ISSN 1064-2293, Eurasian Soil Science, 2017, Vol. 50, No. 3, pp. 263–275. © Pleiades Publishing, Ltd., 2017.
Original Russian Text © M.A. Smirnova, M.I. Gerasimova, 2017, published in Pochvovedenie, 2017, No. 3, pp. 275–288.

GENESIS AND GEOGRAPHY OF SOILS

Orders in the Soil Classification System of Russia: Taxonomic Distance as a Measure of Their Adequate Identification

M. A. Smirnova and M. I. Gerasimova*
Lomonosov Moscow State University, Moscow 119991, Russia
**e-mail: summerija@yandex.ru*
Received June 27, 2016

Abstract—Taxonomic distances between pairs of soil orders in the Russian soil classification system have been calculated using a methodology suggested for calculation of taxonomic distances between the Reference Soil Groups in the international soil classification system (WRB). Basing on the data obtained, some proposals for the development of the Russian soil classification system have been formulated. Most of the orders are characterized by considerable taxonomic distances between them, and their identification in the classification system is doubtless. Small taxonomic distances are characteristic of the following pairs of orders: organo-accumulative and structural-metamorphic soils, hydrometamorphic soils and lithozems, and cryometamorphic and eluvial soils. Therefore, criteria for defining some orders, and/or profile formulas for some soil types composing the orders may be revised. The comparison of taxonomic distances between soil orders in the Russian system and between Reference Soil Groups in the international system allows us to suggest their certain similarity.

Keywords: diagnostic properties, Mahalanobis distance, elementary soil processes, WRB
DOI: 10.1134/S1064229317030115

INTRODUCTION

When discussing the principles of a substantive-genetic classification of soils of Russia, the main attention is usually paid to its central unit—genetic soil type, in which substantive criteria are strictly implemented according to the principle: system of diagnostic horizons—>soil type. The next level above the type—soil orders—is identified following the principle of "...integrity of the main soil-forming processes that are manifested in the formation of a horizon common for all the soils of the order" [3, p. 8]. The idea of processes as criteria for specifying orders is inherited by this classification from the system of three-component basic classification developed by Fridland [5], where processes create "the main elements of soil profile", i.e., horizons.

Orders in the classification system by V.M. Fridland and in the new classification system of Russian soils are close in their essence and number. Moreover, in the authorial, some national classifications, and different versions of the World Reference Base for Soil Resources (WRB), the number of high-level units is close to 30. In the latest version of WRB (2014) [14], there are 32 Reference Soil Groups (RSG). If we exclude six tropical RSGs, the number of RSGs is the same as the number of orders in the classification of soils of Russia. The criteria for their identification are diagnostic horizons, while soil-forming processes perform the function of "... better characterization of soils..." in the WRB [p. 4; 14], whereas in the Russian system, they are responsible for the formation of a diagnostic horizon common for all soils of an order [3].

One of the disputable questions, when developing soil classifications, is "correctness" or objectivity of allocating soils to a certain taxonomic group. Many soil scientists point to the expediency, even the necessity of using mathematical methods in the development of a classification system and for its assessment [4, 9, 11, 12, 18]. In the recent decades, various approaches to analyzing the objectivity of existing classifications partly borrowed from biology have been suggested. Among them, the approach based on the calculation of taxonomic distances attracts particular attention.

The calculation of taxonomic distances (Mahalanobis distance) is a mathematical procedure, which serves as a measure of similarity between the objects. For the first time, this procedure was used in anthropology to identify the similarity of human craniums, including those of people who lived in different geographical regions [17]. Since then, it has been used in biological and geographical studies.

In respect to soils, the calculation of taxonomic distances was first made in the 1960s, when some researchers [7, 10, 22] identified taxonomic groups by morphological, chemical, physical, and physicochemical properties (about 30 properties) and developed soil classifications for small areas. Estimates of taxonomic distances were used for the spatial analysis of the data [19, 23]: creation of digital soil maps, quantification of pedodiversity [20, 24], and for grouping soils [4, 8, 21, 26]. In the recent decades, another trend in the application of this procedure—analysis of existing soil classifications—has been shaped. Thus, taxonomic distances were calculated for orders in the classification of Australian soils [19], Reference Soil Groups in WRB [20], soil types in the Hungarian classification [18], and subgroups in the Irish soil classification [23]. National soil classification systems and the WRB were correlated with the use of Mahalanobis distance [16, 25]. The calculation of taxonomic distances contributed to the improvement of the Hungarian soil classification [9, 15, 16, 18]: the number of soil types was reduced from 39 to 15 mainly due to merging soils with minimal values of taxonomic distances.

The aim of this work is to control the correctness of identifying orders in terms of their individual properties, i. e. their "isolation" or remoteness from other orders on the basis of the taxonomic distances calculated between twenty-six[1] orders from the classification of soils of Russia. The paper presents possible proposals for the progress of this classification concerning some orders.

METHODS

The calculation of taxonomic distances (TDs) between orders was carried out according to the procedure proposed in 2010 [20] for the Reference Soil Groups in the WRB version of 2006 [14]. The procedure comprised creation of a matrix of key soil attributes identifying RSGs in the key, calculation of Mahalanobis distance between vectors—columns of the matrix of key attributes, and the construction of a matrix of taxonomic distances between the pairs of RSGs.

The attributes, as the analysis of publications showed, were selected more often according to the key. The matrix of attributes should contain soil properties that allow identifying soil taxa sequentially, namely, the RSGs in the WRB, their analogs in the soil classification of Australia [13], and families in "Soil Taxonomy" [24]. The Hungarian and Irish classifications were verified basing on the matrix with features of the leading soil-forming processes.

In accordance with the key for soil orders that were developed by N.B. Khitrov for the Field Guide of Russia soils, twenty-five soil properties important for diagnostics were selected [3]. Table 1 shows the presence (1) or absence (0) of each property in the soils of an order. It was accepted that sets of properties included into the table adequately describe the soils of orders, and the properties have equal weight, i. e. the procedure was analogous to the method for the assessment of TD between 30 RSGs[2] in the WRB system [14]. A taxonomic distance between soil orders was calculated by the formula [20]:

$$d_{ij} = \sqrt{(x_i - x_j)^T (x_i - x_j)},$$

where d_{ij} is the taxonomic distance between soil orders i and j; x_i and x_j are the vectors-columns of soil properties. The values of d_{ij} are the elements of the matrix of taxonomic distance between soil orders i and j (Fig. 1). The tightness of the relationship between the orders is inversely proportional to the values of taxonomic distance. The highest value of TD corresponds to the number of key soil properties in the matrix. In our case, their number was 5, since the soils were ranked by twenty-five properties. For all orders, modal and minimal TD values were calculated (Table 2).

In addition to the evaluation of taxonomic distances by soil properties, the same procedure was performed for indications of elementary soil-forming processes (ESP). As a generally accepted "standard" to describe ESPs, a description from the monograph of the Institute of Geography of the Russian Academy of Sciences [6] was used. Some processes that are characterized in the monograph, for instance, the input of organic matter, proceed almost in all soils; consequently, they do not have a special importance as differentiating criteria between orders. Therefore, these ESPs were not included into the matrix of key attributes. The presence (1) or absence (0) of a process in the soils of an order was recorded in the following ways: (i) by its mentioning in the description of the order in the text of the classification [2, 3]; (ii) by the prevailing ideas on the genesis of specific horizons (order markers), and (iii) by the assemblage of soil types in the order produced by the combinations of different ESPs, including the major one. For instance, the common feature for all the soils in the order of structural-metamorphic soils is the structural-metamorphic BM horizon, which is derived of [6] the combination of the following events: disintegration of solids, their re-arrangement to produce pedogenic structure, and transformation of clay minerals. The BM horizon, as compared to the parent rock, usually has higher chroma and value in its color due to the newly formed iron oxide and hydroxide minerals, which testifies to the participation of ESPs of brunification and rubification [6]. In addition, the presence of the AEL and BEL horizons in the soils of the order shows that processes of lessivage and partluvation are possible. Under temporary excessive moistening, gleying, gley-induced migration of iron and manganese occur; other processes may be supplementary: carbonatization, segregation of secondary carbonates (BCA horizon), and agrogenic pedoturbation of the soil mass (P and PU horizons).

[1] The order of chemozems was not considered, since in the opinion of the authors and users of the classification, it needs revision.

[2] Minasny with co-authors [20] calculated TDs for 30 RSGs; their calculations did not include Technosols and Stagnosols in accordance with WRB-2006 [14].

Table 1. Key attributes of soils in orders

	Key soil properties of orders	Orders																									
		P	Pz	Al	V	Str	Td	Al-Fe	Mfe	Mstr	CrM	Mpale	Cr	G	AcH	LHac	ACld	Hal	HM	OAc	El	Lith	Abr	AAbr	Az	Tz	Wdev
Horizons present in the soil profile	Peat >50 cm	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Humus or organic	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	0	0	0	1	1
	RY or RU or RJ	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Agro-horizon (except for PB)	0	1	1	1	1	1	1	0	1	0	1	0	1	1	0	1	0	1	1	1	1	0	0	1	0	
	Any eluvial	0	0	0	1	0	1	1	0	1	1	0	0	0	0	0	1	0	0	0	1	0	0	0	1	1	0
	S or SS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1
	BFM	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
	BPL	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
	CR	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	CRM	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0
	ASN/BSN	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	1	1	0
	BHF	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0
	BT	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
	BM	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	1	1	1	0	0
	BCA	0	0	0	0	0	0	0	0	0	0	1	0	0	1	1	1	0	0	0	0	0	1	1	1	1	0
	BI	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	1	1	1	0
	V	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
	CAT	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	1	1	1	1	0
	BMK	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
	G	1	1	1	0	0	1	1	0	0	0	0	0	1	1	0	0	1	0	0	0	0	0	1	1	1	0
	Q	0	0	1	0	0	1	0	0	0	0	0	0	0	1	0	1	0	1	0	0	0	0	1	1	1	0
	TUR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0
Volcanic ash in BAN horizon		0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hard rock within 30-cm layer		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1
Recent alluvium within floodplain		0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1

Hereinafter, the following letter symbols are used for soil orders: P—peat, Pz—torfozems, Al—alluvial, V—volcanic, Str—stratified; Td—texturally differentiated, Al-Fe—Al–Fe-humus, Mfe—iron-metamorphic, Mstr—structural-metamorphic, CrM—cryometamorphic, Mpale—pale-metamorphic, Cr—cryogenic, G—gley, AcH—humus-accumulative, LHac—low-humus carbonate-accumulative, ACld—alkaline clay-differentiated, H—halomorphic, HM—hydrometamorphic, Oa—organo-accumulative, El—eluvial, Lith—lithozems, Abr—abrazems, AAbr—agroabrazems, Az—agrozems, Tz—turbozems, Wdev—weakly developed.

Orders	P	Pz	Al	V	St	Td	Al-Fe	Mfe	Mstr	CrM	Mpale	Cr	G	AcH	LHac	ACld	Hal	HM	OAc	El	Lith	Abr	AAbr	Az	Tz	Wdev
P	0	1	2.24	2.24	2.24	2.24	2.00	1.73	2.24	2.24	2.24	1.73	1.73	2.65	2.45	2.65	1.73	2.00	1.73	2.00	2.00	3.46	2.82	3.46	3.00	2.24
Pz	1	0	2.00	2.00	2.00	2.00	1.73	2.00	2.00	2.45	2.00	2.00	1.41	2.45	2.65	2.45	2.00	1.73	1.41	1.73	1.73	3.61	3.00	3.32	2.83	2.45
Al	2.24	2.00	0	2.45	2.45	2.45	2.24	2.45	2.45	2.83	2.45	2.45	2.00	2.00	3.00	2.45	2.45	1.73	2.00	2.24	2.24	3.87	3.00	3.32	2.83	2.45
V	2.24	2.00	2.45	0	2.00	2.00	1.73	2.00	1.41	2.00	2.00	2.00	2.00	2.83	2.65	2.00	2.45	1.73	1.41	1.00	1.73	3.61	3.32	3.32	2.83	2.45
St	2.24	2.00	2.45	2.00	0	2.45	2.24	2.00	2.00	2.45	2.00	2.00	2.00	2.83	2.65	2.45	2.00	1.73	1.41	1.73	1.73	3.32	3.00	3.32	3.16	2.45
Td	2.24	2.00	2.00	2.00	2.45	0	1.73	2.45	2.00	2.00	2.45	2.45	2.00	2.45	3.00	2.00	2.45	1.73	2.00	1.73	2.24	3.87	3.00	2.65	2.45	2.83
Al-Fe	2.00	1.73	2.24	1.73	2.24	1.73	0	2.24	1.73	2.24	2.24	2.24	1.73	2.65	2.83	2.24	2.24	2.00	1.73	1.41	2.00	3.46	2.83	3.16	2.65	2.65
Mfe	1.73	2.00	2.45	2.00	2.00	2.45	2.24	0	2.00	2.00	2.00	1.41	2.00	2.83	2.24	2.45	2.00	1.73	1.41	1.73	1.73	3.00	3.00	3.61	3.16	2.00
Mstr	2.24	2.00	2.45	1.41	2.00	2.00	1.73	2.00	0	2.00	2.00	2.00	2.00	2.83	2.24	2.00	2.45	1.73	1.41	1.00	1.73	3.32	3.00	3.00	2.83	2.45
CrM	2.24	2.45	2.83	2.00	2.45	2.00	2.24	2.00	2.00	0	2.45	2.00	2.00	3.16	2.65	2.45	2.45	2.24	2.00	1.73	2.24	3.32	3.32	3.32	3.16	2.45
Mpale	2.24	2.00	2.45	2.00	2.00	2.45	2.24	2.00	2.00	2.45	0	2.00	2.00	2.45	2.24	2.00	2.45	1.73	1.41	1.73	1.73	3.00	3.00	3.32	2.83	2.45
Cr	1.73	2.00	2.45	2.00	2.00	2.45	2.24	1.41	2.00	2.00	2.00	0	2.00	2.83	2.24	2.45	2.00	1.73	1.41	1.73	1.73	3.32	3.00	3.61	3.16	2.00
G	1.73	1.41	2.00	2.00	2.00	2.00	1.73	2.00	2.00	2.00	2.00	2.00	0	2.45	2.65	2.45	2.00	1.73	1.41	1.73	1.73	3.32	3.00	3.32	2.83	2.45
AcH	2.65	2.45	2.00	2.00	2.83	2.45	2.65	2.83	2.83	3.16	2.45	2.83	2.45	0	2.65	2.45	2.83	2.24	2.45	2.65	2.65	3.32	2.24	2.65	2.00	3.16
LHac	2.45	2.65	3.00	2.65	2.65	3.00	1.83	2.24	2.24	2.65	2.24	2.24	2.65	2.65	0	2.65	2.65	2.45	2.24	2.45	2.45	2.83	2.45	3.16	3.00	2.65
ACld	2.65	2.45	2.45	2.00	2.45	2.00	2.24	2.45	2.00	2.45	2.00	2.45	2.45	2.45	2.65	0	2.83	1.73	2.00	1.73	2.24	3.32	3.00	2.65	2.00	2.83
Hal	1.73	2	2.45	2.45	2.00	2.45	2.24	2	2.45	2.45	2.45	2.00	2.00	2.83	2.65	2.83	0	2.24	2.00	2.24	2.24	3.32	2.65	3.32	3.16	2.00
HM	2.00	1.73	1.73	1.73	1.73	1.73	2.00	1.73	1.73	2.24	1.73	1.73	1.73	2.24	2.45	1.73	2.24	0	1.00	1.41	1.41	3.46	2.83	3.16	2.65	2.24
OAc	1.73	1.41	2.00	1.41	1.41	2.00	1.73	1.41	1.41	2.00	1.41	1.41	1.41	2.45	2.24	2.00	2.00	1.00	0	1.00	1.00	3.32	3.00	3.32	2.83	2.00
El	2.00	1.73	2.24	1.00	1.73	1.73	1.41	1.73	1.00	1.73	1.73	1.73	1.73	2.65	2.45	1.73	2.24	1.41	1.00	0	1.41	3.46	3.16	3.16	2.65	2.24
Lith	2.00	1.73	2.24	1.73	1.73	2.24	2.00	1.73	1.73	2.24	1.73	1.73	1.73	2.65	2.45	2.24	2.24	1.41	1.00	1.41	0	3.46	3.16	3.46	3.00	1.73
Abr	3.46	3.61	3.87	3.61	3.32	3.87	3.46	3.00	3.32	3.32	3.00	3.32	3.32	3.32	2.83	3.32	3.32	3.46	3.32	3.46	3.46	0	2.45	3.16	3.32	3.61
AAbr	2.82	3.00	3.00	3.32	3.00	3.00	2.83	3.00	3.00	3.32	3.00	3.00	3.00	2.24	2.45	3.00	2.65	2.83	3.00	3.16	3.16	2.45	0	2.45	2.65	3.32
Az	3.46	3.32	3.32	3.32	3.32	2.65	3.16	3.61	3.00	3.32	3.32	3.61	3.32	2.65	3.16	2.65	3.32	3.16	3.32	3.16	3.46	3.16	2.45	0	1.73	3.87
Tz	3.00	2.83	2.83	2.83	3.16	2.45	2.65	3.16	2.83	3.16	2.83	3.16	2.83	2.00	3.00	3.00	3.16	2.65	2.83	2.65	3.00	3.32	2.65	1.73	0	3.46
Wdev	2.24	2.45	2.45	2.45	2.45	2.83	2.65	2	2.45	2.45	2.45	2	2.45	3.16	2.65	2.83	2.00	2.24	2.00	2.24	1.73	3.61	3.32	3.87	3.46	0

Taxonomic distances

0   1–2   2–3   >3

Fig. 1. Taxonomic distances between orders (calculation based on soil properties).

Thus, assessment of taxonomic distances based on ESP is implemented according to specific features of these processes that manifest themselves in soil types and subtypes of the order; their interpretation and terminology are based on the monograph on processes [6] (Table 3, Fig. 2).

RESULTS AND DISCUSSION

Of the two ways to calculate the taxonomic distances between orders, namely, using soil properties and ESP indications, the first way was accepted as the main one. It is more common, better controlled, and more unbiased, since the properties are fixed in the definitions of horizons.

The use of soil properties for calculating taxonomic distances basing on the key for orders has the advantage of reliable choice of properties as attributes, since in the key, the properties important for the diagnostics of the orders have already been selected. These are mostly diagnostic horizons, and the mid-profile horizons (subsoils) predominate among them. Nineteen attributes of twenty-five ones refer to the mid-profile horizons, four attributes are characteristic of the topsoils, and only two properties can be conventionally qualified for "factor" attributes (continuous rock close to the surface, and position of the object on the floodplain). The number of attributes, i. e. the presence of diagnostic horizons in the soils of the order is 4–5. More attributes correspond to more complicated profiles of soils in the order (for instance, texturally differentiated and alkaline clay-differentiated soils), or to many soils in the order having one common and many different horizons (Table 1). The latter case is illustrated by four orders of strongly disturbed soils: agrozems, agroabrazems, abrazems, and turbozems. These soils are integrated in orders by the presence of one of the agro-horizons associated with any mid-profile horizon. The criterion for the turbozems order is the combination of morphons, i.e., fragments of horizons that were displaced and mixed below the agro-horizon by deep ameliorative tillage or ripping.

Abrazems can be either anthropogenic, or natural; they are grouped into an order basing on the outcropping of any of the mid-profile horizons (or its fragments) on the surface. As there are many subsoils in the system, the abrazem order comprises ten soil types. For the same reason, the order of agrozems contains many soils, more than that of abrazems, owing to the combinations of several mid-profile horizons with one of two agro-horizons (19 soil types). Thus, four orders (abrazems, agroabrazems, agrozems, and turbozems) are similar in terms of pedogenetic mechanisms: any well-pronounced mechanical disturbance of the soil profile. In addition, they have similar horizonation: agro-horizon (except for abrazems) + any mid-profile horizon. These orders are far from one another genetically and geographically, and the number of attributes taken into account varies from 7 to 11 at the expense of subsoils (Table 1).

Table 2. Taxonomic distances between orders (calculation based on soil properties): mode and minimum

Orders	Mode	Minimum
Organo-accumulative	1.41	1.00
Hydrometamorphic	1.73	1.00
Eluvial	1.73	1.00
Lithozems	1.73	1.00
Torfozems	2.00	1.00
Volcanic	2.00	1.00
Stratozems	2.00	1.41
Texturally differentiated	2.00	1.73
Iron-metamorphic	2.00	1.41
Structural-metamorphic	2.00	1.00
Cryometamorphic	2.00	1.73
Pale-metamorphic	2.00	1.41
Cryozems	2.00	1.41
Gley	2.00	1.41
Halomorphic	2.00	1.73
Peat	2.24	1.00
Al–Fe-humus	2.24	1.41
Alluvial	2.45	1.73
Alkaline clay-differentiated	2.45	1.73
Weakly developed	2.45	1.73
Humus- accumulative	2.65	2.00
Low-humus carbonate-accumulative	2.65	2.24
Turbozems	2.83	1.73
Agroabrazems	3.00	2.24
Abrazems	3.32	2.45
Agrozems	3.32	1.73

The minimal (2) number of attributes (horizons) falls on halomorphic soils, rzhavozems, cryozems, organo-accumulative soils, and stratozems. The soils of the first two orders are formed within a narrow range of soil-forming conditions. Therefore, they have a limited number of soil types with similar properties, i.e. the orders are relatively uniform. Organo-accumulative soils, on the contrary, have a great number of soil types occurring in all environments due to the diversity of their upper horizons, which is not taken into account in the diagnostics of the order and matrix of attributes: any agro-horizon or natural topsoil is considered there. Soils in stratozems and organo-accumulative orders differ only by their upper horizons, either natural, or agro-horizons, hence, only two properties serve as attributes (Table 1).

The analysis of the table presenting soil properties assigned to orders shows that there are some controversial cases concerning the presence of a diagnostic horizon in the soils of orders. Some cases were noted when soil classification was discussed on the site or in publications. For instance, the presence of an agro-

Table 3. A matrix for attributes of processes (ESP) forming the properties of soils in orders

ESP	Orders*																									
	P	Pz	Al	V	Str	Td	Al-Fe	Mfe	Mstr	CrM	Mpale	Cr	G	AcH	LHac	ACld	Hal	HM	OAc	El	Lith	Abr	AAbr	Az	Tz	Wdev
Input of organic residues	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Transformation of organic residues	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	1	0
Humification	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0
Mineralization of organic matter	0	0	1	0	1	1	1	0	0	0	1	1	0	0	0	0	1	1	1	1	0	1	1	1	0	0
Complexation and migration of humus compounds	0	0	1	0	1	1	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	1	1	1	0	0
Immobilization of humus-mineral compounds	0	0	1	0	0	1	1	1	1	1	1	0	0	1	0	0	0	1	0	1	1	1	1	1	1	0
Disintegration (breakdown)	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0	0	0	0	0
Gypsum-formation	0	0	0	0	0	0	0	1	0	0	0	0	1	1	1	0	0	0	0	1	0	0	0	0	0	0
Carbonatization	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0
Brunification and rubification	0	0	1	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0
Clay formation	0	0	1	1	1	1	1	1	1	1	0	1	1	1	1	0	0	1	1	1	1	1	1	1	0	0
Transformation of clay minerals	0	0	1	0	1	1	1	0	1	0	1	1	0	0	0	0	0	0	1	0	0	0	0	1	0	0
Decomposition of clay silicates	0	1	1	1	1	0	1	1	1	1	0	0	1	1	1	0	0	1	0	0	1	0	1	1	0	0

Table 3. (Contd.)

ESP	Orders*																								
	P	Pz	Al	V	Str	Td	Al-Fe	Mfe	Mstr	CrM	Mpale	Cr	G	AcH	LHac	ACld	Hal	HM	OAc	El	Lith	Abr	AAbr	Az	Tz	Wdev
Structuring of soil mass	0	1	0	1	1	1	0	1	1	1	1	1	1	1	0	0	1	1	0	1	0	0	1	1	0	0
Pedoturbation of soil mass	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Gleying (reduced gley)	0	0	0	1	1	0	0	1	1	1	1	0	0	1	1	1	0	0	1	0	1	1	0	0	0	1
Mottled gleying (oxidized gley)	0	0	0	1	1	0	0	1	1	0	1	1	0	0	1	0	0	0	0	0	1	0	0	0	0	1
Sulfide gleying	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0
Sulfate gleying	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Migration of salts	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	1	1	0	0	0	0	0	0	0	0	1
Alkalinization and de-alkalinization	0	0	0	0	0	1	0	0	0	0	0	0	0	1	1	1	1	1	1	0	0	0	0	1	1	0
Migration of calcium	0	0	1	0	0	0	0	0	0	0	1	0	0	1	1	1	1	1	0	0	1	1	1	1	1	0
Al-Fe-humus migration	0	0	0	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0
Gley migration of iron and manganese	0	0	1	1	0	1	1	0	1	0	0	0	1	0	0	0	1	1	0	0	0	0	1	1	1	0
Partluvation	0	0	0	0	0	1	1	0	1	1	0	0	0	0	0	1	0	0	0	0	0	1	1	1	1	0
Lessivage	0	0	0	0	0	1	0	0	1	1	0	0	0	1	0	1	0	0	0	0	0	1	1	1	1	0
Oxidative segregation and cementation (Fe, Mn, Al, humus)	0	1	0	0	1	1	0	0	0	1	1	1	1	0	1	1	1	0	1	0	0	1	1	1	1	1
Calcareous segregation and cementation	0	0	1	0	0	0	0	0	1	0	1	0	0	1	1	1	0	1	0	0	1	1	1	1	1	0
Gypsum segregation and cementation	0	0	1	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	1	0	1	1	0
Salt segregation and cementation	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0

Orders	P	Pz	Al	V	St	Td	Al-Fe	Mfe	Mstr	CrM	Mpale	Cr	G	AcH	LHac	ACld	Hal	HM	OAc	El	Lith	Abr	AAbr	Az	Tz	Wdev
P	0	1.00	2.65	3.46	3.00	3.61	3.32	3.00	3.61	3.00	3.00	2.45	2.83	3.46	3.61	3.74	3.32	2.83	3.00	1.73	3.00	3.61	3.61	4.12	4.24	2.65
Pz	1.00	0	2.83	3.61	2.83	3.46	3.46	3.16	3.74	2.83	2.83	2.24	2.65	3.61	3.46	3.61	3.16	3.00	2.83	2.00	3.16	3.46	3.46	4.00	4.12	2.45
Al	2.65	2.83	0	3.61	3.16	3.74	3.74	3.74	3.46	3.46	2.83	3.32	3.32	3.00	3.16	3.61	3.74	2.65	3.46	3.16	3.16	3.46	3.74	3.46	3.61	3.74
V	3.46	3.61	3.61	0	3.32	3.00	2.65	2.24	3.32	3.32	3.32	3.16	3.46	4.00	3.87	4.47	4.58	4.00	3.00	3.00	3.32	3.87	3.32	3.61	3.46	3.61
St	3.00	2.83	3.16	3.32	0	3.74	4.00	3.16	3.46	2.83	2.45	3.00	3.00	3.61	3.16	3.32	3.74	3.87	2.83	3.16	3.16	3.74	4.24	4.24	4.36	2.83
Td	3.61	3.46	3.74	3.00	3.74	0	2.45	3.46	3.46	2.83	3.74	3.32	3.00	3.61	4.00	3.87	4.24	3.61	2.83	3.16	4.00	3.74	2.83	2.45	2.24	4.24
Al-Fe	3.32	3.46	3.74	2.65	4.00	2.45	0	2.83	3.16	3.16	3.74	3.00	3.00	4.12	4.24	4.58	4.47	3.61	3.16	2.83	3.46	3.74	2.45	2.83	2.65	4.00
Mfe	3.00	3.16	3.74	2.24	3.16	3.46	2.83	0	2.83	2.83	2.83	2.65	3.32	3.87	3.46	4.12	4.47	3.87	2.83	2.45	2.83	3.16	3.46	3.74	3.61	3.16
Mstr	3.61	3.74	3.46	3.32	3.46	3.46	3.16	2.83	0	2.83	2.83	3.61	3.87	3.32	3.16	3.61	4.69	3.87	3.46	3.74	2.83	2.83	3.16	3.16	3.32	3.74
CrM	3.00	2.83	3.46	3.32	2.83	2.83	3.16	2.83	2.83	0	2.45	2.65	3.00	3.32	3.16	3.32	4.24	3.87	2.45	2.83	3.16	2.83	3.46	3.46	3.32	3.16
Mpale	3.00	2.83	2.83	3.32	2.45	3.74	3.74	2.83	2.83	2.45	0	2.65	3.32	3.00	2.00	3.32	4.00	3.32	2.45	3.16	2.00	2.83	3.46	3.46	3.61	2.83
Cr	2.45	2.24	3.32	3.16	3.00	3.32	3.00	2.65	3.61	2.65	2.65	0	2.45	4.00	3.32	4.24	3.87	3.16	2.65	2.24	2.65	3.87	3.61	3.87	3.74	2.65
G	2.83	2.65	3.32	3.46	3.00	3.00	3.00	3.32	3.87	3.00	3.32	2.45	0	4.00	3.87	4.00	3.32	3.16	3.00	2.24	3.32	4.12	3.61	3.87	3.74	3.32
AcH	3.46	3.61	3.00	4.00	3.61	3.61	4.12	3.87	3.32	3.32	3.00	4.00	4.00	0	2.24	2.45	4.12	3.16	3.00	3.61	3.00	3.32	3.87	3.32	3.46	4.12
LHac	3.61	3.46	3.16	3.87	3.16	4.00	4.24	3.46	3.16	3.16	2.00	3.32	3.87	2.24	0	2.65	4.00	3.32	2.83	2.74	2.45	3.16	4.00	3.46	3.61	3.46
ACld	3.74	3.61	3.61	4.47	3.32	3.87	4.58	4.12	3.61	3.32	3.32	4.24	4.00	2.45	2.65	0	3.61	3.74	3.61	3.87	3.61	3.00	3.87	3.61	3.74	3.87
Hal	3.32	3.16	3.74	4.58	3.74	4.24	4.47	4.47	4.69	4.24	4.00	3.87	3.32	4.12	4.00	3.61	0	3.32	4.00	3.74	4.24	4.24	4.24	4.47	4.58	3.46
HM	2.83	3.00	2.65	4.00	3.87	3.61	3.61	3.87	3.87	3.87	3.32	3.16	3.16	3.16	3.32	3.74	3.32	0	3.32	3.00	3.00	4.12	3.61	3.61	3.74	3.61
OAc	3.00	2.83	3.46	3.00	2.83	2.83	3.16	2.83	3.46	2.45	2.45	2.65	3.00	3.00	2.83	3.61	4.00	3.32	0	2.83	2.83	3.46	3.46	3.16	3.32	3.16
El	1.73	2.00	3.16	3.00	3.16	3.16	2.83	2.45	3.74	2.83	3.16	2.24	2.24	3.61	3.74	3.87	3.74	3.00	2.83	0	2.83	3.74	3.46	4.00	3.87	3.16
Lith	3.00	3.16	3.16	3.32	3.16	4.00	3.46	2.85	2.83	3.16	2.00	2.65	3.32	3.00	2.45	3.61	4.24	3.00	2.83	2.83	0	3.46	3.46	3.74	3.87	3.16
Abr	3.61	3.46	3.46	3.87	3.74	3.74	3.74	3.16	2.83	2.83	2.83	3.87	4.12	3.32	3.16	3.00	4.24	4.12	3.46	3.74	3.46	0	2.83	2.83	3.24	3.46
AAbr	3.61	3.46	3.74	3.32	4.24	2.83	2.45	3.46	3.16	3.46	3.46	3.61	3.61	3.87	4.00	3.87	4.24	3.61	3.46	3.46	3.46	2.83	0	2.00	2.00	4.00
Az	4.12	4.00	3.46	3.61	4.24	2.45	2.83	3.74	3.16	3.46	3.46	3.87	3.87	3.32	3.46	3.61	4.47	3.61	3.16	4.00	4.74	2.83	2.00	0	1.00	4.47
Tz	4.24	4.12	3.61	3.46	4.36	2.24	2.65	3.61	3.32	3.32	3.61	3.74	3.74	3.46	3.61	3.74	4.58	3.74	3.32	3.87	3.87	3.00	2.24	1.00	0	4.58
Wdev	2.65	2.45	3.74	3.61	2.83	4.24	4.00	3.16	3.74	3.16	2.83	2.65	3.32	4.12	3.46	3.87	3.46	3.61	3.16	3.16	3.16	3.46	4.00	4.47	4.58	0

Taxonomic distances

0 | 1–2 | 2–3 | >3

Fig. 2. Taxonomic distances between orders (calculation based on ESP characteristics).

horizon in lithozems resulting in specifying the agrolithozem type seems doubtful. It is not clear whether so many turbozem types in the "*Guide*..., 2008" are expedient, since they are formed to a certain extent due to random combinations of anthropogenic impacts [3]. Nevertheless, to provide a fair measurement of taxonomic distances, the accounting of soil properties should be identical for all orders and performed for a particular classification version.

It is obvious that *the value of taxonomic distance reflects the apartness, or individuality of the order*, which is perceived as the degree of similarity/remoteness in relation to the other orders.

The calculations of taxonomic distances based on *soil properties* showed the following. The modal and minimal TD values were determined for each order (Table 2). The latter characterize the high proximity of the order to the other ones, i.e. its low individuality or apartness. In this case, a question of the correctness of its identification may be raised.

By the mode value, one can assume that a significant part of the orders is characterized by TDs close to two (i.e. orders often differ from the other ones by four attributes), and their identification is beyond doubt. Lower values may evidence an uncertainty and insignificant distinctions between orders. Thus, among the postlithogenic soils with low TDs, gley and quasigley soils are close, as well as organo-accumulative soils and lithozems. The differentiating criterion is the continuous hard rock close to the surface in lithozems, whereas the upper horizons are diverse in the soils of both orders. A strange, at first sight, similarity of organo-accumulative and eluvial soils is explained by the fact that eluvial soils are keyed out by the eluvial horizon in their profiles, while the topsoils are the same in soils of both orders. The highest modal TD values were obtained for four orders of disturbed soils (Table 2); the reasons were considered above. The closest to them were humus-accumulative and alkaline clay-differentiated soils (the average TD values are 2.5 and 2.7, respectively). The maximal remoteness of the disturbed soils from the others is in good agreement with the basic principle of classification—priority of diagnostic horizons in the identification of soil types.

The minimal values of TD in all soils repeat the modal values. Orders of eluvial and organo-accumulative soils are least individual, whereas abrazems, agroabrazems, and low-humus carbonate-accumulative soils differ from the rest ones to the greatest extent. Unlike soils with disturbed profiles, the remoteness of the order of low-humus carbonate-accumulative soils is ambiguous because chestnut soils—members of this order—are close to southern chernozems. However, the elevated TD values of the low-humus carbonate-accumulative soils order may be explained by specifying different sets of diagnostic horizons in these soils despite the small number of soil types in it (3); thus, the order seems to be heterogeneous.

Among other orders in the trunk of postlithogenic pedogenesis, the following pairs are characterized by the maximal TD values: cryometamorphic–humus-accumulative (3.16) and texture-differentiated–low-humus carbonate-accumulative (3.0).

The soils of the organogenic pedogenesis trunk—peat soils and torfozems—differ from one another (TD = 1) only in one property. Weakly developed soils (in the trunk of primary pedogenesis) are the closest to lithozems (TD = 1.73). Both pairs are quite logical from the standpoint of pedogenesis.

The soils of synlithogenic pedogenesis trunk—alluvial, volcanic soils, and stratozems—significantly differ from each other (TDs are 2.00–2.45); whereas, some postlithogenic soils (for instance, hydrometamorphic or organo-accumulative soils) are characterized by lower TD values relative to synlithogenic soils than synlithogenic soils among themselves. Synlithogenic soils occur sporadically and are geographical neighbors of the postlithogenic ones; they are also remote from abrazems (eroded soils), which emphasizes the genetic affinity of alluvial, volcanic soils and stratozems.

Calculation of taxonomic distance on the basis of elementary soil-forming processes generally confirms the results obtained, although there are some differences (Table 3, Fig. 2). As compared to the previous method, the obtained TD values are somewhat higher, the regularities are less distinct, and the disturbed soils are not so contrasting relative to other soils. On the whole, the TD values vary within a range of 2.2–4.8, amounting, on the average, to 3.5 vs 2.4, when calculations were derived of soil properties, since in the case of ESP, more attributes were involved. In addition, several ESPs can participate in the formation of any soil horizon. Agrozems and turbozems also significantly differ from other soils. An elevated apartness is noted for the orders of saline and weakly developed soils, chernozems, and texturally differentiated soils, and this is in good agreement with the generally accepted pedogenetic concepts and images of these soils in terms of ESP system. In other words, these orders have maximal sets of individual processes.

The analysis of the minimal values allows identifying groups of most similar orders (TD = 1). As in the case with the properties-based calculation of TD, the peat soils and torfozems differ only by one attribute. Close were turbozems and agrozems—soils subjected to mechanical impacts, mitigating the differences between initial natural soils. Organo-accumulative and eluvial soils that are characterized by small TD calculated using soil properties are substantially separated from other orders when the calculation was based on the ESPs.

The correctness of identification of soil orders is basically confirmed by calculations of taxonomic distances by both methods. Orders of full-profile soils with a great number of genetic horizons have medium

TD values, i.e. they are adequately discriminated by both methods. The differences between the pairs are more distinct in case of ESP variant, which agrees with the ”process” principles of specifying orders. Chernozems, low-humus carbonate-accumulative soils and cryozems are adequately identified. Small TDs were obtained for organo-accumulative and eluvial soils demonstrating the simplicity of their profiles and uniformity of their properties that are not important as differentiating criteria; the minimal values were obtained for peat soils and torfozems. Almost all the soil orders are maximally remote from abrazems and agroabrazems; the highest TD values were recorded in the pairs “abrazems–alluvial soils” and “abrazems–texturally differentiated soils”.

The obtained results were compared with data on the International Soil Classification—WRB-2006 [14]. Minasny et al. [20] estimated the taxonomic distances using similar methodology, i.e., basing on soil properties enumerated in the key. Twenty-one properties were selected for 30 RSGs. These groups have much in common with the orders [1]. The values of taxonomic distances between RSGs and orders vary little, which is related to the number of attributes involved, namely, 4–5 in both cases (Table 1 and 4).

The orders of disturbed soils were the most remote among those with high modal TD values, whereas among the RSGs, the rock-dependent soils differed mostly from the other soils. These are Arenosols on sands, Regosols on loamy rocks, and Leptosols (analogues of lithozems; hard continuous rock at the depth of 25 cm). The taxonomic distances between these RSGs and many others exceed 3. Histosols and Podzols are also characterized by high TD values, but in relation to a smaller number of groups (Fig. 3). The minimal TDs were recorded in the following pairs: Gleysols–Solonchaks, Fluvisols–Cambisols, Kastanozems–Vertisols, and Solonetzes–Luvisols and Albeluvisols, i.e. soils with the clay-illuvial horizon, which could be well explained from pedogenetic positions. Chernozems are most remote from Podzols, as well as from the above-mentioned rock-dependent soils; however, they are very close to Acrisols—acid yellow ferrallitic soils, which is strange. Solonetzes are far from Cryosols, but close to Luvisols (3.0 and 1.4, respectively). The low individuality is characteristic of Anthrosols and different tropical soils up to the absence of differences between Ferralsols and Lixisols, the central images of which can be referred conventionally to the soils of humid equatorial forests and savannas.

As distinct from the estimates made for the orders in the Russian system, for the RSG attributes, some individual soil properties and even soil-forming conditions are taken into account in the matrix; of minor importance are the diagnostic horizons. For instance, not only alluvial, sandy, peat, gley soils and solonchaks are confined to “floodplains or to the zone of tides and marshes”, but also Podzols and Cambisols. Histosols, Kastanozems, Chernozems, Phaeozems, and Cryosols were referred to soils with “thick organic horizons” (Fig. 3). As a result, TD becomes dependent on the number of RSG properties that, in our opinion, are defined not so strictly as compared to the properties used to construct a matrix of attributes for orders. Nevertheless, in WRB obviously individual parent-dependent RSGs are clearly separated. The rest (non-tropical) soils are identified by TD as individual (Podzols), as drastically differing from each other (Cryosols–Vertisols), and as having some similarity in their properties (Luvisols and Solonetzes). Sometimes, the result seems to be an artifact (small TDs of Anthrosols?).

The comparison with the results of assessing orders by the same methods showed their similarity: in both systems, there is a main massif of soils with moderate differences and groups of the soils that are more isolated from them. Among the latter in WRB are lithogenic soils; in the soil classification of Russia, disturbed soils. The majority of soils are characterized by TDs with the values from 2 to 3; the number of higher values (>3) is higher in the case of RSGs (22% vs 20%), that of lower values (<2) for the orders (19% vs 12%). This overall assessment permits to suggest that the individuality of RSGs and orders is quite comparable.

CONCLUSIONS

(1) Orders refer to the second taxonomic level in the Russian soil classification system, and their diagnostics suggest a definite soil-forming process, implemented in a horizon, which is present in all soil types within the order. In addition to the main process, other processes also form soil types in the orders: all the processes can be considered as combinations of ESPs. In other words, orders are reliably identified by the genetic closeness of the soils — their members.

(2) The accuracy of soil grouping to obtain uniform groups is assessed by taxonomic distances (Mahalanobis distance). The data on taxonomic distances between soils are important for the development and verification of soil classification, which was shown by some foreign researchers. The experience of using the calculation of taxonomic distances for the international soil classification (WRB) was successfully applied for the identical assessment of orders.

(3) The consideration of taxonomic distances between orders obtained by two methods of calculation (according to two groups of criteria) enables us to propose some supplements to the content of orders.

It is expedient to combine *the orders of peat soils and torfozems* and to identify types of drained soils — torfozems among peat soils along with existing types of natural soils; the same approach is used in other orders, where native soils are allocated together with their agrogenic analogues.

Table 4. Key attributes for characterizing Reference Soil Groups (WRB) [20]

Key soil properties	Histosols	Anthrosols	Cryosols	Leptosols	Vertisols	Fluvisols	Solonetzes	Solonchaks	Gleysols	Andosols	Podzols	Plinthosols	Nitisols	Ferrasols	Planosols	Chernozems	Kastanozems	Phaezems	Gypsisols	Durisols	Calcisols	Albeluvisols	Alisols	Acrisols	Luvisols	Lixisols	Umbrisols	Arenosols	Cambisols	Regosols
Soils with thick organic layers	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0
Strong human impact	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Ice-affected soils	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Shallow or strongly gravelly soils	0	0	0	1	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	1	1	1
Cracks and slick-ensides	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0
Floodplains and tidal marshes	1	0	0	0	0	1	0	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0
Alkaline soils	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	1	1	0	1	1	0	0	0	0	0	0	0	0	0
Salt enrichment	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	1	0	1	1	0	0	0	0	0	0	0	0	0	0
Groundwater affected soils	1	0	1	0	0	1	0	1	1	0	0	1	0	0	0	0	0	0	1	0	1	0	1	0	0	0	0	1	1	0
Allophanes or Al-humus complexes	0	0	0	1	0	0	0	0	0	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
Cheluviation and chilluviation	1	0	1	1	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	1	0	1
Accumulation of iron in hydro-morphic condi-tions	0	0	0	1	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dominance of kaolinite and R_2O_3	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0
Sharp textural contrast	0	0	1	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Accumulation of organic matter	1	1	0	0	1	0	1	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	1	0	0	0	0	0
Calcareous	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	1	0	0	0	1	0	0	0	0	1
Accumulation of silica	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0
Soils with a clay-enriched subsoil	0	0	0	0	0	0	1	0	0	0	0	1	1	1	1	1	0	0	0	0	0	1	1	1	1	1	0	0	0	0
Relatively young soils with an acidic dark top-soil	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1
Sandy soils	0	1	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
Moderately or poorly developed soils	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	1	1	1

Reference Soil Groups	Histoisols	Anthrosols	Cryosols	Leptosols	Vertisols	Fluvisols	Solonetzes	Solonchaks	Gleysols	Andosols	Podzols	Plinthosols	Nitisols	Ferralsols	Planosols	Chernozems	Kastanozems	Phaeozems	Gypsisols	Durisols	Calcisols	Albeluvisols	Alisols	Acrisols	Luvisols	Lixisols	Umbrisols	Arenosols	Cambisols	Regosols
Histoisols	0	2.65	1.73	3.32	3.00	2.45	2.83	2.24	2.24	2.83	2.83	3.00	2.83	2.83	2.83	2.24	2.65	2.00	2.83	3.32	2.83	2.45	2.65	2.65	2.83	2.83	3.00	3.00	2.45	3.16
Anthrosols	2.65	0	2.83	3.46	2.45	2.24	2.24	2.45	2.00	2.24	2.65	2.83	2.24	2.24	224	2.00	2.45	2.24	2.65	2.83	2.65	2.24	2.45	2.00	2.24	2.24	2.45	2.83	2.65	3.00
Cryosols	1.73	2.83	0	2.83	3.16	2.65	3.00	2.45	2.45	2.65	3.00	2.83	2.65	2.65	224	2.45	2.83	2.24	2.65	3.16	2.65	2.24	2.45	2.45	3.00	2.65	2.83	3.16	2.65	3.00
Leptosols	3.32	3.46	2.83	0	3.74	3.32	3.61	3.46	3.46	2.65	2.65	3.16	3.00	3.32	3.00	3.46	3.74	3.32	3.61	3.16	3.32	3.00	3.46	3.16	3.61	3.32	2.45	2.83	3.00	2.24
Vertisols	3.00	2.45	3.16	3.74	0	3.00	1.73	2.45	2.83	2.65	3.32	3.16	2.65	2.65	2.65	2.45	1.41	2.24	1.73	2.00	2.24	2.65	2.83	2.45	1.73	2.65	2.83	3.74	3.00	3.32
Fluvisols	2.45	224	2.65	3.32	3.00	0	2.83	1.73	1.73	2.45	2.45	2.65	2.45	2.45	2.45	2.65	3.00	2.83	2.45	2.65	2.45	2.45	2.24	2.24	2.83	2.45	2.24	2.24	1.41	2.83
Solonetzes	2.83	224	3.00	3.61	1.73	2.83	0	2.65	2.65	2.45	3.16	2.65	2.00	2.00	2.00	1.73	2.24	2.00	2.45	2.65	2.45	2.00	2.24	1.73	1.41	2.00	2.65	3.61	2.83	3.46
Solonchaks	2.24	2.45	2.45	3.46	2.45	1.73	2.65	0	1.41	2.24	2.65	2.45	2.24	2.24	224	2.45	2.45	2.65	1.73	2.45	2.24	2.24	2.00	2.00	2.65	2.24	2.45	2.83	1.73	3.32
Gleysols	2.24	2.00	2.45	3.46	2.83	1.73	2.65	1.41	0	2.24	2.65	2.45	2.24	2.24	224	2.45	2.83	2.65	2.24	2.83	2.24	2.24	2.00	2.00	2.65	2.24	2.45	2.45	1.73	3.32
Andosols	2.83	224	2.65	2.65	2.65	2.45	2.45	2.24	2.24	0	2.45	2.65	1.41	2.00	2.00	2.24	2.65	2.45	2.45	2.65	2.45	2.00	2.24	1.73	2.45	2.00	1.73	3.00	2.45	2.45
Podzols	2.83	2.65	3.00	2.65	3.32	2.45	3.16	2.65	2.65	2.45	0	2.65	2.45	2.83	2.83	3.00	3.32	2.83	3.16	3.32	2.83	2.45	3.00	2.65	3.16	2.83	2.65	2.24	2.45	2.45
Plinthosols	3.00	2.83	2.83	3.16	3.16	2.65	2.65	2.45	2.45	2.65	2.65	0	2.24	1.73	224	2.45	3.16	3.00	2.65	3.16	2.24	2.24	1.41	2.00	2.65	1.73	2.45	3.16	2.24	3.32
Nitisols	2.83	224	2.65	3.00	2.65	2.45	2.00	2.24	2.24	1.41	2.45	2.24	0	1.41	1.41	1.73	2.65	2.45	2.45	2.65	2.45	1.41	1.73	1.00	2.00	1.41	2.24	3.00	2.45	2.83
Ferralsols	2.83	224	2.65	3.32	2.65	2.45	2.00	2.24	2.24	2.00	2.83	1.73	1.41	0	1.41	1.73	2.65	2.45	2.45	2.65	2.45	1.41	1.00	1.00	2.00	0.00	2.24	3.32	2.45	3.16
Planosols	2.83	224	2.24	3.00	2.65	2.45	2.00	2.24	2.24	2.00	2.83	2.24	1.41	1.41	0	1.73	2.65	2.45	2.45	2.65	2.45	1.41	1.73	1.00	2.00	1.41	2.24	3.32	2.45	3.16
Chernozems	2.24	2.00	2.45	3.46	2.45	2.65	1.73	2.45	2.45	2.24	3.00	2.45	1.73	1.73	1.73	0	2.00	1.73	2.65	2.83	2.65	1.73	2.00	1.41	1.73	1.73	2.45	3.46	2.65	3.32
Kastanozems	2.65	2.45	2.83	3.74	1.41	3.00	2.24	2.45	2.83	2.65	3.32	3.16	2.65	2.65	2.65	2.00	0	1.73	2.24	2.00	2.24	2.65	2.83	2.45	2.24	2.65	2.83	3.74	3.00	3.32
Phaeozems	2.00	224	2.24	3.32	2.24	2.83	2.00	2.65	2.65	2.45	2.83	3.00	2.45	2.45	2.45	1.73	1.73	0	2.83	2.65	2.45	2.00	2.65	2.24	2.45	2.45	2.65	3.32	2.83	3.16
Gypsisols	2.83	2.65	2.65	3.61	1.73	2.45	2.45	1.73	2.24	2.45	3.16	2.65	2.45	2.45	2.45	2.65	2.24	2.83	0	2.24	2.00	2.45	2.24	224	2.00	2.45	2.65	3.32	2.45	3.16
Durisols	3.32	2.83	3.16	3.16	2.00	2.65	2.65	2.45	2.83	2.65	3.32	3.16	2.65	2.65	2.65	2.83	2.00	2.65	2.24	0	2.24	2.65	2.83	2.45	2.65	2.65	2.45	3.16	2.65	3.00
Calcisols	2.83	2.65	2.65	3.32	2.24	2.45	2.45	2.24	2.24	2.45	2.83	2.24	2.45	2.45	2.45	2.65	2.24	2.45	2.00	2.24	0	2.45	2.24	2.24	2.45	2.45	2.24	3.00	2.00	2.83
Albeluvisols	2.45	224	2.24	3.00	2.65	2.45	2.00	2.24	2.24	2.00	2.45	2.24	1.41	1.41	1.41	1.73	2.65	2.00	2.45	2.65	2.45	0	1.73	1.00	2.00	1.41	2.24	3.00	2.45	2.83
Alisols	2.65	2.45	2.45	3.46	2.83	224	2.24	2.00	2.00	2.24	3.00	1.41	1.73	1.00	1.73	2.00	2.83	2.65	2.24	2.83	2.24	1.73	0	1.41	2.24	1.00	2.45	3.16	2.24	3.32
Acrisols	2.65	2.00	2.45	3.16	2.45	224	1.73	2.00	2.00	1.73	2.65	2.00	1.00	1.00	1.00	1.41	2.45	2.24	2.24	2.45	2.24	1.00	1.41	0	1.73	1.00	2.00	3.16	2.24	3.00
Luvisols	2.83	224	3.00	3.61	1.73	2.83	1.41	2.65	2.65	2.45	3.16	2.65	2.00	2.00	2.00	1.73	2.24	2.45	2.00	2.65	2.45	2.00	2.24	1.73	0	2.00	2.65	3.61	2.83	3.16
Lixisols	2.83	224	2.65	3.32	2.65	2.45	2.00	2.24	2.24	2.00	2.83	1.73	1.41	0.00	1.41	1.73	2.65	2.45	2.45	2.65	2.45	1.41	1.00	1.00	2.00	0	2.24	3.32	2.45	3.16
Umbrisols	3.00	2.45	2.83	2.45	2.83	224	2.65	2.45	2.45	1.73	2.65	2.45	2.24	2.24	224	2.45	2.83	2.65	2.65	2.45	2.24	2.24	2.45	2.00	2.65	2.24	0	2.83	1.73	2.24
Arenosols	3.00	2.83	3.16	2.83	3.74	224	3.61	2.83	2.45	3.00	2.24	3.16	3.00	3.32	332	3.46	3.74	3.32	3.32	3.16	3.00	3.00	3.16	3.16	3.61	3.32	2.83	0	2.24	2.65
Cambisols	2.45	2.65	2.65	3.00	3.00	1.41	2.83	1.73	1.73	2.45	2.45	2.24	2.45	2.45	2.45	2.65	3.00	2.83	2.45	2.65	2.00	2.45	2.24	224	2.83	2.45	1.73	2.24	0	2.83
Regosols	3.16	3.00	3.00	2.24	3.32	2.83	3.46	3.32	3.32	2.45	2.45	3.32	2.83	3.16	3.16	3.32	3.32	3.16	3.16	3.00	2.83	2.83	3.32	3.00	3.16	3.16	2.24	2.65	2.83	0

Taxonomic distances

0 1–2 2–3 >3

Fig. 3. Taxonomic distances between Reference Soil Groups of WRB from [2].

The order of low-humus carbonate-accumulative soils contains soil types close genetically (and geographically), but with a great number of diagnostic horizons, which overestimates the values of taxonomic distances. It seems reasonable to revise the profile formulas of soils in this order.

The order of turbozems is characterized by high TD values due to the diversity of morphons, hence, initial horizons, and types of soils. It may make sense to merge some types within the order.

On the other hand, small taxonomic distances between some orders (for instance, between organo-accumulative and structural-metamorphic soils, hydrometamorphic soils and lithozems, cryometamorphic soils and eluvial soils), different in their geneses, can serve an impetus to revise the diagnostics of soils in these orders. Probably, it is feasible to check the differentiating criteria for orders and/or formulas of soil types in orders, and in extreme cases, to relocate soil types among orders.

(4) The consideration of taxonomic distances in two classification systems shows the compatibility of the estimates for the orders and Reference Soil Groups, and this is in agreement with the ideas on soil genesis.

ACKNOWLEDGMENTS

This work was supported by the Russian Foundation for Basic Research (project no. 16-35-60056 mol_a_dk).

REFERENCES

1. M. I. Gerasimova, "Principles, structure and taxonomic units in the Russian and international (WRB) systems of soil classification," Byull. Pochv. Inst. im. V.V. Dokuchaeva, No. **79**, 23–35 (2015).
2. *Classification and Diagnostic System of Russian Soils* (Oikumena, Smolensk, 2004) [in Russian].
3. *Field Guide for Correlation of Russian Soils* (Dokuchaev Soil Science Inst., Moscow, 2008) [in Russian].
4. V. A. Rozhkov and E. B. Skvortsova, "Tectology of soil megasystems: universal principles of organization and analysis of data," Eurasian Soil Sci. **42**, 1073–1082 (2009).
5. V. M. Fridland, *General Principles and Elements of the Basic Classification of Soils and the Program for Its Development* (All-Union V.I. Lenin Acad. Agric. Sci., Moscow, 1982) [in Russian].
6. *Elementary Pedogenetic Processes: Conceptual Analysis, Characteristics, and Systematics* (Nauka, Moscow, 1992) [in Russian].
7. O. W. Bidwell and F. D. Hole, "An experiment in the numerical classification of some Kansas soils," Soil Sci. Soc. Am. Proc. **26**, 263–268 (1964).
8. F. Carre and M. Jacobson, "Numerical classification of soil profile data using distance metrics," Geoderma **148**, 336–345 (2009).
9. M. Fuchs, V. Lang, T. Szegi, and E. Micheli, "Traditional and pedometric approaches to justify the introduction of swelling clay soils as a new soil type in the modernized Hungarian Soil Classification System," Catena **128**, 80–94 (2015).
10. F. D. Hole and M. Hironaka, "An experiment in ordination of some soil profiles," Soil Sci. Soc. Am. Proc. **24**, 309–312 (1960).
11. J. J. Ibañez and M. Ruiz-Ramos, "A mathematical comparison of classification structures: the case of USDA Soil Taxonomy," Eurasian Soil Sci. **39**, 712–719 (2005).
12. J. J. Ibañez, M. Ruiz-Ramos, and A. M. Tarquis, "Mathematical structures of biological and pedological taxonomies," Geoderma **134**, 360–372 (2006).
13. R. F. Isbell, *The Australian Soil Classification* (Commonwealth Scientific and Industrial Research Organization, Collingwood, 1996).
14. IUSS Working Group WRB, *World Reference Base for Soil Resources, World Soil Resources Reports No. 103* (Food and Agriculture Organization, Rome, 2006).
15. V. Lang, M. Fuchs, I. Waltner, and E. Micheli, "Soil taxonomic distance, a tool for correlation: as exemplified by the Hungarian brown forest soils and related WRB reference soil groups," Geoderma **192**, 269–276 (2013).
16. V. Lang, M. Fuchs, I. Waltner, and E. Micheli, "Taxonomic distance measurements applied for soil correlation," Agrokem. Talajt. **59** (1), 57–64 (2010).
17. P. C. Mahalanobis, "Analysis of race mixture in Bengal," J. Proc. Asiat. Soc. Bengal **23**, 301–333 (1927).
18. E. Micheli, M. Fuchs, V. Lang, T. Szegi, and K. G. Szabone, "Methods for modernizing the elements and structure of the Hungarian Soil Classification System," Agrokem. Talaj. **63** (1), 69–78 (2014).
19. B. Minasny and A. B. McBratney, "Incorporating taxonomic distance into spatial prediction and digital mapping of soil classes," Geoderma **142**, 285–293 (2007).
20. B. Minasny, A. B. McBratney, and A. E. Hartemink, "Global pedodiversity, taxonomic distance, and the World Reference Base," Geoderma **155**, 132–139 (2010).
21. L. Ramirez-Lopez, T. Behrensa, K. Schmidta, R. A. Viscarra Rosselc, J. A. M. Dematted, and T. Scholtena, "Distance and similarity-search metrics for use with soil vis-NIR spectra," Geoderma **199**, 43–53 (2013).
22. P. K. Sarkar, O. W. Bidwell, and L. F. Marcus, "Selection of characteristics for numerical classification of soils," Soil Sci. Soc. Am. Proc. **30**, 269–272 (1966).
23. R. P. O. Simo, R. Schulte, J. A. Corstanje, and R. E. Hannam, "Creamer validating digital soil maps using soil taxonomic distance: a case study of Ireland," Geoderma Reg. **5**, 188–197 (2015).
24. N. Toomanian and I. Esfandiarpoor, "Challenges of pedodiversity in soil science," Eurasian Soil Sci. **43**, 1486–1502 (2010).
25. C. W. van Huyssteen, E. Micheli, M. Fuchs, and I. Waltner, "Taxonomic distance between South African diagnostic horizons and the World Reference Base diagnostics," Catena **113**, 276–280 (2014).
26. B. K. Waruru, K. D. Shepherd, G. M. Ndegwa, P. T. Kamoni, and A. M. Sila, "Rapid estimation of soil engineering properties using diffuse reflectance near infrared spectroscopy," Biosyst. Eng. **12**, 177–185 (2014).

Translated by L. Kholopova