the result of the classification process and the true BUSCs are, as a rule, soil images and natural laws of soil formation.

4.4 Should soil classification systems be genetic or morphological?

To begin with, in philosophy and science, including soil science, there is no generally accepted concept of genetic classification, and the term genetic classification can be understood differently (Krasilnikov, Martí and Arnold 2009, 11; Rozova 1986, 59). As a result, in soil science, the concepts of genetic and morphological classifications are often replaced by each other (Nikiforova et al. 2019). Therefore, we need to clarify what this term means. In soil science, the term genetic classification refers to a classification in which modern soils are divided according to soil formation conditions (or soil-forming factors), which determine the genesis and properties of soils. At the same time, the term genetic classification system refers to a classification system that reflects these soil formation conditions.

There are two main opposite approaches to soil classification: morphological, that is, focused on the diagnostic properties of soils and, above all, diagnostic horizons (Bridges 1990), and genetic, of which the former became dominant (Hartemink 2015). On the one hand, compared to morphological ones, genetic classification systems provide a deeper understanding of the genesis of the classification objects and a forecast of possible changes in them (Dupré 2006, 31, quote according to Hjørland 2017, 108). Here is what Kubiëna writes in this connection: "the knowledge of the genesis of a property is very important in systematics since only by this can a property or a unit of properties be fully known and understood … describing things in nature without any efforts to understand them means only a beginning of science, not science itself" (Kubiëna 1958). On the other hand, it is widely believed that the soil genesis can be reflected in SCSs both directly (through the soil-forming factors or landscape features) and indirectly, in a "hidden" form (through the diagnostic soil properties) (Basinski 1959; Smith 1983; Lebedeva and Gerasimova 2009; Rozanov 1982). Moreover, indirect reflection is usually considered more correct due to the widespread notion that soils should be classified as such, regardless of the soil-forming factors, that is, in the same way as other natural objects (IUSS Working Group WRB 2015, 4; Leeper 1952); otherwise, instead of soils, more general concepts, such as landscapes, geobiocenoses, and ecosystems, will be classified (Beckmann 1984; Sokolov 1978).

As another argument against genetic soil classification, the fact is advanced that soils reflect not only current soil formation conditions, but also past ones, due to which the dependence of soil properties on soil-forming factors is not always linear (Krasilnikov, Martí and Arnold 2009, 10; Phillips 1996; Targulian and Goryachkin 2004). Finally, the genesis of soils is considered to be based on implicit knowledge and, therefore, a shaky basis for soil classification (Nachtergaele et al. 2002). As a result, today SCSs based on grouping soil profiles as combinations of diagnostic horizons are considered as genetic (Krasilnikov, Martí and Arnold 2009, 11-12).

The refusal to include soil formation conditions in a SCS is connected, in our opinion, with the unwillingness to mix genetic (landscape) features with the diagnostic properties of soils as independent natural bodies, which is quite understandable. However, such a "mixing" simply will not happen if we use genetic (landscape) features as differentiating criteria, and diagnostic properties as diagnostic ones. The fact is that differentiating criteria are considered to be essential (internal) properties of objects, "which are causes of many other properties; or, at any rate, which are sure marks of them" (Mill 1882, 872), whereas diagnostic ones are considered to be formal (external), in many cases, morphological properties of objects of classification, which are determined by differentiating criteria. Properties without any content of essential character cannot be considered as differentiating (Muir 1962). In addition, differentiating criteria serve to divide objects into classes and subclasses, whereas diagnostic ones serve to identify them (Rozova 1986, 18, 25, 95; Subbotin 2001, 28-29, 55-57).

It should be emphasized that, following Dokuchaev, many soil scientists were in favor of including genesis in SCSs (Basher 1997; Basinski 1959; Cline 1962; Dobrovol'skii 2005; Florea 2012; Juilleret et al. 2016; Knox 1965; Smith 1983; Sokolov 1991). Explaining this position, Florea (2012) stresses that genesis "helps to the understanding of the soil cover in landscape, contributing to a more efficient and of high quality soil survey." In 1965, Knox dreamed of a SCS based on some kind of soil-landscape units. Another weighty argument for including genesis in SCSs is that modern society needs more and more information about the environment, including information on landscape features (Krasilnikov and Arnold 2009, 329). Therefore, the advantage of many morphological SCSs is that they already contain landscape features, however, not on a systematic basis. See, for example, the "U.S. Soil Taxonomy" (Bockheim et al. 2014; Smith 1986; Soil Survey Staff 1999).

4.5 What type and method of constructing soil classification systems is more fruitful?

Another unresolved issue is the type (hierarchical, non-hierarchical) and method of constructing SCSs. On the one hand, it is stated (Nachtergaele et al. 2002): "[R]igid hierarchic ranking may result in a false sense of correctness not suited for many of the soil studies undertaken and often leading to a loss of soil information." It is also believed that hierarchical systems are "subjective, expert-dependent structures, which facilitate the search and recall of objects within the system rather than being a reflection of any real organization of entities into natural groups" (see Krasilnikov, Martí and Arnold 2009, 11). On the other hand, hierarchical structures are considered irreplaceable because they "optimize the flow of information" (Ibáñez and Boixadera 2002), may constitute a system of objective laws of soil formation reflecting their subordination (Sokolov 1991), and help "to more holistically combine soil formation factors with soil geography and pattern" (Miller and Schaetzl 2016).

As for the method of constructing SCSs, it is believed there are two ways: descending (top-down, segregating, analytic, and usually genetic) and ascending (bottom-up, aggregating, synthetic, non-genetic) (Arnold 2002; Manil 1959; Muir 1962). Arnold (2002) considers that it is possible to use both methods. He writes: "it is possible to start with the domain and divide it and subdivide it and so on" and "it is also possible to group the individuals, then group the groups, and so on." However, there is also another point of view. For example, Sokolov (2004, 176) states that "if we set ourselves the purpose of creating a classification that would be a synthesis of our knowledge of soils and reflect the basic laws of soil formation, then it can only be built as top-down."

4.6 How to make soil classification systems evolutionary?

There is still no clear answer to the question of how to make SCSs evolutionary[3] (dynamic, non-static), although the need to resolve this issue is recognized (Basinski 1959; Pokrovsky 2014; Rozanov 1977, 4; 1982; Schelling 1970). For example, according to Schelling (1970), we currently classify "merely momentary glimpses" of soils, which is not enough. To make SCSs evolutionary, Manil (1959) proposes including paleopedological characteristics at the lower categories of SCSs, and Kovda (1973, 377-428) proposes using the soil age and the stages of soil development as criteria for soil division. Mamai (2005) believes that statistical and dynamic classifications together should constitute one system. Finally, acording to the philosopher Subbotin (2001, 61), for the classification system to be evolutionary, it must have a time axis of coordinates.

5.0 Officially recognized national and international and some underdeveloped soil classification systems

In the introductory part of this section, it should be said that SCSs are the result of the consensus among experts and, therefore, they are "closed systems," which are developed, adopted, and changed by the institutions responsible for soil classification and/or soil mapping (Krasilnikov, Martí, Arnold and Shoba 2009, 35). This distinguishes them from biological systems that are "open and grow continuously over time with the inputs of the whole scientific community involved in the detection of new taxa." It should also be borne in mind that, as is in all other sciences, in soil science, classification organizes the knowledge accumulated at the moment (Smith 1965). This means that it develops and improves with the development of soil science, with the expansion and deepening of knowledge about soils (Rozova 1986, 51).

Some structure features of officially recognized national and international SCSs, as well as some underdeveloped SCSs, namely taxonomic levels (or, in accordance with contemporary theories of classification, degrees or orders; the same applies to hierarchical levels), levels of archetypes and criteria for division of soils are shown in Figures 1 and 2, respectively. In more detail, features of these SCSs are described below.

5.1 Common features

In general, SCSs are similar and not fundamentally different from each other. They are characterized by the presence of taxonomic levels (including levels of archetypes), confusion between differentiating and diagnostic criteria, the lack of objective rules for the selection and ranking of criteria for division of soils, as well as violation of the rules for logical division of concepts.

5.1.1 Presence of taxonomic levels, including levels of archetypes

Acording to Shreyder (1983) and Krasilnikov, Martí and Arnold (2009, 5-30), almost all SCSs are intuitively based on the concept of archetypes, that is, original central images or concepts, prototypes of soils. Many of the archetypes existed before the advent of modern scientific classification systems. For example, Krasilnikov, Martí and Arnold (2009, 18) explain the meaning of this term in soil classification as follows:

> Most natural classifications grew from pre-scientific ones, mostly non-verbal concepts of archetypes … At the initial stage of the development of modern soil classification, soil types in the sense of V.V. Dokuchaev and his successors were archetypes. The names of soil types were mainly borrowed from folk soil classifications: the words chernozem, solod, solonetz, rhendzina were used by Russian, Ukrainian and Polish peasants for ages. The use of indigenous soil names reinforced the use of the archetypes in scientific soil classifications.

Currently in soil science, archetypes are considered the basic taxonomic units, represented mainly by soil types, as well as series and reference groups. Archetypes are characterized by sets of features. For example, in the Russian school of soil science, soils of the same genetic type are similar in: 1) input of organic substances and their transformation and decomposition; 2) decomposition of the mineral mass and synthesis of mineral and organo-mineral neoformations; 3) migration and accumulation of substances; 4) soil profile structure; and, 5) measures to improve and maintain soil fertility (Rode 1975, 254). In addition, archetypes form the initial basic taxonomic levels of SCSs after which they are grouped and/or divided, forming higher and lower levels. Usually in SCSs, there is only one level of archetypes; two levels (one for landscapes and one for soil profiles) are present in SCSs using the concept of soil series related to landscapes and parent materials (Krasilnikov, Martí and Arnold 2009, 24-26). Thus, the creation of SCSs does not begin from the zero-level represented by the initial set (universe) of soils but from the archetype levels and then continues in an upward and/or downward direction. Most of the officially recognized SCSs have levels obtained because of dividing archetypes and their grouping. For example, in the Russian SCS (Shishov et al. 2004) and the "U.S. Soil Taxonomy" (Soil Survey Staff 1999), the upper hierarchical levels (sections, trunks and orders, sub-orders, respectively) are built by grouping archetypes represented by soil types and great groups of soils, respectively, whereas lower levels (subtypes, genuses and subgroups, families, etc.) are built by dividing archetypes. However, this method of building SCSs contradicts the concept of a hierarchical classification system. Therefore, SCSs having levels of archetypes can be called "pseudo-hierarchical," since they only seem to be hierarchical, but, in fact, they are not.

It should also be said that some SCSs, for example, the French SCS (AFES 1998) and the WRB (IUSS Working Group WRB 2015) are considered reference databases without any or little hierarchy (Krasilnikov, Martí and Arnold 2009, 41). There are also classification systems created in the form of tables, but this can be considered an exception to the general rule. An example is the SCS of the Republic of South Africa (Soil Classification Working Group 1977).

5.1.2 Confusion between differentiating and diagnostic criteria

Differentiating criteria are among the most important classification elements that determine the success of the development and operation of a natural classification system (Subbotin 2001, 29) and ultimately its scientific character (Mill 1882, 872). Differentiating criteria are used for classification of objects, and diagnostic criteria are used for their identification (classifying). However, in existing SCSs, diagnostic criteria or a mixture of differentiating and diagnostic criteria replace differentiating ones. Moreover, in most cases, in officially recognized SCSs, diagnostic criteria play a leading role in this mixture, whereas in underdeveloped SCSs, the opposite is often the case. As a result, these SCSs are artificial rather than natural and genetic, and do not solve most of the scientific problems facing soil classification.

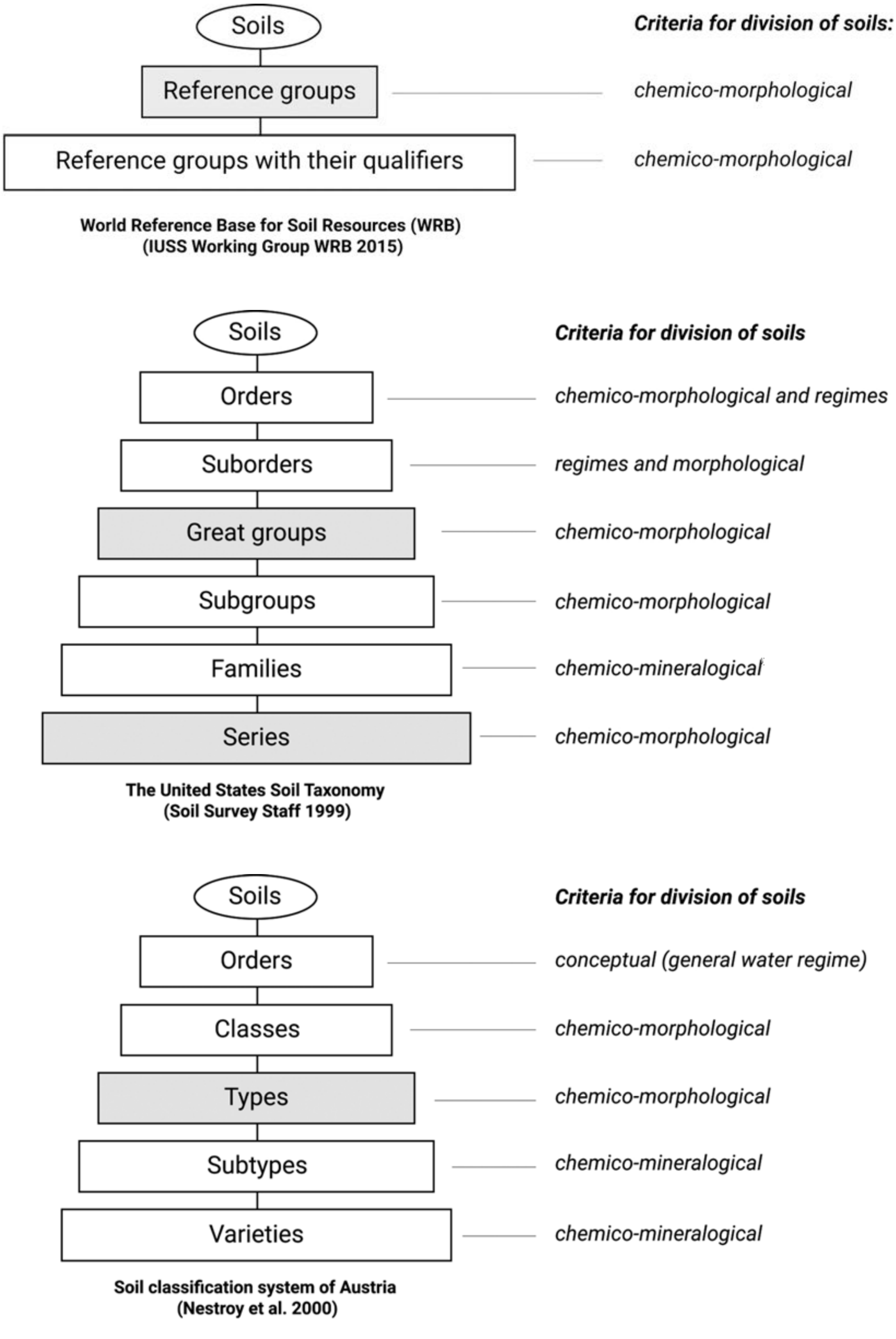
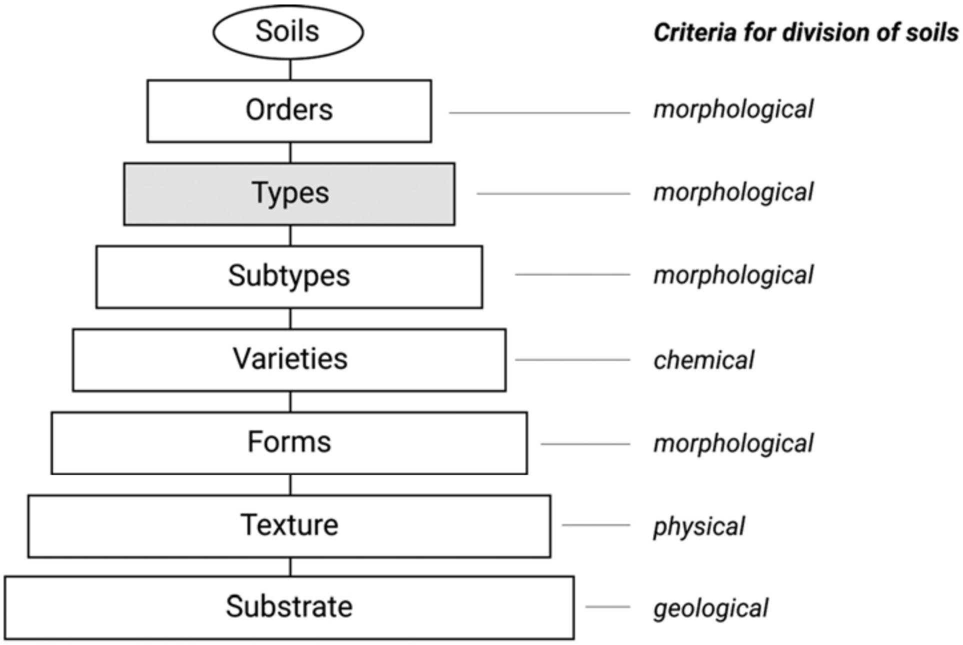
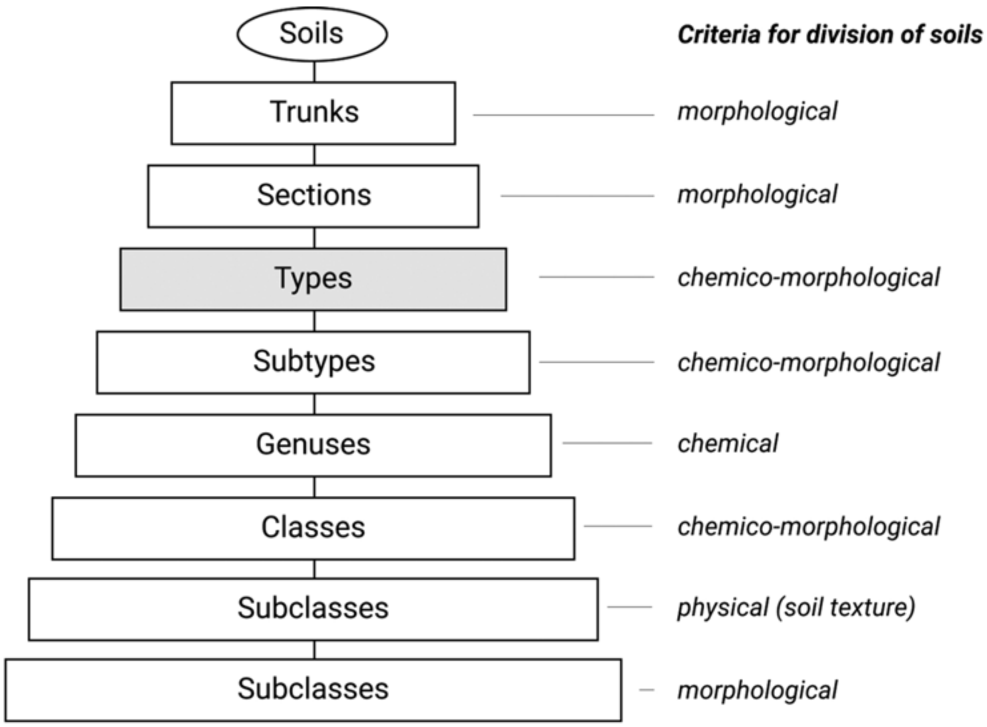


Figure 1. Structure features of some officially recognized national and international SCSs. Note: the book by Krasilnikov, Martí, Arnold and Shoba (2009) was used in the preparation of the figure.



Soil classification system of Slovakia
(Sobocká 2000)



Russian soil classification system
(Shishov et al. 2004)

Figure 1 (cont.)

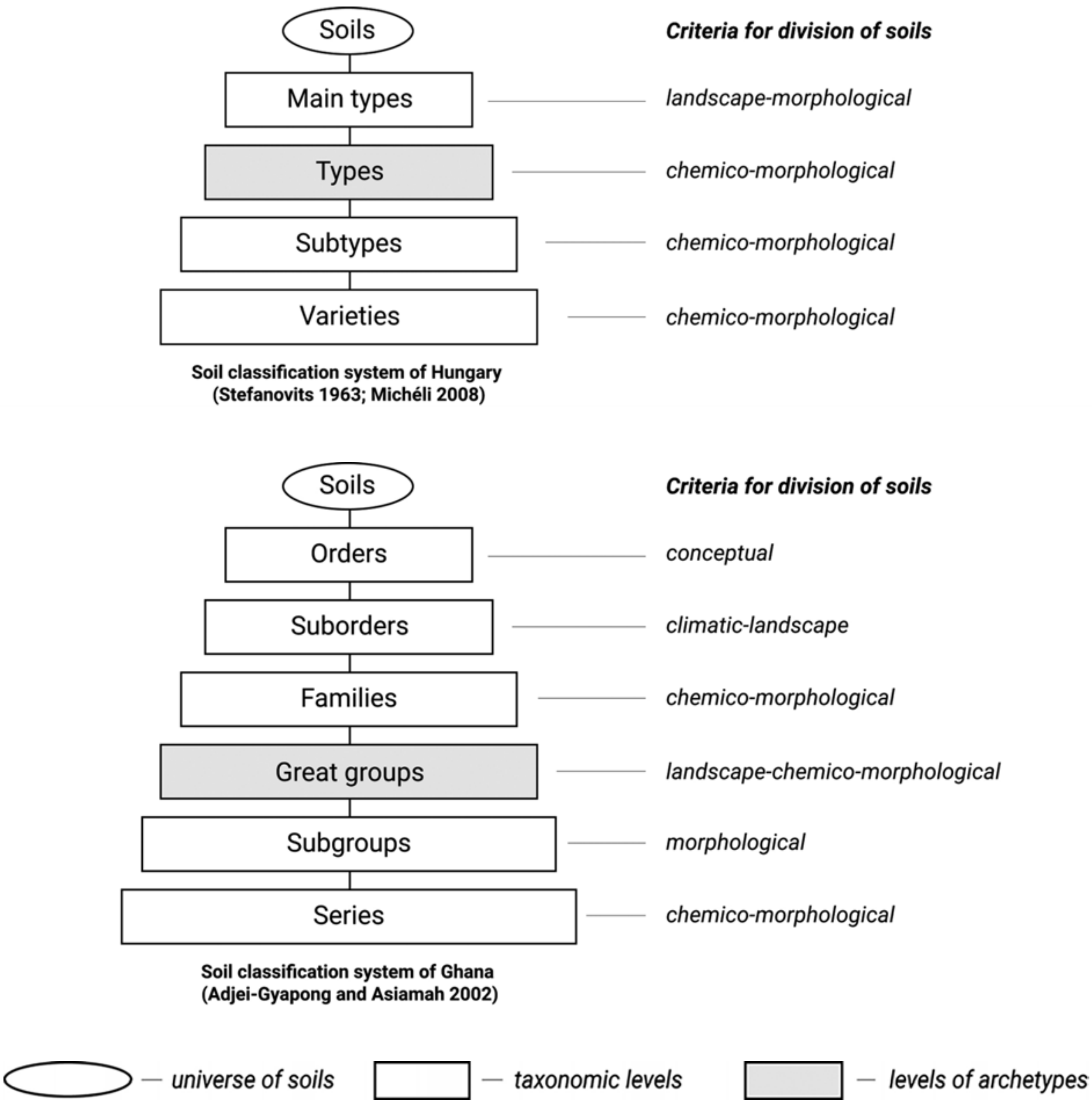


Figure 1 (cont.)

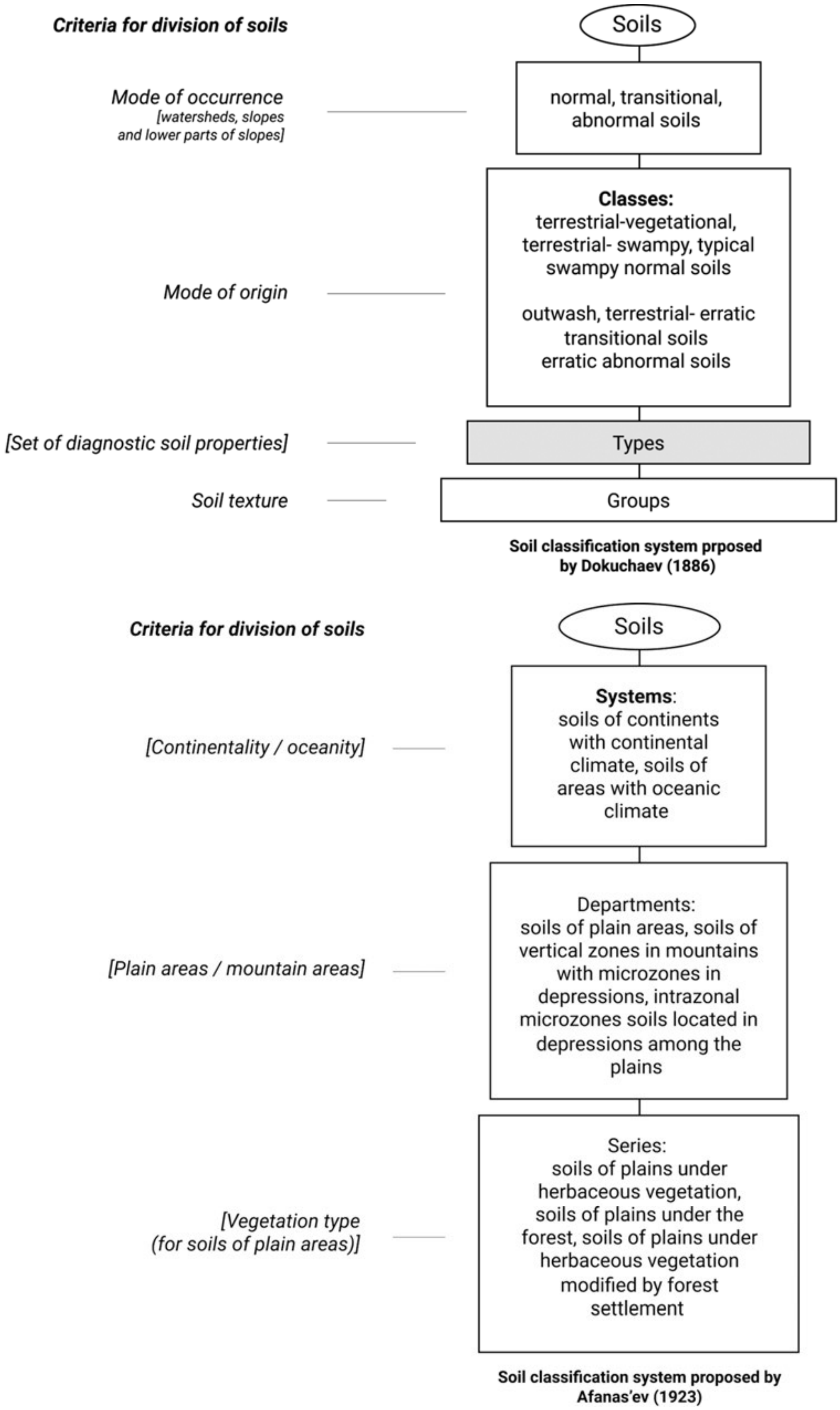
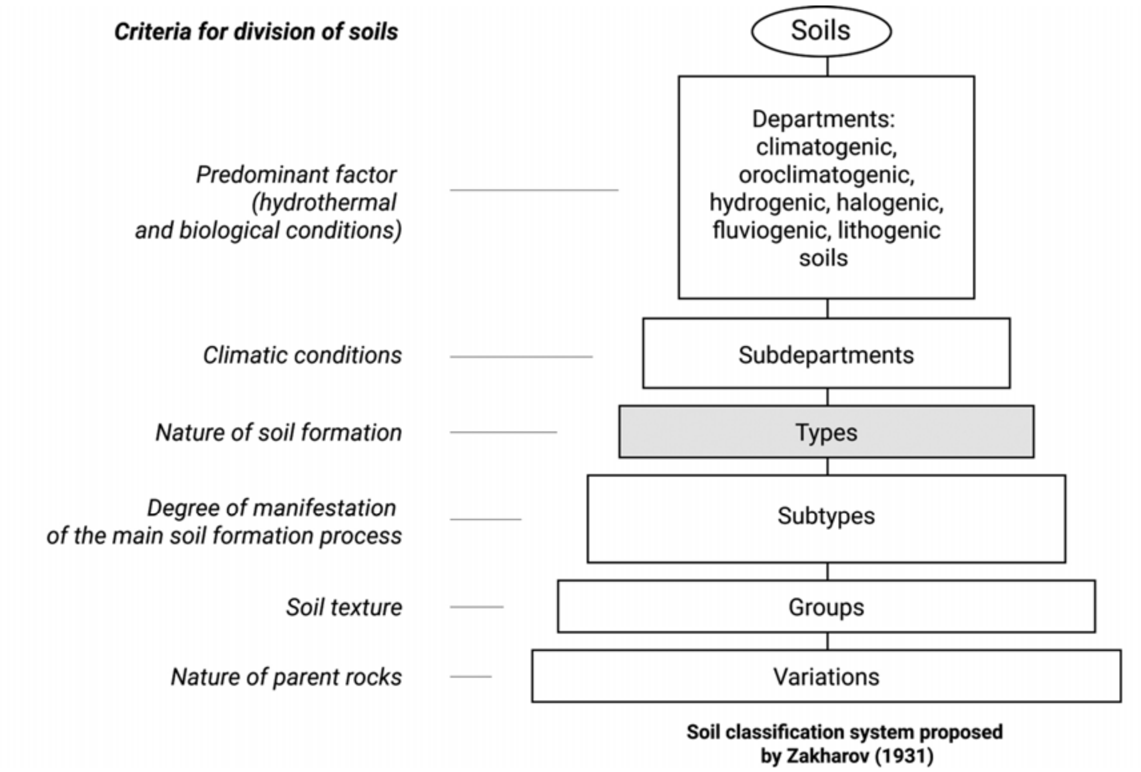


Figure 2. Structure features of some underdeveloped SCSs. Note: Criteria for division of soils enclosed in square brackets are not directly named as such by the authors of SCSs but extracted from the explanatory notes to these SCSs.



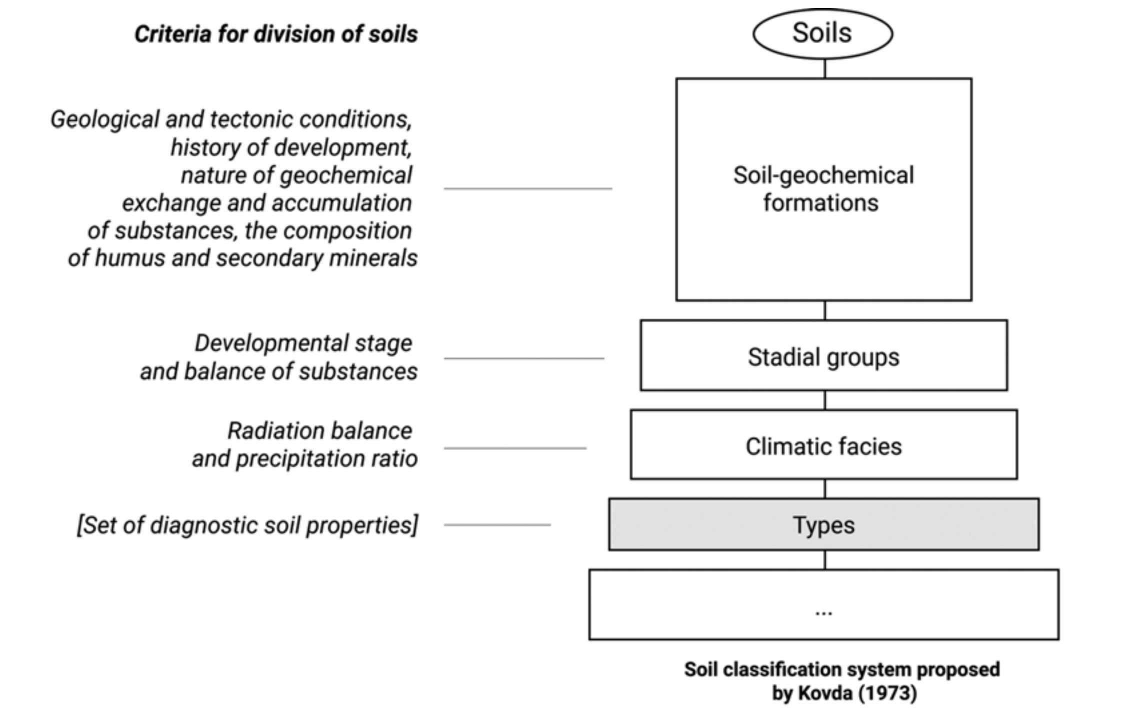


Figure 2 (cont.)

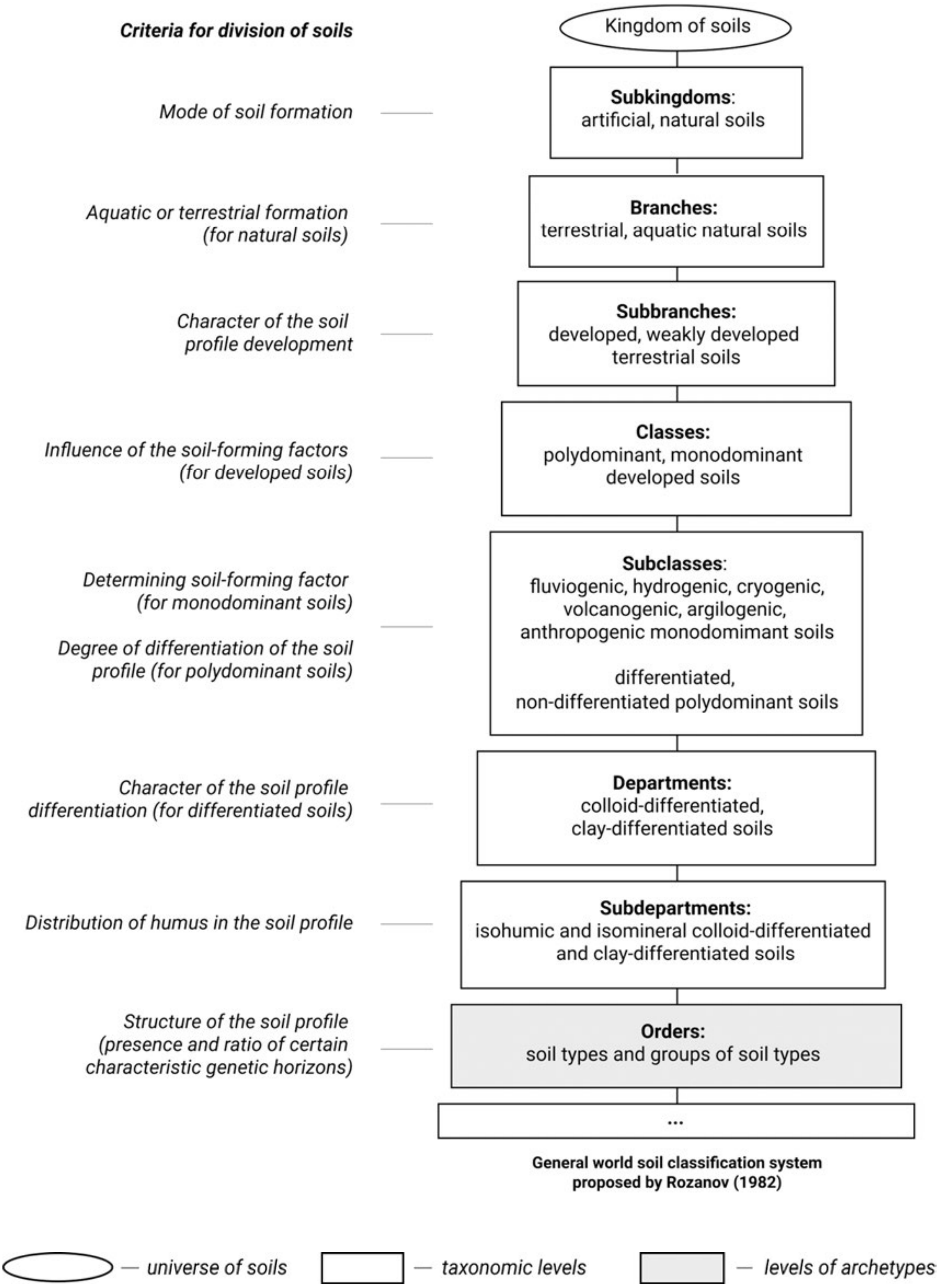


Figure 2 (cont.)

5.1.3 Violations of the rules for logical division of concepts

When using diagnostic criteria instead of differentiating criteria (or when using a set of differentiating criteria instead of a single differentiating one) at a time (that is, when dividing one class of objects), the rules for logical division of concepts are inevitably violated, and this makes the classification systems logically incorrect (Armand 1975, 141-151; Arnold 2002; Sokal 1974). There are many examples of such violations in SCSs:

1) in the Russian SCS, at the upper level of trunks, criteria for division of soils are the ratio of lithogenesis and soil formation and, at the same time, the nature of parent materials (Shishov et al. 2004);
2) in the German SCS, at the level of classes, criteria for division of soils are a similar stage of soil evolution and the dominant pedological processes (Ad-hoc-Arbeitsgruppe Boden 2005); and,
3) in the WRB, at the level of reference soil groups, they are mainly "characteristic soil features produced by primary pedogenetic process, except where special soil parent materials are of overriding importance" (IUSS Working Group WRB 2015, 8).

A rare exception is the SCS proposed by Rozanov (1982), which, at least at the upper levels, follows the rules for logical division of concepts; however, since it has an archetype level, it cannot be called purely genetic.

5.1.4 Lack of objective rules for the selection and ranking of criteria for division of soils

Currently, there are no objective rules for the selection and ranking of criteria for soil division (Nachtergaele et al. 2002); however, according to Rozova (1986, 163), no classification system can exist without such rules. Thus, it can be concluded that most SCSs are: 1) morphological (non-genetic); 2) artificial (not natural); 3) empirical (non-fundamental), that is, "based on several factors at the same level of categorization" (Manil 1959); 4) formal and descriptive (or descriptive with explanations), since "the qualitative diversity of the analyzed objects is simply stated" or partially explained in them (Rozova 1986, 54; 56-57); 5) pseudo-hierarchical; and, 6) static with some, if any, evolutionary elements. Evolutionary elements are present, for example, in the German SCS (Ad-hoc-Arbeitsgruppe Boden 2005), which follows the Kubiëna's scheme "from the simplest poorly developed soils to the most complex, polygenetic ones" (Krasilnikov and Arnold 2009, 123). Another example is the SCS of the United Kingdom (Avery 1980), in which soil development stages are included at the highest level.

However, why are SCSs artificial? According to classiology, artificial systems are empirical, not based on a substantial theory, and simply document the similarities and differences between objects (Subbotin 2001, 69-70; Hjørland 2017, 111). They only help to achieve the visibility of many soils and ensure the effectiveness of their search; however, they do not reveal their nature (Rozova 1986, 204). In addition, soils in them are not "in an order according to their essential character" (Robinson 1950, 153, quote according to Muir 1962). According to Kubiëna (1958), this means that SCSs are built using a synthetic, rather than an analytical approach to the criteria for division of soils, and the presence of archetypes in them confirms this. In this regard, Kubiëna (1958, italics in original) notes: "Every artificial system of grouping is *only* possible by synthesis and by avoiding any kind of analytical approach." He also emphasizes (1958) the "important role of analysis (in its wider sense) in soil research and the need to avoid synthesis as much as possible if the aim is the establishment of a natural system of soils and not just a rapid grouping."

In conclusion of this section, it should be added that, out of the officially recognized SCSs, only three cover the whole world. These are the "U.S. Soil Taxonomy" (Soil Survey Staff 1999), the WRB (IUSS Working Group WRB 2015) and the French SCS (AFES 1998). The first two SCSs are used all over the world, and the third is only potentially suitable for the classification of world soils (Krasilnikov and Arnold 2009, 328).

5.2 Features for which soil classification systems differ from each other

The features for which SCSs differ from each other are:

1. Criteria for division of soils, which are usually represented by various "soil and environmental parameters" (Baruck et al. 2016, 6), for example, the morphological and chemical properties of soils, characteristics of climatic and soil regimes, as well as their combinations (Krasilnikov, Martí and Arnold 2009, 12; 26);
2. Methods for determining and measuring criteria for division of soils;
3. Archetypes, which are represented by various soil types, groups, series, etc.;
4. The number of taxonomic levels;
5. Taxonomic names;
6. Names of soils; and,
7. Objects that are included in them in addition to soils. For example, in addition to terrestrial natural soils, different SCSs include soil-like superficial bodies (subaquatic soils, bare rocks, soils strongly transformed by

agricultural activities, urban soils, and transported materials) and their combinations (Krasilnikov and Arnold 2009, 329).

6.0 Existing proposals for solving soil classification problems

To solve soil classification problems, the following is usually suggested:

– Correlation and harmonization of officially recognized SCSs. In 1998, this task was assigned to the WRB (IUSS Working Group WRB 2015), recommended by IUSS as a soil correlation system for all soil scientists (Nachtergaele et al. 2002).
– Development of a theoretical basis for soil classification. This is considered one of the most important tasks of soil science (Ibáñez and Boixadera 2002; Sokolov 2004, 165). In this regard, Polynov (1933, 45, quote according to Sokolov 2004, 165) notes: "[I]f the classification does not satisfy, then it is obvious that the theory is not completely consistent." Rozova (1986, abstract) expresses a similar position: "The basis of the classification problem is the need to transfer science from the empirical stage of development to the theoretical one."
– Objectivization of the soil classification process. On the one hand, it is believed that the use of innovative pedometric approaches, usually called objective, should greatly assist in the development of a universal SCS (Hempel et al. 2013; McBratney et al. 2003; Michéli et al. 2016; Nachtergaele et al. 2002). On the other hand, it is believed that the arguments of pedometricians are unjustified, and that "developments in pedometrics cannot replace the lack of theoretical studies" (Ibáñez and Boixadera 2002).
– Development of improved quantitative diagnostics (Hartemink 2015; Krasilnikov and Arnold 2009, 132; Nagy et al. 2016). For example, according to Nagy et al. (2016), "The application of faster, efficient, and more objective measurements can bring revolution to the classification of soils."
– Creation of SCSs in the process of mapping and on its basis (Rozanov 1977, 4).

7.0 The "soil-landscape classification system"

The analysis of officially recognized and some underdeveloped SCSs, as well as definitions of soils from the point of view of classiology and the systems approach allowed us to identify their disadvantages and propose an interdisciplinary approach to the creation of a universal SCS (Nikiforova and Fleis 2018; Nikiforova et al. 2019). This approach was tested on the example of the European part of Russia in the process of multiscale soil-landscape GIS mapping (Fleis et al. 2016; Nikiforova et al. 2014; 2018). As a result, the scheme of SLCS was developed, which is fundamentally different from the existing SCSs and overcomes their shortcomings. This can be seen in Figure 3, if one compares it with Figures 1 and 2. The main features of SLCS are listed below:

– SLCS is based on the following definitions of the concepts natural soil and natural landscape developed by the author:

> Natural soil is a material system and, at the same time, a derived element of a higher order material system, namely the natural landscape. Natural landscape consists of both the soil itself and the basic elements—rocks, air, water, and living and dead organisms. All landscape elements are material substances with homogeneous properties and are interrelated and interconnected with each other. The boundaries of natural landscapes and associated soils coincide (Mamai 2005, 31; 38). This follows from the systemic (that is, from the point of view of the systems approach) definition of natural soils and landscapes. Therefore, soil is a unique landscape element, since only soil arises and develops by interaction and interrelation of all other elements (Solntsev [1948] 2006). For example, air as one of the basic landscape elements cannot arise because of the interaction and interrelation of soil, water, rocks and organisms; the same applies to all other basic landscape elements.

– SLCS combines soil and landscape classification systems and, therefore, has two classification objects, which are at the same time its BUSCs. These objects are natural landscape system and its derived element—the soil, which is at the same time a self-sufficient system.
– SLCS is being developed as a complete hierarchy—from the general to the particular and from top to bottom, starting with the "zero" level, represented by the initial sets (universes) of all-natural landscapes and soils, and ending when BUSCs, that is, soil and landscape individuals, are reached.
– Its hierarchical levels are not taxonomic and have numbers instead of names.
– The successive division of natural landscapes in it is carried out in accordance with differentiating criteria and leads to the simultaneous division of associated soils.
– The differentiating criteria are determined by the essential character of soils, which consists in the fact that soils are, on the one hand, material systems, and on the

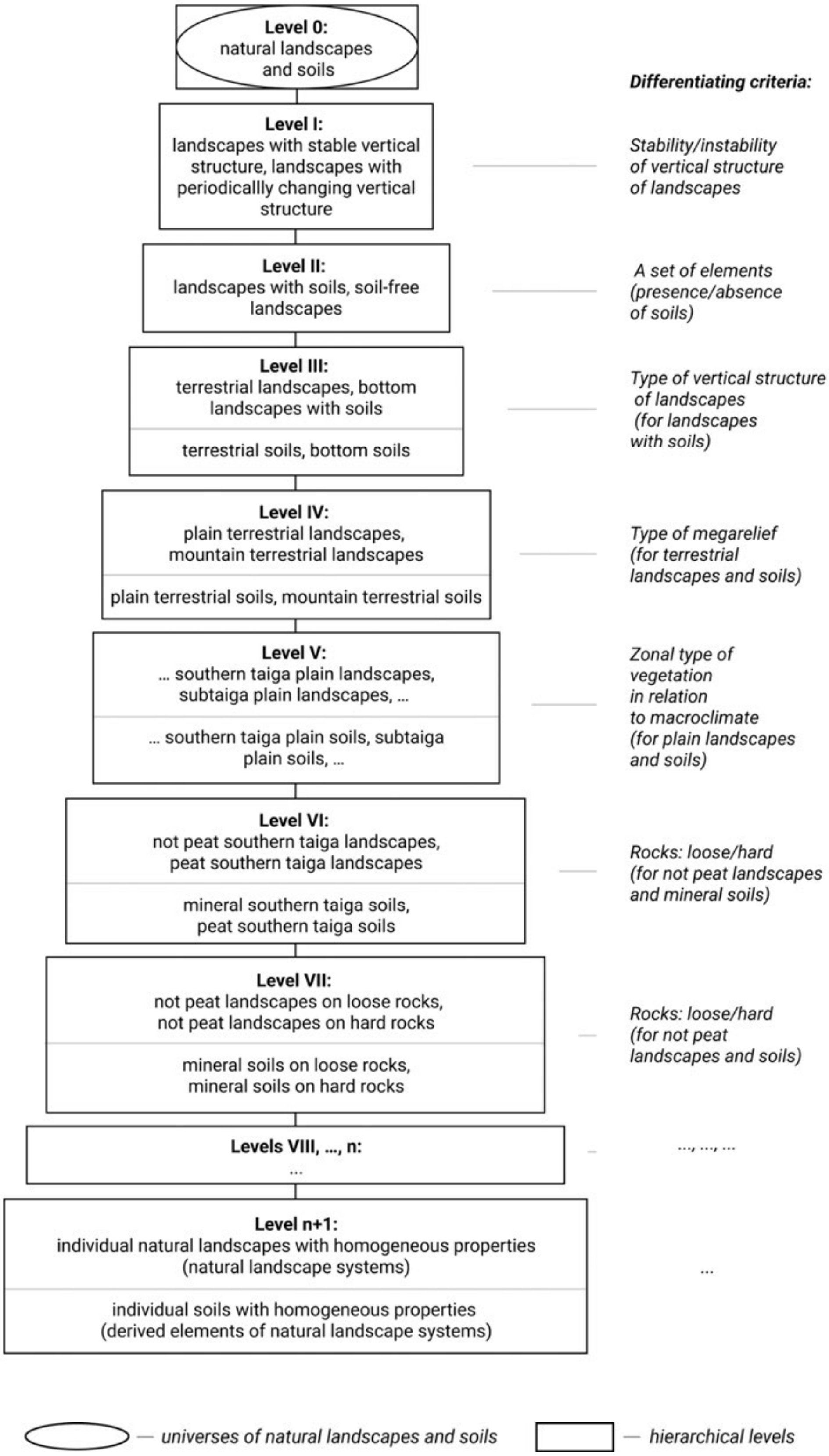


Figure 3. Structure features of SLCS.

other, derived elements of natural landscapes (material systems of a higher order). At the first three levels of classification, differentiating criteria are the main features of natural landscape systems, and at lower levels (in classification branches with soils), they are essential properties of the basic landscape elements.

- Differentiating and diagnostic criteria are separated in SLCS. Differentiating criteria determine diagnostic criteria and are used to divide soils and landscapes into classes (that is, for their classification). Diagnostic criteria are diagnostic properties of soils and landscapes and are used for the identification (classifying) soils and landscapes. The relation and subordination of the concepts described above can be represented in the form of the following chain: essential character of soils→differentiating criteria→diagnostic criteria→diagnostic properties. Diagnostic criteria are defined for all developed classes and subclasses of landscapes and associated soils, as well as for the soil as such, and presented in an online version of SLCS (http://geocnt.geonet.ru/en/landscapes_classification_first.step).
- The selection and ranking of differentiating criteria are subject to the rules developed (Nikiforova et al. 2019).
- SLCS functions as a classification system, as well as a diagnostics system.
- Due to the separation of differentiating and diagnostic criteria in SLCS, it is possible to identify the relationship between the features of landscapes and the properties of their basic elements, on the one hand, and the diagnostic properties of soils and landscapes, on the other. Thanks to this, the USC is able to solve scientific problems.
- SLCS integrates information on natural soils and landscapes.
- SLCS forms a new soil and landscape nomenclature, which reflects soil and landscape properties. Full names of soils and landscapes are obtained by combining their names at all hierarchical levels of a certain branch.
- SLCS includes natural terrestrial and bottom landscapes with and without soils, which allows determining the conditions under which the process of soil formation begins, and, therefore, to find the boundaries beyond which soil formation is impossible.
- SLCS is being developed in the process of multiscale soil-landscape GIS mapping.
- SLCS pursues both scientific and practical (applied) purposes and is, therefore, intended for scholars and practitioners in various fields of human activity who use soil and landscape information in their work.

In general, SLCS can be characterized as natural, genetic, hierarchical, and static. In the future, it is expected that SLCS will combine the basic classification system with practical ones and will be interactive. It can also be interactive and evolutionary (i.e., have a time axis of coordinates), which will make it possible to distinguish between new and "old" (that is, completed due to changes in the properties of the main elements of the landscape) diagnostic soil properties, which are evidence of current and past soil-forming processes, respectively. In addition, we consider SLCS as a basis for a SCS with anthropogenic soils and landscapes. All this can significantly contribute to the inventory, modeling, and forecasting of natural soils and landscapes.

8.0 Conclusion

It can be concluded that none of the officially recognized national and international and underdeveloped SCSs can serve as the basis for creating a universal SCS, because they do not achieve most of scientific purposes that are set for them. To solve soil classification problems, an outside perspective is needed, that is, the use of classiology and the systems approach. Such an interdisciplinary approach allowed us to identify the causes of failures in creating a universal SCS, use both parts of the second version of the definition of soils proposed by Dokuchaev (1886) as a basis for SLCS, overcome most of the shortcomings of the existing SCSs, and suggest a way to make progress in soil classification.

Notes

1. Rozhkov (2012): "Classiology can be defined as a science studying the principles and rules of classification of objects of any nature. The development of the theory of classification and the particular methods for classifying objects are the main challenges of classiology."
2. Blauberg and Iudin (2000): General systems theory (open system) approach is "a trend in methodology based on studying objects as systems." According to von Bertalanffy (1968), a system is an entity, consisting of closely interrelated and interacting elements, and a system element is a minimal structural system unit with homogeneous properties; elements of material systems are material substances.
3. In soil science, as in Russian landscape science (Mamai 2005), there is a fairly clear separation of genetic and evolutionary classifications. Genetic classifications include those in which soils are subdivided into classes and subclasses depending on the conditions of their formation (that is, soil-forming factors), and evolutionary those in which soils are subdivided depending on the main stages of their formation and development over time. However, in other sciences, as a rule, there is no such separation

between genetic and evolutionary classifications (see Gnoli 2018).

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