BALTIC FORESTRY

http://www.balticforestry.mi.lt
ISSN 1392-1355
eISSN 2029-9230

Baltic Forestry 2020 26(2): 472
Category: research article
https://doi.org/10.46490/BF472

Soil-forming processes in profile textural-differentiated forest soils of the Cis-Carpathian region, Ukraine

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Pankiv, Z., Malyk, S. and Yamelynets, T. 2020. Soil-forming processes in profile textural-differentiated forest soils of the Cis-Carpathian region, Ukraine. *Baltic Forestry* 26(2): article id 472. https://doi.org/10.46490/BF472.

Received 13 March 2020 **Revised** 12 October 2020 **Accepted** 28 October 2020

Abstract

Throughout the history of soil science development, one of the most controversial issues was the explanation of the genesis of the profile textural-differentiated soils influenced by forest vegetation and climate conditions within the Cis-Carpathian region, Ukraine. Scientists' views on the formation of the eluvial-illuvial, namely granulometric content, and profile differentiation have been and remain ambiguous due to the contradictory criteria of diagnosing the processes of eluvial soil degradation (lessivage, podzolization, eluvial-gleying process) and the almost similar results of these processes. The complexity and ambiguous interpretation of the genetic nature of the profile textural-differentiated soils of the Cis-Carpathian region necessitates the development of clear diagnostic criteria for revealing their genetic nature. The purpose of the work is to establish the diagnostic criteria of elementary soil-forming processes in profile textural-differentiated forest soils of the Cis-Carpathian region based on the analysis of data on soil properties previously collected by the authors.

It has been established that in sod-podzolic soils formed under forest, the main profile-forming elementary process of soil formation is podzolization, which is characterized by the negative values of the eluvial-accumulative coefficients and the coefficient of change of the silicate part for the upper three horizons. The processes of lessivage and segregation are of little intensity in this type of soils. The main profile-forming elementary processes of soil formation in brown-podzolic soils (Neocambic Gleyic Retisols) are lessivage and inner soil argillization with little podzolization, the eluvial-gleying process and segregation effects.

Keywords: forest soils, argillanes, neoplasms, ortsteins, podsolization, elementary soil-forming processes, Cis-Carpathian region

Introduction

The Cis-Carpathian region, located in the transition zone between the southwestern edge of the Podillia Upland and the northeast slopes of the Ukrainian Carpathians, is characterized by differences in the topography, climatic and biological factors of soil formation, which led to the formation of different soil, genesis, morphology and spectrum of soil-forming processes (Smaga 2016, Pankiv et al. 2019a). The complex genetic nature of the Cis-Carpathian soils, the diversity of interpreting morphological features, the lack of uniform diagnostic features of elementary soil-forming processes (ESP) and the complexity of the analytical determination of a number of indicators have led to the discussions between representatives of different soil-science schools at their level of taxonomic classification (Pankiv et al. 2019b). Profile textural-differentiated soils (non-classification concept that combines different soils with vertical differentiation of granulometric and gross chemical composition of fine soil in the soil profile) of humid regions of the world (Luvisols, Retisols, Planosols, Acrisols, etc.) are formed on loamy and clay substrates of different genesis, they are one of the most organised and informational capacities (Bronnikova et al. 2005, Quénard et al. 2012, Smaga 2016, Pankiv et al. 2020). Two types of profile textural-differentiated soils – sod-podzolic (Stagnic Retisols) and brown-podzolic (Neocambic Gleyic Retisols) ones (WRB 2014) – which have a similar set of genetic horizons, are distinguished on the basis of a soil research in the Cis-Carpathian region within Ukraine, but their profiles are formed with the participation of different elementary soil-forming processes, their orientation and intensity.

The main aim of this study is to analyze and establish a set of morphological features and diagnostic criteria of elementary soil processes to distinguish them among different types of profile textural-differentiated soils.

Materials and methods

The Cis-Carpathian region is a mountainous terraced plain, within which the distribution of soils and vegetation is conditioned by altitudinal zonation. Altitude causes the increasing of precipitation and decreasing of the sum of active and average annual air temperatures. Profile textural-differentiated soils of the Cis-Carpathian region were formed on Pleistocene alluvial and alluvial-diluvial deposits. Based on the soil maps development in the Cis-Carpathian region, we have selected 3 forest study plots, within which the soil sections have been laid (Figure 1).

The study plot of "Hirne" (H) is located within the Drohobych Upland on the fourth Dnister floodplain terrace (h = 325 m a.s.l.; 49°10'30.6"N 23°42'24.6"E). The soils were formed under oak forests (*Quercus robur* L.) (1st class of soil quality, stocking level is 0.6–0.7). The lower vegetation layer formed by hornbeam (*Carpinus betulus* L.), hazel (*Corylus avellana*), and buckthorn (*Frangula alnus*), the well-developed grass cover includes male fern (*Dryopteris filix-mas* (L.) Schott) and wild strawberry (*Fragaria vesca* L.). Formation of soils under deciduous forests led to the dominance of the podzolic process (acid hydrolysis), acid reaction of the soil solution (pH_{KCl} = 3.9–4.5), high hydrolytic acidity, and humate-fulvate type of humus. The annual rainfall is 685 mm, the sum of active temperatures is 2,455°C and annual air temperature is 7.6°C.

The study plot of "Loyeva" (L) is located within the Prut-Bystrytska Upland on the sixth Dnister floodplain terrace (Loyeva level; h = 570 m a.s.l.; 48°33'59.8"N 24°37'30.8"E). The soils have formed under mixed oak-spruce forest (*Quercus robur* L., *Picea abies* (L.) Karst.) with an admixture of aspen (*Populus tremula* L.), hornbeam (*Carpinus betulus* L.), and birch (*Betula pendula* Roth.). The lower vegetation layer formed by hazel (*Corylus avellana* L.). The grass cover is represented by *Aegopodium podagraria, Viola reichenbachiana,* and *Galium odoratum*. The formation of soils under mixed forests led to the dominance of lessivage and in-soil loaming processes with an acid reaction of the soil solution (pH_{KCl} = 3.4– 4.7), high hydrolytic acidity (6.5–12.50 mmol/100 g) and fulvate type of humus. The annual rainfall is 765 mm, the sum of active temperatures is 2,360°C and annual air temperature is 7.0°C.

The study plot of "Kamin" (K) is located within the Prylukvynska Upland on the seventh Dnister floodplain terrace (Krasnaya level; h = 515 m a.s.l.; 48°55'51.7"N 24°17'09.5"E). The soil surface is turfed and mounded. Vegetation cover represented by the following meadow weeds: *Matricaria recutita, Myosotis arvensis, Pulmonaria obscura, Elymus repens, Acroptilon repens*, and typical shrub vegetation consisting of *Prunus spinosa, Crataegus oxyacantha,* and *Salix viminalis*. The annual rainfall is 771 mm, the sum of active temperatures is 2,350°C and annual air temperature is 6.8°C.

Morphological features have been studied, and soil samples have been taken from all genetic horizons, soil-forming rocks, and soil neoformations (nodules, concretions, argillans, and cutans of iron oxides) in the field conditions within Neocambic Gleyic Retisols (study plot "Hirne", Figure 2) and Stagnic Retisols (study plot "Loyeva", Figure 3). All soil samples were taken in 6-fold repetition with further statistical treatment (Pankiv et al. 2019a, Pankiv et al. 2019b).

The silt fraction has been washed from soil samples under laboratory conditions according to the method proposed by Gorbunov (1960). The gross chemical composition has been determined in soil samples, silt fraction, nodules, ortsteins, concretions and argillans according to the method proposed by Arinushkina (1970). The granulometric composition of soil, argillans, ortsteins, concretions, and nodules have been determined by the method proposed by Kachinskii with the preparation of soil by the pyrophosphate method according to the Dolgov and Lichmanova procedure (Kachinskii 1965). Based on the results of the gross chemical composition of silt, fine soil, and soil

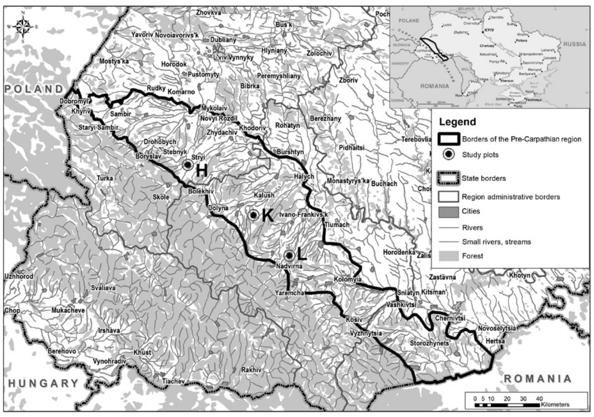

Figure 1. Map of the location of forest study plots within the Pre-Carpathian region (Ukraine)

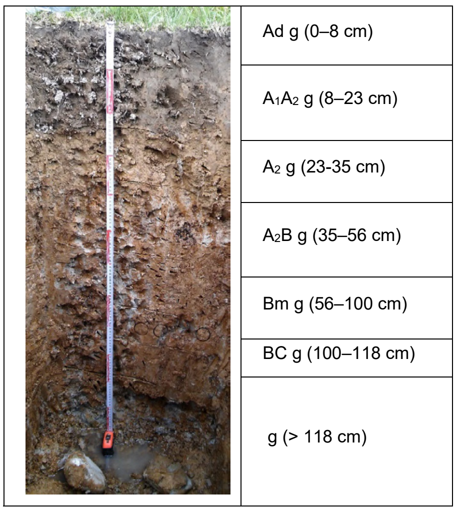

Figure 2. Brown podzolic soil profile (Neocambic Gleyic Retisols) (Pankiv et al. 2019a, Pankiv et al. 2019b)

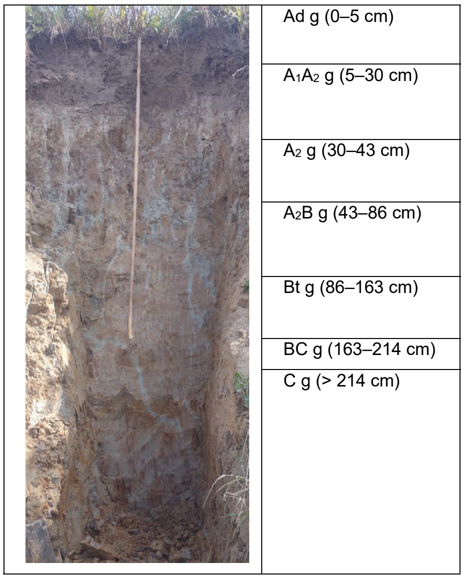

Figure 3. Sod-podzolic soil profile (Stagnic Retisols)

neoformations, molar ratios were calculated according to the method proposed by Harrassowitz (profile differentiation indices) (1926), "leaching factor" according to G. Jenny's method (1931), E*A* coefficients of Fe_2O_3, R_2O_3, E*At* (total eluvial-accumulative coefficient for all oxides) and E*Am* (eluvial-accumulative coefficient of all oxides except oxide-witness) according to Rode's method (2008). To establish the genesis of nodules, concretions and argillan, the accumulation factor (Cx) has been calculated (Dawson et al. 1985). Hydrolytic acidity has been calculated by Kappen's method (Mineev 2001).

Results

Soil science has never had any restrictions on the rules for selecting the main diagnostic features, and their number and variety should be sufficient to form a genetic concept for soil type formation (Bockheim 2000). In this case, in each group, all the basic properties and combinations of soils must be substantiated, and if certain soil properties do not receive a process explanation, then new elementary soil-forming processes (ESPs) should be singled out (Karavaeva et al. 1992, Zaidelman 2007). The process analysis of the profile textural-differentiated soils of the Cis-Carpathian region has made it possible to distinguish several basic ESPs as follows: podzolization, lessivage, argillization, eluvium-gleying, and segregation, which shape their morphological features and physicochemical properties (Cernescu 1934, Smaga 1996, Polchyna 2014). The ambiguity of the genesis of profile textural-differentiated soils of the Cis-Carpathian region attributes to the fact that different processes form a similar morphological profile.

The main process for forest soils is process of podsolization, which is not uniquely interpreted, so there are several classical theories in the scholarly literature as follows: colloid-chemical, biochemical, and physico-chemical ones (Phillips 2007, Cornu et al. 2014). Several criteria were used to diagnose the podzolization process: SiO_2 accumulation in A_2 horizons; accumulation of SiO_2 in the silt fraction in A_2 horizons; and expansion of the ratios of $SiO_2 : Al_2O_3$ and $SiO_2 : Fe_2O_2$within the profile (Polchyna 2014). Smaga diagnoses the process of podzolization in the soils of the Cis-Carpathia by the molar ratios of losses of $SiO_2 : Al_2O_3$ and eluvial-accumulative coefficients of aluminium (EAC Al_2O_3) (Smaga 1996). We used the results of our own morphological studies to diagnose the process of podzolization in profile textural-differentiated soils of the Cis-Carpathian region (presence of light eluvial horizon, presence of soil neoformations (skeleton in upper horizons, sesquans (cutans of iron oxides) on the verge of structural units in B mg and BC g horizons) confirmed by analytical laboratory indicators (eluvial-accumulative coefficients, coefficient of change of silicate part, indices of granulometric differentiation (silt to physical clay ratio, indicator of the degree of profile differentiation) (Table 1).

The negative values of the eluvial-accumulative coefficients and the coefficient of change of the silicate part, which are diagnosed only in the upper (A_1A_2 g and A_2 g) horizons, the small number of skeletons and the absence of sesquan (cutans of iron oxides) indicate a minimum intensity of the process of podzolization in brown-podzolic soils. In sod-podzolic soils, the negative values of the eluvial-accumulative coefficients and the coefficient of change of the silicate part are characteristic of the three upper horizons (A_1A_2 g, A_2 g and A_2B g), and the narrowing of the molar ratios in silt fraction $SiO_2 : R_2O_3$ and A_2 g

Table 1. Diagnostic criteria of the process of podzolization in profile-differentiated forest soils of the Pre-Carpathian region (Ukraine)

Name of ESP	Criteria
Podzolization	Negative value of E*At* and E*Am* in silt friction for A_1A_2 g horizon
	Negative value of E*At* та E*Am* in fine soil for A_1A_2 g and A_2 g horizons
	Negative value of E*A* Fe_2O_3 та EA R_2O_3 in silt friction A_1A_2 g horizon
	Negative values of E*A* Fe_2O_3, E*A* Al_2O_3, E*A* R_2O_3 у A_1A_2 g and A_2 g horizons in fine soil
	Coefficient of change of the silicate part in fine soil for A_1A_2 g and A_2 g horizons <1,0
	Narrowing of the molar relations in fine soil $SiO_2 : Al_2O_3$, $SiO_2 : Fe_2O_3$ and $SiO_2 : R_2O_3$
	Narrowing of the molar ratios in silt fraction of $SiO_2 : Al_2O_3$, $SiO_2 : Fe_2O_3$ and $SiO_2 : R_2O_3$
	Presence of skeleton (SiO_2) in A_1A_2 g and A_2 g horizons
	Presence of sesquans (cutans of iron oxides) on the verge of structural units in the B mg and BC g horizons
	Presence of an eluvial horizon, with a power exceeding 10 cm

horizons, as well as sesquan (cutans of iron oxides) in Bm g and BC g horizons indicate a greater intensity of the podzolization process.

Profile differentiation of soils formed on loamy rocks can be caused by the process of lessivage, i.e. moving silt particles from the eluvial horizon without their chemical destruction in pores and cracks under the action of gravitational waters and relocation in lower horizons. This theory was proposed in the 1920s by K.D. Hlinka and O.N. Sokolovskii (Hlinka 1927, Sokolovskii 1927). Subsequently, N. Cernescu and F. Duchaufour formulated the concept of lessivage, the process of peptization, washing of silt parts from the surface of grains of coarse-grained (sandy or coarse-grained) material and their removal in an unbroken state from the eluvial horizon (Cernescu 1934, Duchaufour 1951).

We have established that morphologically lessivage in profile textural-differentiated soils of the Cis-Carpathian region is diagnosed by the presence of argillan (clay cutans) in the illuvial horizon, the formation of which is caused by the transfer of fine particles from the upper horizons by gravitational flux of water and suspension transfer of silt. We diagnosed the process of lessivage by the results of the granulometric composition of argillan and its comparison with the granulometric composition within same horizon, the positive values of the eluvial-accumulative (EA) coefficients in silt fraction and fine soil in the illuvial part of the profile, and uniform distribution within the profile of the ratio $SiO_2 : R_2O_3$ and $SiO_2 : Al_2O_3$ in the silt fraction. The positive valuei of EA *Fe_2O_3*, EA *Al_2O_3* and EA *R_2O_3*, and the values of the coefficient of change of the silicate part in the A_2B g, B mg and BC g horizons more than 1.0 confirm the process of lessivage in profile textural-differentiated soils (Table 2) (Pankiv et al. 2019a).

In brown-podzolic soils, in B mg and BC g horizons, argillans (clay cutans), which cover inclusions of boulders and pebbles, are clearly expressed, and their particle size distribution is silt-heavy clay, which is the most reliable feature of lessivage. Uniform distribution within the profile of $SiO_2 : R_2O_3$ and $SiO_2 : Al_2O_3$ ratios in silt fraction, positive values of EA coefficients in the A_2B g, B mg and BC g horizons, and the values of the coefficient change of the silicate part in A_2B g, B mg and BC g horizons of more than 1.0 confirm the process of lessivage. Instead, sod-podzolic soils lack argillans (clay cutans), and the $SiO_2 : R_2O_3$ and $SiO_2 : Al_2O_3$ ratios in the silt fraction are narrowed from the upper horizons to the rock and the values of the coefficient change in silicate part of B mg and BC g horizons being 1.0 indicate the minimum intensity of the process of lessivage in sod-podzolic soils.

Inner soil argillization is the process of clay formation *in situ* owing to transformative clay formation from primary layered silicates and the synthesis of clay minerals. The result of inner soil argillization is the accumulation of silt in any part of the profile without identifying the causes of such accumulation (Table 3) (Karavaeva et al. 1992). The process of inner soil argillization is characterized by a positive balance of oxides in silt fraction, the presence of nodules within the entire profile, the value of the coefficient of change of the silicate part in silt fraction of more than 1.0, and the values of accumulation coefficient of Mn_3O_4 in nodules and argillans of more than 1.0 (Pankiv et al. 2017, Pankiv et al. 2019a).

The process of inner soil argillization is characteristic of brown-podzolic soils, in which, due to the destruction of primary and secondary minerals *in situ*, a powerful illuvial metamorphic horizon is formed. The presence of nodules that have *in situ* genesis and high values of the

Table 2. Diagnostic criteria of the process of lessivage in profile-differentiated forest soils of the Pre-Carpathian region (Ukraine)

Name of ESP	Criteria
Lessivage	Uniform distribution within the profile of $SiO_2 : R_2O_3$ and $SiO_2 : Al_2O_3$ in silt fraction
	Presence of argillan (clay cutans) within the B mg and BC g horizons
	Silty-heavy clay granulometric composition argillan, which is heavier in comparison with the content horizon, and silt content in argillan more than 50%
	Positive values of E*At* and E*Am* in A_2B g, B mg and BC g horizons in silt fraction
	Positive values of E*At*, and E*Am* in fine soil for A_2B g, B mg and BC g horizons
	Positive values of E*A Fe_2O_3* and E*A R_2O_3* in A_2B g, B mg and BC g in silt fraction
	Positive values of E*A Fe_2O_3*, E*A Al_2O_3* and E*A R_2O_3* in A_2B g, B mg and BC g in fine soil
	Coefficient of change of silicate part in fine soil in A_2B g, B mg and BC g horizons >1.0

Table 3. Diagnostic criteria of the process of inner soil argillization in profile-differentiated forest soils of the Pre-Carpathian region (Ukraine)

Name of ESP	Criteria
Inner soil argillization	Positive balance of oxides in silt fraction
	Coefficient of change of silicate part in silt fraction >1.0 in the whole profile
	Maximum hydrolytic acidity and pH KC1 in A_2B g and B mg horizons
	Presence of nodules within the entire profile, the chemical composition of which is almost identical with the content horizon, indicating their *in situ* genesis
	>10.0 value of Mn_3O_4 accumulation factor in nodules
	Mn_3O_4 accumulation factor in argillans >1.0

Mn_3O_4 accumulation factor confirms the process of inner soil argillization. In sod-podzolic soils, the illuvial horizon is textural, the formation of which is caused by an increase in the content of silt brought from the upper horizons.

The silt process – the destruction of clay silicates during the gleying process with subsequent transfer or the segregation of the products of destruction and residual accumulation of silica (Rozanov 1988) – has a significant influence on the formation of light eluvial horizons. Zeidelman believes that gley process in a stagnant type of water regime is the only reason for the formation of an eluvial horizon. Therefore, the main feature of the gleying process is the release of ferrum and, consequently, the formation of the light eluvial horizon (Zeidelman 2007). To diagnose the eluvial-gleying process, we used the following criteria: no smooth expansion of the $SiO_2 : R_2O_3$ ratio down the profile, expansion of the $SiO_2 : Fe_2O_3$ ratio, expanded $SiO_2 : Fe_2O_3 / SiO_2 : A1_2O_3$ ratios. The eluvial-gleying process in profile textural-differentiated soils was diagnosed by Fe_2O_3 losses relative to the parent rock, an even ratio of $A1_2O_3 : Fe_2O_3$ in silt fraction and fine soil, and the predominance of loss of iron over loss of aluminium (Table 4).

In brown-podzolic soils, the insignificant predominance of Fe_2O_3 losses over Al_2O_3 losses indicates a minimal intensity of the eluvial-gleying process in them, unlike sod-podzolic soils, in which the losses of Fe_2O_3 are 2–3 times greater than the losses of Al_2O_3. The diagnostic feature of the eluvial-gleying process in sod-podzolic soils is the presence of concretions, which are formed because of the redox conditions and have an excit genesis.

The above-mentioned processes in profile textural-differentiated soils are complemented by segregation, the process of formation of charges that grow on subparallel surfaces and differ from the surrounding material by their chemical composition and morphological properties (Rozanov 1988, Quenard et al. 2011, Cornu et al. 2014). Segregation processes in profile textural-differentiated soils are caused by redox conditions with the active participation of soil microorganisms. The process of segregation has been diagnosed by the presence of nodule neoplasms and the positive values of the accumulation factor (Cx) of the following elements in them: Mn_3O_4 (9.0– 53.6), CaO (1.3–3.4), MgO (1.1–1.6), Na_2O (1.1–1.4), K_2O (1.0–1.1); by the presence of orshteins and positive values of Cx in them: Fe_2O_3 (2.7), Al_2O_3 (1.0–1.9), CaO (1.2–1.7), Mn_3O_4 (1.4–1.6), TiO_2 (1.0) (Table 5). The process of segregation cannot occur without the gleying process, which mobilizes elements with variable valence into the solution (Karavaeva et al. 1992).

Conclusions

It has been established that the main elementary soil-forming processes that form the genetic profile of profile textural-differentiated forest soils are lessivage, podzolization, inner soil argillization, eluvial-gleying process and segregation. Based on the obtained results we can conclude that in sod-podzolic soils, the main profile forming ESPs are podzolization, which is characterized by the negative values of the eluvial-accumulative coefficients and the coefficient of change of the silicate part for the upper three horizons (A_1A_2 g, A_2 g та A_2B g), the presence of the skeleton in the A_1A_2 g and A_2 g horizons and sesquans (cutans of iron oxides) in B mg and BC g

Table 4. Diagnostic criteria of gley-eluvial process in profile-differentiated forest soils of Pre-Carpathian region (Ukraine)

Name of ESP	Criteria
Gley-eluvial	Uniform profile distribution of ratio $Al_2O_3 : Fe_2O_3$ in silt fraction
	Uniform profile distribution of ratio $Al_2O_3 : Fe_2O_3$ in fine soil
	Uniform ratio in silt fraction $\frac{SiO_2 : Fe_2O_3}{SiO_2 : Al_2O_3}$
	Uniform ratio fine soil $\frac{SiO_2 : Fe_2O_3}{SiO_2 : Al_2O_3}$
	Predominance of Fe_2O_3 losses over Al_2O_3 losses in the A_1A_2 g and A_2 g horizons in fine soil
	Presence in the eluvial horizon of round and oval concretions, which are composed by concentric rings of black and ocher color, and the oxide accumulation factor >1.0

Table 5. Elements accumulation coefficient (Cx) in the ortsteins and nodules of the profile textured-differentiated soils of the Pre-Carpathian region (Ukraine)

Genetic horizon / depth of sampling	SiO_2	Al_2O_3	Fe_2O_3	R_2O_3	TiO_2	CaO	MgO	K_2O	Na_2O	Mn_3O_4
Brown podzolic soil profile (Neocambic Gleyic Retisols), nodules										
A_2 g (25–35 cm)	0.82	0.99	0.98	0.99	0.71	3.41	1.64	1.18	1.42	43.66
A_2B g (40–50 cm)	0.97	0.99	0.98	0.99	1.04	2.04	1.17	0.91	1.28	53.66
Bm g (70–80 cm)	0.98	0.96	0.97	0.97	1.09	1.39	1.22	1.02	1.10	9.00
Sod-podzolic soil profile (Stagnic Retisols), ortsteins										
A_1A_2 g (5–30 cm)	0.90	1.20	2.80	2.00	1.15	1.43	0.40	0.85	0.76	1.40
A_2 g (30–40 cm)	0.88	1.90	2.74	2.32	1.04	1.73	0.47	0.91	0.86	1.61
A_2B g (60–70 cm)	0.89	1.09	2.70	1.89	1.02	1.20	0.76	0.81	0.82	1.46
C g (220–230 cm)	0.92	0.99	2.65	1.82	0.92	0.79	0.57	0.84	0.83	1.60

horizons and eluvial-gleying, which is characterized by a significant predominance of Fe_2O_3 losses over Al_2O_3 losses and the presence of concretions. The processes of lessivage and segregation have little intensity. The main profile-forming ESPs in brown-podzolic soils are lessivage and inner soil argillization with little podzolization, the eluvial-gleying process and segregation effects. Significant action of lessivage in brown-podzolic soils is indicated by the argillans (clay cutans) presenting in B mg and BC g horizons, and their particle size distribution is heavier within the same horizon and an uniform distribution within the ratios $SiO_2 : R_2O_3$ and $SiO_2 : Al_2O_3$ in the silt fraction. The process of inner soil argillization in brown-podzolic soils is characterized by a positive balance of oxides in the silt fraction, the presence of nodules and ortsteins within the entire profile, the coefficient of change of the silicate part in silt fraction is more than 1.0, the accumulation factor of Mn_3O_4 in nodules and ortsteins is more than 1.0. Implementation of the uniform diagnostic features for profile textural-differentiated forest soils of the Cis-Carpathian region will allow to solve genetic and classification problems. The profile textural-differentiated soils of Cis-Carpathia have a similar system of genetic horizons and morphological properties formed with the participation of the elementary soil-forming processes of different intensity and direction. It is stated that these soils can be identified and separated on the type level, which is based on the morphological features of soil neoplasms, their chemical composition and the proposed diagnostic criteria of the elementary soil-forming processes.

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