The Systems Approach in Soil Science and Landscape Science

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Abstract: The article describes the current state of the systems approach in two closely related scientific disciplines - soil science and landscape science. It is shown that, despite the widespread recognition of the need to apply the systems approach to solving topical theoretical and practical problems in these disciplines, it remains unrealized. This is manifested in the prevailing view of soils as systems rather than as elements of higher-order systems, the mixing of the basic landscape elements with their properties, the recognition of landscape systems and elements as spatially heterogeneous formations, the different understanding of emergent properties, structure, hierarchy of soil and landscape systems, and, as a result, in the absence of their unified system definitions, basic classification systems, consistent multiscale global maps, and, finally, a hierarchical decision-making system for sustainable management, protection and assessment of soils and landscapes. It is shown that such a situation is largely due to the conceptual-terminological confusion around the systems approach in philosophy. At the end of the article, the authors share their own experience in applying the systems approach in soil science and landscape science.

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1.0 Introduction

It is known that topical problems remain unresolved in soil science and landscape science. The most important of these problems are the absence of unified definitions, basic classification systems, and consistent global multiscale maps of soils and landscapes. To correct this situation, it is proposed to use the systems approach (SA) (Basher 1997; Churchman 2010; Freeman et al. 2015; Gardner 1993; Hartemink 2016; Ibáñez and Boixadera 2002; Karpachevsky 1981, 238-41; Lin 2014; Miklós et al. 2019; Naveh 2000), the originator of which is considered to be Bertalanffy (1968).

In soil science and landscape science, the concept of soils and landscapes as systems arose from the very birth of these disciplines and is associated with the name of V.V. Dokuchaev (Dobrovolskii 2005; 1996; Karpachevsky 1981, 238), and this despite the fact that the latter did not use the terminology of the SA. However, for example, Berg (1915) already used the system terminology, defining the landscape as "a single harmonious whole". At the same time, all attempts made so far to use the SA in soil science and landscape science have failed, which is largely due to the problems of the SA itself and, above all, to the conceptual-terminological confusion that exists around it in philosophy (Nikiforova 2023; Uyomov 1978, 37-57). In order to somehow overcome this problem, we have generalized the philosophical definitions of the SA and some of its key concepts (Table 1).

The article describes the current state of the SA in both soil science and landscape science, since these scientific disciplines are closely related through the objects of their study. It demonstrates the existing ideas about soil and landscape systems, their emergent properties, structure and place in the hierarchy of systems. The experience of the authors in the use of the SA is presented, which shows the importance and possibility of applying of the SA in soil science and landscape science.

It must be borne in mind that the main attention in the article is paid to natural landscapes as systems and natural soils as elements of these systems, since other aspects of the SA are practically not touched upon in soil science and landscape science.

2.0 The current state of the SA in soil science and landscape science

2.1 The SA: arguments for and against

The need for the SA in soil science and landscape science is well recognized (Basher 1997; Churchman 2010; Francis et al. 2004; Freeman et al. 2015; Gardner 1993; Gardner 1991; Gerrard 1981; Haigh 1985; Hartemink 2016; Ibáñez and Boixadera 2002; Isachenko 1981; Karpachevsky 1981, 238-241; Klijn 1994; Lin 2014; Miklós et al. 2019; Miller 1993; Naveh 2000; Phillips 1998; Sochava 1978; Solntsev 1981; Tress, B. and Tress, G. 2001; Vasilievskaya et al. 2000, 17-19; Zonneveld 1972), which is largely due to its interdisciplinarity and significant integration potential. For example, Gardner (1993) believes that it can help to "piece together

SA	-	a direction of the methodology of scientific knowledge, which consists in the consideration of objects as systems and elements of systems. A distinction is usually made between material, abstract (conceptual), and material-abstract systems.
Material system	-	a structurally organized integral whole of interconnected and interdependent material elements.
Elements of the material system	-	the minimum constituent parts of the system with relatively homogeneous properties. The division of the system elements leads to the exit from the system and the transition to the system of a lower hierarchical level.
Emergent property of a system	-	a property that arises as a result of the interconnection and interaction of the system elements, which is inherent in the system as a whole, and not in any of its individual elements.
Structure of a material system	-	the arrangement of the system elements relative to each other and stable connections between them, affecting the properties of the system and its elements.
The hierarchy of material systems	-	the order of subordination of systems, each of which is simultaneously an element of a higher order system. Different systems (that is, systems with different sets of elements) are located at different hierarchical levels. Identical systems (that is, systems with the same set of elements) are located at the same hierarchical level.

Table 1. Generalized philosophical definitions of the SA and its key concepts.

soil science from its nearly countless divisions and subdivisions", and Miklós et al. (2019, 159) that only it can "provide a theoretical-methodical base for the creation of an integrated spatial information system usable for multiple purposes". There is also an opinion that classification and mapping of soils and landscapes (Brevik et al. 2016; Gerasimova et al. 2010, 82; Isachenko 1961, 6-7; Marbut 1922; Vasilievskaya et al. 2000, 15-16), as well as their sustainable management, protection and assessment (Basher 1997; Isachenko 1975; Klug 2012; Miklós et al. 2019, 1-6; Müchera et al. 2010) are impossible without the SA.

However, in philosophy, the SA is criticized for insufficient theoretical justification, the inability to formulate a unified definition of a system and unjustified hopes to integrate scientific knowledge with its help (Adams et al. 2013; Churchman 1979; Rousseau 2017). The reasons for the failures of the SA in science are associated with the identification of systems with objects, and the SA with an integrated approach, which consists in a simple summation of data from different sciences (Kazaryan 2004). In soil science, the SA is criticized for the conceptual nature of soil genesis models generated using it, which cannot be thoroughly tested (see Florea 2012).

2.2 Existing ideas about soil and landscape systems

Despite the fact that both soils and landscapes are unequivocally recognized as systems, there is still no common understanding of the SA and its key concepts in soil science and landscape science. For example, there are various synonyms for the terms "the SA" and "elements of the system" (Table 2).

There is also no consensus on which objects should be considered systems and what are their emergent properties in soil science and landscape science, which is discussed in the next section.

2.2.1 What are systems and their emergent properties in soil science and landscape science

In soil science, in addition to soils, soil individuals (pedons), soil landscapes bodies (Schelling 1970), soil catenas (Dijkerman 1974), and soil landscapes (Huggett 1975; Schelling 1970) are considered as systems; and in landscape science (in addition to landscapes) as geosystems (Demek 1978; Isachenko 1981; Miklós et al. 2019, 11; Sochava 1978), ecosystems (Ibáñez and Boixadera 2002; Grunwald 2009; Lin 2014; Miller 1993), geocomplexes (Śleszyński 2021), and natural-territorial complexes (Olsevich 1982; Rikhter 1969).

Soil and landscape systems are classified as material (Neef 1967), open (Dijkerman 1974; Mikhailova et al. 2020; Naveh 2001), complex (Antrop 2000; Francis et al. 2004; Ibáñez and Boixadera 2002; Mikhailova et al. 2020; Reuter et al. 2010), dynamic (Juma 2001, 12; Nikitin 2001; Reuter et al. 2005), and evolving or self-organizing (Grunwald

Synonymous terms for "SA"	Approach:	
	"general system"	(Haigh 1985)
	"holistic systems"	(Naveh 2000)
	"systematic"	(Miklós et al. 2019,xxi)
	"geosystems"	(Miklós et al. 2019; Sochava,1975)
	"system based"	(Basher 1997)
	"system-level"	(James et al. 2021)
	"the earth-systems"	(see Bockheim and Gennadiev 2010)
	"integrative"	(Gerrard 1993)
	"integrated"	(Gardner 1991; Miklós 2015; Miklós 2019)
	"holistic"	(Brevik et al. 2015; James et al. 2021)
	"environmental-centered"	(Grunwald 2009)
Synonymous terms for "elements of the system"	"components"	a widely used term
	"parts", "integral parts", "the simplest parts"	(Hartemink 2016; Grunwald 2009; Neef 1967)
	"subsystems"	(Ibáñez and Boixadera 2002; Karpachevsky 1981; Kiryushin 2018; Targulian and Sokolova 1996)

Table 2. Synonyms for the terms "the SA" and "elements of the system" in soil science and landscape science.

2009; Huggett 1976; Young and Crawford 2004). Soil systems are also considered to be relatively stable (Huggett 1976), equilibrium (Bushnell 1943) or "spontaneously moving towards a state of equilibrium" (Chesworth 1973). At the same time, in quantitative studies of soil genesis, individual soil profiles are often referred to as closed systems, which, according to Schelling (1970), is "usually not entirely true".

Soil fertility is recognized as an emergent property of soil systems (Nicolodi and Gianello 2015), and "natural conditions that ensured the emergence and existence of life" (Shalnev 1999) are recognized as emergent properties of landscapes.

2.2.2 Soil systems as elements of higher order systems

The understanding that soils are not only separate systems, but also elements of systems of a higher order (or hierarchical level), arose in soil science quite a long time ago (Gerrard 1981; Huggett 1975; Karpachevsky 1981, 240; Mitchell 1973). Moreover, it is argued that this idea usually directly or indirectly underlies all soil research (Karpachevsky 1981, 240). But what systems include soils as elements? Most often these systems are called landscapes (Gerrard 1981; Hartemink 2016), ecosystems (Grunwald 2009; Ibáñez and Boixadera 2002; Lin 2014; Miller 1993), and geosystems (Isachenko 1981; Miklós et al. 2019, 11; Nikolayev 2006; Sochava 1978), less often, biogeocenoses (Karpachevsky 1981, 175; Kiryushin 2018, 155), the biosphere (Dobrovolskii et al. 2001; Ibáñez and Boixadera 2002), and the Earth system (Hartemink 2016; Targulian and Sokolova 1996). On the whole, it can be stated that the idea of soils as elements of systems of a higher order is much less common than the idea of soils as separate systems.

2.2.3 Elements of soil and landscape systems

Confusion also exists around the elements of soil and landscape systems. For example, the elements of natural soil systems usually include soil horizons, less often, the soil skeleton, plasma and solution subsystems (Huggett 1975), or soil mineralogy, chemistry, physics, and biota (Churchman 2010). The elements of natural landscape systems include various material objects, properties of material objects, ecosystems, regimes (Table 3). At the same time, there is an opinion that only material objects can be landscape elements (Mamai 2005, 17).

The material elements of the natural landscape system are divided into the basic elements (rocks, air, water, flora and fauna), without which the landscape does not exist, and one derived element, the soil, formed as a result of the interaction of the basic elements (Mamai 2005, 21; Solntsev 1948). It is obvious that this division is based on the definition of soils by Dokuchaev (1886, 227), which states that "soils are natural bodies that are rock horizons found on and near the surface of the earth and more or less altered as a result of the combined action of water, air and various types of living and dead organisms". At the same time, according to other researchers, the basic elements of the landscape include the environment and its factors (Dijkerman 1974; Grunwald 2009; Hartemink 2016; see Jenny 1941, 6).

Landscapes and their elements are sometimes considered spatially homogeneous and therefore indivisible (Neef 1967). However, the point of view is more widespread, according to which landscapes and their landscape elements are spatially heterogeneous formations (Brown et al. 2002; Forman and Godron 1981; Olson 1995; Pickett and Cadenasso 1995; Urban et al. 1987).

Elements of anthropogenic-natural (human-modified) landscape systems can include population (Neef 1967), artificial structures, the elements of land use and their connections (Miklós et al. 2019, 11).

2.2.4 Structure of landscape systems

Usually, vertical (layered) and horizontal (spatial, morphological) structures of landscape systems are distinguished. The vertical structure is understood as a set of landscape elements that form an ordered sequence of geohorizons, as well as vertical connections between them (Nikolaev 2006, 27). When classifying landscapes, a vertical structure is used as a differentiating criterion. For example, Rikhter (1969) divides landscapes into terrestrial, water, terrestrial-ice, etc. The horizontal structure of landscape systems refers to the composition and horizontal organization of landscape elements, including morphological components (Wu 2012), the spatial pattern of landscape elements and the connections between them and ecosystems (Gökyer 2013), a certain set of relationships between landscape elements that are related to each other and form one complex system (Antrop 2000).

2.2.5 Examples of soil and landscape definitions containing key concepts of the SA

Conceptual and terminological confusion around the SA and its key concepts in soil science and landscape science is the reason for the absence of unified system definitions of natural soils and landscapes that fully meet the requirements of the SA. Therefore, here we give examples of those soil and landscape definitions, which, although they are not system, nevertheless contain some key system concepts (Table 4).

2.3. Existing ideas about the hierarchy of systems

As a rule, both soil and landscape systems are considered to be hierarchically organized. At the same time, ideas about

		Material objects:		
Rocks (parent material and subsoil)		"the upper part of the earth's crust"		(Solntsev 1948)
		"geological subsoil"		(Neef 1967)
		"the geological base"		(Miklós et al. 2019, 11)
		"soil creating substratum"		(Miklós et al. 2019, 11)
		"solid inorganic elements"		(Hole,1978)
Air		"masses of surface air"		(Solntsev 1948)
		"air"		(Miklós et al. 2019, 11)
		"gas inorganic elements"		(Hole 1978)
Water		"natural water"		(Solntsev 1948)
		"water bodies"		(Miklós et al 2019, 11)
		"liquid inorganic elements"		(Hole 1978)
Organisms	plant	"vegetation"		(Solntsev 1948)
		"flora"		(Miklós et al. 2019, 11; Neef 1967)
	animal	"wild animals"		(Solntsev 1948)
		"fauna"		(Miklós et al. 2019, 11; Neef 1967)
	plant and animal	"organic elements"	"biota"	(Hole 1978)
			"dead organic material"	(Hole 1978)
Soils		"soils"		(Miklós et al. 2019, 11; Neef 1967; Solntsev 1948)
		Properties of material objects:		
Properties of rocks (parent material and subsoil)		"relief"		(Neef 1967)
		"landforms"		(Pichugina 2010)
		components of slope ("gradient", "curvature")		(Schaetzl 2013)
		"lithological composition of rocks"		(Pichugina 2010)
		"permeability of rocks"		(Schaetzl 2013)
Properties of water		"depth to water table"		(Schaetzl 2013)
Properties of plant organisms		"layers of vegetation"		(Pichugina 2010)
		Ecosystems		(Forman 1995a, 13; Forman 1995b; King 2005)
		Regimes:		
		"climate" (long-term weather regime)		(Neef 1967)
		"tectonic regime"		(Pichugina 2010)

Table 3. What is meant by elements of natural landscape systems in soil science and landscape science.

Soil	"not only a product of the interaction of organisms and rocks, but also a system of these interactions"	(Polynov 1934)
	"a complex polyfunctional and polycomponent open multiphase structural system with fertility in the surface layer of the weathering crust of rocks, which is a complex function of rocks, organisms, climate, relief and time"	(Kovda and Rozanov 1988, 7)
	- "not merely the sum of minerals, organic matter, water and air, but the product of their interactions"	(Juma 1999)
	- "a complex open system, a natural body in which biosphere, lithosphere, atmosphere and hydrosphere come together".	(Ibáñez and Boixadera 2002)
Landscape	- a naturally constructed system of interconnected and interdependent smaller natural territorial complexes.	(Solntsev 1948)
	- a natural combination of geographic components (relief, climate, surface water, soils, vegetation, fauna), which are in complex interaction and interdependence and form a single inextricable system.	(Kalesnik 1968)
	- a heterogeneous land area composed of a cluster of interacting components that is repeated in a similar format throughout.	(Olson 1995)
	- "a complex whole that is more than the sum of its composing parts".	(Antrop 2000)
	- a geosystem of the regional dimension, consisting of interconnected local geosystems formed on a single morphostructure and in a specific climate.	(Nikolaev 2006)
	- a complex system of space, location, georelief and other mutually, functionally interconnected material natural elements, in particular the geological base, soil creating substratum, soil, water bodies, air, flora and fauna, as well as their connections.	(Miklós et al. 2019)

Table 4. Examples of soil and landscape definitions containing key concepts of the SA.

this organization differ significantly. For example, according to Basher (1997), the hierarchy of soil systems can be represented as the following chain: soil profiles → pedons → toposequences → soil mapping units → landscapes, and according to Deikerman (1974), as another chain: soil continuum → soil landscapes → soil landscape bodies → soil horizons → macrostructural units (peds) → microstructural units. The seminal work on the application of the theory of hierarchy to landscape systems is considered the monograph by Allen and Starr (1982) (see King 2005). Urban et al. (1987), Klijn (1994), Wu and Loucks (1995), Brown et al. (2002) Francis et al. (2004), Nikolaev (2006, 17-20) and Reuter et al. (2010) also studied hierarchy of systems. For example, King (2005) defines a hierarchically organized system as "a system of ordered systems within systems" with different levels of organization, and Nikolaev (2006, 21) calls the landscape the nodal unit of the hierarchy of geosystems.

It is important to pay attention to the fact that both in soil science and landscape science, the concepts of "hierarchy of systems" and "classification hierarchy" (or "taxonomic hierarchy") are mixed with each other. For example, Nikolaev (2006, 27-28) writes: "From small to large, they [natural geosystems of various spatio-temporal scales] constitute a multi-stage system of taxa called the hierarchy of natural geosystems", which is presented as the following chain: landscape sphere - geographical belts – continents, oceans - subcontinents - physical-geographical countries - regions - provinces - districts - landscapes - [...]". However, the concept of "a multi-stage system of taxa" is not identical to concept the "hierarchy of natural geosystems".

3.0 The authors' experience in the application of the SA in soil science and landscape science

The realization of the need to use the SA in soil science and landscape science came to us when creating an agroecological ameliorative map at a scale of 1: 1,500,000, which was supposed to contain information not only on soils, but also on all soils-forming factors (or, in accordance with the terminology of the SA, essential properties of landscapes and their basic elements). To develop the legend of such a map, a hierarchical classification system was required that would systematically reflect soil-landscape relationships.

In developing the hierarchical classification system, called the Soil-Landscape Classification System (SLCS), the key was understanding how to capture the derived nature of soils so that it was not just a declaration. It turned out that for this it is necessary to divide landscapes with soils according to those essential properties of their basic elements that determine the essential properties of the associated soils. In this case, the division of landscapes is accompanied by the simultaneous division of soils, and instead of two classification systems (soil and landscape), we get one - soil-landscape.

The SLCS is based on the system concept of natural soils and landscapes developed by us. The main provisions of this concept are as follows:

- Natural landscape is a structurally organized developing material system, consisting of interacting and interdependent material elements and characterized by relatively homogeneous properties. A distinction is made between landscapes with soils (or soil landscapes) and landscapes without soils (for example, steep slopes, glaciers, blown sands). At the same time, natural landscape is an element (the minimum spatially homogeneous structural unit) of a higher order system, namely the landscape sphere.
- Natural soil is a structurally organized developing material system, consisting of interacting and interdependent elements, namely the mineral skeleton, water, air and organisms (living and dead) of the soil. At the same time, natural soil is a derived element of the natural landscape system, as it arises only because of the interaction of the basic landscape elements, namely rocks (parent material and subsoil), air, natural waters, living and dead organisms. It is also characterized by relatively homogeneous properties.
- There are no landscapes without basic elements, but there are landscapes without derived element (soil).
- In a vertical section, horizontal layers of landscape elements are arranged in a certain order relative to each other, forming a vertical structure, which affects interaction and, as a consequence, the properties of landscapes and their elements.
- All natural landscapes without soils have one emergent property: the emergence of conditions favourable for the existence of life on the Earth.
- All natural soil landscapes have one emergent property: the emergence of conditions favourable for the existence and development of life on the Earth.
- All natural soils have one emergent property: biogenic accumulation of chemical elements under the influence of vegetation.
- All natural landscapes (both with and without soils) are systems of the same order, so they occupy the same level in the hierarchy of systems.
- Compared to landscape systems, soil systems are systems of a lower order..
- The boundaries of the natural landscape and soil systems, as well as the boundaries of all basic landscape elements, coincide.
- Natural landscapes are the basis of anthropogenic-natural landscapes.

It was clear from the very beginning that the development of the SLCS was not possible outside of the multiscale soil-landscape GIS-mapping and a shared hierarchical information system (Kim et al. 2021). Figures 1a, 1b, and 1c show examples of the SLCS visualization within this information system. When considering this figure, it should be borne in mind that it reflects not the hierarchy of soil and landscape systems, but the levels of the SLCS, each of which contains landscape systems and associated soil systems. The fact is that the division of landscape systems in the process of classification leads to the simultaneous division of soil systems associated with these landscape systems, therefore soils and landscapes occupy the same classification levels (Nikiforova et al. 2019).

In the future, such an information system will allow not only the development, visualization and use of the SLCS, but also the global integration of information on soils and landscapes, including information on their evolution, sustainable management, protection and assessment. The main stages of applying the SA in soil science and landscape science, culminating in the global integration of information on soils and landscape, are shown in Figure 2.

A detailed description of our experience in the application of the SA in soil science and landscape science can be found in previously published articles (Fleis et al. 2016; Nikiforova et al. 2020; Nikiforova 2019; Nikiforova et al. 2019; Nikiforova and Fleis 2018; Nikiforova et al. 2014), which substantiate the proposed ways of solving the problems of a unified definition, basic conceptual classification, and global multiscale mapping of soils and landscapes from the standpoint of the SA.

4.0 Conclusion

Despite the widespread recognition of the need to apply the SA in soil science and landscape science, it remains unrealized. This is evidenced by the consideration of soils primarily as separate systems, and not as derived elements of the higher order systems (soil landscapes), the mixing of the basic landscape elements with their properties, the recognition of the spatial heterogeneity of landscape systems and their elements, different interpretation of emergent properties, structure and hierarchy of soil and landscape systems, and, as a result, the absence of unified system definitions of soils and landscapes that would be used for their classifica-

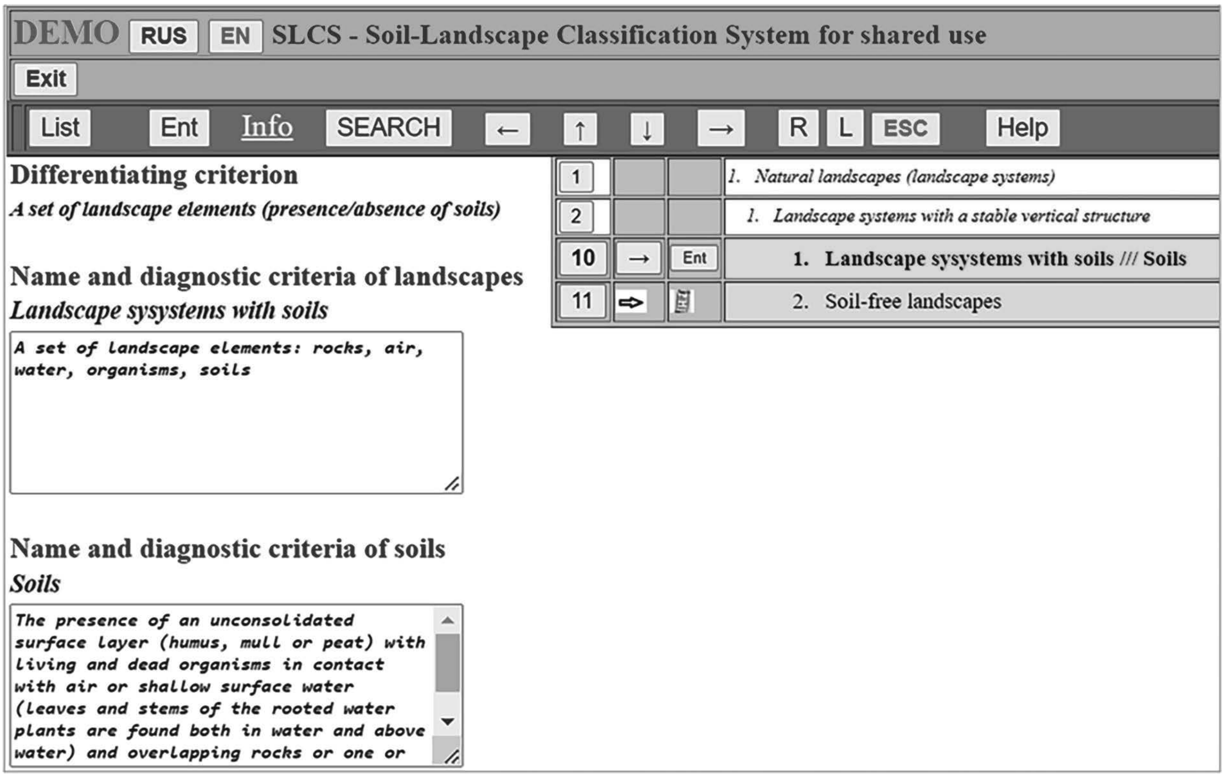

Figure 1a.

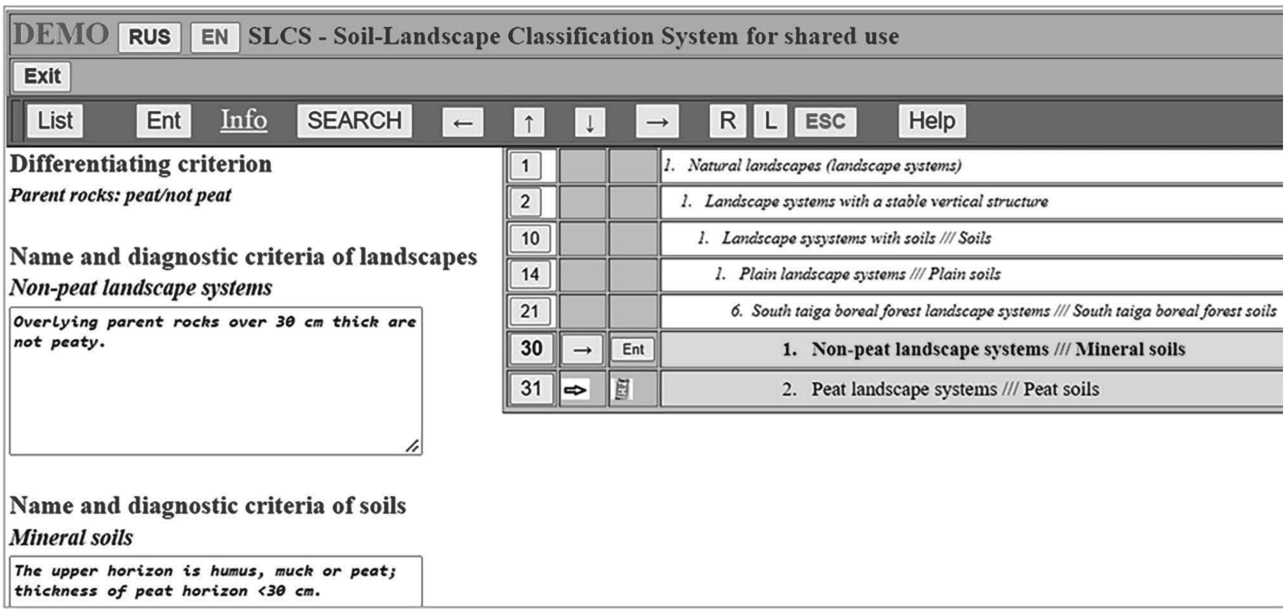

Figure 1b.

tion and mapping. Meanwhile, the SA, when properly applied, can help in solving topical theoretical and, therefore, practical problems of soil science and landscape science, and above all, the development of a basic conceptual classification system, global multiscale expert GIS-mapping, and a hierarchical decision-making system for sustainable management, protection and assessment of soils and landscapes. It is clear that the solution of these problems will mean the transition of soil science and landscape science to a qualitatively new, higher level of development.

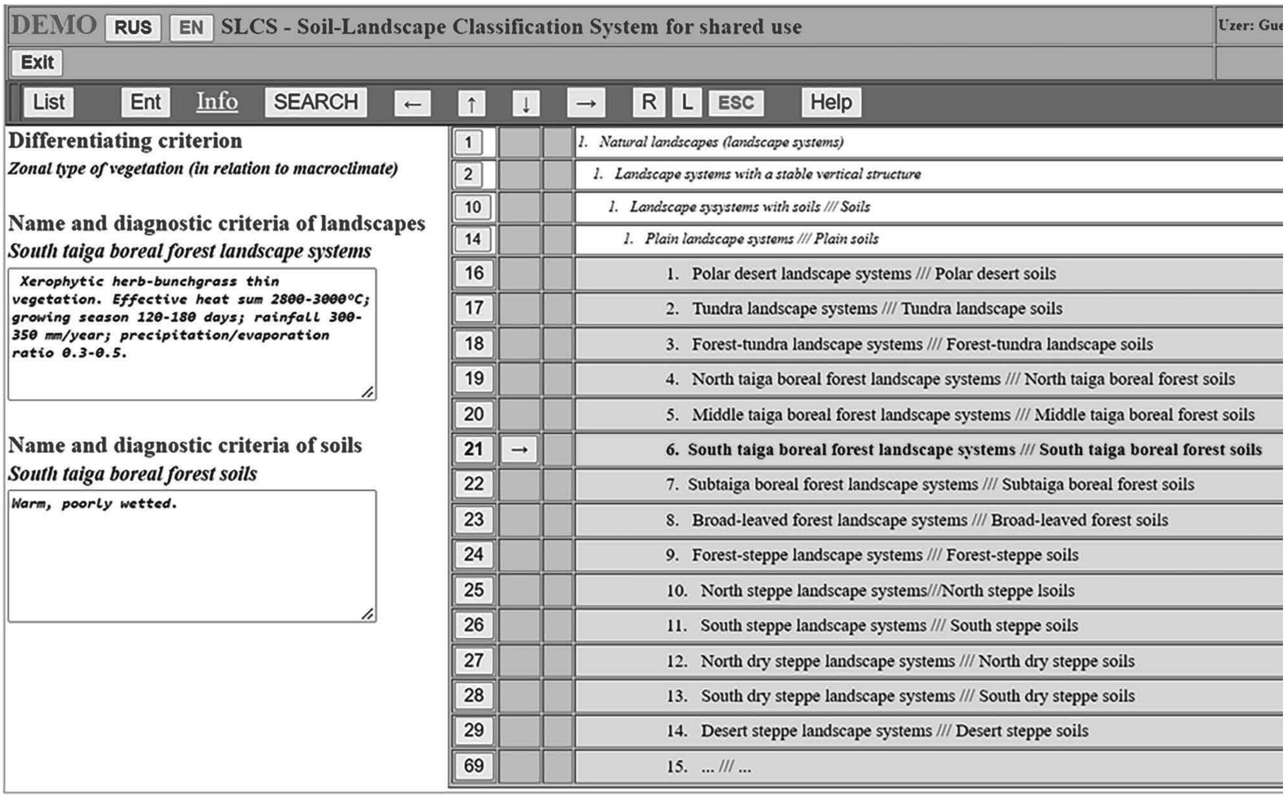

Figure 1c.

Figures 1a, 1b and 1c. Examples of visualization of the SLCS within the framework of a shared hierarchical information system.

Notes:
1. Lines with the names of landscapes and associated soils of interest to the user are highlighted in yellow.
2. The two boxes on the left show differentiating and diagnostic criteria of landscapes and associated soils of interest to the user.
3. Beige-colored landscapes and associated soils are classified according to the same differentiating criterion as yellow-colored landscapes and soils.

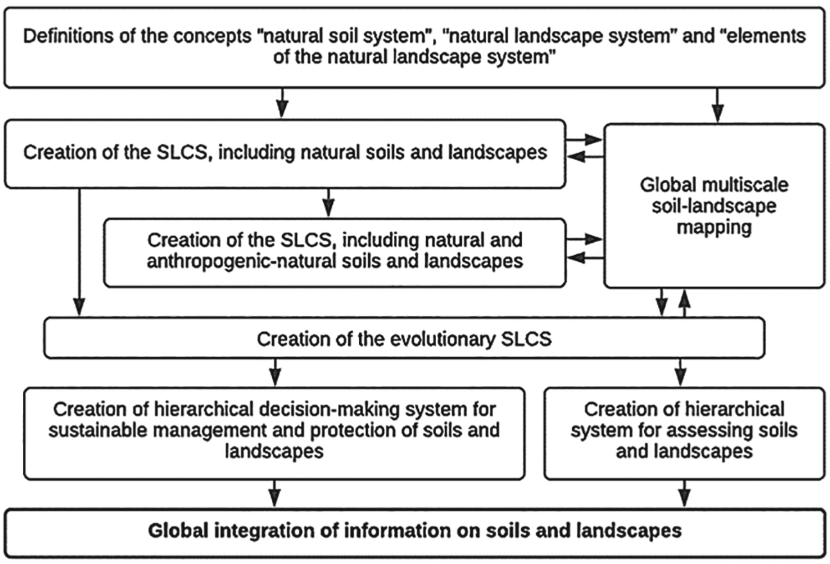

Figure 2. The main stages of applying the SA in soil science and landscape science.

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