Review

RECENT EROSION-ACCUMULATION PROCESSES RESPONSE IN A SOIL CLASSIFICATION SYSTEM – A REVIEW

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Abstract

The redistribution of soil mass in erosion-accumulation areas leads to many changes in soil properties and to changes in the horizonation of soil profiles. Research on soils occurring in erosion-accumulation areas is not sufficiently developed in terms of their classification. Especially colluvial soils formed by accumulation in toe-slope positions are particularly problematic, in various classifications they are ordered into different taxonomic levels, i.e. in many respects inconsistent and unsystematic. The aim of the presented contribution is to characterize and classify colluvial soils for the new version of the Morphogenetic Soil Classification System of Slovakia, i.e. to find a taxonomic level within the classification system, based on the knowledge gained from soil surveys in erosion-accumulation areas of Slovakia. An overview of classification approaches used for these soils in some national and international soil classification systems (WRB 2015 and 2022) was made. The terminologically unsuitable concept of colluvial soils, which is usually linked to geomorphology or sedimentology was resolved in WRB 2022 by introducing a new classification concept distinguishing *solimovic material* which is a recent heterogeneous, predominantly soil material with organic matter content, resulting from the transport of eroded material down by the slope and its accumulation in lower concave positions. Typification of soil profiles and definition of diagnostic criteria is a tool for creating a taxonomic unit at the level of soil type, subtype or form. The demand to distinguish colluvial soils as a new soil type was initiated by practical land users from the perspective of evaluating production potential and soil quality.

Keywords: soil classification system, soil taxonomy, colluvial material, solimovic material, soil diagnostics

INTRODUCTION

Soil erosion is one of the most widespread processes of soil degradation in Slovakia and worldwide. Surface water runoff and tillage are the two main erosion factors active in Slovakia, while wind has a much smaller impact. Wind erosion is relatively limited due to the significant potential of vegetation to protect the soil and the appropriate soil moisture regime that prevents its drying out. Studies aimed at mapping soil erosion in agriculturally used uplands of Slovakia (Fulajtár 1994, 2001, Fulajtár & Janský 2001, Fulajtár *et al.* 2016, Jenčo e*t al.* 2020) have shown a large territorial extent of eroded areas. Almost all slopes steeper than 4 degrees are eroded to some extent and approximately 15% of uplands are heavily eroded (i.e. most of the A and B horizons are removed). Most of the eroded soil material is deposited at the footslopes and in concave depressions, such as periglacial valleys. Only a small part of the eroded soil is transported for long distances and enters watercourses (brooks and rivers) and most of soil material transported by rivers is deposited in manmade water reservoirs as natural lakes are very rare in Slovakia.

The redistribution of soil material by soil erosion and sedimentation leads to significant changes in soil properties, including new layering of soil horizons. The resulting soil horizon arrangements depends on the mutual balance of two opposing processes, i.e. erosion and sedimentation. Soil erosion which is prevalent on the most affected slopes leads to the transformation of mollic A-horizons and B-horizons into ochric A-horizons, and the original soils of the Slovak uplands (especially Chernozems and Luvisols) are degraded to varying degrees and Regosols are forming on the steepest slopes (Fulajtár *et al.* 2016, Jenčo *et al.* 2020). Conversely, the deposition of eroded material at the footslopes create thick accumulations of soil material enriched in organic matter and clay. In smaller depressions, these accumulations are only a few tens of cm thick, and the affected soils can be classified as "accumulated" or "buried" subtypes of original soils (Fulajtár 2009) while in larger depressions and at the footslopes they can be 2 – 3 m thick. They can be distinguished from aerial and satellite images and can be mapped because usually they appear much darker than soils of their elevated surroundings (Fulajtár 1994). However, their classification is not clear and there are problems with defining explicit criteria to distinguish them from some other soil types. This problem can be solved if these soils would be classified as Colluvisols.

Colluvisols, as sedimentary soils with various morphology and occurrence usually in concave positions of erosion-accumulation slopes, have characteristics that cannot be compared with other soil types. Their origin is linked to natural and anthropogenic factors (Zádorová & Penížek 2021, Lal 2001). The resulting Colluvisol profiles depends on the speed, intensity and duration of two alternating opposing processes: sedimentation and erosion, with sedimentation prevailing. The occurrence of Colluvisols is not tied to geographical zones, they arise wherever a loose substrate occurs and are most developed in areas with agriculturally cultivated slopes (Zádorová & Penížek 2018, Bell & Boardman 1992, Dotterweich 2013, Larsen *et al.* 2016).

Colluvial soils are formed usually at footslopes, but also in depressions in different segments of slopes, where the slope is significantly diminished and the surface transport capacity of surface runoff is reduced. There is an accumulation of predominantly humic soil material eroded by water sheet, rill or gully erosion and by ploughing erosion (Fulajtár & Janský 2001). The largest areas of colluvial soils in Slovakia are at the interfaces of hills and alluvial plains and denudation plateaus dissected by periglacial ravines without permanent water flows, which are built mainly by loess covers, Neogene basin fillings, river terraces, *etc.*

Colluvisols are not formed by deposition of non-humus material, nor do they include alluvial cone soils (proluvium), which also arise because of reduced slope inclination (Fulajtár & Janský 2001). Alluvial cones are deposited mainly by permanent or seasonal watercourses, which are also fed by subsurface water sources (shallow subsurface lateral runoff through gravitational pores in soils and their subsoils as well as groundwater). Alluvial cones arise at the mouth of mountain valleys into lowlands and basins, where significant decrease of the watercourse bed inclination and the water transport capacity occur. The material of alluvial cones differs from colluvium in grain size, often it has a high stone content and absence or low content of humus. The low organic matter content is very typical feature of alluvial cones, and it has several reasons. In the mountains, the humus soil horizons are thin and surface runoff and erosion due to steeper and longer slopes more often create linear forms that attack also the deeper soil layers and thus not only A horizons, but also the B horizons and C horizons is eroded (Fulajtár & Janský 2001).

In addition, a significant proportion of the alluvial cone material is also made up of coarse-grained material eroded from the bottom and banks of the watercourse. Many alluvial cones are predominantly gravelly sands, which can be distinguished from gravelly sands of river floodplains and terraces due to the poor processing of the material, which remains partly sharp-edged, as mountain streams transport the eroded material only over short distances, which is not enough for its processing. Currently, due to the increasing mechanization of forestry and mountain agriculture, alluvial cones also contain material eroded by rill and gully erosion from unpaved roads (Foucher *et al.* 2014). Another important difference between alluvial cones and colluvial materials is their age. Alluvial cones are much older. They were formed already during ice ages. Over time, humus horizons form on the proluvial material, but they are not as thick as in the case of sub-slope colluvium, where predominantly soil material is deposited usually containing a significant amount of humus.

Colluvisol identification

Zachar (1960) already used morphological features (especially the presence or absence of diagnostic horizons and their thickness) to identify erosion. His scale has 5 classes: a) less than 1/10 of the original soil profile eroded, b) 1/10 to 1/3 of the soil profile eroded, c) 1/3 to 2/3 of the soil profile eroded, d) more than 2/3 of the soil profile eroded, but not the entire profile, d) the entire soil profile eroded.

Colluvisols are sedimentary soils that do not arise primarily through pedogenetic processes *in situ* but are linked to geomorphological and sedimentary processes (Goudie 2004, Miller & Juilleret 2020). In practice, these are erosion and gravitation processes that lead to the formation of colluvial materials, which can be found in all geographical zones. In our conditions, their formation was already influenced (in addition to erosion processes), also by solifluction processes (underflow), i.e. the flow of mud (soil saturated with water) on the frozen subsoil under the influence of gravity (Růžičková & Růžička 2001, Lacerda 2007, Lang 2003). For paleo-ecologists and geoarchaeologists, it provides valuable knowledge useful for landscape reconstruction (Kühn *et al.* 2017). They are a reservoir of soil organic carbon in the form of buried humus horizons (Zádorová & Penížek 2018).

The formation of colluvial soils can also be associated with long-term human management of the landscape, i.e., it is linked to agricultural use of soils in undulating terrain (Leopold & Völkel 2007, Kühn *et al.* 2017, Houben *et al.* 2006, Govers *et al.* 1994). Colluvial soils can be used as indicators of landscape development in terms of precise dating of events. Colluvisols are presented as a paleo-ecological geo-archive of the landscape, and their dating can be used to calculate organic carbon stocks (Zádorová *et al.* 2015).

Description and diagnosis of colluvial soils

Zádorová & Penížek (2018) propose a basic definition of two types of colluvial soils:

1. Colluvial soils – recent undeveloped soil formed by the accumulation of colluvial material without signs of post-positional pedogenesis, i.e. accumulation processes are dominant and the *in-situ* development of pedogenetic features has limited impact;
2. Soil on colluvial material – formed by various soil-forming processes from colluvial sediment during slope stabilization and minimal redistribution of colluvial material. In this case, a new soil type can be diagnosed.

Sobocká & Jambor (1998) assessed the thickness of the humus A horizon of Chernozems in southeastern part of the Danube Lowland affected by erosion using the so-called micro-catenas (i.e. the entire slope was not surveyed, only a selected slope segments involving certain geometric form were studied). The transects were selected according to the map of geometric forms of relief in a representative manner with approximately uniform slope inclination and uniform slope length. The relationship, or rather the dependence of the distribution of Chernozem subtypes on the morphometric parameters of the relief was investigated. Each micro-catena on each geometric form of relief was characterized by its arrangement of soil units. The results of the survey became the starting point for mapping several soil associations under the conditions of erosion processes of the Chernozem area.

Sobocká (2001) monitored the development of water erosion processes and its impact on the change of soil typology in the transition zone between the Trnava Loess Upland and the footslopes of the Little Carpathians (Kočín site). The assessing of erosion impact was based on comparing the recent field observations with 30-year-old archive materials of the General Survey of Agricultural Soils accomplished in 1960s. During this period, the dependence of the soil properties on slope inclination and morphology and soil textural composition was evaluated. Some Luvisols have changed to eroded Luvisols and on the steepest slopes where erosion was strongest the final phase of the soil degradation was reached and the Luvisols were changed to Regosols. In the concave relief forms, a significant increase in the accumulation of soil mass was recorded, which for the first time in Slovakia led to a proposal to create a new soil type of colluvial soils. Sobocká & Skalský (2002) and Sobocká (2003) evaluated field measurements in the Chernozem area (Brestovany site) and classified the soil type as Colluvisol.

Lehotský (2001) evaluated erosion-accumulation catena in the pilot hilly area of Bzince pod Javorinou. He observed the following degradation of Luvisols:

– In the rectilinear (i.e. most eroded) part of the catena, the change in the profile horizontation resulted in removal of the ochric humus horizon exposing the compacted Bt-horizon on soil surface. Its compaction values were 2 times higher (3 – 5 MPa) than the values in other parts of catena, where the A-horizon was preserved.
– In the rectilinear part of the catena, the values of humus content, and pH, as well as the content of the 0.001 – 0.01 mm texture fraction decreased to 56%, 74%, or 75% of the values of the reference site (flat relief).

Fulajtár (2001) investigated changes in soil types due to erosion and mineralization in Rišňovce pilot area. He noted several profile transformations:
– Transformation of leached Chernozem with B-horizon to Chernozem with A/C calcareous profile from the surface;
– Transformation of Luvic Chernozem to typical Luvisol;
– Transformation of Chernozem to Regosol.

In addition, he assessed changes of basic soil parameters due to anthropogenic erosion that significantly reduce soil fertility, such as decrease of organic matter content and deterioration of its quality (this process affects all transformed soils), increase of carbonate content (erosion of decarbonated Chernozems with B-horizon is a specific case of re-carbonization), decrease of sorption capacity, water holding capacity and nutrient content.

It should be noted that the classification of these soils is quite diverse, and in different countries they are expressed at different taxon levels (Zádorová & Penížek 2018). However, most important principle is that colluvial soils should represent the soils formed by recent sedimentation of colluvial material, on which there are no signs of any soil-forming process running *in situ*. The soil stratigraphy is determined by the thickness of the accumulated material and sedimentary stratification differing by skeleton, grain size, carbonate and soil organic carbon content. The buried original soil types are preserved everywhere under the colluvial deposits (Zádorová & Penížek 2018).

Based on detailed studies, these authors consider several types of colluvial soil formation:

Type A – intensive and long-term erosion disrupts the profile of exposed soils with source material ranging from humic to mineral material;

Type B – intensive and long-term erosion disrupts the profile of deep soils; the accumulated material is predominantly of the humic type without significant differentiation;

Type C – intensive and long-term erosion disrupts the profile of soils, the colluvial material is stratified (rapid layering of soil sediments) and is built up from diverse consolidated and unconsolidated materials.

For all Colluvisols the profile horizontation can be expressed as A/AP – M – fA – FB – C, where the M horizon is a horizon created by the displacement of soil mass by water and gravity downwards and is located above the buried horizons of original soil.

Basic soil properties show great vertical heterogeneity, and this also applies to the stratigraphy of Colluvisol's profiles. Colluvisols often show the decrease in soil organic matter in the surface parts of the profile, while in the lower parts it increases. The occurrence of risky (inorganic) elements and organic pollutants is in affinity with soil fractions and represents a mix of anthropogenic interventions over the last 100 – 200 years (Zádorová *et al.* 2013).

Colluvisols classification

The classification of Colluvisols is a real problem in many countries. There is noted international inconsistency in the definition of the terms Colluvisol, Koluvizem, colluvial material but their involvement in the soil classification system is also quite variable. Based on an overview of several soil classification systems (FAO, Germany, Russia, Austria, Czech Republic, Hungary, France, USA) we have attempted to evaluate soils that are known worldwide under the names Colluvisols, Kolluvizems, Stratozems, Cumulative Antrosols, *etc.* Their common characteristic is the occurrence of a surface horizon (including the Ap-topsoil horizon) formed by long-term transport and accumulation of humus horizon material because of several soil-forming factors, but primarily by erosion-accumulation. Zádorová & Penížek (2018) provided a table of classifying Colluvisols or colluvial materials by selected national and international classification systems. Their comparison will facilitate further study and classification of Colluvisols (Table 1). Similar correlations were made according to Sobocká (2003).

Table 1
Overview of the colluvial soils concepts in international and national classification systems (modified by the authors based on Zádorová & Penížek 2018)

Classification / state	**Name of colluvial soil/ material**	**Taxonomic level**	**Higher taxonomic level**	**Concept of the colluvial soil**	**Thickness of colluvial horizon**
WRB 2014	Colluvic material	diagnostic material	–	Accumulation of colluvial material (soil layer or substrate)	20 cm
WRB 2022	Solimovic material	diagnostic material	–	Accumulation of colluvial material (soil layer or substrate)	20 cm
USA	Cumulic	Sub-group	–	Accumulation of humus material, anthropogenically conditioned	40–60 cm
Czechia	Koluvizem	Soil type	Fluvisols	Accumulation of humus material, anthropogenically caused	50 cm
France	Colluviosol	Reference group	×	Colluvium as a soil-forming substrate	50 cm
Hungary	Sediment soils	Soil type	×	Colluvium as a soil-forming substrate, erosive deposition of stratification begins in the upper 50 cm	-
Germany	Kolluvisol	Soil type	Anthropogenic soils (*Terrestrische anthropogene Böden*)	Soil sediment, humus content corresponds to the A horizon, anthropogenic soil	40 cm

Classification / state	Name of colluvial soil/ material	Taxonomic level	Higher taxonomic level	Concept of the colluvial soil	Thickness of colluvial horizon
Poland	Gleby deluwialne czarnoziemne Gleby deluwialne wlasciwe	Soil type	Chernozemic soils *(Gleby czarnoziemne)* Weakly developed soils *(Gleby slabo uksztaltowane)*	Accumulation of humic colluvial material Accumulations of colluvial material, anthropogenically caused	50 cm 50 cm
Austria	Kolluvisol	Soil type	Colluvium and anthropogenic soils *(Kolluvien und Anthrosole*)	Accumulation of humus material	40 cm
Russia	Several soil types of Stratozems	Soil type	Stratozem	Periodic accumulation of sediments burying the original soil	40 cm
Slovakia	–	Periodic accumulation of sediments burying the original soil accumulated: covered, or overlying forms of soil types	–		–
x – formation of soil profile on colluvial material					

It should be noted that if involving anthropization in soil classification, it will be necessary to distinguish in detail between the natural and anthropogenic erosion, with the definition of intermediate stages of their differentiation. These problems are currently addressed by the USDA Soil Taxonomy proposals, according to which accelerated erosion belongs to anthropogenically induced processes (Soil Survey Staff 1999).

In the case of the Russian soil classification, a post-abrasive horizon was defined for the classification of Abrazems, respectively Erozems. Stratozems in the Russian soil classification system (Shishov *et al.* 2004) are included in the group of synlithogenic soils. This group involves different soils with one common feature: the material of the surface horizon has been transported and accumulated, and it forms a stratified horizon enriched in organic matter with a thickness of > 40 cm. This horizon lies on the original soil or soil-forming substrate. Stratified layers are formed either by water or wind accumulation, or also by artificial sedimentation (for example, when using irrigation water) or by the application of mineral or organic materials. This sedimentation tends to be long-term and acts syngenetically with other soil-forming factors. They are similar to alluvial soils but merging them together into one group is not considered, since the genetic interpretations of Stratozems are incompatible with the traditional concept of alluvial soils. The division of Stratozems at the level of type is based on the properties of the surface horizon as well as the thickness of the stratified sequence. For example, light Stratozems AY-RY-(/A-B-C/) have a stratification profile > 100 cm thick and a light-humus horizon > 40 cm thick formed under natural vegetation conditions lying on a buried profile. If Stratozems have an agrogenetically transformed surface horizon, their subtypes are distinguished according to the nature of the buried soil, for example, light Agro-Stratozems have PY-RY-(/A-B-C/). If the accumulation process is known, the name of Stratozems can be specified at the subtype level (e.g. water-sedimentary, aeolian-accumulative, irrigation-accumulative). Buried soil does not show signs of an ongoing pedogenetic process.

In the most recent internationally used classification systems, namely WRB (IUSS Working Group 2015, IUSS Working Group 2022) and the American Soil Taxonomy (Soil Survey Staff 1999), Colluvisols are not included into higher taxonomic classes. "Cumulic" is a taxonomic term used at the subgroup level (*extragrade*) for soils that have an excessively thick mollic or umbric epipedon (40, 50 or 60 cm thick, depending on the taxa), relatively gentle slopes, and an irregular distribution of organic carbon with depth. It is identified for soils in aggradation landscape positions that regularly receive fresh sediments, such as a sloping or concave footslopes. The relief surface is generally not stable enough to form a well-developed bedrock, or the sedimentation rate is slow enough to form a strong continuous epipedon.

Considerations about creating a new soil type for the accumulated form of erosion-affected soils (Colluvisol) were respected in the case of German soil classification (Arbeitskreis für Bödensystematik der DBG 1998), Austria (Nestroy *et al.* 2000), and the Czech Republic (Němeček *et al.* 2001, Němeček *et al.* 2011). Colluvisols with a strong A-horizon taxonomically at the soil type level are listed in the Polish Soil Classification System (Kabala *et al.* 2019). The Czech Soil Classification System (Němeček *et al.* 2011) classifies Colluvisols together with fluvial soils similarly to the Hungarian Soil Classification System (Michéli *et al.* 2019). In the German (Ad-hoc-AG Boden 2005) and Austrian classifications (Nestroy *et al.* 2011), Colluvisols (Kolluvisole) are categorized as lower units of anthropogenic soils. In the WRB 2015, colluvial materials are listed and one of the criteria is the occurrence of artifacts (IUSS Working Group WRB 2015).

We presented the concept applied in the French Soil Classification System (Baize (ed.) 1998, Chartin *et al.* 2011) and similarly in the concept of Colluvic material used by WRB 2015 (IUSS Working Group 2015). In this cases, colluvial soils are not defined according to specific properties, but by the formation of soil mass on colluvial material of different origin and properties. These are often soils that we identify as soils formed on colluvial material, and they have Ah+M > 40 cm and represent certain type of substrate displacement (fluvial, aeolian or anthropogenic).

In the German soil classification system (Arbeitkreis für Bodensystematik der DBG 1998), Colluvisols are classified as terrestrial Cultisols (terrestrial anthropogenic soils). The soil type Colluvisol (YK) is defined as soil with an Ah/M/II profile of transported (transferred) humic soil material (solum sediment, the humus content of which corresponds to the definition of Ah-horizons). The horizon was formed either by surface runoff from slopes and accumulating the sediment at the foothills, in depressions and small valleys, or by wind erosion, or by local displacement due to cultivation (e.g. tillage erosion which frequently transport soil mass from convex parts of fields).

Subtypes: diagnostic horizons (M – migrated material)

- Normal subtype, when M > 40 cm – normal Kolluvisol (YKn) (in German)
- Transitional subtypes with differentiated types of horizon characteristics:
  - Podzol-Kolluvisol (PP-YK), with a sequence of podzolic horizons in M < 15 cm
  - Pseudogley-Kolluvisol (SS-YK) S or transitions S from 40 – 80 cm, Sw-M > 40 cm depth
  - Gley-Kolluvisol (GG-YK) Go and transitional horizons from 40 – 80 cm.

Němeček *et al.* (2001) and Němeček *et al.* (2011) classify Koluvizems (*in Czech*) as fluvial soils. He defines them as soils with the Ap-Az – horizon sequence, formed by the accumulation of erosional sediments on the lower parts of slopes, in concave slope elements and in terrain depressions. The thickness of the accumulated horizon must be > 25 cm. He classifies the diagnostic horizon Az as a cultural humus horizon and defines it as a layering of material from humus horizons. He adds that the delineation of Kolluvizems will help in assessing the actual erosion and identifying the dating of deforestation. He distinguishes several subtypes: modal (m), pseudogleyic (g), carbonate (c), arenic (r), and pelic (p).

Nestroy (2001) in the Austrian Soil Classification classifies Kolluvisols (*in German*) in the order: terrestrial soils, classes: Kolluvisols and Anthrosols. Kolluvisols are soils that have arisen as a result of natural processes, are predominantly deep and consist of initially accumulated erosion material (transported by wind and water) and, except for the A-horizon, do not show *in situ* formed genetic horizons. Kolluvisols can arise from Cambisols, Chernozems, *etc.* The soils mainly occur in concave positions and due to soil material enriched with humus, and due to their depth and water supply, they are in many cases classified as highly valuable soils that attract pioneer tree species such as alder and willow. These soils are further divided according to the carbonate content as subtypes (carbonate, non-carbonate) and waterlogging as varieties (Gley, Pseudogley).

Colluvial material in the WRB 2022 is replaced by the newly introduced term Solimovic material (IUSS Working Group WRB 2022). The traditional use of the term Colluvic by geologists, geomorphologists or pedologists varies in different countries, therefore, to avoid inconsistencies, Miller & Juilleret (2020) proposed this new term. The characteristics are like those in the previous edition of WRB but are supplemented with a more detailed characteristic. Solimovic material (Solimovic from Latin *solum* = soil and *movere* = to move) is a mineral material (IUSS Working Group WRB 2022) that:

1. is found on slopes, footslopes, toeslopes, fans, in depressions, above barriers, along gullies or similar relief positions, originating from upslope positions where it was subject to diffuse erosion; and
2. is not of fluvial, lacustrine, marine or mass movement origin; and
3. one or more of the following:
   a. if burying a mineral soil, it has a lower bulk density than the uppermost layer of the buried soil; or
   b. has ≥ 0.6% soil organic carbon; or
   c. has a Munsell colour chroma of ≥ 3 moist; or
   d. contains artefacts and/or black carbon of any size; or
   e. has ≥ 100 mg kg_{-1} P in Mehlich-3 extract; and
4. does not form part of a diagnostic horizon other than a cambic, chernic, mollic or umbric horizon.

Identification of solimovic material in the field

The fine earth of the Solimovic material can be of any particle size, including small fragments. The solimovic material is not perfectly sorted, and may show some gross stratification, but stratification is not a typical feature due to the diffuse or chaotic nature of the deposition process. The solimovic material tends to occupy gently sloping to moderately steep slopes (2 – 30%). Black carbon or small artefacts such as pieces of brick, pottery, and glass may be present in the solimovic material. In many cases, solimovic material has a lithic discontinuity at its base.

The upper part of the solimovic material shows characteristics (fine earth texture, colour, pH, and soil organic carbon content) like the surface layer of the source in the neighbourhood. In extreme cases, the profile in the solimovic material reflects the eroded soil profile of the upward slope positions, with topsoil material buried under the former subsoil material. Good indication in the landscape is varying colour of the soil surface between convex and concave positions.

Accumulation by rapid mass movements such a in landslides or slumps do not meet the set of diagnostic criteria for solimovic material. In agricultural environments, solimovic material usually has a high base saturation. This is the result of liming or fertilization before and/or after having been eroded. Solimovic material is not bound to water bodies (e.g. rivers, lakes), and therefore it can be distinguished from fluvial material. In foothill positions, fluvial and solimovic material can be sedimented alternately, or grade into each other and may be difficult to differentiate.

If such soil is on a flat surface, it should be considered a product of fluvial processes, if the slope exceeds 2%, it is a sub-slope sedimentation of colluvial material. Fluvial material is usually better sorted by grain size and can have a pronounced layering, with the layers differing in grain size and organic matter content.

Zádorová *et al.* (2013) also describes a colluvial-alluvial belt fed by slope and water sediments. The areal differentiation of soil types is relatively difficult due to the minimal slope gradient and requires detailed field survey and soil analysis. A relatively large part of the delineated areas falls into the transection zone between the base of the slope and the floodplain. The boundary between Colluvisols and adjacent soils is relatively difficult to determine, especially at the Colluvisol/Fluvisol contact areas. Since both Colluvisols and Fluvisols are young soils with low morphological diversity, irregular dispersion of organic matter and often stratified character (Němeček *et al.* 2001), their differentiation can be difficult in some cases. In case when the distinction is not possible, it is appropriate to separate such an area as a separate mapping unit and call it a colluvial-alluvial belt (Rommens *et al.* 2006).

In earlier soil classification system of Slovakia (VÚPOP & SPS 2000), the diagnosis and classification of soils affected by erosion according is done at the level of soil type (change of eroded Luvisol or Chernozem to Regosol), variety (chemical change of soil reaction) and form (erosion, accumulated, covered, overlying). A separate accumulated diagnostic horizon was not introduced (Sobocká 2003). A similar status is also in the latest edition of the Morphogenetic Classification System of Soils of the Slovakia (SPS & VÚPOP 2014). The following erosion-accumulative features are defined within the framework of erosion-accumulation features:

- Eroded (ee): erosion has affected part of the solum, but diagnostic horizons have been preserved to such an extent that they meet the criteria of original soil type;
- Accumulated (rea): increase in the thickness of the surface horizon by gravitational accumulation of soil material within the same polypedon (usually in concave relief forms);
- Covered (ep): cover with recent new sediments (source from other polypedons) with a thickness of up to 60 cm due to gravitational accumulation or fluvial activity;
- Overlying (ey): genetic horizons of buried soil (including fossil soils) are found at a depth greater than 60 cm

The thickness of the colluvial material is problematic. The most widely used limit is 50 cm in almost all reviewed soil classification systems.

Zádorová & Penížek (2018) propose dividing the soil type Koluvizem (*in Czech*) into the following subtypes:

- humus with a predominance of humus containing colluvial material
- stratified with stratification of colluvial layers based on the content of organic matter, different colour, change in texture, etc.
- inverse with colluvial material having decrease in the content of organic matter (eroded materials of B + C horizons).

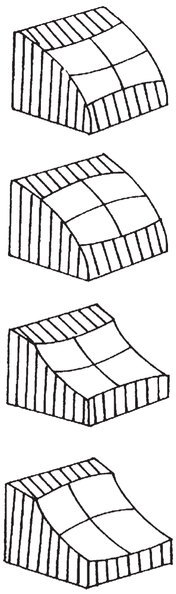
The following transitional types were distinguished: arenic, pelic, carbonate, luvic, cambic and pseudogleyic.

The aim of the presented study is to describe the colluvial material, characterize its location and soil horizonation within the studied soil profiles and find a classification at a level of higher taxonomic order (soil type, soil group). Based on this study a proposal will be submitted to Slovak Soil Classification Committee to consider Koluvizems (*in Slovak*) as a new soil group with Koluvizem soil type and probably several subtypes in the revised version of the Morphogenetic Soil Classification System of the Slovakia. This idea is based on a demand of soil classification users working in soil survey activities, land evaluation and soil services for landowners, farmers and agricultural enterprises.

MATERIAL AND METHODS

The evaluation of colluvial soils and the proposal for their classification as Colluvisols are based mainly on the authors' own long-term research, both on conventional field surveys (Fulajtár 1994, 2009, Fulajtár & Janský 2001, Sobocká 2001, 2003, Sobocká & Jambor 1998, Sobocká & Skalský 2002, Balkovič *et al.* 2013) and on the use of Remote Sensing methods (Fulajtár 1994, Fulajtár 2001, Fulajtár & Janský 2001, Fulajtár *et al.* 2016, Jenčo *et al.* 2020). The methodology according to Čurlík & Šurina (1998) was applied in the field surveys. International literature was another important source of knowledge, especially the studies from areas with similar geographical conditions (Bell & Boardman 1992, Chartin *et al.* 2011, Dotterweich 2013, Foucher *et al.* 2014, Govers *et al.* 1994, Kühn *et al.* 2017, Lang 2003, Larsen *et al.* 2016, Lehotský 2001, Leopold & Völkel 2007, Miller & Juilleret 2020, Penížek & Borůvka 2006, Růžičková & Růžička 2001, Terhorst 2000, Tesař *et al.* 2008, Van Oost *et al.* 2000, Zádorová *et al.* 2009, 2013, 2015, Zádorová & Penížek 2018, 2021). The sources for the proposed classification were the classification systems listed in Table 1.

The basic goal of terrain mapping and classification is to distinguish Colluvisols from other soil types present in the studied area. A key task in identifying the colluvial locations is, for example, the localization of inflex points at the convex-concave transition of the slope shape, where sedimentation of eroded material occurs (Sobocká & Jambor 1998). These places can be as potential sites for eroded and accumulated material formation. An inflex point is a point on the function graph, the point at which the curvature of the graph changes from convex to concave. For illustration, we present the basic geometric forms of the relief (Fig. 1) (Sobocká & Jambor 1998). Convexity or concavity can be determined using the second derivative. If $f''(x) > 0$ ($f''(x) < 0$ holds for every × `∈ (a.b), then the function is convex (concave) in the interval (a, b).



F_{XX} – convex-convex geometric form

F_{XK} – convex-concave geometric form

F_{KX} – concave-convex geometric form

F_{KK} – concane-concave geometric form

Fig 1 Geometric relief forms (Sobocká & Jambor 1998)

To identify the impacts of erosion processes in the soil profile of Luvisols in the Trnava loess upland, the erosion-accumulation catena methodology was used (Sobocká 2001, 2003). The basic prerequisite for identifying erosion processes in a soil profile is the establishment of erosion-accumulation catenas in transects characterizing reference (representative) localities. A catena is the name of a relief-soil sequence and is understood as a transect of a slope, the boundary of which is represented by a watershed, or peak on one side, and a watercourse, or bottom of the slope on the other side. Changes in soil properties occur both in the soil body itself, i.e. in a vertical section, and in the direction along the slope.

The basic analysis of catenas consists of a) detailed geomorphological mapping; b) pedological sounding and soil sampling; c) interpretation and comparison. Transects were established in the site of the Kočín watershed, which is characterized by a hilly type of relief with the occurrence of Luvisol types and subtypes developed mainly from carbonate loess. The main soil-degradation factor is surface water erosion causing an average annual erosion run-off of 15 – 20 t. $1ha^{-1}$. The altitude is 200 – 250 m above sea level, the average annual temperature is 9.3° C, the average annual precipitation is 550 – 600 mm. Two transects were established – in the southern and northern exposures of the same location. General characteristics: orographic unit, relief, exposure, average annual precipitation, average annual temperature, precipitation frequency, erosion rate, land use, vegetation cover, anti-erosion measures.

Transect characteristics: catena position, microrelief (geometric form), altitude, relative elevation, slope, slope length.

Morphological characteristics of pedons: soil classification horizon signature, soil-forming substrate, topsoil thickness, thickness of the 2nd horizon, solum thickness, assumed original solum thickness, difference between actual and assumed solum thickness, colour (Soil Standard Colour Charts), moisture and consistency, grain size and skeleton, structure, presence of new forms, rooting and biological activity, carbonates.

Analytical characteristics: grain size distribution (fine earth <2 mm), textural differentiation coefficient, textural triangle, bulk density, pH/KCl, pH/H_2O, carbonate content (%), organic carbon content (%), humus content (%), cation exchange capacity, P and K nutrient content.

Similar survey and analyses were used for catenas in the village Brestovany (Trnavska upland) with dominating of Chernozem soil type. As a part of the catena sequence evaluation, the physic-chemical characteristics were analysed and evaluated, especially the changes in soil texture, pH, carbonate content, Cox (humus), CEC and nutrient supply.

All results became the starting point for the determination of soil sequences, or associations with a new view on the development of current Luvisols and Chernozems of the loess upland, strongly affected by erosion.

RESULTS AND DISCUSSION

Based on the field research and analysis of soil samples, the following soil types were identified on the site, where Chernozems originally formed: dividing ridges with a minimum slope are covered mainly by modal (typical) Chernozem; with an increasing slope replaced by its eroded forms, which in the steepest parts of the slopes pass into soils with a minimum C_{ox} content. These can be designated as modal or calcareous Regosols according to the nature of the parent material. In depressed concave forms, accumulated, or rather, covered or overlying soil materials with various characteristics and stratification occur almost everywhere.

Representative profile 1: **Colluvial soil in the Chernozem area (Fig. 2).**
Description:
Classification (MSCS 2014): Chernozem typic covered calcareous
Signature: ČMmc^{ep}
Proposed classification: Chernozemic Koluvizem
Signature: KLb
Site: Brestovany (Trnava district)
Altitude: 140 m above sea level
Orographic unit: Trnava upland
Climate (Džatko & Sobocká 2009): sufficiently warm dry with mild winters with an average amount of precipitation of up to 550 mm
Land use: arable land
Crop: wheat
Terrain relief: lower part of concave slope (3 – 5°)
Parent material: loess
Soil profile:

Akpc 0 – 20 cm: 10YR 4/4 – 6 (wet matrix colour), slightly moist, loose, loamy, crumbly, strong biological activity (animal channels, coprolites), carbonate horizon of topsoil, clear transition to

Ckc 20 – 52 cm: 10YR 6/4, 5/4, 4/4, (wet matrix colour), slightly moist, loose, loamy, crumbly, strong biological activity (animal channels, coprolites), carbonate horizon of topsoil, distinct transition to

Amc´ 52 – 68 cm: 10YR 3/2, (wet matrix colour), moist, loamy, friable, weak subangular blocky, carbonate mycelia, medium or strong biological activity, buried relict mollic A horizon, distinct transition to

A/Cc´ 68 – 78 cm: 10YR 4/4, 6/4, (wet matrix colour), moist, friable, loamy, weak subangular blocky, carbonate mycelia, rare occurrence of worm channels and coprolites, buried transition horizon, gradual transition to

Cc´ >78 cm: 10YR 6/4, 6/7, (wet matrix colour), loess (buried parent material), moist, firm, loamy, structureless, carbonate mycelia and concretions, weak biological activity.

As it was mentioned, the eroded material is transported over a certain distance, which can vary considerably. Most of it is deposited in concave slope waves along the slope and at the footslopes extending further towards the floodplain. Only a small amount of material is washed out into the watercourse. In these accumulation positions, the original Chernozem is covered with allochthonous organo-mineral or mineral material. The loess itself can be exposed to accelerated erosion in extreme cases and covers the original soil profiles. Therefore, this transported material is heterogeneous, often covered by the loess material with low organic matter content.

Representative profile 2: **Colluvial soil in the Luvisol area (Fig. 3)**
Description:
Classification (MCSC 2014): Luvisol typic covered
Signature: HMm^{ep}
Proposed classification: Luvic Koluvizem
Signature: KLh
Site: Rišňovce
Altitude: 206 m above sea level
Orographic unit: Nitra Uplands – Zálužianska upland
Climate (Džatko & Sobocká 2009): moderately warm dry with mild winters,
with an average amount of precipitation up to 670 mm
Land use: arable land
Crop: corn, observation after harvest

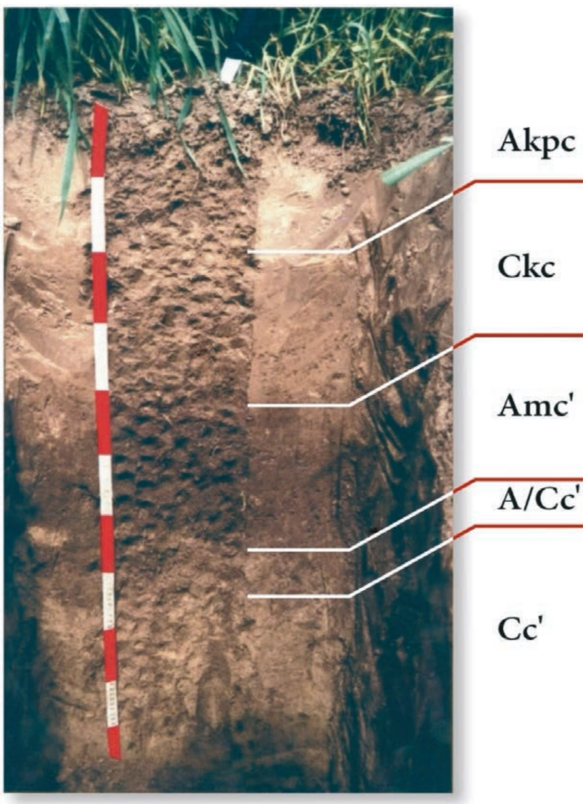


Fig. 2 Representative profile 1

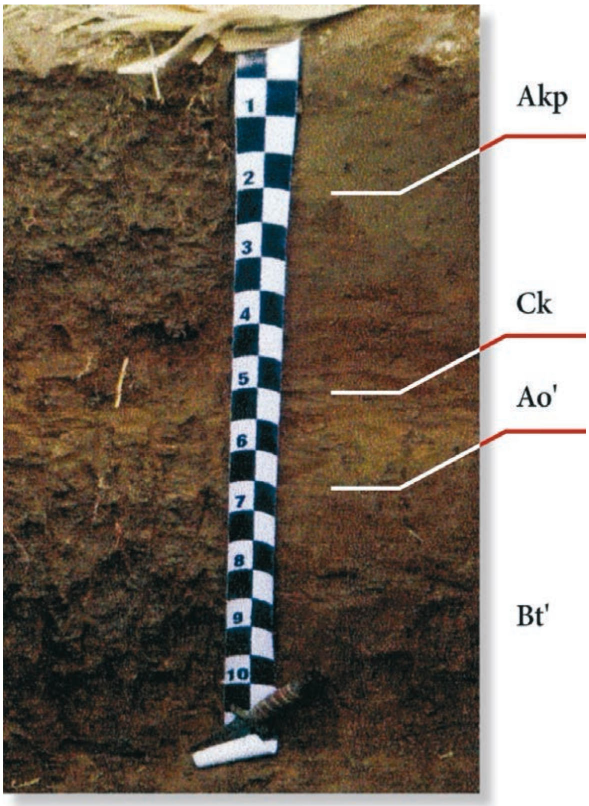


Fig. 3. Representative profile 2

Terrain relief: lower part of concave slope (3 – 5°)

Soil-forming substrate: loess

Soil profile:

Akp (0 – 20): 10 YR 3/5 (wet matrix colour), slightly moist, friable, loamy to clayey, coarse subangular blocky, without new formations and clay coatings, without rooting, clear transition to

Ck (20 – 55 cm): 10 YR 4/4 (wet matrix colour), slightly moist, firm, clayey, presence of weak clay coatings, without rooting, clear transition to

Ao´ (55 – 75 cm): 7.5 YR 3/4 (wet matrix colour), slightly moist, firm, loamy to clayey, buried horizon, coarse angular, without new formations and coatings, without rooting, clear transition to

Bt´ (> 75 cm): buried original Bt horizon, 7.5 YR 3/4 to 4/4 (wet matrix colour), slightly moist, firm, clayey-loamy, presence of clay coatings, without rooting.

The results confirm the previously presented assumption that a large part of the current Chernozems and Luvisols of loess uplands under given precipitation and temperature conditions are soils of the past and recently the pedogenesis is not active. Instead, a retrograde pedogenetic processes take place, such as the degradation of mollic A horizons due to ploughing, aeration, mineralization of organic matter, erosion and re-carbonatization of the upper part of the soil profile. Erosion-accumulation processes therefore significantly participate in the reshaping of the soil profile, which is reflected by changing horizontation, morphology, different chemical-physical properties and finally, different soil classification.

It was found that Chernozems or Luvisols with a “quasi-typical” sequence of soil horizons can be found only in the upper parts of the catenas (on flat ridges and plateaus). Here the cultivated Chernozems or Luvisols with a high humus content but with clay leaching (i.e. without textural differentiation) prevail.

On the convex slope forms (occupying the middle parts of catenas) the association of cultivated subtypes of Chernozems, Luvic Chernozems, calcareous Luvisols and calcareous Regosols (created by transformation of entirely eroded Chernozems and Luvisols) occur. No significant shift of clay particles was recorded here, organic matter content is usually reduced by erosion, most soils are carbonate throughout the whole soil profile and have a weakly alkaline soil reaction.

The concave slope forms prevailing in the lower parts of catenas are occupied by an association of cultivated soil subtypes of Chernozems and Luvisols covered by deposited soil material, which are classified in Slovak classification (according to a different thickness of the depositions) as accumulated, covered, or overlying. They have texture finer than the soils of upper convex slopes as they are enriched by fine particles eroded from above. They can have high organic matter content, but if the above slope is strongly eroded also the subsoil poor in organic matter and rich in carbonates can be transported from the slope and thus some accumulation layers can be poor in organic matter and can have an alkaline soil reaction.

The footslope parts of catenas are the weak point of the classification of erosion-accumulation Chernozems and Luvisols soil complex. To solve this problem a new classification is proposed for strongly deposited Chernozems and Luvisols which do not show diagnostic signs of pedogenesis *in situ* but are formed by sedimentation and have signs of sedimentary stratification showing that soil material was transported from the upper parts of the surrounding area. The sedimentary layers differ especially by texture, organic matter content, colour and some other morphological features (e.g. carbonate content, stoniness, structure, *etc.*). We propose to designate these soils as diagnostic material for a new soil type with a specific soil profile horizontation – colluvium. The definition will depend on several characteristics, but especially on the thickness and colour of the deposited soil material.

Colluvisol diagnostics

The translocation of soil material down by the slope and its accumulation in concave depressions and on footslopes is an important soil transforming process and it can result in formation of new soil types (Leigh & Webb 2005). We propose to distinquish the colluvial horizon (Ck), which is a colluvial parent material from which soils develop. In German classification such material is referred to as migrated (M) horizon (Arbeitkreis für Bodensystematik der DBG 1998). M horizon is defined as a mineral soil horizon formed by sedimentation of Holocene soil material resulting from translocation, fluvial activities, washing out, downslope ploughing, *etc.*

The basic diagnostic Ck-horizon of colluvium is formed by translocated and transformed soil material partially enriched with humus, sometimes stratified and showing different colours and texture. Under colluvial soil there is usually buried original soil with identifiable original horizon or their remnants. These soils are found in the concave relief forms, depressions and on footslopes of hills They do not involve soils developed on alluvial deposits. They can arise as a result of erosion-accumulation processes, aeolian processes, anthropic processes such as tillage erosion, irrigation, *etc.* Therefore, their classification into higher taxonomic groups in different classification systems is understood differently.

Other criteria for distinguishing Colluvisols are the depositional origin of the soil material, the organic matter content determined by the C_{ox} parameter (%), colour (the lower limit of the colour based on the Munsell colour tables) and the soil depth. Organic matter content should reach at least the requirements of an ochric A horizon and a thickness of more than 50 cm. This would logically complete the currently incomplete set of the thickness classes of deposited material in recent Slovak soil classification expressing three soil forms – accumulated, covered, overlying.

In southern Poland, a colluvial soil with an A horizon exceeding 4 m has been found (Schmitt & Rodzik 2006). The bright coloured spots occurring at the footslope do not indicate soil loss, but rather the accumulation of mineral loess material. This means that the colluvium itself is covered with non-humic material in some parts of the slope, which results in sub-fossilization of the soil profile and retrograde soil development.

For the Slovak Soil Classification System, we propose as the basic diagnostic horizon of colluvium the Ck-horizon, formed by transport and subsequent accumulation of soil material enriched with humus, sometimes stratified, and distinguishable by colour. We propose its thickness to A+Ck > 50 cm. An accompanying feature of colluvium is the frequent occurrence of buried soil with preserved its original horizon, or their remnants. The formation of colluvium is conditioned by the erosion-accumulation activity of water, aeolian activity or anthropic influence (e.g. ploughing). Their inclusion in a higher taxonomic group is still under discussion.

Colluvisol classification

Colluvisol (Koluvizem *in Slovak*) is a soil that is not found as a separate soil type in the MSCS & SPS (2000) but only as a soil form "accumulated". Soil forms represent the lowest taxonomical level of Slovak soil classification and there is need to upgrade it to higher taxonomical levels. Sobocká (2001) suggests considering it as a soil type having Ck-horizon as a basic diagnostic horizon. The Ck-horizon represent a soil horizon created by the transport and subsequent deposition of soil material enriched with humus, sometimes stratified with different colours. Under it, there is usually buried soil with the original horizons or their remnants. Koluvizems are found in the footslopes of hills, in concave relief forms, in depressions but not on alluvial deposits. Although they may have a soil profile similar to Fluvisols, i.e., they may be similar to alluvial soils, their genetic basis is different.

The main reason to establish a separated soil type for colluvial soils is the practical needs of soil mapping. Previous experience has shown that it is inappropriate to determine the soils under thick deposits of new material on the basis of original soil horizons, which are at a considerable depth and often may not even be within the reach of a dug soil pits or drilled probes. In such a case, the newly deposited material, which was eroded and transported from the slope should be evaluated as the current soil, becauses its genesis, the environmental, phytoecological and agroecological properties do not correspond anymore to original soil, which was buried and recently is in such depth that its impact on recent life of vegetation and agricultural production is very limited.

At our studied sites the accumulation of soil material was manifested along the entire transect in all investigated probes. The greatest accumulation was recorded in the concave-concave (KK) form of relief in the lower part of the transect, where the soil profiles were classified as Regosols with an overlain to buried form. We propose to evaluate such a soil type as Koluvizems (KL) in accordance with the works of

Sobocká (2003) and Zádorová *et al.* (2009). We propose to introduce a new soil type (Koluvizem) into the Slovak classification system, as it is in several other national and international soil classification systems.

Definition of Koluvizem

Koluvizem is a soil that has formed from footslope accumulations of humic silicate or carbonate fine-grained material without a skeleton, or with a small amount of skeleton, which has been displaced from the immediate surroundings as a result of water erosion (natural, or more often anthropogenic (accelerated by man) and tillage erosion, meeting the criteria of a humus soil horizon. The modal subtype is without other diagnostic horizons; the other subtypes have remnants or signs of buried diagnostic horizons.

These are initial soils from unconsolidated sediments that accumulated at the footslopes either by rainwater, surface washing or solifluction.

Proposal to include Koluvizem in the revised version of the MSCS

Proposal to separate a group of colluvial soils (they can also be in the group of anthropogenic and fluvial soils):

Soils with an ochric A horizon or a mollic A horizon formed from colluvial sediments (Ck horizon) having a thickness of the total A and Ck horizon complex greater than 50 cm (A+Ck ≥ 50 cm) and below the Ck horizons usually the original buried soil, or remnants of some soil horizons occur.

KOLUVIZEM (KL)

(1) without other surface diagnostic horizons or their signs	…**typical** (KLm)
(2) with the signs or remnant of the mollic Am horizon of Chernozem	…**chernozemic** (KLb)
(3) with the signs or remnant of luvic Bt horizon of Luvisols	…**luvic** (KLh)
(4) with the signs or remnants of cambic Bv horizon	…**cambic** (KLk)
(5) with the signs or remnant of gleyic G horizon	…**gleyic** (KL_G)
(6) with the signs or remnant of mottled Bg horizon	…**pseudogleyic** (KLg)
(7) with the cultivated Akp horizon to a depth of 35 cm	…**kultizemic** (KLa)

Basic sequence of horizons: A-Ck-A´-(B)-C.

Other properties

Koluvizems are soils from young erosion deposits that were deposited very quickly (several centuries to millennia), which are stratigraphically relatively monotonous, but a certain stratigraphic variety may be manifested depending on the fluidity or phasing of accumulation processes. Individual layers may differ in colour (humus content) and grain size. Transitions are mostly very gradual (diffuse), but gradual or sharp transitions may also occur. A common phenomenon is that the humus content is greater and the colour darker in the lower layers and gradually decreases and pales towards the surface, because erosion, after removing the surface soil humus horizons removes more and more material from deeper, less humus-rich or non-humus-rich layers of the surrounding soils.

CONCLUSIONS

Koluvizems, or a broader group of colluvial soils at a high taxonomic level, are defined in some national classification systems, especially in the Central and Western European countries (Czech Republic, Germany, Austria, Poland, France).

There are several problematic points that need to be considered when studying the classification of Koluvizems and their definition in relation to other soil types. First, it should be noted that colluvial soils are morphologically inconspicuous and the minimum thickness of the colluvial horizon is the main diagnostic criterion (apart of their position in concave terrain forms). Second, there is a considerable variability in the form of the colluvial horizon, resulting mainly from a strong dependence on the source material, which in many cases makes the identification of colluvial soils difficult.

Yet we do not consider solimovic material in the sense of the WRB 2022, also due to the currently used term "colluvial material" in Slovak pedology.

We recommend further research on colluvial soils, which should focus especially to their history and *in situ* emerging pedogenesis, as well as the classification of colluvial soils into higher taxonomic units.

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