ASSESSMENT OF RESTORATION PROCESSES IN RECLAIMED COPPER ORE MINING EMBANKMENTS

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ABSTRACT. The object of the present study is a reclaimed embankment from copper mining. The research aims to evaluate the restoration processes in the reclaimed embankment - soil formation, restoration of soil fertility, and restoration of microflora. According to an assessment, the restoration processes are in the initial stage. The soils formed are of a primitive structure of the type OF (OFS) - OFS - C. An organic layer was formed. Humus is of the fulvate-humate type. The composition of the microflora is dominated by bacilli (an indicator of self-cleaning processes of the soil).

Key words: restoration, reclaimed lands, copper mining

ОЦЕНКА НА ПРОЦЕСИТЕ НА ВЪЗСТАНОВЯВАНЕ В РЕКУЛТИВИРАНИ НАСИПИЩА ОТ ДОБИВА МЕДНИ РУДИ

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Резюме. Обект на настоящето изследване е рекултивирано насипище от добива на мед. Изследването цели да бъдат оценени възстановителните процеси в рекултивираното насипище - почвообразуване, възстановяване на почвеното плодородие и възстановяване на микрофлората. Съгласно направена оценка възстановителните процеси са в начален етап. Формирали са се почви са с примитивен строеж от типа OF (OFC) – OFC – C. Формиран е органичен слой. Хумусът е от фулватно-хуматен тип. В състава на микрофлората преобладават бацилите (показател на протичане на процеси на самоочистване на почвата).

Ключови думи: възстановяване, рекултивирани терени, добив на мед

Introduction

The continuous and intensive extraction of copper ores leads to serious impacts on the environment. Although mining activities are carried out on relatively small areas, they cause infrastructural changes and environmental pollution with a large territorial scope and duration (even after the liquidation of the companies) (Pavlov, 2018).

The restoration of disturbed areas because of mining is one of the most important directions in the field of environmental protection. It aims to restore the ecological value in the territories affected by mining (Zheleva - Bogdanova, 2010; McDonald et. al., 2016) and restore the ecosystem so that it provides ecosystem services (Leia et. al., 2016; McDonald et al., 2016).

The presence of two horizons – A and C – is characteristic of recultivated land. When morphologically describing the horizons, A-C horizons are usually found in very young soils (<10 years), and in some older profiles (> 30 years) the onset of formation of B horizons (*Cambic*) has been reported (Onweremadu, 2007). Another important indicator of how soil functions and influences its physical, chemical, and biological properties is soil texture (Lilić et. al., 2014). Man-made soils are characterised by the content of sand particles above 50% (Maiti and Saxena, 1998; Kumar et al., 2015). The composition of the embankments includes sulphide minerals (pyrite (FeS_2), chalcopyrite ($CuFeS_2$), etc.), which are a prerequisite for an acidic pH ~ 5.5. The accumulation of organic matter and total nitrogen is directly dependent on the location of the reclaimed land and the type of vegetation. The rate of organic layer accumulation varies from 0.6-2.4 cm per year (Insam and Domsch, 1988). It has been established that in disturbed lands the phosphorus content is insufficient and difficult to restore. Low phosphorus content is characteristic of reclaimed land (Kumar et al., 2015). The composition of the microflora in recultivated lands is poorer than that in natural soils. Even 15 years after reclamation, no success can be achieved in its restoration (Nusturova et al., 1991).

The present work aims to study the extent of ongoing restoration processes in reclaimed lands disturbed by copper mining according to selected indicators.

Methods and materials

Study area

The study area is reclaimed land disturbed by copper mining. The area is in the Western Stara Planina Mountain at an altitude of 1300 - 1340 m. The studied land has a slope of 35-40 degrees. Reclamation was conducted 6 years ago.

During reclamation, the terrain was divided into two sample sites. The first site was untreated, and the second site was treated (liming: 262 kg/da, fertilisation: 4.5:4.5:4.5 kg/da NPK). The trial sites were forested with spruce (*Picea excelsa* Link.) and sycamore (*Acer pseudoplatanus* L.).

Materials

Three soil profiles (SP) were taken for the purpose of the analysis. Soil profile 1 (SP1) was taken from the untreated plot of the field, forested with *A. pseudoplatanus* L. Soil profile 2 (SP 2) and soil profile 3 (SP 3) were taken from the treated plot, forested with *Picea abies* L. Soil profile 2 is in the middle of the slope, and soil profile 3 - at the toe of the slope.

Methods

Soil physical and physicochemical properties were studied to determine the soil conditions. A morphological description was carried out in each of the soil profiles. The soil texture was determined according to ISO 11277. Soil reaction (pH) was measured potentiometrically by ISO 10390. The humus content was measured by the Tyurin titrimetric (Tt) method. Total nitrogen in the soil was determined by the Kjeldahl method, assimilable forms of potassium and phosphorus - by the method of Petko Ivanov. Microbiological analyses have been carried out, using the standard dilution methods and medium culture media (Bacteriological agar and Czapek Dox Agar) in three replicates at a controlled temperature of 27º C (Nusturova et al., 1991; Grudeva et al., 2007). Microbiological analyses included the determination of: Ammoxifying bacteria batteries (Czapek Dox Agar) (a), Bacillus (Bacteriological agar), actinomycetes (Czapek Dox Agar), and fungi (Czapek Dox Agar).

The obtained data have been processed and interpreted to establish the degree and speed of recovery processes in the recultivated terrains. The soil texture is determined by the scale of FAO (2006), active soil acidity - by the Malinova scale (2010); content of organic carbon and enrichment of humus with nitrogen (C/N) – by the Artinova scale (2014); the total nitrogen content – by the Vanmechelen scale (1997); available phosphorus and available potassium - by the Penkov scale (1996).

Results

Analysis of soil condition

The soils in the studied sample areas have an OF-(OFC)-C profile formed because of the young age of the restored areas – 6 years. The formed organic layer has a thickness between 1-3 cm. SP1 and SP 2 have a layer of litter - 1 cm, and SP3 - 3 cm. The thickest layer of litter is formed in *P. abies* L. afforestation. The test point is located at the heel of the slope. Probably under the influence of water erosion (accounted for in the morphological analysis), some of the accumulated plant remains on the slope are moved to the heel of the slope (despite the erosion control silt fence). Accumulation rates of organic matter varies between 0.20 cm/y (SP1 and SP2) and 0.60 cm/y (SP3). The rate of formation is below average according to literature data (Barnhisel et al., 2000). However, it is larger compared to reclaimed areas located at a higher altitude in the same region (Stefanova, 2022). The rate of organic matter accumulation is related to applied reclamation improvements and the location of the sample point along the slope.

The soil texture before and after reclamation are presented in Fig. 1.

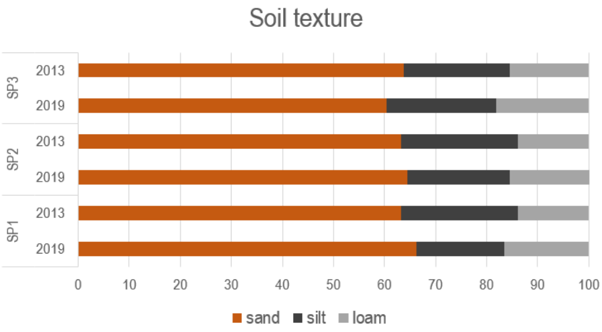

Fig. 1. Soil texture (2013 and 2019), %

The soil texture of technogenic soils is loamy sand. The particle of sand predominates - over 60% in all soil profiles, followed by silt (17.0 % – 21.0 %) and clay (15.0 % – 18.0 %). A high sand content is a prerequisite for deteriorated soil air and soil moisture-holding capacities.

The investigated soils were also of loamy sand soil texture before reclamation (Petrov, 2019). Positive changes in soil texture were observed in 2019. In SP1, the sand content decreased from 63.8 % to 60.4 %, and silt and clay increased from 20.7 % to 21.4 % and from 15.4 % to 18.1%, respectively; in SP2 and SP3, the sand content (SP2 from 63.2 % to 66.2% and SP3 from 62.2 % to 64.4 %) and clay (SP2 from 13.8 % to 17.2 % and SP3 from 13.8 % to 15.2 %) increased respectively at the expense of the silt fraction (SP2 from 23.0 % to 20.0% and SP3 from 22.9 % to 17.2 %). In all samples over the years, the fraction of sand was above 60.0 %, but the amount of clay in 2019 exceeded 15.0 %. The formation of clay particles shows improvement of the structure of reclaimed soils and ongoing recovery processes in the soil.

Data on soil acidity, humus content and nutrients are presented in Table 1.

Table 1. *Soil acidity and basic agrochemical parameters of soils*

Soil profile	Depth	pH (H2O)	C	N	P_2O_5	K_2O
	cm	-	%		mg/100g	
SP1	1-0	6.6	0.74	0.07	0.006	12.0
	0-20	5.3	0.34	0.03	0.005	7.7
SP2	1-0	7.2	1.56	0.12	0.003	22.3
	0-20	7.1	0.27	0.07	0.002	11.0
SP3	3-0	6.3	1.49	0.14	0.004	16.0
	0-20	5.1	0.20	0.06	0.002	8.5

Soil acidity varies in the different profiles (depending on the location of the sample point and on the depth) from highly acidic to very slightly alkaline. In the surface layer, the soil reaction is as follows: SP1 and SP3 – a neutral reaction and SP2 - a slightly acidic reaction. The pH in SP3 is in the range that provides optimal conditions for plant nutrition and favours their development (Malinova, 2010), for the *P. abies* L. as well (plants selected for restoration). Spruce is known to grow best at a pH in the 4.3-7.4 range (Petrova, 2013).

In the subsurface layer, the soil reaction is as follows: SP2 - a neutral reaction, SP1 - a moderate acid reaction, SP3 - a highly acidic reaction. A neutral soil reaction was observed in SP2, which is limed. There is a clear tendency: the pH value in the depth of the profiles decreases. No connection has been established with the land reclamations carried out. The soils in SP2 and SP3 are limed, but nevertheless the soils in SP1 have a higher pH than SP3. This is probably due to the forested species - *Acer pseudoplatanus* L. SP2 and SP3 are forested with *Picea abies* L. It is characteristic that the spruce litter has a very strongly acidic reaction. The average pH $_{(H2O)}$ for leaf mass fraction is 4.21, for wood – 4.48, and for reproductive organs and seeds – 5.02 (Filcheva and Malinova, 2015). The soil acidity before and after reclamation are presented in Fig. 2.

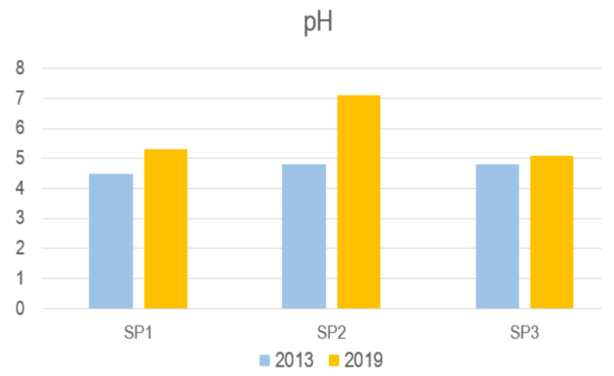

Fig. 2. Soil acidity (2013 and 2019)

The pH varies in the very acidic range - pH – 4.5-4.8 before reclamation. In 2019, a positive change was reported regarding the parameter. The pH rose to neutral (7.1). It is likely that the slope of the terrain has an effect on soil acidity. It is assumed that part of the acidic water infiltrates in depth, and another part is carried out along the slope (this accelerates the neutralisation process). However, no further increase in soil reaction can be expected. It is known that soil-forming materials (mine waste) are inherently acidic and contain sulphur in high concentrations (Petrov, 2019).

The content of organic carbon varies from very low (below 1.0 %) to low. In the surface layer, it is as follows: very low in SP1 (0.74 %) and SP2 (1.56 %) and low in SP3 (1.49 %), and in the subsurface layer it is very low in all sample areas (0.20 – 0.34 %) (Table 1). The highest content of organic matter was registered in afforestation with *P. abies* L., and the lowest amount - in afforestation with *A. preudoplatanus* L. This can be explained by the fact that sycamore is characterised by a slower decomposition of plant residues. It is known that in the leaf litter of the species the bacterial population is significantly lower, as is the C:N ratio (Janukauskaite, 2013). A trend of decreasing organic carbon content in depth was found. The coefficients of the decrease of organic carbon content in depth are as follows 2.18 times (SP1), 5.78 times (SP2), 7.45 times (SP3).

In all three sample areas, there is a positive trend for organic carbon content compared to 2013. It increased up to 14 times in SP2 (Fig. 3). This is due to the nature of the mining waste, the lack of humus materials for reclamation and the environmental conditions in the area.

The content of total nitrogen is very low in all soil profiles (in the surface layer: 0.06 to 0.07 %, and in the subsurface layer: 0.03 to 0.07%) (Table 1.).

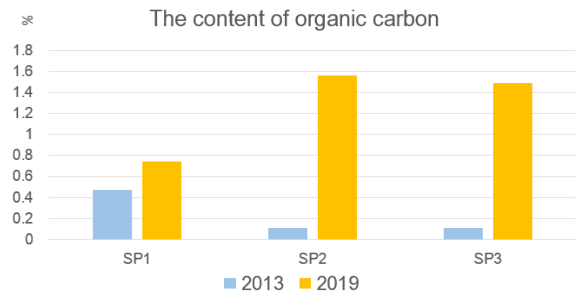

Fig. 3. The content of organic carbon (2013 and 2019), %

A relationship with the treatment of the trial areas is noted. In the fertilised test areas, the amount of total nitrogen was greater (SP2 (0.07 %) and SP3 (0.06 %)). In SP2, the amount of total nitrogen in the surface layer was less compared to SP3. The difference is probably due to the location of the sampling points – SP2 is in the middle of the slope. Reference is assumed of the element towards the toe of the slope, a result of water erosion. Although the amount of nitrogen is very small, its presence is extremely important. The content of the element is a limiting factor for the restoration of disturbed lands (Sever, 2008).

The content of total nitrogen was estimated to be very low in 2013 and 2019. However, an increase of the element was found in all the sampled areas (Fig. 4). In the treated soil profiles SP2 and SP3, the amount of nitrogen increased significantly compared to 2013 (up to 11 times in SP2 and up to 10.5 times in SP3).

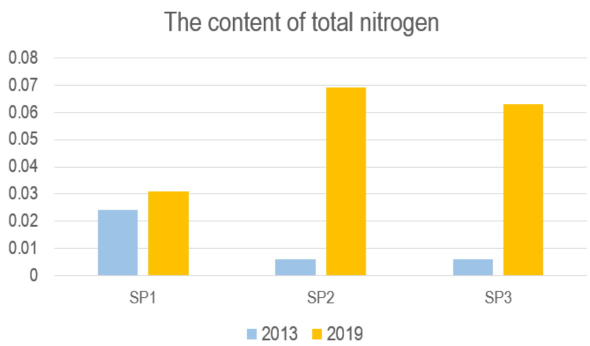

Fig. 4. The content of total nitrogen (2013 and 2019), %

The value of the C:N ratio varies from 17.7 to 21.5 (SP1 – 17.5, SP2 – 21.5, SP3 – 17.7) in the surface layer and from 1.8 to 6.4 (SP1 – 1.8, SP2 – 6.4, SP3 – 5.5) in the subsurface layer. The tendency to decrease its value in the depth of the profile was found. In the surface layer, nitrogen enrichment is low in SP1 and SP3 (17.5 and 17.7), and very low in SP3 (21.5). This is associated with a high degree of humus mineralisation. In the subsurface layer, nitrogen enrichment is very high - below 7.0 (indicator of low mineralisation of organic substances (Artinova, 2014)).

The content of available phosphorus (P_2O_5) is very low in all soil profiles. In the surface layer, the content of the element varies from 0.004 to 0.006 mg/100g, and in the subsurface layer - from 0.002 to 0.005 mg/100g (Table 1). Phosphorus accumulates in the surface layers and follows a decreasing trend with depth, like nitrogen. Decreasing is probably due to absorption of the element by plants over time, its being carried away in depth or its blocking due to the acidity and heavy metal content. Although SP2 and SP3 were treated with combined fertilisers, the phosphorus content was higher in SP1 - untreated. This is probably due to the fact that the litter of *A. pseudoplatanus* L. accumulates a greater amount of the element (Hobbie, 2006).

The content of available phosphorus (Fig. 4) followed a decreasing trend in all sampled areas from 5.1 mg/100g in 2013 to 0.002 mg/100g in 2019. A certain part of the element is probably blocked by the heavy metal ions characteristic of the embankment (Petrov, 2019), while another part is absorbed by the plants. When liming the sites, part of the element is probably also blocked by calcium (in insoluble compounds). As can be seen, the introduction of fertilisers did not lead to an increase in the phosphorus content in the soil.

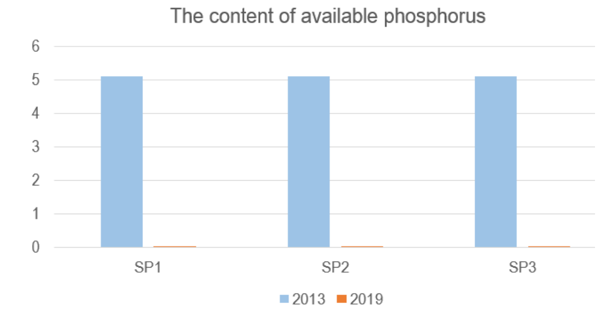

Fig. 5. The content of available phosphorus (2013 and 2019), mg/100 g

The content of available potassium (K_2O) in the soil profiles varies from very poor (7.7 mg/100g) to good (22.3 mg/100g) (Table 1). A tendency was established to decrease the content of the element in depth. In the surface layer, the content of available potassium varies - very low (SP1 – 12.0 mg/100g), moderate (SP3 – 16.0 mg/100g), good (SP2 – 22.3 mg/100g).

Although *A. pseudoplatanus* L. accumulates a greater amount of potassium (Wen, 1984), in the *P. abies* L. forested sample sites, the content of the element is higher (moderate to good). In the subsurface layers, the content of absorbable potassium varies from very low (SP1 – 7.7 mg/100g) to low: very low (SP2 (11.0 mg/100g) and SP3 (8.5 mg/100g)). A higher content was reported in the fertilised sample sites.

The low values of the element are completely within the expected range. They are probably due to the fact that the element has been absorbed by the plants, a long period has passed since the introduction of mineral fertilisers. It is also possible that it has been carried away in depth (it is characterised by easy solubility and mobility (Petrov, 2019)). In 2013, the content of available potassium in the subsurface layer (Fig. 6) was very low (7.4 mg/100g) to low (13.6 mg/100g).

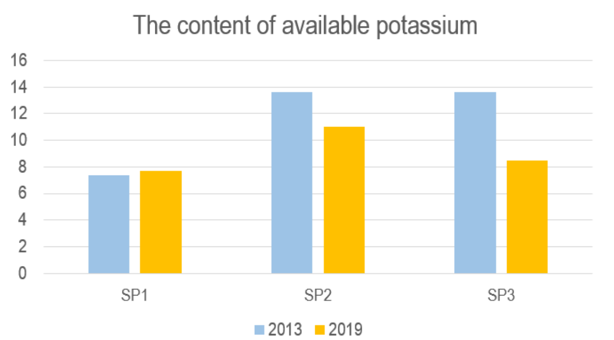

Fig. 6. The content of available potassium (2013 and 2019), mg/100g

A decrease in the content of the element was also reported in 2019, by defining the content of the element as very low.

Analysis of microflora restoration

One of the most important prerequisites for the restoration of ecosystems in disturbed terrains is the amount and activity of microorganisms in the soil. Their activity is related to processes of soil development, in the decomposition and circulation of nutrients, and the presence of pollutants. The results for the composition and quantity of the microflora in the recultivated terrain is presented in Table 2.

Table 2. *Quantitative and qualitative composition of the soil microflora*

SP	Depth	Total microflora	Bacilli	Non-spore forming bacteria	Fungi	Actino-mycetes
	cm	number of colonies x10³/g substrate				
SP1	1-0	2100	800	0	100	1200
	0-20	740	160	260	0	320
SP2	1-0	2700	800	1900	0	0
	0-20	160	80	40	0	40
SP3	5-0	25600	19600	6000	0	0
	0-20	5890	4840	250	0	800

Microbiological analyses showed a different amount of total microflora in the three profiles. In the surface layers of the soils, the highest amount of the total microflora was reported in all sample areas. A clear tendency to decrease the amount of microflora in depth was found. This is probably due to the better aeration, the content of organic matter in the surface layers compared to that in depth. The percentage distribution of the soil microflora (by groups of microorganisms) does not follow the same trend in all profiles and depths. The composition of the microflora is dominated by bacilli and non-spore-forming bacteria.

The high content of bacilli is related to the self-purification processes of the soil. What is also characteristic of them is that they participate in the more advanced phase of mineralisation of organic substances (Nustorova, 1995). In depth, their number decreases. In a similar type of object at depth, the number of bacilli decreases due to the inhibitory effect of pollutants on them (ibid).

From the spore bacteria, there are representatives of the species: *B. cereus*, *B. mycoides*, *B. megaterium*, and *B. subtilis*. The composition has significant differences in the different soil horizons and depths.

The predominant species is *B. megaterium* – assimilating mineral nitrogen. This species has a dominant role in forest soils, as it participates in the degradation of organic compounds. What is also characteristic of B. megaterium is that they prevail in soils with more active mineralisation processes (Nustorova and Gencheva, 1988).

B. mycoides is distributed in the smallest quantities. This is explainable given the fact that this bacillus is most sensitive to heavy metal contamination and is usually characteristic of ecologically clean areas.

Table 3. *Composition of the bacillary microflora*

SP	Depth	*B. mycoides*	*B. megaterium*	*B. cereus*	*B. subtilis*
	cm	number of colonies x10³/g substrate			
SP1	1-0	0	100	100	0
	0-20↓	0	20	20	0
SP2	1-0	0	0	200	0
	0-20↓	0	0	20	0
SP3	5-0	100	4400	500	0
	0-20↓	100	1180	30	0

The species is distributed in PP 1.3. Its appearance speaks positively about the recovery processes occurring in the recultivated soils. It is known that the species can be used as an indicator species for low levels of pollution. (Nustorova and Gencheva, 1988, Nustorova, 1995).

In general, the composition of bacilli is too poor, which can be taken as an indicator that the microbiocenosis is still in the process of formation.

Although in small quantities, the presence of actinomycetes was observed in the test areas. Their presence is a sign of active mineralisation processes. Actinomycetes are known to be excellent degrading agents. They survive in extreme conditions (e.g. lack of sufficient nutrients) and synthesise surfactants that accelerate the biodegradation process (Yankova et al., 2016; Malcheva, 2020).

There are no mold fungi in the studied soils (except for the surface layer of SP1). The reason for this is probably the low nitrogen and carbon content. This group of microorganisms is characterised by a strong dependence on environmental conditions - amount of nitrogen, moisture, pH.

The data show that in the treated sample areas SP2 and SP3, the content of total microflora is higher than in the untreated sample areas. This is probably due to the higher amount of nutrients (especially nitrogen), the higher content of organic matter, and probably the lower mobility of the available heavy metals and metalloids (Petrov, 2019) (due to liming).

Conclusion

The data from the conducted research show that recovery processes are taking place in the research area in initial stage.

The technical and biological methods of reclamation have a positive effect on the formation of the soil profile, the soil texture, the soil acidity, the content of organic carbon and total nitrogen.

The ongoing elementary processes of soil formation (in the recultivated lands) lead to the formation of soils possessing the properties of the soil's characteristic of the area.

The established content of available phosphorus and available potassium in all sample areas indicates depletion of the elements (imported with the carried out mineral fertilisation). The results give reason to believe that it is necessary to carry out additional fertilisation in the future (as a corrective measure).

It was established that the composition of the microflora in the three subsites is dominated by bacilli, an indicator of self-purification processes of the soil. In general, the composition of bacilli is too poor, which can be taken as an indicator that the microbiocenosis is still in the process of formation. The data show that the amount of total microflora is directly dependent on the ameliorative activities carried out.

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