Morphological and chemical properties of soils within geological complexes affected by sulfuric acid in forest-steppe of the Central Russian Upland (Russia)

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Abstract. In the Central Russian Upland, black soils become contaminated by toxic substances containing sulfuric acid, which leak from non-recultivated stockpiles of coal mines. Sites for studying properties of soils that represented main geocomplexes of this region were selected using GIS analysis. Background Haplic Chernozems occupy interfluvies and slopes; Phaeozems are located at dry gullies. Stockpiles serve parent materials for Spolic Technosols (Arenic/Loamic, Dystric, Sulfidic, Phytotoxic) characterized by high contents of sulfates and total organic carbon (TOC). Burned stockpiles were occupied by less toxic Spolic Technosols (Loamic, Eutric, Phytotoxic), which had a neutral reaction in topsoils and relatively low contents of sulfates and TOC. Remediation with different substrates and phytoremediation resulted in the creation of Technosols (Dystric, Loamic, Molic, Organotransportic). Deluvial/proluvial deposits were occupied by soils with lithic discontinuities that were identified as Regosols over Phaeozems. Near to stockpiles, there were Dystric Colluvic Stagnic Regosols (Arenic/Loamic, Lamellic, Loaminovic, Sulfidic, Phytotoxic), which had strong and moderate acidity and the high content of sulfates that was lower than that in Spolic Technosols (Dystric). Phaeozems (Loamic, Loaminovic, Phytotoxic) within impact zones of stockpiles had lithic discontinuities due to the surface redeposition of materials washed off the tips, decreased acidity and increased contents of sulfates.

1. Introduction

Serious environmental problems within coal mining areas are associated with land-use conflicts [1, 2]. In the Tula Region of Russia such conflicts are predetermined by the following reasons: 1. an absence or an incompleteness of land remediation measures following unplanned closures of mines within the Moscow Lignite Basin; 2. a high population density and 3. re-ploughing of agricultural lands, which were abandoned in the 1990s. For the last 25 years, the Tula Region has been regarded as a natural experimental site, studies of which allow for obtaining data on directions and rates of degradation processes within natural complexes, the development of new soils and the effectiveness of land remediation measures [2–4].

Spoil tips and stockpiles contain toxic substances that leak into surrounding landscapes due to combined effects of climatic conditions and an imperfect management of local coal mines, in particular, waste storage practices [5]. Materials of mine spoils containing pyrite and lignite (brown coal) and stored...
on the land surface are mechanically transported and transformed by natural processes. The natural colonization of mine spoils by ruderal vegetation leads to primary soil formation on these technogenic parent materials [6, 7], while highly fertile Chernozems and Phaeozems within impact zones of spoil tips and fans undergo irreversible degradation due to the impact of sulfuric acid leakages from stored wastes [2].

The aim of the present study was to conduct a combined analysis of morphological and chemical properties of soils that developed as a result of a spontaneous closure of coal mines within the Tula Region.

2. Materials and methods
Changes in the soil-vegetation cover under either decreasing or increasing technogenic impacts, which are directly or indirectly connected with coal mining, reflect the current development of soils within the forest-steppe zone of the Central Russian Upland.

2.1. Study area
The study was conducted within an area of 10 thousand hectares in the Kireevskii and Uzlovskii districts of the Tula region, where 13 coal mines operated until the mid-1990s and left behind spoil tips and stockpiles that have heights of 30–70 m and volumes of 1–3 million m³ each (Figure 1).

![Figure 1. Location of the study area.](image)

According to [2, 8], areas of mine spoils are occupied by four main soil types including Technosols, Chernozems, Phaeozems and Regosols over Phaeozems. These soil types were characterized by us in seven different sites (Table 1), which were associated with the former coal mines and characterized by different phases of soil development [8].
Table 1. Soils and vegetation studied at industrial mining geocomplexes in the Tula region within the Moscow Lignite Basin.

| Sites                                                                 | Soils                                                                 | Vegetation [2]                      | % of the total area of industrial mining geocomplexes |
|----------------------------------------------------------------------|----------------------------------------------------------------------|-------------------------------------|------------------------------------------------------|
| Non-recultivated spoil tips and crest-topped stockpiles              | Spolic Technosols (Arenic/Loamic, Dystric, Sulfidic, Phytotoxic) on toxic technogenic materials | Single specimens                    | 5                                                   |
| Pyrogenically transformed spoil tips and stockpiles                  | Spolic Technosols (Loamic, Eutric, Phytotoxic) on technogenic materials | Communities of pioneer species      | 23                                                  |
| Flat-topped stockpiles                                              | Eutric Regosols (Loamic, Technic, Phytotoxic) on technogenic materials | Pioneer species and species-poor phytocenoses | 19                                                  |
| Stockpiles after phytoremediation                                   | Technosols (Dystric, Loamic, Molic, Organotransportic)                 | Species-poor phytocenoses           | 2                                                   |
| Deluvial-proluvial fans                                             | Dystric Colluvic Stagnic Regosols (Loamic, Lamellic, Loaminovic, Sulfidic, Phytotoxic) | Single specimens                    | 3                                                   |
|                                                                      | Dystric Colluvic Stagnic Regosols (Loamic, Lamellic, Loaminovic)        | Species-poor phytocenoses           | 24                                                  |
| Subsidence zones related to spoil tips                              | Chernic Phaeozems (Loamic, Loaminovic, Phytotoxic)                      | Species-poor and cultivated phytocenoses | 11                                                  |
| Subsidence zones unrelated to spoil tips                             | Chernic Phaeozems (Loamic, Loaminovic)                                  | Cultivated, species-poor and species-rich phytocenoses | 13                                                  |

2.2. Methods
Soil descriptions were performed in accordance with [9]. Soils and horizons were named using [10]. Soil color at field moisture was determined using the Munsell color system.

Samples were taken from each genetic horizon of 9 soil profiles, which made 81 samples in total. In all soil samples, pH values were measured in suspension (with a 1 : 2.5 soil : water ratio) using an Expert-pH meter (Russia) at the Faculty of Geography of the Lomonosov Moscow State University and the total organic carbon (TOC) contents were determined using the titrimetric method with phenylanthranilic acid. In a 1 : 2.5 soil : water ratio extract, carbonates and bicarbonates were determined by potentiometric titration with 0.02 M H₂SO₄ to pH 8.4 and 4.4, respectively. Sulphates was precipitated as BaSO₄ and determined turbidimetrically [11].

The data obtained were statistically processed. Standard parameters of descriptive statistics (mean and standard deviation) were determined and mean values were compared using the Mann Whitney U test.
3. Results

3.1. Soils of background geocomplexes

Background geocomplexes, which are free from prolonged influences of the runoff contaminated by sulfuric acid, are occupied by Haplic Chernozems (Aric, Loamic) and Chernic Phaeozems (Loamic) formed on calcareous loess-like loams. The studied Haplic Chernozems (Aric, Loamic) were characterized by pH values increasing with depth, from 4.9±0.5 within the A horizon to 5.1±1.0 within the C horizon. The vertical distribution of CaCO₃ concentrations was characterized by a minimum within the A horizon and a maximum within the C horizon, which was predetermined by the pH distribution pattern. Contents of TOC decreased with depth from 3.1±0.8% within the A horizon to 0.3±0.1% within the C horizon. Sulfates (SO₄²⁻ ions) were present throughout the profile, with a maximum in the parent material. The studied Chernic Phaeozems (Loamic) were characterized by insignificant variations in pH values, generally low contents of carbonates with a maximum in topsoil, TOC concentrations decreasing with depth and significant contents of SO₄²⁻ with a maximum in topsoil.

3.2. Soils of spoil tips and stockpiles

Non-recultivated spoil tips and stockpiles served as parent materials for Technosols. In particular, Spolic Technosols (Arenic/Loamic, Dystric, Sulfidic, Phytotoxic) were formed on unvegetated unsorted deposits with varied proportions of lignite, pyrite, marcasite and sandstone. These soils were acidic (pH of 2.4–3.6) and rich in sulfates (474 mg/100 g of soil) and TOC (8.6–16.9%).

Pyrogenically transformed spoil tips and stockpiles with characteristic whitish colors and inclusions of melted (due to very high temperature during ignition of piled materials) materials were occupied by Spolic Technosols (Loamic, Eutric, Phytotoxic) (Table 2). Their topsoil (0–40 cm), where toxicity had decreased under the impact of heat, differed from that of non-pyrogenic Technosols (Arenic/Loamic, Dystric, Sulfidic, Phytotoxic) by twice as low TOC content (p-value < 0.01), 4 times lower sulfate content (p-value < 0.00001), twice as high pH (p-value 0.000001) and 13 times higher content of carbonates (p-value = 0.003). In subsoil (40–200 cm) of Spolic Technosols (Loamic, Eutric, Phytotoxic), the values of considered parameters corresponded to an intermediate level between those in topsoil of Spolic Technosols (Eutric and Dystric) and subsoil of Spolic Technosols (Loamic, Eutric, Phytotoxic).

The phytoremediation of stockpiles resulted in the creation of Technosols (Dystric, Loamic, Molic, Organotransportic) consisting of a 40-cm thick organomineral recultivation layer (pH 6.0) underlain by a 1-m-thick mineral recultivation layer, which covers the unsorted compacted coal-containing material of stockpile.

3.3. Soils of fans

Deluvial-proluvial fans around spoil tips and stockpiles were characterized by the formation of Dystric Colluvic Stagnic Regosols (Loamic, Lamellic, Loaminovic, Sulfidic, Phytotoxic) with lithic discontinuity, i.e., their upper layers are derived from redeposited materials of spoil tips and lower layers – from chemically transformed Pheaeozems or Chernozems affected by sulfuric acid. The thickness of redeposited stratified materials decreased from 130 cm at the foot of a pile to first centimeters further away. O-horizons were found in soil profiles developed within vegetated areas of the fans. Topsoil of the studied Dystric Colluvic Stagnic Regosols (Loamic, Lamellic, Loaminovic, Sulfidic, Phytotoxic) was moderately acidic (pH of 3.4–5.1) and impoverished in sulfates (3.9 mg/100 g) in comparison to that of Spolic Technosols (Arenic/Loamic, Dystric, Sulfidic, Phytotoxic) on non-recultivated spoil tips and stockpiles (p-value < 0.00001). Humus horizons of buried Chernozems and Phaeozems, as compared to their background equivalents, had a stronger acidity with an insignificantly decreased carbonate content, but significantly increased contents of sulfates (multiplied by 4.6; p-value = 0.024) and TOC (p-value = 0.001). Subsoil of buried Chernozems and Phaeozems was weakly acidic (nearly neutral) and more calcareous than their topsoil (Table 3).

Toxic compounds were present in soils of deluvial fans directly adjacent to spoil tips (Dystric Colluvic Stagnic Regosols (Loamic, Lamellic, Loaminovic, Sulfidic, Phytotoxic)), but absent from soils
of proluvial fans developed under more hydromorphic conditions. As compared to soils of deluvial fans, soils of proluvial fans were weakly acidic and non-calcareous and had significantly (p-value = 0.038) higher contents of sulfates (up to 21 mg/100 g) within the upper part of profile, above lithic discontinuity. Lower down, the A horizon of the buried soil had significantly higher pH (p-value = 0.05) and carbonate content (multiplied by 25, p-value = 0.01) and lower TOC content (decreased by 6.5 times; p-value = 0.0012). Subsoil of the buried soil was characterized by a further increase in pH values along with a decrease in TOC and negligible quantities of sulfates and carbonates.

**Table 2.** Main morphological features of soils studied in the Kireevskii and Uzlovskii districts of the Tula region.

| Soila                              | Horizon, depth, cm | Munsell color moist | Textureb | Structurec | Rootsd | Boundary Shape | Distinctness |
|------------------------------------|-------------------|---------------------|-----------|------------|---------|----------------|--------------|
| Spolic Technosols                 | Chu, 0–100        | 5Y2.5/2             | S/L       | no         |         |                |              |
| (Arenic/Loamic, Dystric, Sulfidic, |                    |                     |           |            |         |                |              |
| Phytotoxic) on toxic technogenic   |                    |                     |           |            |         |                |              |
| materials                          |                    |                     |           |            |         |                |              |
| Spolic Technosols                 | Cu, 0–40          | 2.5Y2.5/1           | L         | no         |         |                |              |
| (Loamic, Eutric, Phytotoxic) on    |                    |                     |           |            |         |                |              |
| toxic technogenic materials        |                    |                     |           |            |         |                |              |
| Dystric Colluvic Stagnic           | Chu, 0–100        | 2.5/N               | Ls        | blocky f1  |         | Wavy           | Abrupt       |
| Regosols (Loamic, Lamelllic,       | Ab, 100–130        | 2.5/N               | CL        | crumby f2  |         | Wavy           | Abrupt       |
| Loaminovic, Sulfidic, Phytotoxic)  | Bwgb,130–180      | 10YR4/5             | CL        | blocky f1  |         | Wavy           | Abrupt       |
| on toxic materials of deluvial fans| C, 180–220        | 10YR5/6             | CL        | blocky f1  |         | Wavy           | Abrupt       |
| Dystric Colluvic Stagnic           | Bs, 0–65          | 2.5/N               | L/CL      | no m2      |         | Wavy           | Abrupt       |
| Regosols (Loamic, Lamelllic,       | Arb, 65–150       | 2.5/5PB             | CL        | blocky m2  |         | Wavy           | Abrupt       |
| Loaminovic) on non-toxic           | Bwrb,150–175      | 10YR5/4             | CL        | blocky f1  |         | Wavy           | Abrupt       |
| materials of proluvial fans        | Cr, 175–200       | 10YR6/4             | CL/ C     | blocky f1  |         |                |              |
| Chernic Phaeozems (Loamic,         | C, 0–35           | 7.5YR2.5/1          | L/ CL     | no f2      | Smooth | Abrupt         |              |
| Loaminovic, Phytotoxic) on         | Ab, 35–125        | 2.5Y2.5/1           | CL        | massive f1 |         | Wavy           | Abrupt       |
| carbonated loess like loams        | Bwrb,130–185      | 10YR5/6             | CL        | blocky     |         | Wavy           | Abrupt       |
| Eutric Regosols (Loamic, Technic,  | O, 0–4            | 10YR4/1             | L         | no f2      | Smooth | Abrupt         |              |
| Phytotoxic) on toxic technogenic   | Bs, 4–16          | 5YR6/8              | L         | no f1      | Smooth | Abrupt         |              |
| materials                          | C, 16–35          | 2.5Y3/2             | CL        | massive f1 |         |                |              |
| Technosols (Dystric, Loamic,       | O, 0–4            | 10YR2/1             | CL        | crumby f3  |         | Wavy           | Abrupt       |
| Molic, Organotransportic)          | Ak, 4–28          | 10YR2/1             | CL        | crumby f2  |         | Wavy           | Abrupt       |
|                                   | Cox, 28–47        | 10YR5/4             | CL        | massive    |         | Wavy           | Abrupt       |
|                                   | Ckh, 47–65        | 10YR5/(3–4)         | CL/L      | massive    |         |                |              |
| Haplic Chernozems (Aric, Loamic)   | A, 0–50           | 10YR3/2             | CL        | grainy m3  |         | Wavy           | Abrupt       |
| on loess like carbonated           | Bw, 50–90         | 10YR5/6             | CL        | blocky f2  |         | Wavy           | Abrupt       |
| loams                             | Ck, 90–210        | 7.5YR4/6            | CL        | blocky     |         |                |              |
| Chernic Phaeozems (Loamic) on      | A, 0–140          | 5Y2.5/1             | CL        | grainy c3  |         | Wavy           | Abrupt       |
| carbonated loess like loams        | Ckg, 140–180      | 10YR5/4             | CL        | massive f2 |         | Wavy           | Abrupt       |
|                                   | Cr,180–210        | 10YR5/6             | CL/L      | massive    |         |                |              |

*a Named according to [10].

*b Texture classes: CL – Clay loam, L – Loam, S – sand.

*c Structure: M – massive, SBC – fine subangular blocky-crumbling, SB – subangular blocky, SAB – subangular-angular blocky, P – coarse blocky-prismatic.

*d Roots: f – fine, m – medium, c – coarse, 1 – single, 2 – few, 3 – many.
### Table 3. Chemical properties of soils studied in the Kireevskii and Uzlovskii districts of the Tula region.

| Soil                              | Horizon | Proxy<sup>a</sup> | pH  | TOC, % | SO<sub>4</sub><sup>2-</sup>, mg/100g | CaCO<sub>3</sub>, % |
|-----------------------------------|---------|-------------------|-----|--------|------------------------------------|---------------------|
| Spolic Technosols (Arenic/Loamic, Dystric, Sulfidic, Phytotoxic) | Chu     | M                 | 2.8 | 8.6    | 475.0                             | 0.2                 |
|                                   |         | SD                | 0.4 | 4.8    | 517.0                             | 0.1                 |
| Spolic Technosols (Loamic, Eutric, Phytotoxic)                    | Chu     | M                 | 6.4 | 3.6    | 107.0                             | 2.8                 |
|                                   |         | SD                | 1.7 | 2.2    | 43.0                              | 2.4                 |
|                                   | Chu     | M                 | 3.2 | 7.4    | 184.0                             | 0.1                 |
|                                   |         | SD                | 0.7 | 0.7    | 26.0                              | 0.1                 |
| Dystric Colluvic Stagnic Regosols (Arenic/Loamic, Lamellic, Loaminovic, Sulfidic, Phytotoxic) | Chu     | M                 | 3.9 | 10.6   | 3.9                               | 0.3                 |
|                                   |         | SD                | 0.6 | 0.5    | 0.1                               | 0.3                 |
|                                   | Ab      | M                 | 4.2 | 9.4    | 18.0                              | 0.6                 |
|                                   |         | SD                | 6.1 | 1.8    | 1.0                               | 0.2                 |
|                                   | Bwgb    | M                 | 5.7 | 3.3    | 9.9                               | 0.3                 |
|                                   |         | SD                | 3.6 | 14.1   | 16.0                              | 29.5                |
|                                   | C       | M                 | 5.5 | 1.5    | 17.0                              | 0.4                 |
|                                   |         | SD                | 0.1 | 0.3    | 0.1                               | 0.2                 |
| Dystric Colluvic Stagnic Regosols (Loamic, Lamellic, Loaminovic)  | Bs      | M                 | 5.7 | 12.2   | 7.4                               | 0.01                |
|                                   |         | SD                | 0.2 | 5.7    | 6.9                               | 0.02                |
|                                   | Ab      | M                 | 1.9 | 1.1    | 22.3                              | 0.2                 |
|                                   |         | SD                | 0.2 | 0.1    | 0.1                               | 0.3                 |
|                                   | Bwgb    | M                 | 6.3 | 0.4    | <0.01                             | 0.02                |
|                                   |         | SD                | 0.1 | 0.2    | <0.01                             | 0.03                |
|                                   | Cr      | M                 | 6.0 | 0.2    | <0.01                             | 0.02                |
|                                   |         | SD                | 0.1 | 0.2    | <0.01                             | 0.03                |
| Chernic Phaeozems (Loamic, Loaminovic, Phytotoxic)                 | C       | M                 | 6.2 | 9.3    | 0.2                               | 11.5                |
|                                   |         | SD                | 0.2 | 2.4    | 0.1                               | 23.0                |
|                                   | Ab      | M                 | 6.2 | 4.3    | 0.2                               | 2.6                 |
|                                   |         | SD                | 0.3 | 1.2    | 0.1                               | 3.7                 |
|                                   | Bwrb    | M                 | 6.3 | 0.9    | 0.4                               | 0.1                 |
|                                   |         | SD                | 0.2 | 0.4    | 0.2                               | 0.3                 |
|                                   | C       | M                 | 6.3 | 0.4    | <0.01                             | <0.01               |
|                                   |         | SD                | 0.1 | 0.1    | 0.1                               | <0.01               |
| Haplic Chernozems (Aric, Loamic)                                    | Ap      | M                 | 4.9 | 3.1    | 0.6                               | 0.6                 |
|                                   |         | SD                | 0.5 | 0.8    | 1.8                               | 0.6                 |
|                                   | Bw      | M                 | 5.2 | 0.5    | 9.5                               | 3.7                 |
|                                   |         | SD                | 0.6 | 0.6    | 19.0                              | 4.0                 |
|                                   | Ck      | M                 | 5.1 | 0.3    | 22.0                              | 6.7                 |
|                                   |         | SD                | 1.0 | 0.1    | 53.0                              | 2.5                 |
| Chernic Phaeozems (Loamic)                                            | A       | M                 | 5.8 | 4.7    | 43.0                              | 0.2                 |
|                                   |         | SD                | 0.2 | 2.3    | 41.0                              | 0.2                 |
|                                   | Ckg     | M                 | 5.9 | 0.4    | 1.3                               | 0.1                 |
|                                   |         | SD                | 0.2 | 0.2    | 1.0                               | 0.1                 |
|                                   | Cr      | M                 | 5.8 | 0.3    | 12.0                              | 0.01                |
|                                   |         | SD                | 0.1 | 3.4    | 20.0                              | 0.02                |

<sup>a</sup> M – mean, SD – standard deviation.
Subsidence zones, both related and unrelated to spoil tips, were occupied by Chernic Phaeozems (Loaminovic), which differed from their background equivalents by stronger development of hydromorphic features. In addition, soils of subsidence zones related to spoil tips were characterized by transformation of calcareous pedofeatures and/or their replacement by gypsum pedofeatures under the impact of solutions containing sulfuric acid. Surface deposits of technogenic materials had nearly neutral pH values, high contents of TOC (9.3±2.4%) and low contents of carbonates and sulfates. Buried topsoil was distinguished by twice as low TOC contents (p-value = 0.04), with values of other parameters similar to those in the overlying technogenic material. Buried subsoil was distinguished by an absence of carbonates and higher concentrations of sulfates due to influences of acidic solutions.

4. Discussion

Forest-steppe soils within impact areas of coal mines of the Moscow Lignite Basin develop under a continuous influence of sulfuric acid solutions discharged from spoil tips and stockpiles [2, 4, 8], which leads to changes in their morphological and physical properties.

In particular, soil pH decreases and contents of TOC, sulfates increase with increasing influences of sulfuric acid solutions, according to previous research on coal mine areas located in different geographical regions [12–15]. However, there are different properties in previously unstudied soils that develop on pyrogenically-transformed spoil tips and stockpiles with incinerated coal residues, completely oxidized sulfides and alkaline medium.

Concentrations of $\text{SO}_4^{2-}$ ions in technogenic materials steadily decreased in the following sequence of studied soils: Spolic Technosols (Dystric, Sulfidic) – Spolic Technosols (Eutric) – Dystric Colluvic Stagnic Regosols, with negligible values in thin technogenic layers deposited over Chernic Phaeozems.

TOC contents were very high in Technosols (Dystric), Dystric Colluvic Stagnic Regosols and Chernic Phaeozems (Loaminovic, Phytotoxic) due to the presence of coal particles. Spolic Technosols (Loamic, Eutric, Phytotoxic) had lowest TOC contents because the coal residues had burned off. Humus horizons of buried soils had highest TOC contents due to additions of coal dust.

The pH of A-horizons had lowest values in Dystric Colluvic Stagnic Regosols (Loamic, Lamellic, Loaminovic, Sulfidic, Phytotoxic) and maximal values in Chernozems. Buried A-horizons of Chernozems and Phaeozems and their surface equivalents had similar pH values, which can be explained by a high buffer capacity of these soils [16–19].

Sulfates in the studied soils had autochthonous and allochthonous origins. Autochthonous sulfates had contents of up to 0.3 mg/100 g in native soils and were also present in technogenic soils on spoil tips, where they were formed during a microbiological oxidation of sulfide minerals [20–23]. The content of $\text{SO}_4^{2-}$ in the buried A horizon of Dystric Colluvic Stagnic Regosols (Loamic, Lamellic, Loaminovic) was 28 times higher (p-value < 0.001) than that in the A horizon of background Haplic Chernozems. Contents of $\text{SO}_4^{2-}$ in mineral horizons and parent materials of Dystric Colluvic Stagnic Regosols (Loamic, Lamellic, Loaminovic, Sulfidic, Phytotoxic) and Haplic Chernozems had insignificant differences.

Contents of carbonates were comparable in humus horizons of buried and background Chernozems. In their mineral horizons, carbonate contents significantly increased with increasing distance from the sources of acidic solutions, i.e., spoil tips and stockpiles of coal mines.

5. Conclusion

The development of soils of industrial coal mining landscapes of the Moscow Lignite Basin was affected by technic substances including acidic compounds. The character and intensity of such technogenic impact predetermined morphological features and chemical properties of soils.

Spolic Technosols (Arenic/Loamic, Phytotoxic) formed on stockpiles and spoil tips consisted of unsorted materials that contained fragments of coal and enclosing rocks. Toxicity of such materials decreases after burning, which resulted in sulfide oxidation.

Deluvial and proluvial fans within impact zones of spoil tips and stockpiles were characterized by the formation of Dystric Colluvic Stagnic Regosols (Arenic/Loamic, Lamellic, Loaminovic) with lithic
discontinuities. Their topographic positions predetermined different degrees of transformation of redeposited technogenic materials and buried soil materials. Technogenic materials of Dystric Colluvic Stagnic Regosols (Arenic/Loamic, Lamellic, Loaminovic) were acidic, enriched in TOC and sulfates. Chernic Phaeozems (Loamic, Loaminovic, Phytotoxic) within impact zones of spoil tips and stockpiles were also characterized by a presence of lithic discontinuity (under a technogenic layer of less than 40 cm in thickness), low acidity and high contents of sulfates. Contents of TOC and sulfates increased in buried soil layers, with insignificant changes in acidity.

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References
[1] Zinovieva O M, Kolesnikova L A, Merkulova A M and Smirnova N A 2020 Analysis of environmental problems in coal mining regions Ugol’ 10 62–7 (in Russian)
[2] Sharapova A V, Semenkov I N, Lednev S A, Karpachevsky A M and Koroleva T V 2020 Biochemical potential of self-development of post-technogenic mining-industrial geocomplexes of the Moscow coal basin Ugol’ 10 56–61 (in Russian)
[3] Krechetov P, Chernitsova O, Sharapova A and Terskaya E 2019 Technogenic geochemical evolution of chernozems in the sulfur coal mining areas J. Soils Sediments 19 3139–54
[4] Lednev S A, Sharapova A V, Semenkov I N, Karpachevsky A M and Koroleva T V 2020 Plant successions on coal mines’ waste piles in forest-steppe of the Tula oblast Izv. Ross. Akad. Nauk. Seriya Geogr. 84 239–45 (in Russian)
[5] Bragina P S, Tsibart A S, Zavadskaya M P and Sharapova A V 2014 Soils on overburden dumps in the forest-steppe and mountain taiga zones of the Kuzbass Eurasian Soil Sci. 47 723–33
[6] Bragina P S and Gerasimova M I 2014 Pedogenic processes on mining dumps (a case study of southern Kemerovo oblast) Geogr. Nat. Resour. 35 35–40
[7] Sokolov D A, Androkhonov V A, Kulizhskii S P, Domozhakova E A and Loiko S V 2015 Morphogenetic diagnostics of soil formation on tailing dumps of coal quarries in Siberia Eurasian Soil Sci. 48 95–105
[8] Sharapova A V, Semenkov I N, Lednev S A, Karpachevsky A M and Koroleva T V 2017 Self-development of mining landscapes of the old coal mining district in tula region Ecol. Ind. Russ. 21 54–9
[9] Barham P, Begg E, Foote S, Henderson J, Jansen P, Pert H, Scott J, Wong A and Woolner D 2006 Guidelines for soil description Fourth edition
[10] FAO 2015 World reference base for soil resources 2014 International soil classification system (Rome: FAO)
[11] Reeuwijk L P (ed) 2002 Procedures for soil analysis (Wageningen: ISRIC FAO)
[12] Yang L, Song J, Bai X, Song B, Wang R, Zhou T, Jia J and Pu H 2016 Leaching behavior and potential environmental effects of trace elements in coal gangue of an open-cast coal mine area, inner mongolia, China Minerals 6 6020050
[13] Pandey B, Agrawal M and Singh S 2016 Ecological risk assessment of soil contamination by trace elements around coal mining area J. Soils Sediments 16 159–68
[14] Kuter N, Dilaver Z and Gül E 2014 Determination of suitable plant species for reclamation at an abandoned coal mine area Int. J. Mining, Reclam. Environ. 28 268–76
[15] Krechetov P, Kostin A, Chernitsova O and Terskaya E 2019 Environmental changes due to wet disposal of wastes from coal-fired heat power plant: A case study from the Tula Region, Central Russia Appl. Geochemistry 105 105–13
[16] Pampura T B, Pinskiy D L, Ostroumov V G, Gershevich V D and Bashkin V N 1993 Experimental study of the buffer capacity of Chernozem contaminated with copper and zinc Eurasian Soil Sci. 25 27–38
[17] Bogdanova M D 1994 Comparative characterization of susceptibility of Russian soils to acidifying impact Eurasian Soil Sci. 26 50–62
[18] Kolesnikov S I, Yaroslavtsev M V, Spivakova N A and Kazeev K S 2013 Comparative assessment of the biological tolerance of chernozems in the south of Russia towards contamination with Cr, Cu, Ni, and Pb in a model experiment Eurasian Soil Sci. 46 176–81
[19] Minkina T M, Miroshnichenko N N, Fateev A I, Motuzova G V., Mandzhieva S S, Sushkova S N and Biryukova O A 2015 Features of microelement composition of ordinary chernozems of the Azov and lower Don regions Am. J. Agric. Biol. Sci. 10 111–5
[20] Solntseva N P, Rubilina N Y, Gerasimova M I and Alistratov S V 1992 Alteration of the morphology of leached Chernozems in a coal-mining district Eurasian Soil Sci. 24 46–58
[21] Nikiforova E M and Solntseva N P 1986 Technogenic flows of sulphur in humid landscapes of coal-mining areas. Vestn. Mosk. Univer. Ser. Geogr. 3 52–9 (in Russian)
[22] Solntseva N P, Gerasimov M I and Rubilina N Y 1991 Morphogenetic analysis of soils transformed by technology Sov. Soil Sci. 23 87–94
[23] Solntseva N P 2002 Trends in soil evolution under technogenic impacts Eurasian Soil Sci. 35 6–16