Changes in soils of Central Russian forest-steppe under the impact of sulfur coal mining (the Moscow basin)

Alexander Kostin (*alexanderk640@gmail.ru*), Pavel Krechetov, Olga Chernitsova and Elena Terskaya,
Lomonosov Moscow State University, Department of Geography, Moscow, Russian Federation

CC BY

Purpose

The aim of the study was to examine the post-mining evolution of natural soils under the impact of supply of technogenic material from the spoil heaps and changes of the terrain (formation of dump tailings, as well as subsidence areas over the mined space) in abandoned sulfur coal mining areas.

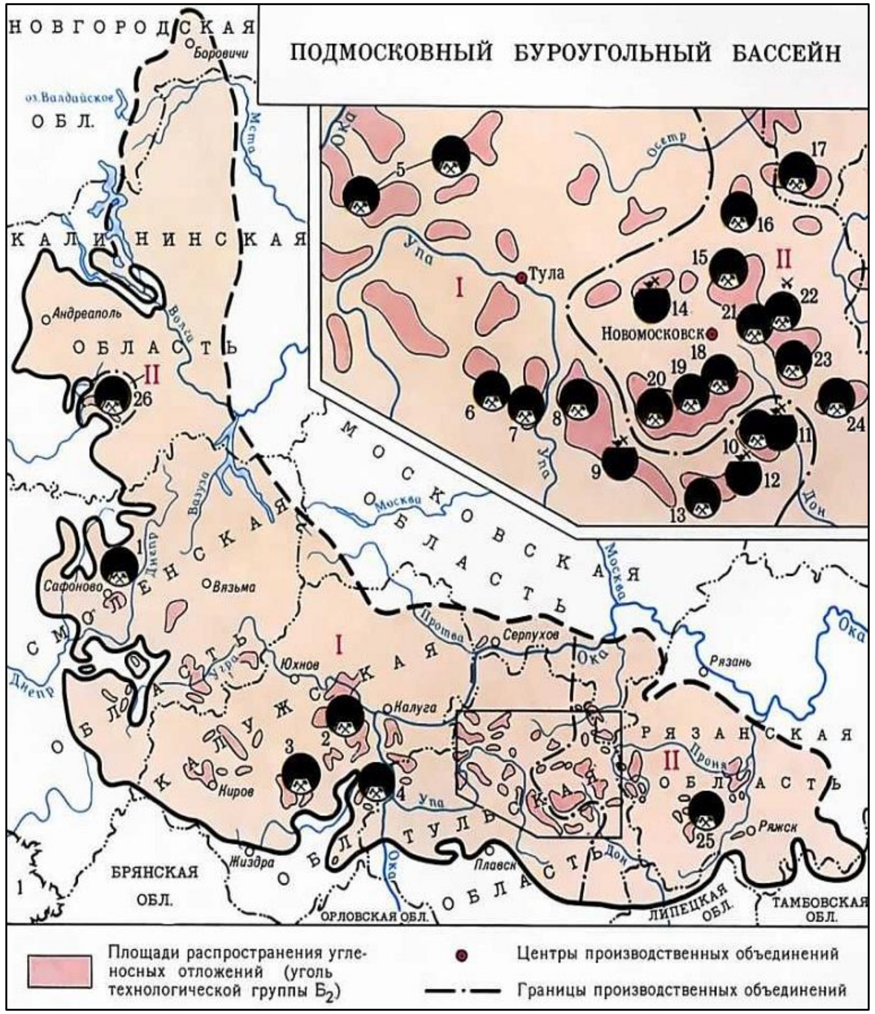
We had to:

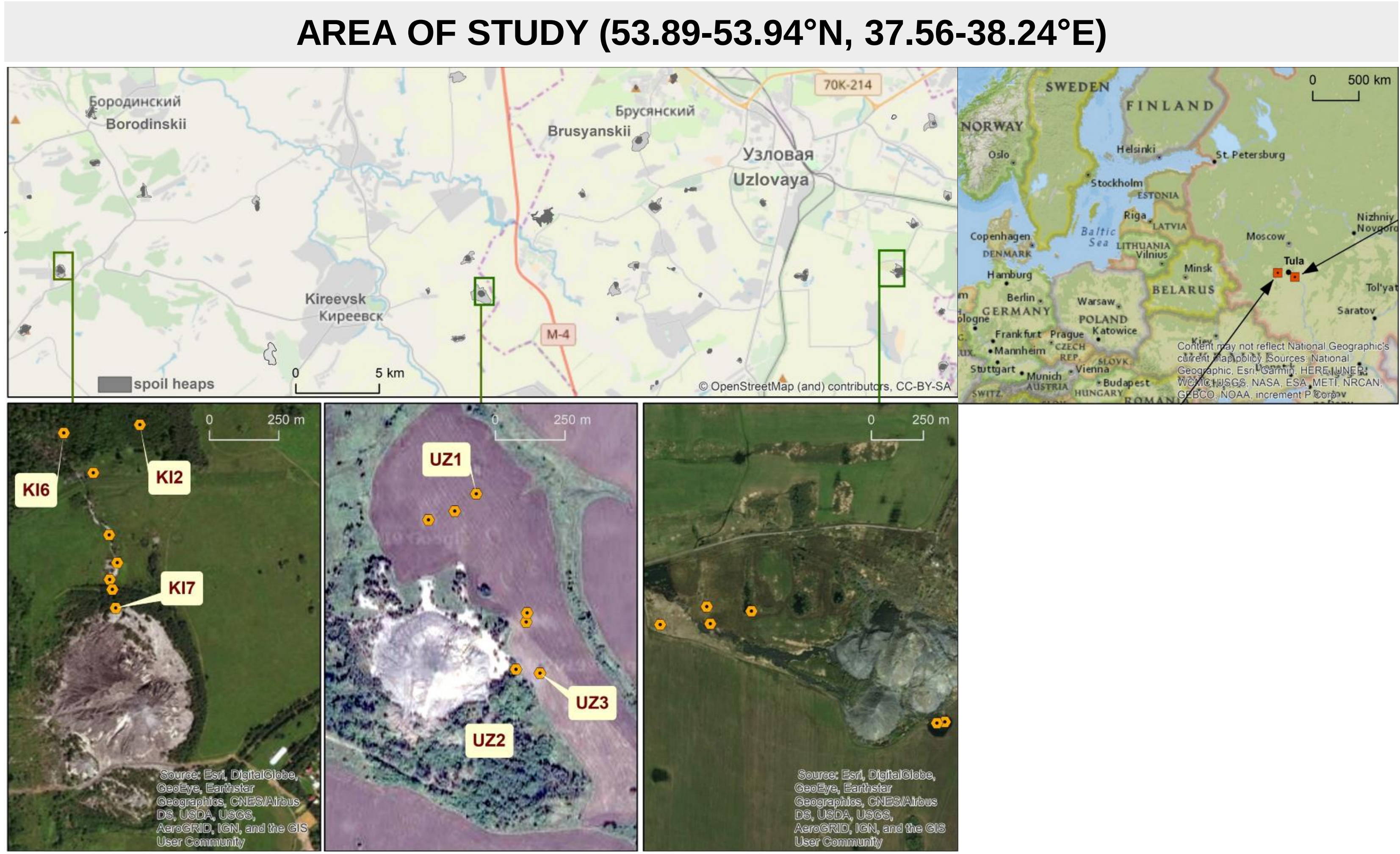
- to identify factors and mechanisms of changes in elemental composition and soil properties;

- to determine general patterns and define specific processes of transformation of soil morphology impacted by technogenic material from the spoil heaps and formation of mine subsidence;

- to conduct a comparative analysis of chemical composition of liquid and solid phases of natural and technogenically transformed soils affected by technogenic fluxes from waste sulphide-bearing dumps and mine subsidence

Study odjects – antropogenic spoil heaps (conical dumps), mine subsidence and technogenically transformed spoil heaps



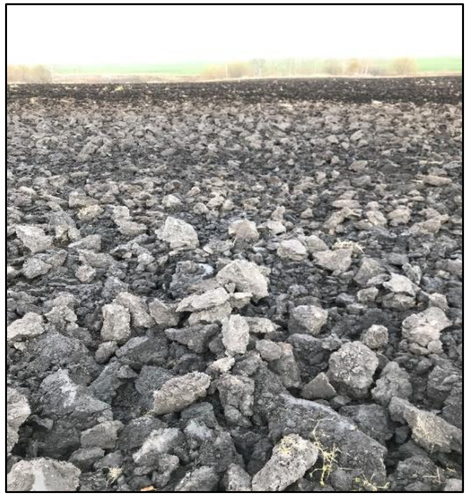


Site «Kireevsk» Site «Uzlovaya»

Technogenically-created landscapes in the coalmine areas

Conical spoil heap and dump tailing at the «Uzlovaya» site

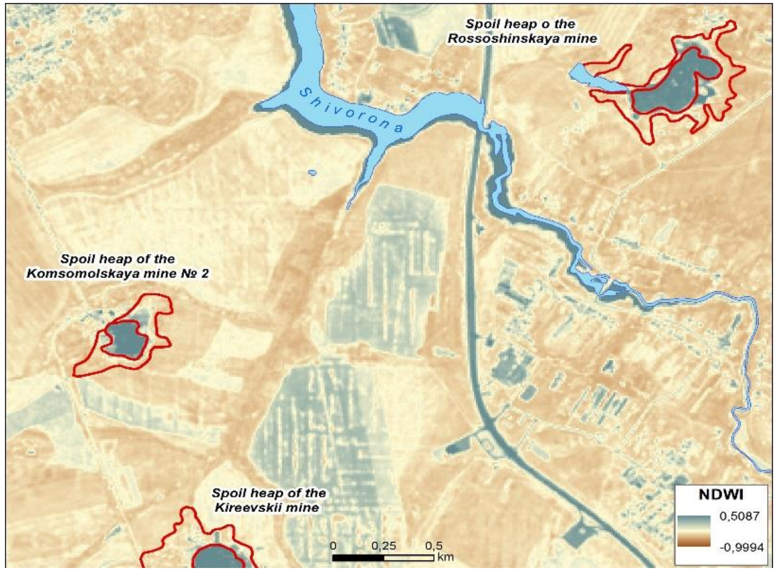
Subsidence area over mined space on the arable land (the «Uzlovaya» site)

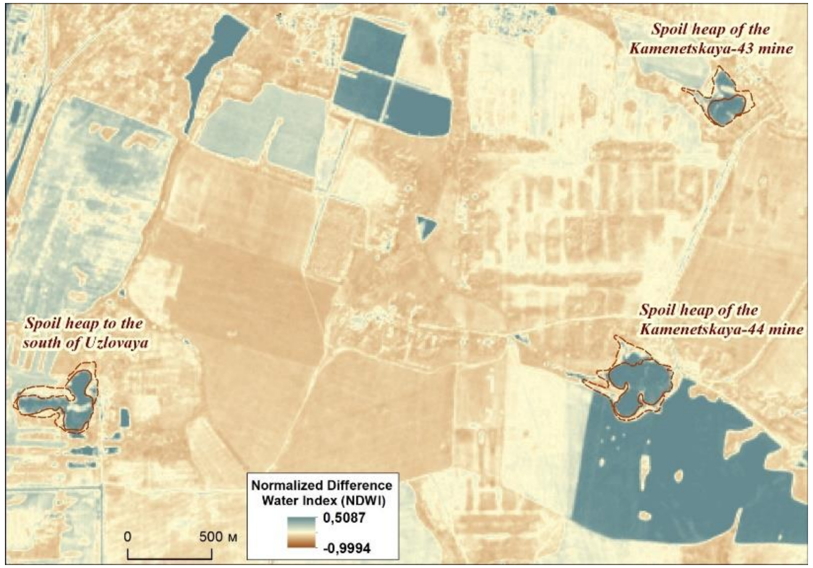


Subsidence area near spoil heap located to the south of Uzlovaya site (ESRI Imagery)

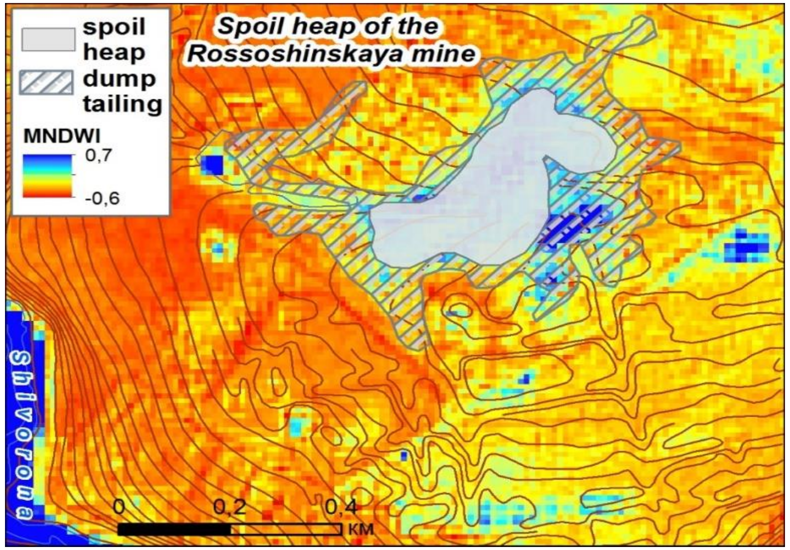
Analysis of changes in soil cover of forest-steppe landscapes under the impact of coal mining using remote sensing data

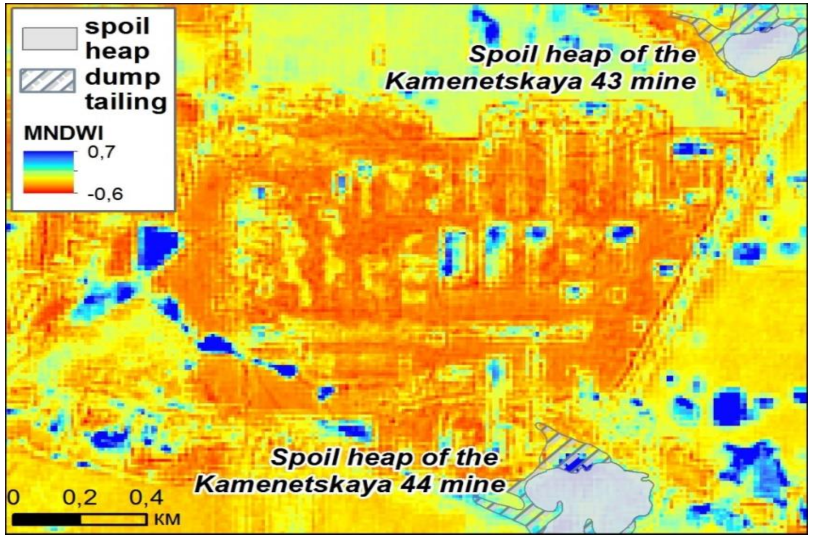
Sentinel 2A images for different seasons





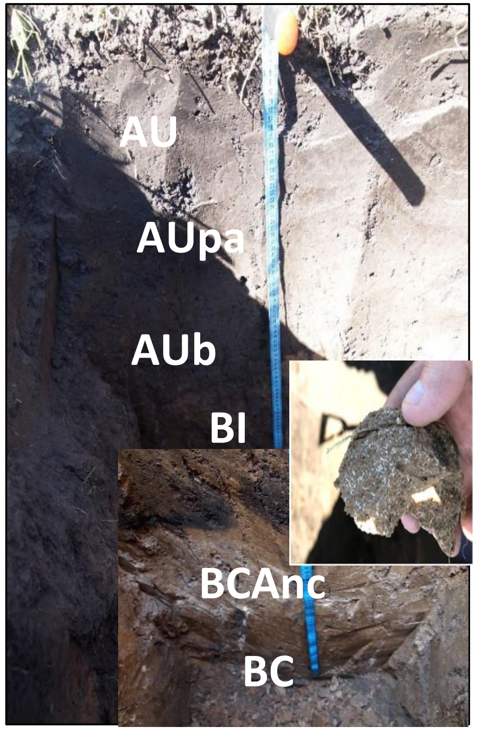
«Waffle» pattern of subsidence area over mined space revealed through the Normalized Difference Water Index (NDWI) calculated from the Sentinel 2A image for July 26th, 2017 (Uzlovaya site)



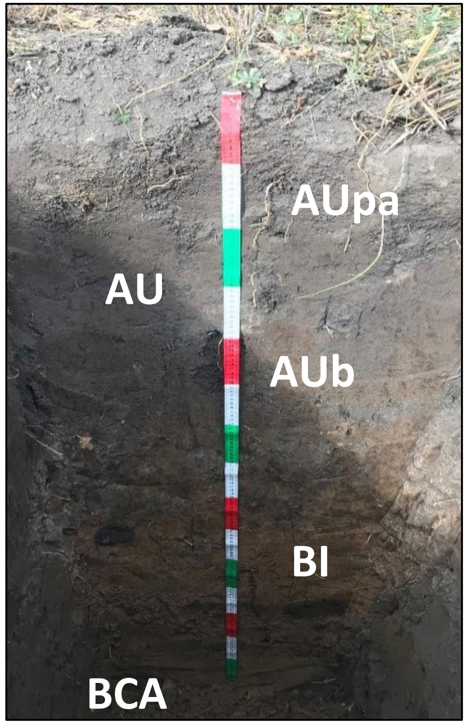


Water Index (MNDWI) calculated from the Sentinel 2A image for 12nd April, 2018. Blue sites detect water (waterlogged subsidence areas)

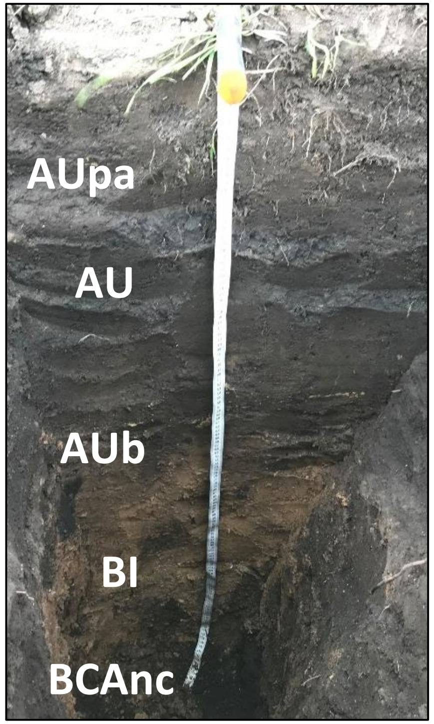
Haplic Phaeozems (site «Uzlovaya»)



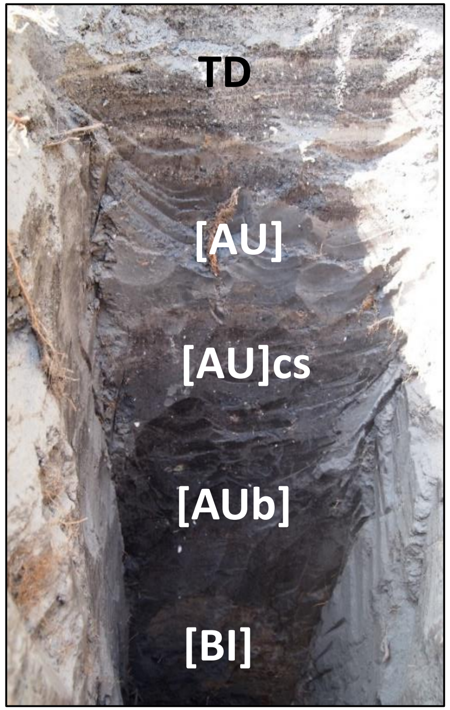
Chernozem leached arable (Haplic Phaeozem (Anthric) (WRB 2014))



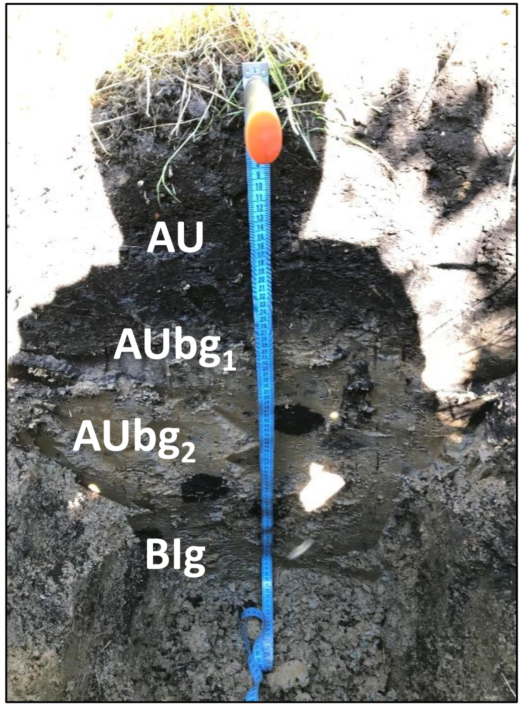
Chernozem podzolized arable (Haplic Phaeozem (Anthric) (WRB 2014))



Chernozem leached arable in mine subsidence (Haplic Phaeozem (Anthric) (WRB 2014))

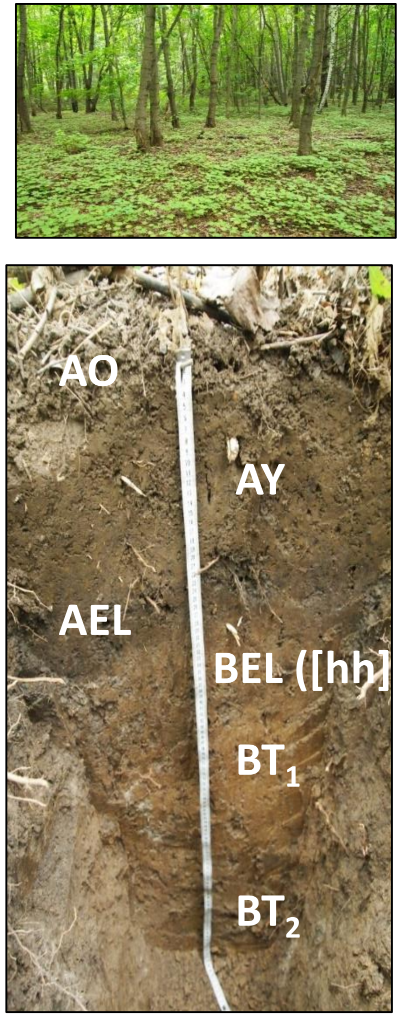


Chernozem gypsified technogenically transformed



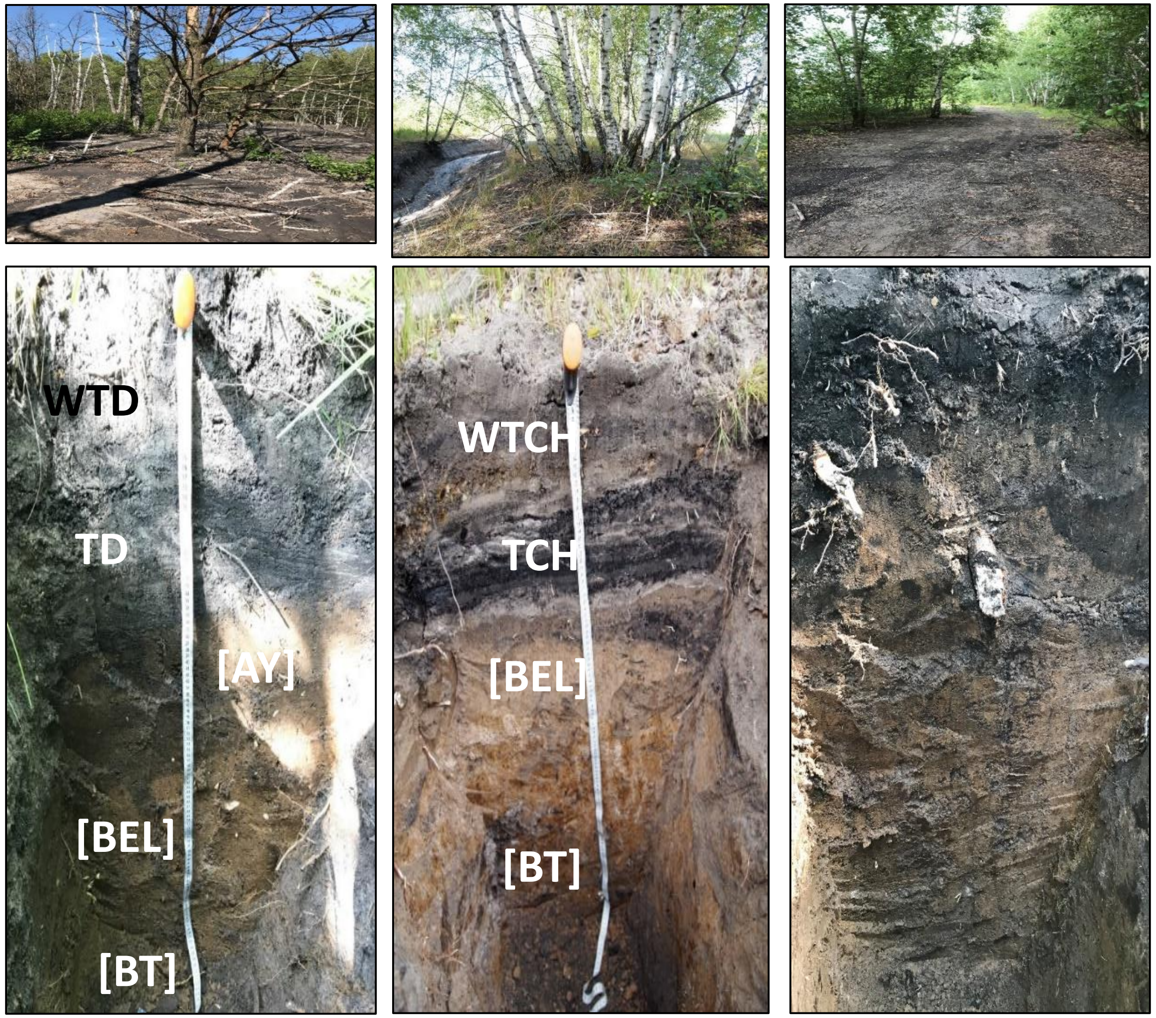
Meadow chernozemic (Haplic Phaeozem (WRB 2014))

Greyzemic Phaeozems (site «Kireevsk»)



Grey forest soil (Greyzemic Phaeozem WRB 2014))

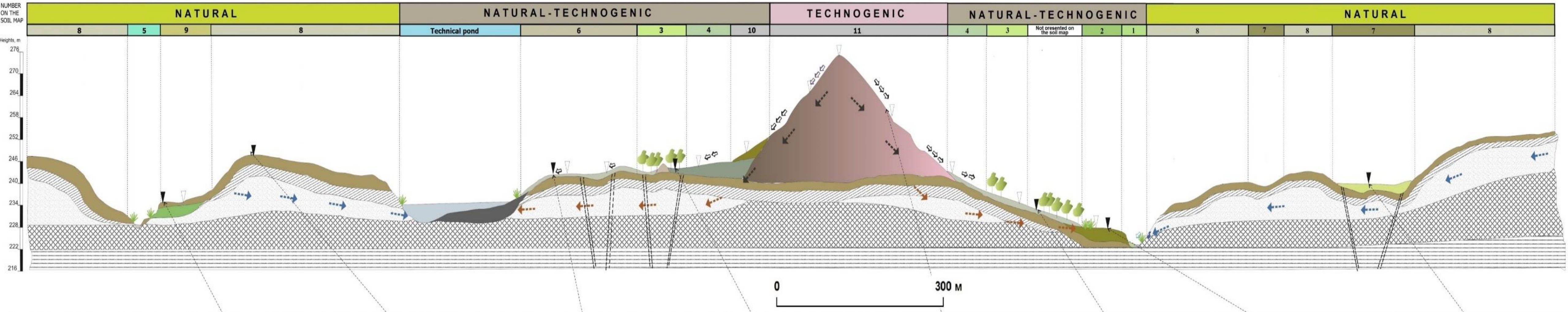
Grey forest arable soil (Greyzemic Phaeozem (Anthric) WRB 2014))



Grey forest soil technogenically transformed

Soddy gley soil in mine subsidence (Umbric Gleysol WRB 2014))

CATENARY SEQUENCE OF NATURAL, NATURAL-TECHNOGENIC AND TECHNOGENIC SOILS



Soddy, poorly developed (low thickness of humus horizon) on technogenic deposit displaced from the spoil heap

Meadow-chernozemic (Haplic Phaeozem (WRB 2014))

Chernozem leached, arable (Haplic Phaeozem (Anthric) (WRB 2014))

Chernozem leached, technogenically transformed, non-calcareous, overlapped by the layer of technogenic deluvium

Soddy, poorly developed (low thickness of humus horizon) on deluvial deposit overlapping buried chernozem leached, technogenically transformed, non-calcareous

Technogenic deposits (spoil heap and dump trail)

Chernozem leached, technogenically transformed, gypsym, non-calcareous, overlapped by the layer of technogenic deluvium

Soddy, poorly developed on the technogenic proluvial deposit overlapping buried meadow-chernozemic soil

Chernozem leached ground gleiyic with the low depth of carbonates

Formation of chemical composition of erosion products of sulphude-bearing dumps

1)Biochemical oxidation of sulphides

1) $2FeS_{2(s)} + 7O_2 + 2H_2O \longrightarrow 2Fe^{2+} + 4SO_4^{2-} + \mathbf{4H^+}$

Pyrite (marcasite)

2)* $2Fe^{2+} + O_2 + \mathbf{4H^+} \longrightarrow Fe^{3+} + 2H_2O$

3) $FeS_{2(s)} + + 14Fe^{3+} + 8H_2O \longrightarrow 15Fe^{2+} + 2SO_4 + \mathbf{16H^+}$

4) $Fe^{3+} + 3H_2O \longrightarrow Fe(OH)_{3(s)} + \mathbf{3H^+}$

pH=2-2,5

Pyrite and marcasite concretions in overburden rocks («Kireevskaya» coal mine)

* The reaction is going with the participation of Fe-oxidizing thionic bacteria (Thiobacillus ferrooxidans, Thiobadilus thiooxidans)

Formation of chemical composition of erosion products of sulphude-bearing dumps

2) Hydrolysis of clay minerals (aluminosilicates)

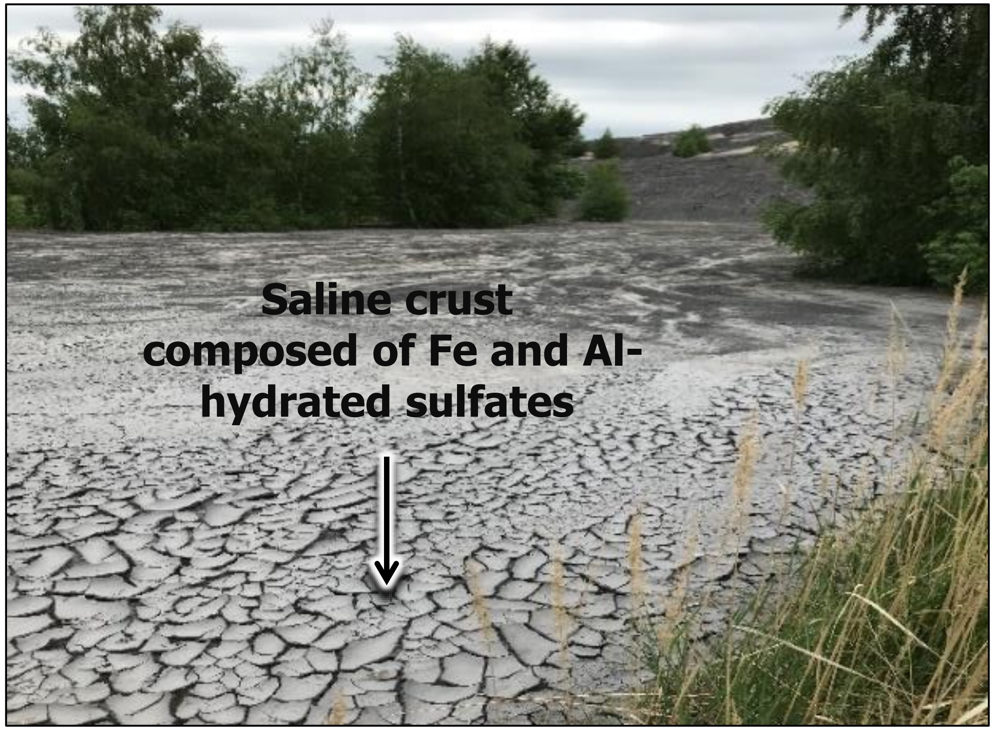
$$NaAl_3SiO_8 + 6H^+ + 2H_2O \longrightarrow 3K_{0,33}Al_{2,33}Si_{3,67}O_{10}OH + 10H_4SiO_4 + 6K^+ + Q$$

$$Al^{3+} + 3H_2O \longrightarrow Al(OH)_3 + 3H^+$$

3) Acid dissolution

$$Al(Si_4O_{10})(OH)_8 + 6H^+ \longrightarrow 4Al^{3+} + H_4SiO_4 + 8H_2O$$

$$2Al(OH)_3 + 3H_2SO_4 \longrightarrow Al_2(SO_4)_3 + 6H_2O$$



Chemical properties of waste dumps

Site	Coal deposit	№	Operation	pH	TDS, μS/cm	Composition of readily soluble salts (mmol$_c$/dm^3)							Titratable acidity (mmol$_c$/dm^3)		Fe, mmol$_c$/dm^3	
						HCO_3^-	Cl^-	SO_4^{2-}	Ca^{2+}	Mg^{2+}	K^+	Na^+	H^+	Al^{3+}	Fe^{2+}	Fe^{3+}
«Kireevsk»	Skuratovskoe	6	1946-1955	2.3	21400	ND[1]	ND	250	360	9.8	0.04	10.8	591.8	34.2	47.7	61.3
	Lipkovskoe	6	1955-1986	2.6	5940	«	1.7	52.1	15.7	0.7	0.1	0.8	42.2	19.7	6.9	116.3
«Uzlovaya»	Dedilovo-Uzlovskoe	2	1952-1964	2.5	9800	«	0.2	104.2	15	5.9	0.1	8.7	147.3	39.1	3.8	103.8
		44	1951-1997	2.2	20500	«	0.1	208.3	330	9	0.1	11	507.7	65	17.9	96.6

*ND[1] – not detected

Spoil heap and dump tailing at the «Kireevsk» site

Chemical properties of acid mine drainage (AMD)

Site	Coal deposit	№	Operation	pH	TDS, µS/cm	Composition of readily soluble salts ($mmol_c/dm^3$)							Titratable acidity ($mmol_c/dm^3$)		Fe, $mmol_c/dm^3$	
						HCO_3^-	Cl^-	SO_4^{2-}	Ca^{2+}	Mg^{2+}	K^+	Na^+	H^+	Al^{3+}	Fe^{2+}	Fe^{3+}
«Kireevsk»	Skuratovskoe	6	1946-1955	5.3	998	0.1	0.2	9.3	10.7	1.2	0.1	0.5	0.2	ND	ND	ND
	Lipkovskoe	6	1955-1986	4.3	1624	ND	0.1	16.0	18.9	0.9	0.1	0.1	0.7	7.8	ND	0.6
«Uzlovaya»	Dedilovo-Uzlovskoe	44	1951-1997	5.6	1584	0.2	0.03	15.2	25.3	1.5	0.03	0.1	2.6	ND	29.2	6.5

*ND[1] – not detected

Acid mine drainage
at the «Kireevsk» site

Chemical composition of dump tailings

Site	Coal deposit	№	Operation	pH	TDS, μS/cm	Composition of readily soluble salts ($mmol_c/dm^3$)							Titratable acidity ($mmol_c/dm^3$)		Fe, $mmol_c/dm^3$	
						HCO_3^-	Cl^-	SO_4^{2-}	Ca^{2+}	Mg^{2+}	K^+	Na^+	H^+	Al^{3+}	Fe^{2+}	Fe^{3+}
«Kireevsk	Skuratovskoe	6	1946-1955	3.8-4.4	481-3360	ND	0.1-2.8	2.0-30.1	1.4-33.2	0.2-6.1	0.1-0.5	0.1-1.4	0,4-3,6	0,1-6,6	0,1-0,6	0,3-1,6
	Lipkovskoe	6	1955-1986	3.5-4.2	235-1582	ND	0.1-0.8	1.2-24.3	1.4-13	0.1-0.5	0.1-0.3	0.1-0.9	0,5-9,4	0,4-11,1	0,1-0,4	0,1-0,2
«Uzlovaya»	Dedilovo-Uzlovskoe	2	1952-1964	3.7-4.4	333-2400	ND	0.1-1.7	0.8-26	1.9-40,3	0.2-2.4	0.1-0.3	0.1-0.5	0,4-4,3	0,1-11,5	0,1-1,3	0,1-2,6
		44	1951-1997	3.4-4.1	862-1177	ND	0.2-0.6	11.3-20.4	6.9-21,6	0.1-4.7	0.1-0.2	0.1-0.6	1,6-14	0,7-4,5	0,1-3.2	0,1-5,7

*ND[1] – not detected

Dump tailing at the «Uzlovaya» site

Elemental composition of soils (Greyic Phaeozems)

Horizon	Depth, cm	S_{total}, %	SiO_2	Al_2O_3	Fe_2O_3	Fe_2O_3/SiO_2	Al_2O_3/SiO_2
Grey forest soil (natural site)							
AY	0_17	ND[1]	86,5	7,5	0,9	0,01	0,09
AEL	17_22	ND	77,5	14,4	3,6	0,05	0,19
BEL[hh]	22_29	ND	76,7	15,0	4,7	0,06	0,20
BT1	29_78	ND	74,1	15,2	5,2	0,07	0,20
BT2	78_110	ND	73,7	15,4	5,4	0,07	0,21
Grey forest soil technogenically transformed, overlapped by the dump tailing							
WTD	0_7	0,4	72,2	19,6	3,0	0,04	0,27
TD[2]	7_56	0,5	70,8	19,7	3,1	0,04	0,28
[AY]	56_70	0,6	72,8	16,2	5,4	0,07	0,22
[BT1]	70_85	ND	75,2	16,4	5,7	0,08	0,22
[BT2]	85_110	0,2	80,4	14,8	4,6	0,06	0,18

[1]ND – not detected; [2]TD-technogenic deposit

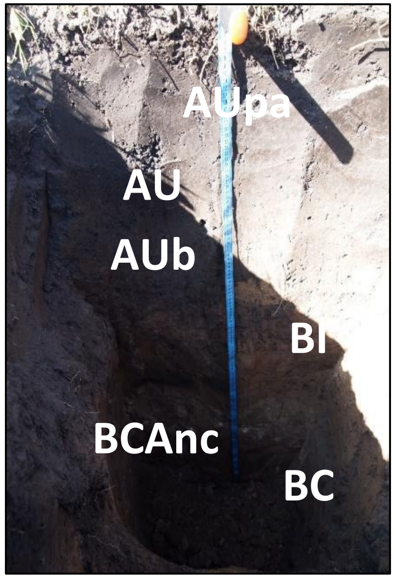
Elemental composition of soils (Haplic Phaeozems)

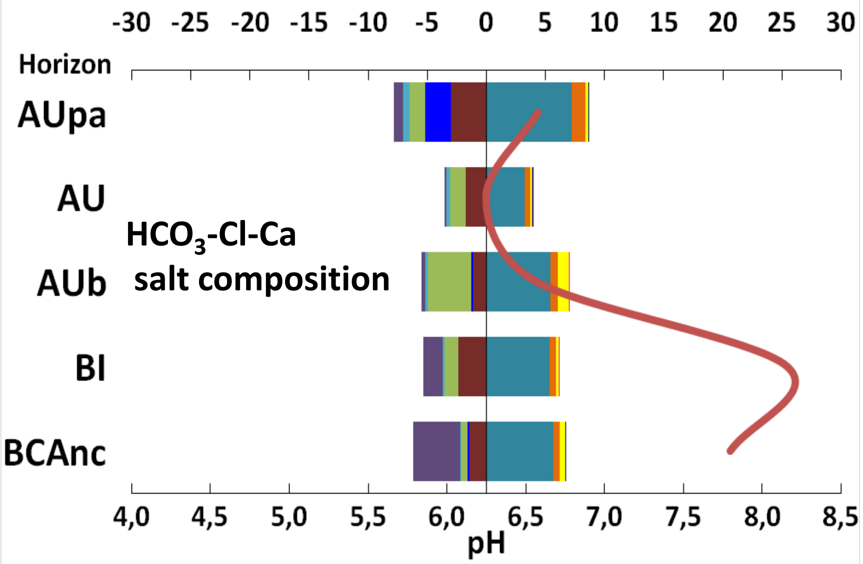
Horizon	Depth, cm	S_{total}, %	SiO_2	Al_2O_3	Fe_2O_3	Fe_2O_3/SiO_2	Al_2O_3/SiO_2
Chernozem arable leached (natural site)							
AUpa	0_33	ND	74,8	12,3	4,4	0,06	0,16
AUb	33_52	ND	75,3	13,5	4,7	0,06	0,18
BI	52_96	ND	75,2	14,5	4,9	0,06	0,19
BCAnc	96_116	ND	61,8	13,7	4,2	0,07	0,22
BC	116_150	ND	74,5	14,3	4,6	0,06	0,19
Chernozem arable gypsified technogenically transformed with a plowed dump tailing							
TDAUpa	0_21	0,4	70,8	20,5	4,5	0,06	0,29
[AUpa]	21_46	0,1	72,6	18,5	3,8	0,05	0,25
[AU]cs	46_69	0,05	74,3	13,2	4,6	0,06	0,18
[AUb]	69_118	ND	74,9	13,8	4,8	0,06	0,18
[BI]	118_150	0,05	74,4	14,8	4,8	0,07	0,20

[1]ND – not detected; [2]TD-technogenic deposit

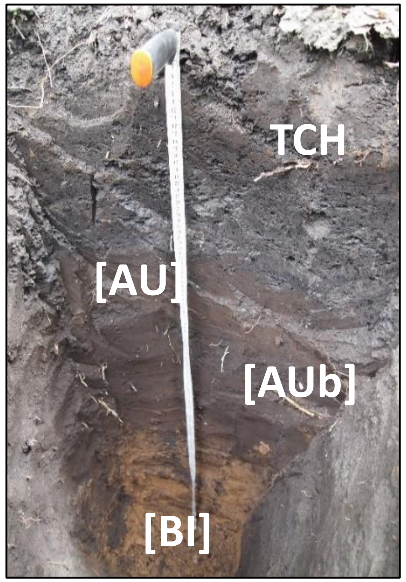
Composition of soil liquid phase, $cmol_c\ L^{-1}$

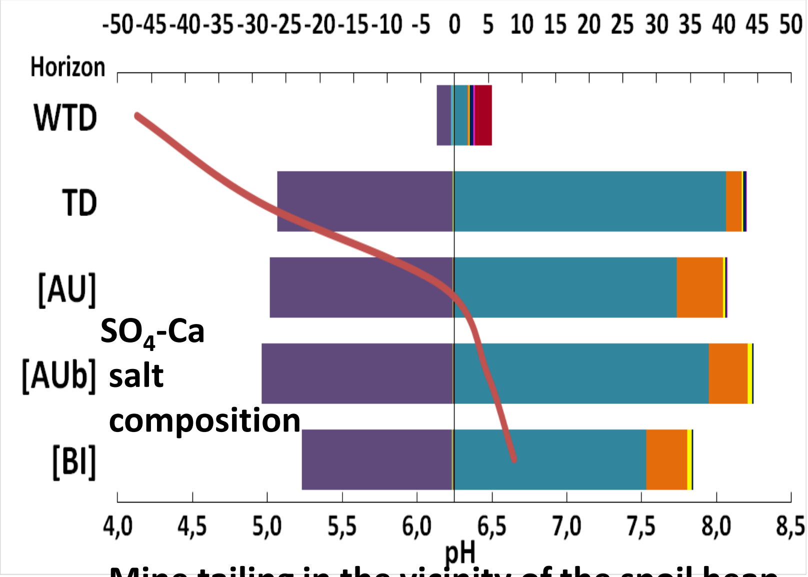
Chernozem leached arable (natural site)





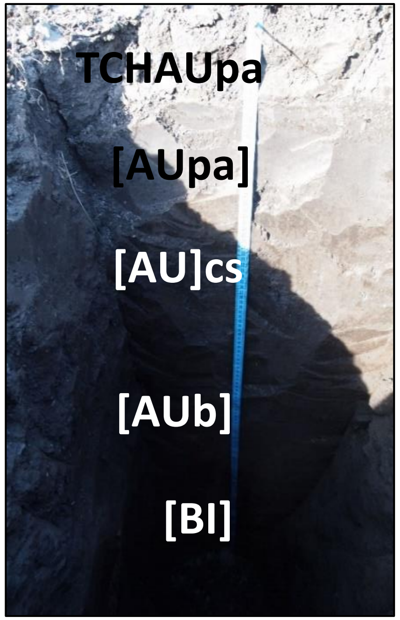
Chernozem technogenically transformed

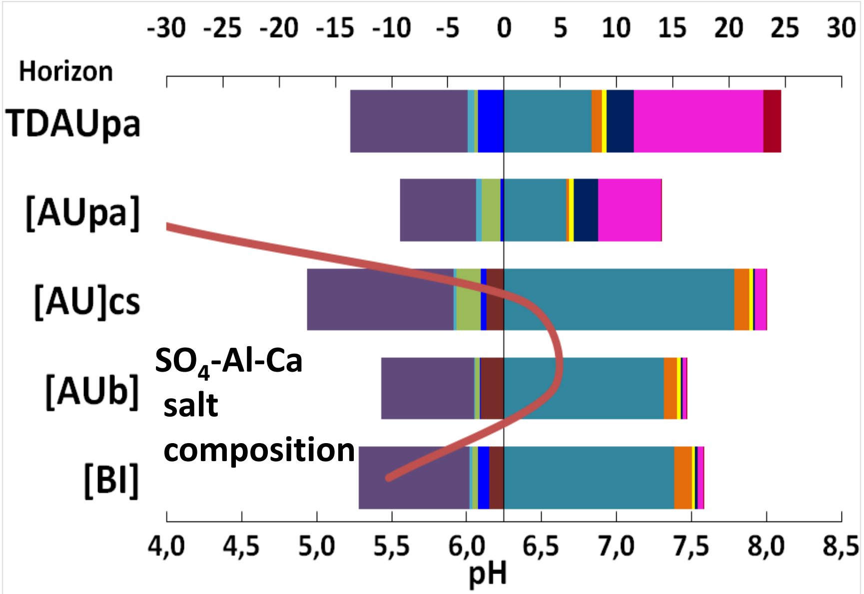




Mine tailing in the vicinity of the spoil heap

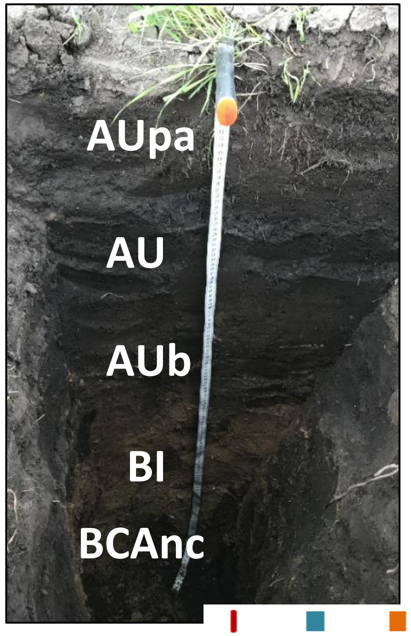
Chernozem technogenically transformed

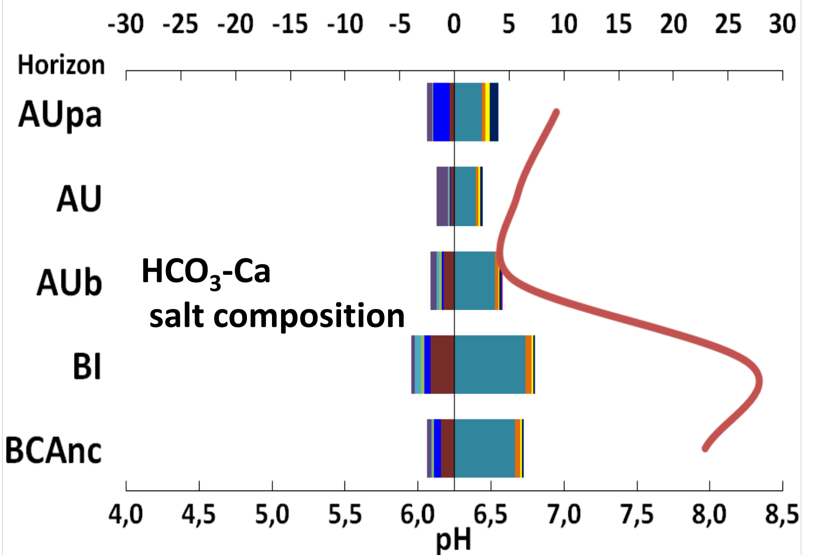


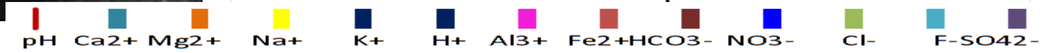


Middle part of the dump tailing

Chernozem leached arable in mine subsidence

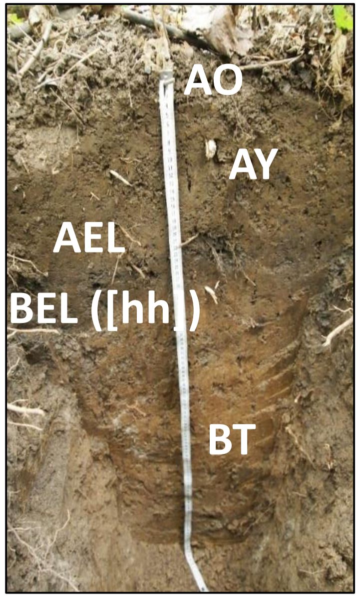


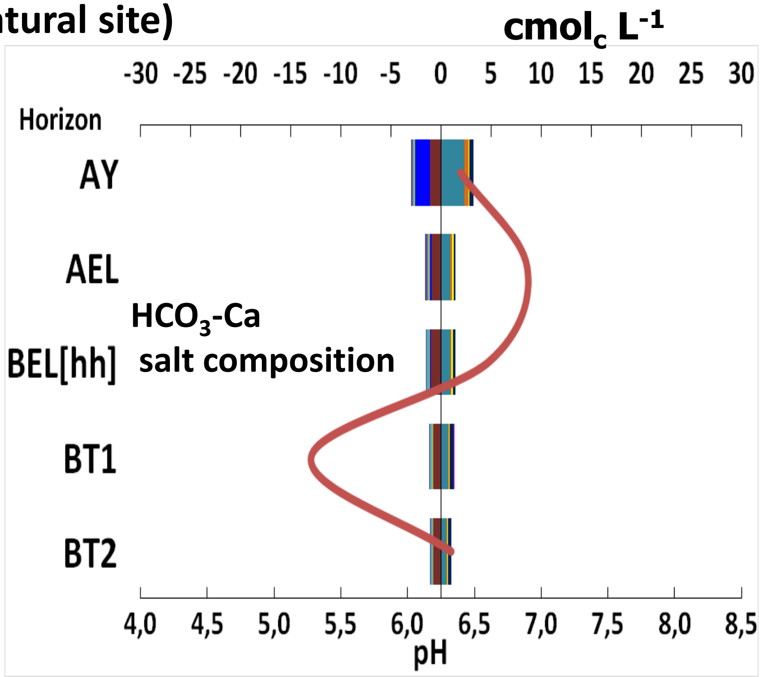




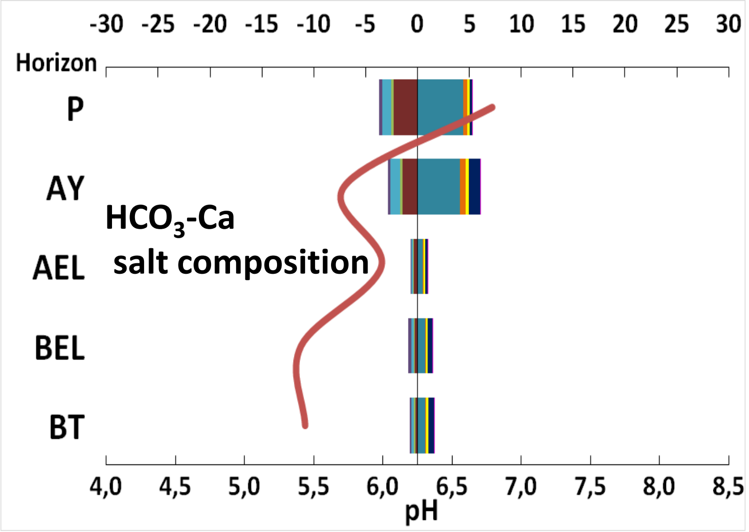
Composition of soil liquid phase, $cmol_c\ L^{-1}$

Grey forest soil (natural site)



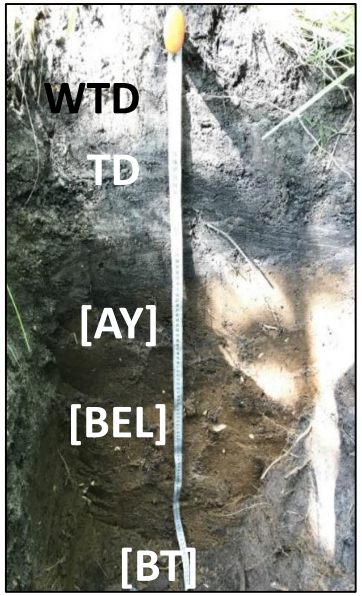


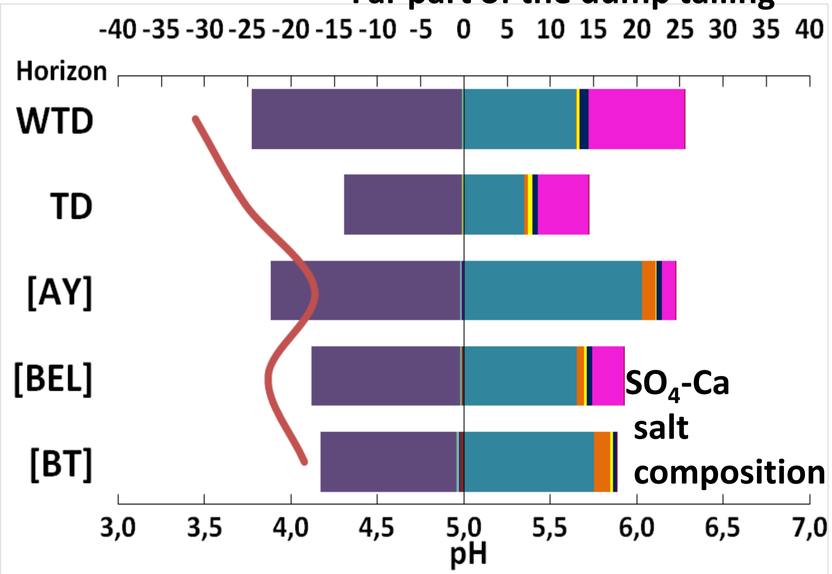
Grey forest arable soil (natural site)



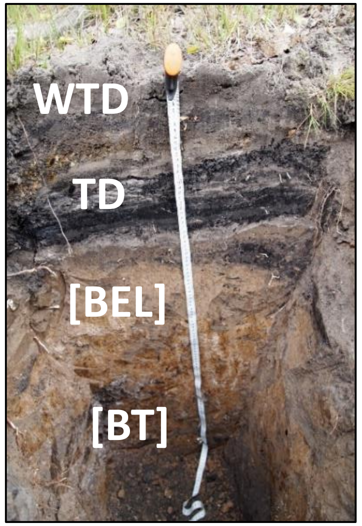
Grey forest soils technogenically transformed

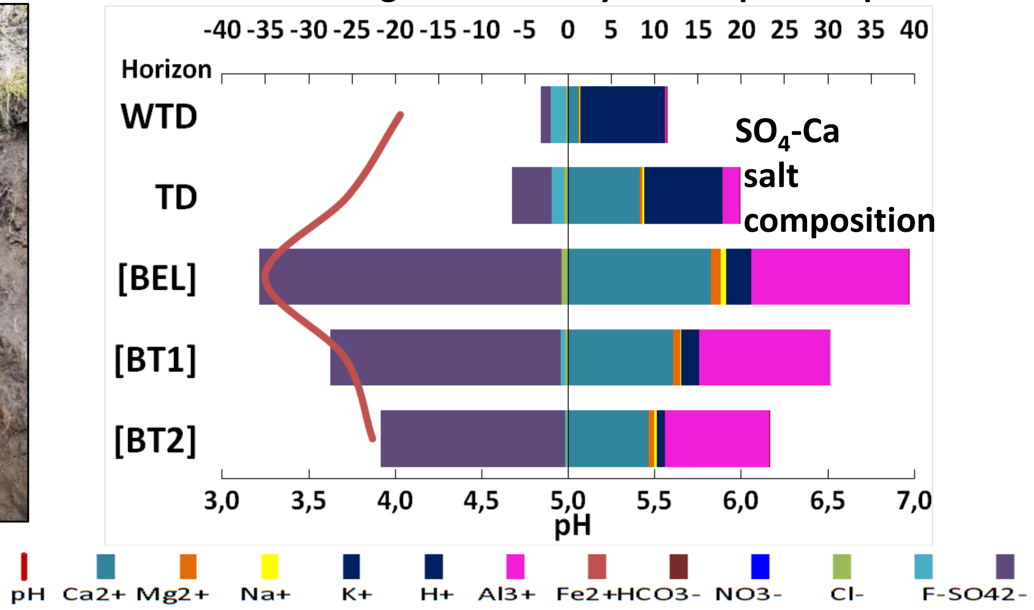
Far part of the dump tailing





Mine tailing in the vicinity of the spoil heap





Liquid phase of technogenically transformed soils*

Horizon	Soil moisture, %	pH	The degree of saturation of soil solutions in relation to solid phases (number of times)			
			$Fe(OH)_2$	$Fe(OH)_3$	$Al(OH)_3$	$CaSO_4$
Grey forest soil technogenically transformed, overlapped by the dump tailing						
WTD	28,0	3,5	0,6	>1000	>1000	8,7
TD	28,5	3,7	1,5	>1000	>1000	3,5
[AY]	24,5	4,1	>1000	>1000	>1000	11,6
[BEL]	18,8	3,9	0,5	>1000	>1000	6,9
[BT]	17,2	4,1	>1000	>1000	>1000	7,2
Chernozem gypsified technogenically transformed, overlapped by the dump tailing						
TD	20,5	3,9	1,1	>1000	>1000	1,5
[AU]	29,7	4,3	>1000	>1000	>1000	23,7
[AU]cs	20,2	4,7	>1000	>1000	>1000	4,0
[AUb]	18,3	5,2	>1000	>1000	>1000	13.5
[BI]	17,5	5,1	>1000	>1000	>1000	2.0
Chernozem arable gypsified technogenically transformed with a plowed dump tailing						
TDAUpa	25,2	3,7	39,6	>1000	>1000	3,1
[AUpa]	29,0	3,7	0,9	>1000	>1000	1,7
[AU]cs	29,7	6,4	315,1	>1000	>1000	7,9
[AUb]	23,5	6,6	>1000	>1000	>1000	4,2
[BI]	24,8	5,5	>1000	>1000	>1000	5,1

*according to data of soil solutions displaced by ethanol

oversaturated unsaturated

Secondary formation of gypsum in technogenically transformed soils

Horizon	Soil moisture, %	pH	The degree of saturation of soil solutions in relation to CaSO4 (number of times)*
Chernozem gypsified technogenically transformed, overlapped by the dump tailing			
TCH	20,5	3,9	1.5
[AU]	29,7	4,3	23.7
[AU]cs	20,2	4,7	4.0
[AUb]	18,3	5,2	13.5
[BI]	17,5	5,1	2.0
Chernozem arable gypsified technogenically-transformed with a plowed dump tailing			
TCHAUpa	25,2	3,7	3.1
[AUpa]	29,0	3,7	1.7
[AU]cs	29,7	6,4	7.9
[AUb]	23,5	6,6	4.2
[BI]	24,8	5,5	5.1
Grey forest soil technogenically transformed, overlapped by the dump tailing			
WTCH	28,03	3,5	8,7
TCH	28,54	3,7	3,5
[AY]	24,51	4,1	11,6
[BEL]	18,80	3,9	6,9
[BT]	17,22	4,1	7,2
Grey forest soil technogenically transformed, overlapped by the dump tailing			
WTCH	17,1	4,0	0,1
TCH	18,5	3,7	1,7
[AY]	25,4	3,3	13,4
[BEL]	10,7	3,7	8,8
[BT]	14,5	3,9	6,1

*according to data of soil solutions displaced by ethanol

oversaturated

unsaturated

Mechanisms of formation of secondary gypsum in soils:

1. During the ion-exchange reactions:

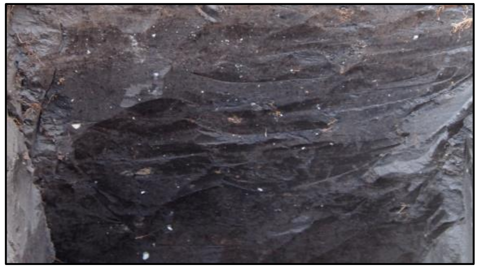
SAC $[Ca^{2+}]+H_2SO_4=$SAC $[H^+]+CaSO_4$

2. As a result of decomposition of carbonates in soils with sulfuric acid solutions:

$CaCO_3+H_2SO_4+7O=CaSO_4+H_2O+CO_2$

3. Due to the supply of water-soluble $CaSO_4$ with AMD and it precipitation in soils

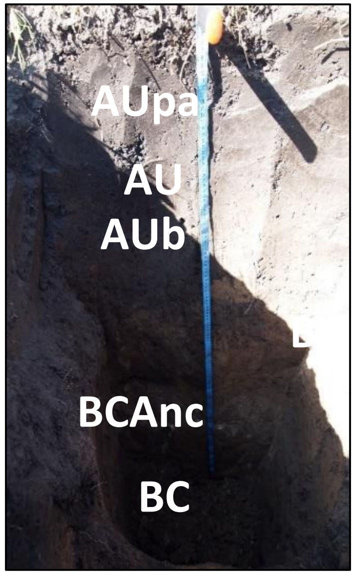
***SAC – soil adsorption complex**

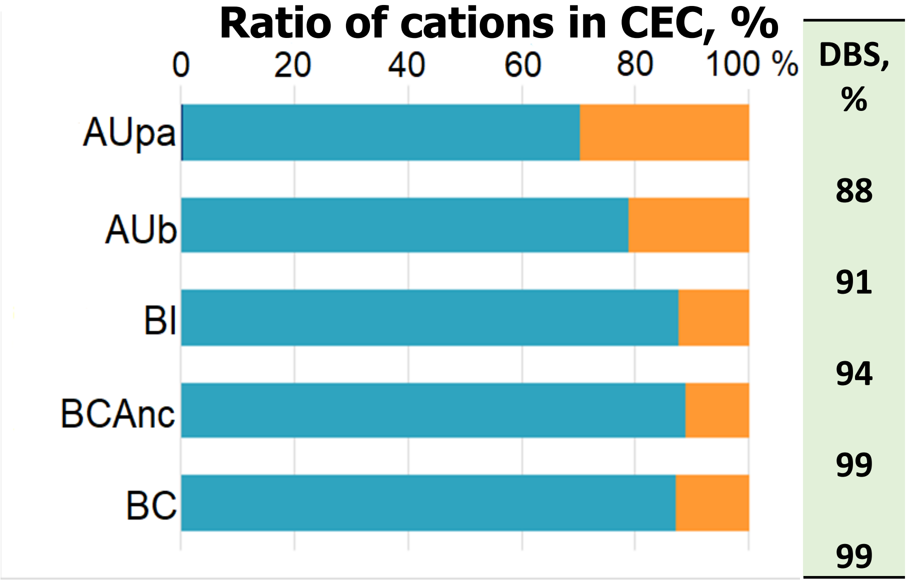


Neogypsans in A horizon of leached chernozems, overlapped by the dump tailing

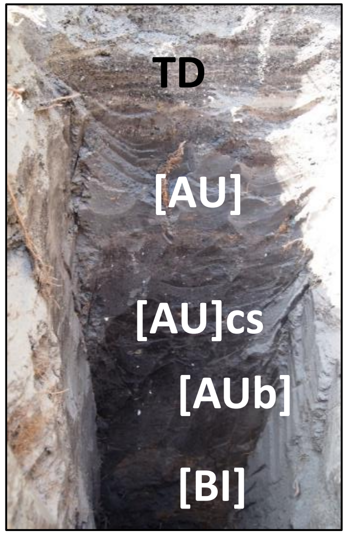
Transformation of soil cation-exchange complex

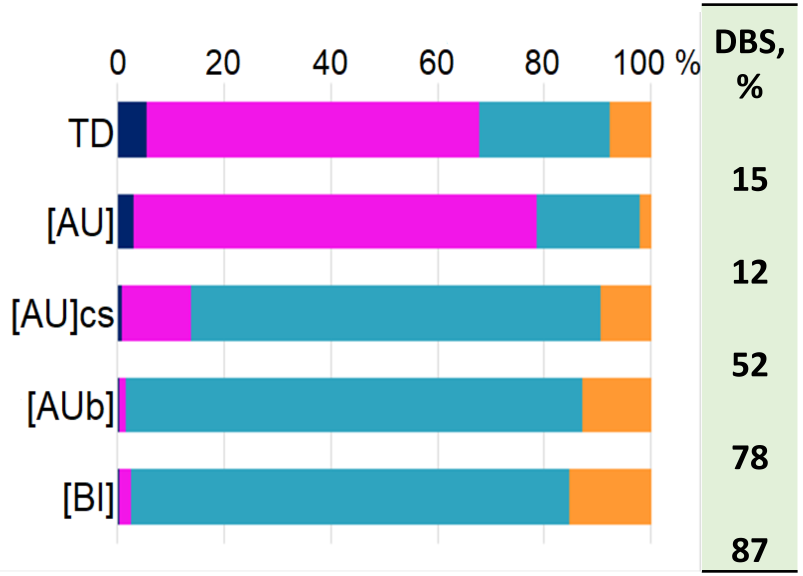
Chernozem leached arable (natural site)



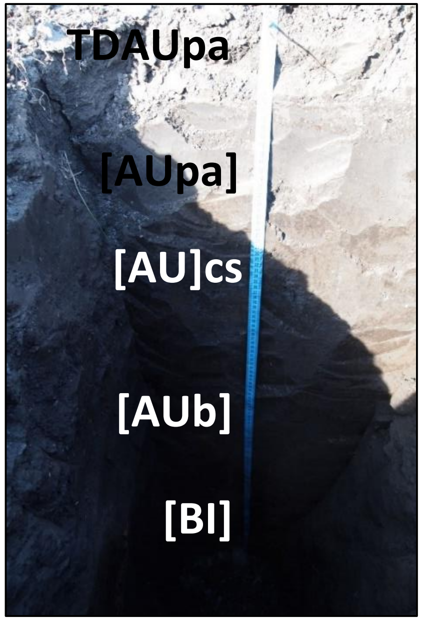


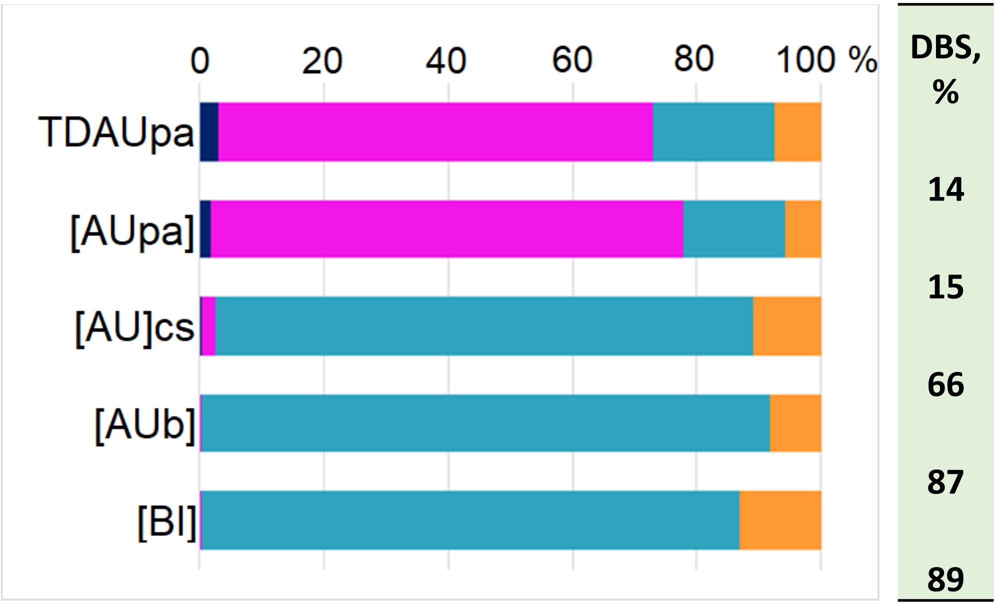
Chernozem technogenically transformed, overlapped by the dump tailing





Chernozem arable technogenically transformed with a plowed dump tailing





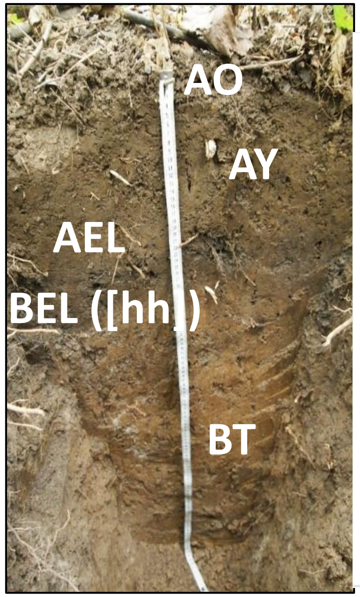
H^{+} Al^{3+} Ca^{2+} Mg^{2+}

*Degree of base saturation (DBS) (%) $= \frac{(Ca^{2+} + Mg^{2+})}{(Ca^{2+} + Mg^{2+} + \text{Hydrolytic acidity})}$

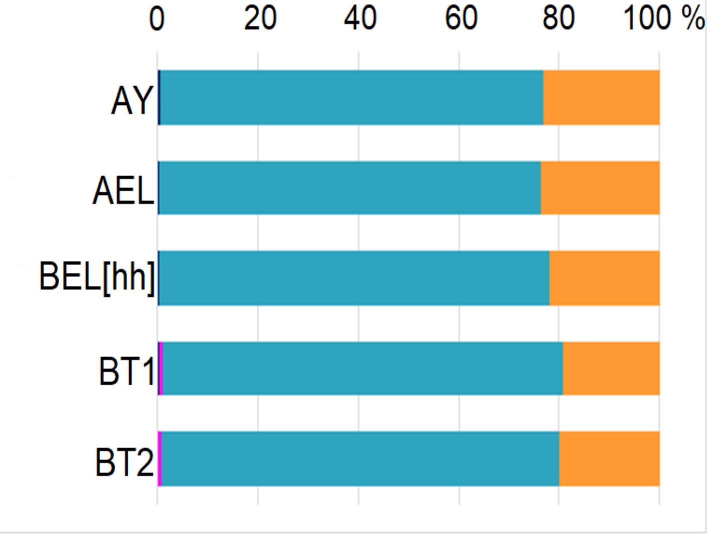
Transformation of soil cation-exchange complex

H^+ Al^{3+} Ca^{2+} Mg^{2+}

Grey forest soil (natural site)

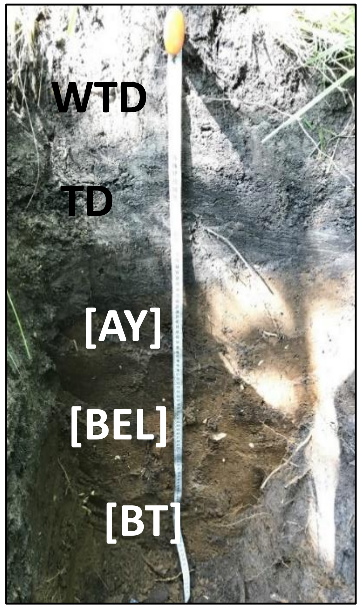


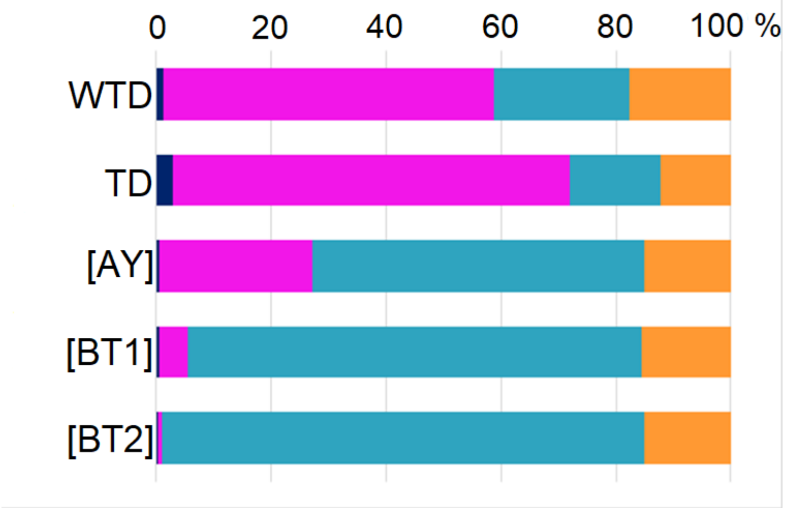
Ratio of cations in CEC, %



DBS, %
79
86
91
94
98

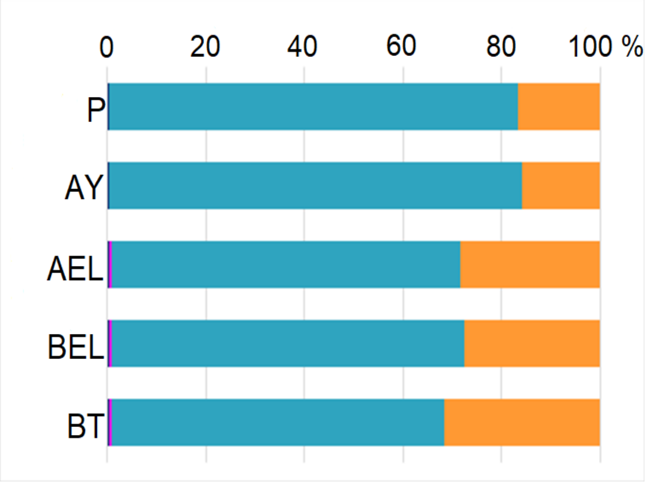
Grey forest soils technogenically transformed



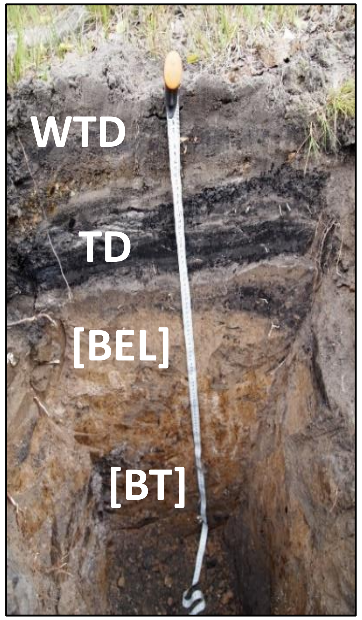


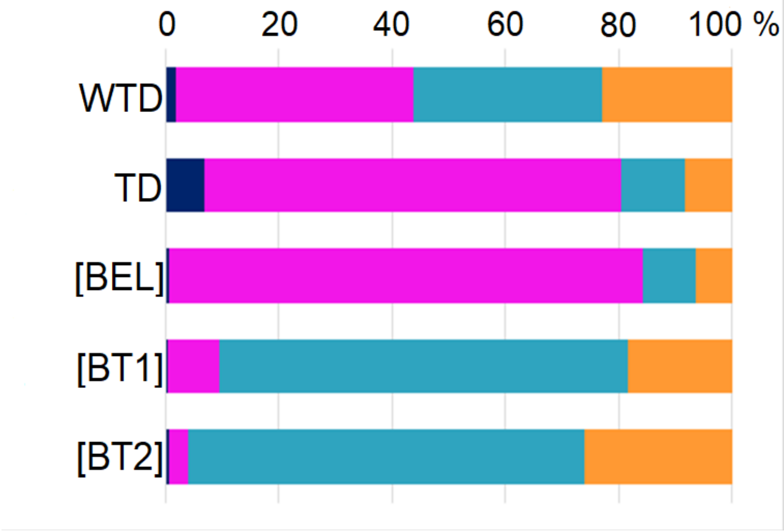
DBS, %
7
9
46
78
85

Grey forest arable soil (natural site)



DBS, %
94
95
91
90
91

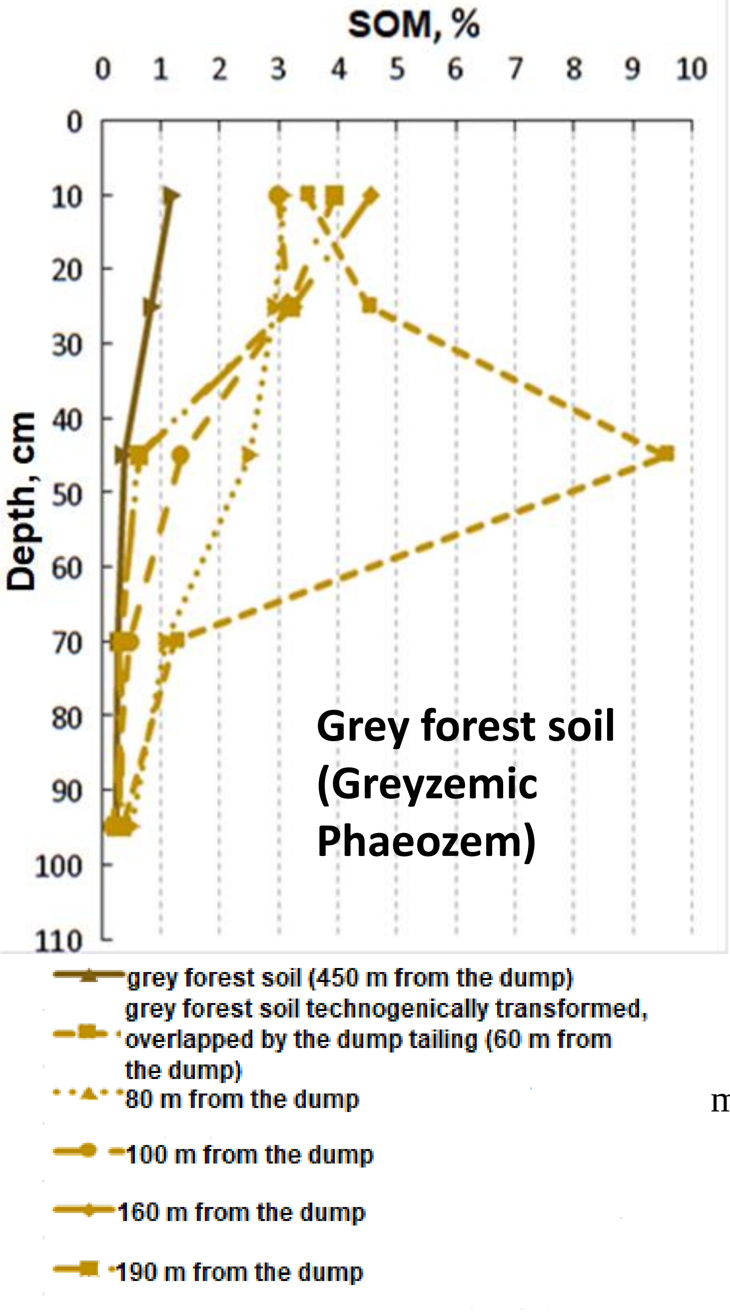




DBS, %
11
7
14
80
85

*Degree of base saturation (DBS) (%)

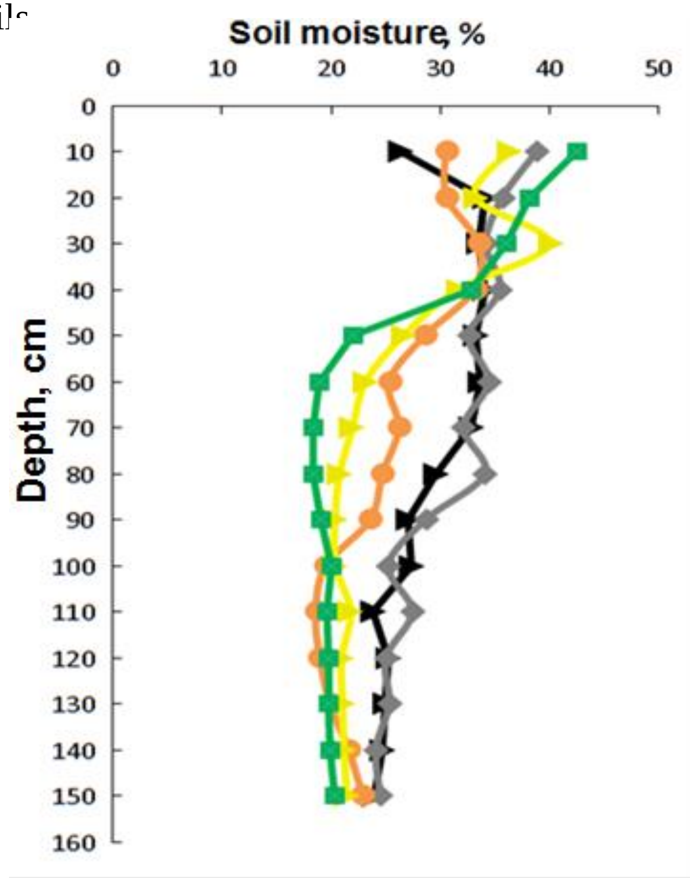
Vertical differentiation of SOM and moisture in soils impacted by coal mining

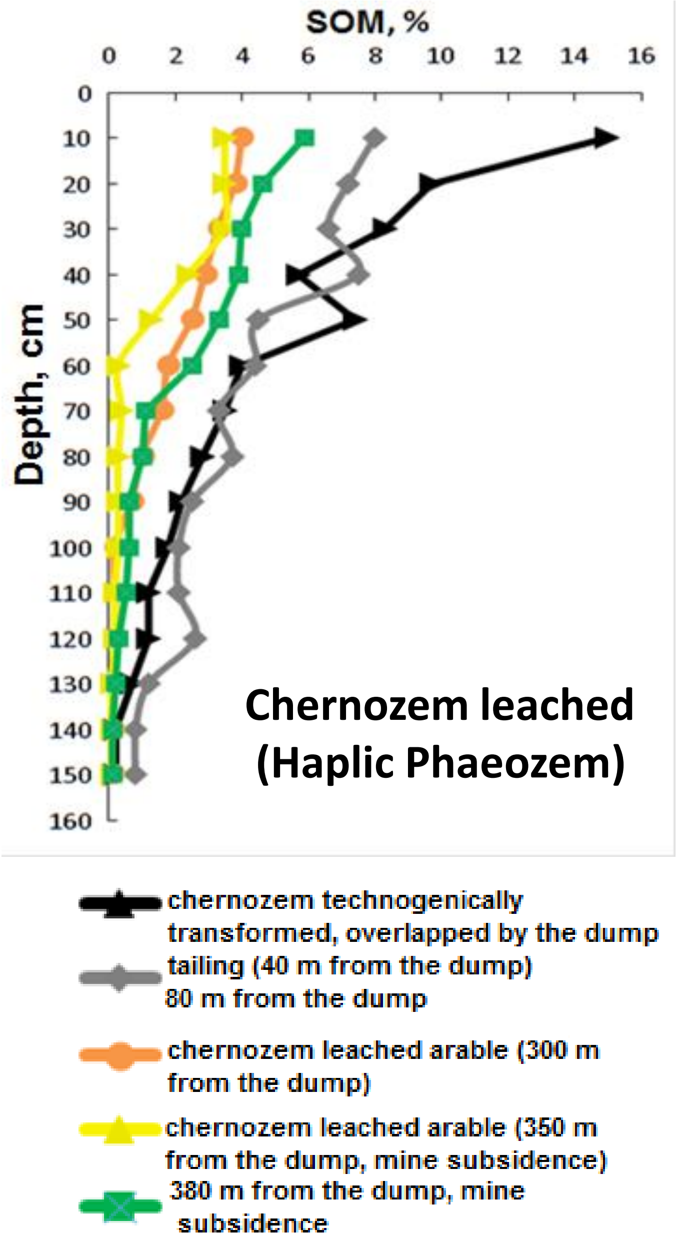


Carbonaceous particles in pore space of soils

Carbonaceous and clay films on soil peds

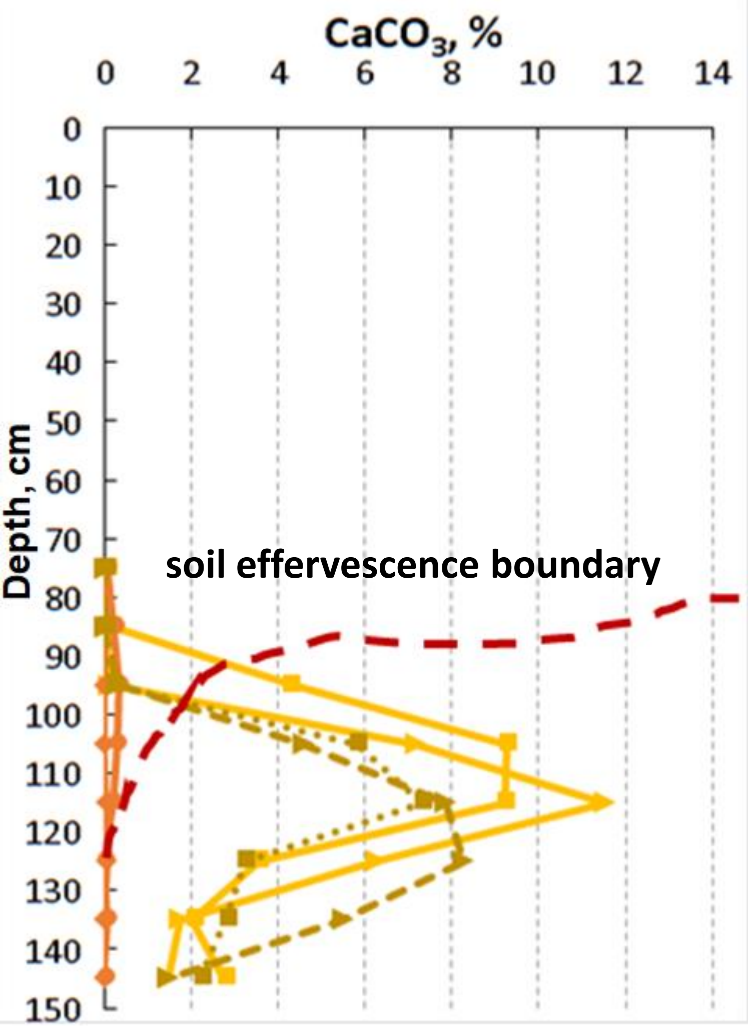
mine subsidence





Vertical differentiation of carbonates in chernozems impacted by coal mining

Chernozem arable leached and podzolized (natural) – chernozem arable leached (mine subsidence)



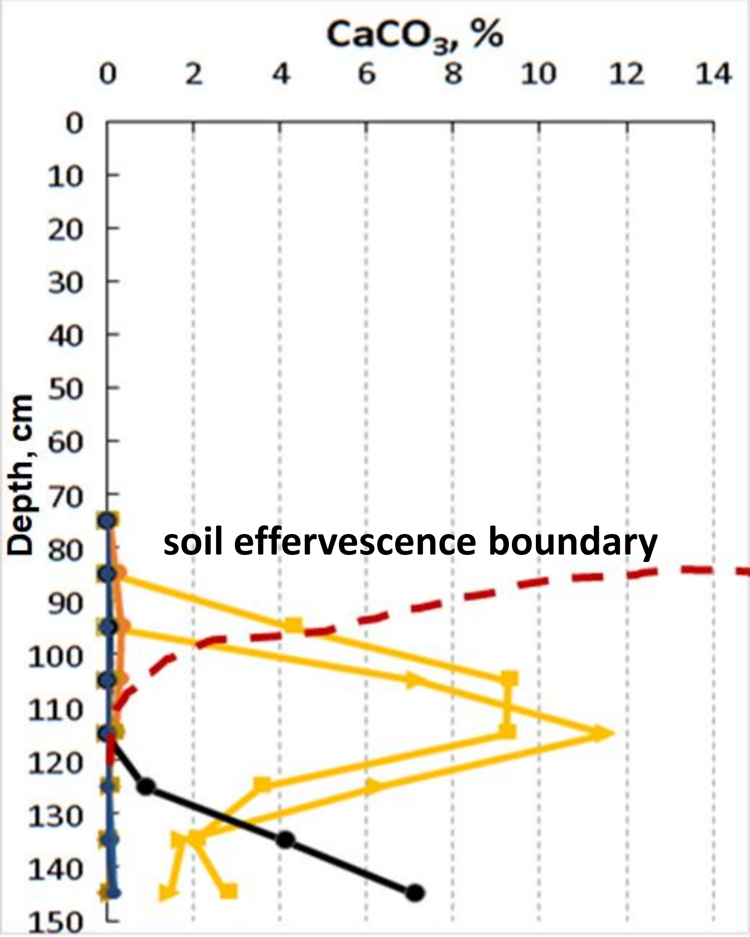
Neocalcans nodule in Bca horizon

Neocalcans micellar in Bca horizon

- chernozem leached arable (280 m from the dump)
- chernozem leached arable (300 m from the dump)
- chernozem podzolized arable (350 m from the dump)
- chernozem podzolized arable (400 m from the dump)
- chernozem leached arable (230 m from the dump, mine subsidence)
- chernozem leached arable (260 m from the dump, mine subsidence

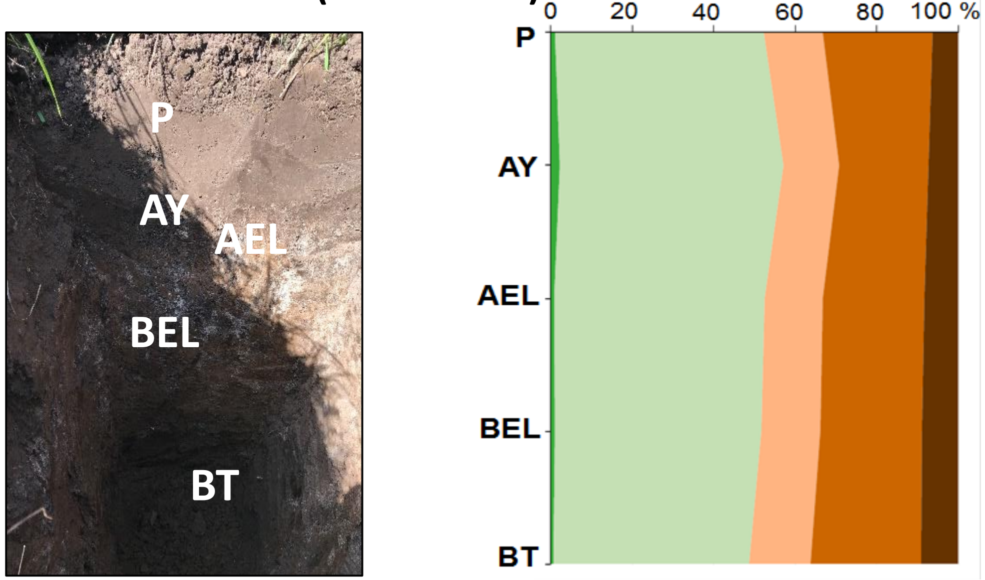
Chernozem arable leached and podzolized (natural) – chernozem technogenically transformed

- chernozem leached arable (280 m from the dump)
- chernozem leached arable (300 m from the dump)
- chernozem leached podzolized (350 m from the dump)
- chernozem leached podzolized (400 m from the dump)
- chernozem technogenically transformed, overlapped by the dump tailing (20 m from the dump)
- chernozem technogenically transformed, overlapped by the dump tailing (40 m from the dump)
- chernozem technogenically transformed, overlapped by the dump tailing (50 m from the dump)
- chernozem arable technogenically transformed with a plowed dump tailing (80 m from the dump)
- chernozem arable technogenically transformed with a plowed dump tailing (80 m from the dump)
- chernozem arable technogenically transformed with a plowed dump tailing (90 m from the dump)
- chernozem arable technogenically transformed with a plowed dump tailing (100 m from the dump)

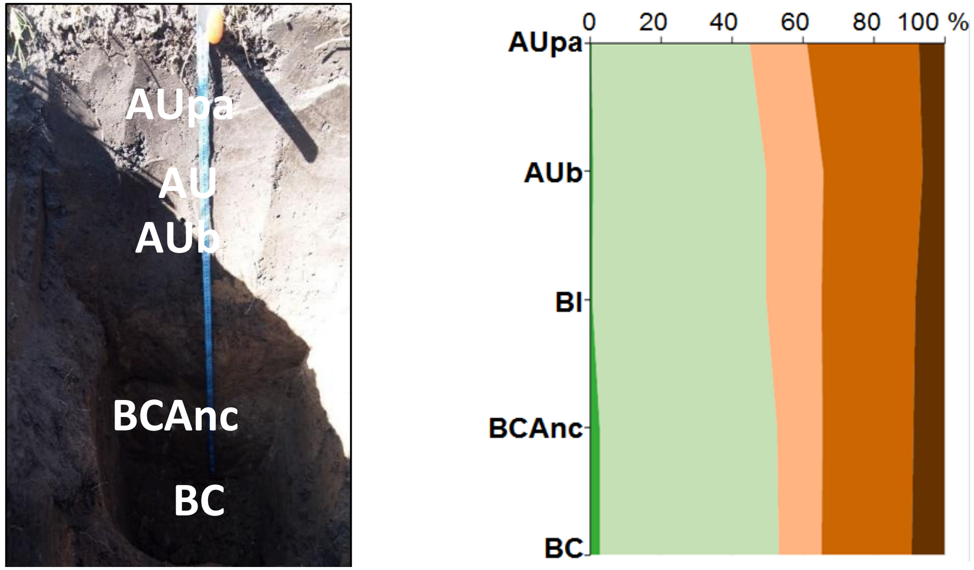


Changes in soil texture

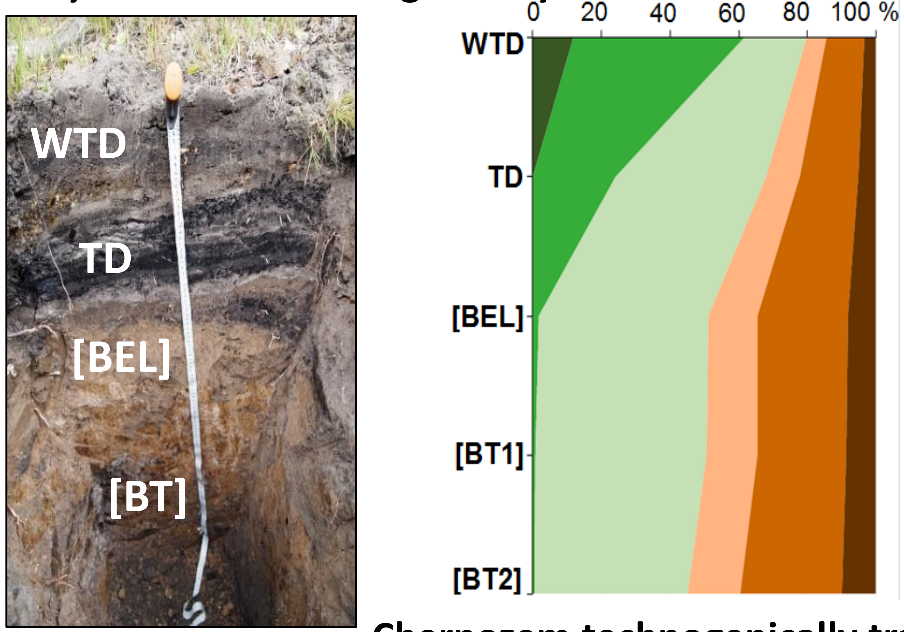
Grey forest arable soil (natural site)



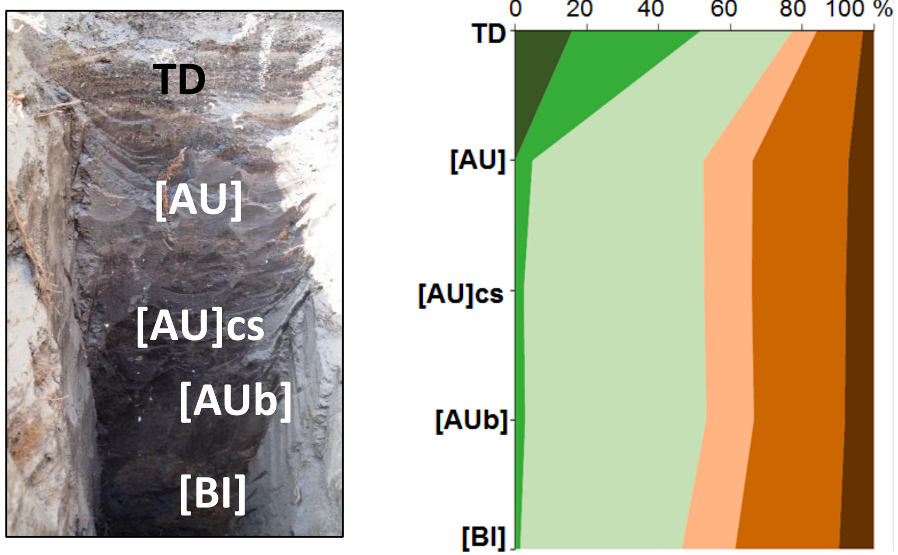
Chernozem leached arable (natural site)



Grey forest soil technogenically transformed



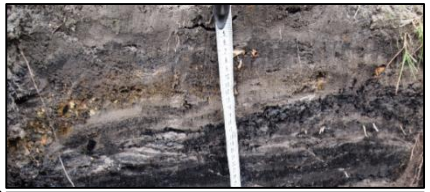
Chernozem technogenically transformed



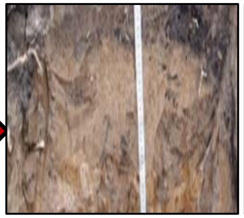
0,25-1 mm 0,05-0,25 mm 0,01-0,05 mm 0,005-0,01mm 0,001-0,005 mm <0,001 mm

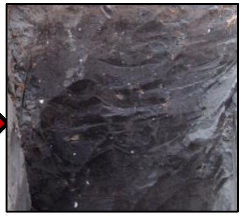
Alteration of soil morphology in coal mining areas of Moscow basin

Technogenically caused processes		
General for grey forest soils and chernozems	**Transformation of the soil profile**	Physical destruction of the soil profile due to mining works and erosion. Formation of technogenic deposits (up to 50 cm in thickness and more) on the soil surface. Overlapping of soils by technogenic deposits.
	Compaction	Filling of soil pore space with finely dispersed material. High compaction of soil mass and low porosity.
	Changes in morphology of soil structural aggregates	Granular and cloggy aggregates were replaced by cloddy, lumpy, and nutty ones. Changes in morphology of Fe-neoformations in soils (nets and crusts).
	Vertical migration of solutions and suspensions	Leaching and redeposition of dust and silt. Intensification of mobility of organo-mineral compounds.
	Transformation of organic carbon profile	Slowing down the decomposition of organic matter (substitution of humus-accumulative process by humus-destructive process). Intensification of eluvial process (formation of black carbonaceous films on faces of soil peds). High content of organic matter of coal origin (carbonaceous particles) in the pore space of soils. Removal of soil organic matter.
Grey forest soils	**Changes in colour of the soil profile**	Activation of acid hydrolysis (bleaching of the soil mass, increment of silans and skeletans on soil peds) in eluvial horizons (BEL) along with intensive ferrugination in illuvial horizons (BT). Formation of ochreous and rusty-brown iron nodules and patches of Fe oxides and hydroxides on faces of structural units. Soils in subsidence has signs of gleying (grayish and smoke blue shades) throughout the profile.
Chernozems	**Formation of secondary gypsum**	Formation of gypsum in soil profile.
	Leaching of carbonates	Lowering of effervescence depth and upper boundary of Ca-neoformations to the BC-C horizon or leaching of carbonates beyond the soil profile.








Conclusions

- Long-term supply of sulfide-bearing technogenic material to the environment led to the significant geochemical transformation of soils. Releasing of acid mine drainage (AMD) with the high content of Ca, Fe and Al sulfates also affected chemical properties and morphological features of soils.
- The formation of deposits 15-50 cm in thickness and admixture of pyritized technogenic waste material with high amount of organic carbon of coal origin to the upper horizons led to changes in the morphology of natural soils. In soil genetic horizons, specific cutans with high content of coal particles appeared due to transport of coal material from the waste dumps to the surface of soils. As a result of filling the soil pore space with material from the dumps, the upper soil horizons became compacted.
- Properties of newly formed soils differ significantly from natural soils. We identified the transformation of the composition of soil solutions. Soils with the technogenic transformation of the profile were characterized by acidification and Ca-Al-SO_4 salinization of soil profile along with the increasing of the content of H^+ and Al^{3+} ions and changes in the composition and the ratio of exchangeable cations. Cation exchange lead to displacement of Ca^{2+} and Mg^{2+} ions by Al^{3+}, H^+, Fe^{2+} and, perhaps, by Fe^{3+} in soil adsorption complex (exchangeable H^+ and Al^{3+} in soils up to 60-70%).
- In grey forest soils (Greyzemic Phaeozems) the intensification of podzolization process (bleaching of an eluvial horizon, the increment of silans and skeletans, and sometimes, the ferrugination of an illuvial horizon) could be noted.
- AMD dissolves carbonates and the upper boundary of the carbonate horizon of the impacted leached chernozems (Haplic Phaeozems) lowered. Gypsum neoformations (neogypsans) appeared in leached Haplic Phaeozems.
- We observed coal cutans in all soils with the technogenic transformation of soil profiles. Development of subsidence areas over the mined space altered the direction of soil formation processes (automorphic soil formation of chernozems changed to semi-hydromorphic with excessive moistening), and signs of gleying and peat accumulation appeared. The depth of occurrence of carbonates in Haplic Phaeozems lowered due to excessive moistening. New patterns of soil cover structure have formed that could be detected using remote sensing data and GIS-analysis.
- Complex of properties of technogenic soils in the vicinity of spoil heaps has no analogues in natural forest-steppe landscapes of the Russian Plain.

Thank you for your attention!