Environmental Feasibility of Forest Reclamation of Mining Dumps of the Western Donbass

Vasiliy Zverkovsky[1], Mykola Kharytonov[2], Iryna Klimkina[3], Svitlana Sytnyk[2], Viktoriia Lovynska*[2], Svitlana Mykolenko[2], Giovani Pardini[4], Eva Margui[4]

[1]Oles Honchar Dnipropetrovsk National University
pr. Gagarina, 72, Dnipro, 49000, Ukraine. E-mail zverkovsky@yahoo.com
[2]Dnipropetrovsk State Agrarian and Economic University
S. Yephremova Street, 25, Dnipro, 49000, Ukraine
E-mail: kharytonov.m.m@dsau.dp.ua, glub@ukr.net
[3]National Mining University
pr. Dmytra Yavornytskoho, 19, Dnipro, 49000, Ukraine. E-mail irina_klimkina@ukr.net
[4] University of Girona
Aurelia Capmany, 61, 17003 Girona, Spain. E-mail giovanni.pardini@udg.edu

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Abstract

The content of heavy metals in different structure elements from aboveground phytomass and of some tree species on the mining rock within the Steppe of Ukraine was analyzed. The investigation values of aboveground phytomass for experimental cultures on the recultivation plot were better than for those growing on the mine rock. Heavy metals accumulation by the functional parts of plants largely depended on soil or substrate contamination rate. The concentration of manganese decreased in the leaves of the trees in the reclamation site in comparison with the trees grown on the mine dump.

Key words: *mine rock, trees species, reclamation, heavy metals.*

Аннотация

Проанализировано содержание тяжелых металлов структурных элементов надземной фитомассы, некоторых видов деревьев на горном отвале в Степи Украины. Исследуемые показатели надземной фитомассы экспериментальных культур на участке рекультивации были лучшими, чем для деревьев, растущих на горной породе. Накопление тяжелых металлов в функциональных частях растений в значительной степени зависело от степени загрязнения субстрата произрастания. Концентрация марганца уменьшилась в листьях деревьев на участке рекультивации по сравнению с деревьями, выросшими на шахтном отвале.

Ключевые слова: *шахтный отвал, древесные виды, рекультивация, тяжелые металлы.*

Introduction

Western Donbass is a powerful coal-mining region. High rates of its industrial and economic development cause environment anthropogenic transformation in the area over 12 thousand hectares. Every year dumping sites are replenished by more than 4 millions of cubic meters of mine rock (Kharytonov, 2007). In this regard using mine rocks for reclamation of subsided areas and building of dams is considered.

The wastes stored in tailings and heaps are subjected to continuous erosion processes and chemical reactions releasing soluble metal compounds easily up taken by the biota. The metal removal rate is thought to be dependent on the filtering capacity of the waste materials as well as by waste material stability to the weathering process.

It has postulated that the rocks and mud of the coal tailings spread all over the Western Donbas district contain trace elements of the first class of hazard (Kharytonov and Kroik, 2011). The greatest concentrations of metals correspond to the mine waste rocks and mud showing strong acidic reaction.

Coping with a large number of sites with serious environmental and health impacts is complicated. Often the liable owners are missing or not willing to charge or afford environmental remediation especially in countries with more flexible directives. In some cases the government is

* Kontaktinis asmuo / Corresponding author

held accountable. But the huge financial liability attached to any systematic rehabilitation program represents a challenge that far exceeds the financial or organizational resources of any one regional actor. The situation is further aggravated by the lack of expertise required to take practical responsibility for dealing with sound reclamation of mine sites and the associated issues.

Many years forest plantation creation in difficult soil-hydrological conditions was associated with the anthropogenic subsidence in areas of Western Donbass. The methods of forest restoration for lands disturbed by coal industry in the steppe zone of Ukraine were developed. Comprehensive study of forest ecosystems in etalon and reclaimed areas was conducted due to this. The forest restoration approaches were tested for anthropogenic landscapes resulting from: a) subsidence of the areas; b) changes in the hydrological regime or flooding; c) degradation of forest and agricultural land; d) degradation of soil and vegetation; e) emissions of saline mine water; f) intensive formation of industrial dumps; g) ***severe imbalance*** in food chain relations technogenesis. At the mine dump sites of the Wester Donabss in the technogenicaly negative forms of relief experimental-production forest restoration sites with a total area of 60 hectares were created.

During last 40 years biogeocenological comprehensive study on the development of methods of phytomelioration on disturbed lands was conducted. In particular, study was dedicated to defining of optimal design of remediation layer, finding promising types of forest plants and forestry measures to improve the stability and durability of ecosystems on land restored after anthropogenic degradation (Travleyev, Belova et al., 2005).

To evaluate the biogeocenlogic role and functional significance of plants in the process of restoration of disturbed lands, the physical and chemical properties of mine rocks and artificial soil of the remediation layer and their change during long-term remediation measures were monitored (Kharytonov, 2007). It was established that mine dumps are mainly filled with debris of the lower coal beds which originate form shallow seas of the Carboniferous Period. Without implementation of any remediation measures, territories occupied with such dumps will remain vegetation free areas for many years and will be the source of chemical pollution. Due to specific landscapes features it looks like "industrial desert".

Lithological structure of the strata of rocks is quite variable – in some places more plastic rocks (clays, mudstones) dominate, in other fragile (sandstones, siltstones. In completely different hydrothermal conditions and atmosphere pressure and also under the impact of biological factors, rocks are rapidly eroded with generation of new chemical and biogenic products. These processes are accompanied with significant changes in rocks' properties which cause expansion (ingrowths of trophy and aggregation, improvement of physical properties) or narrowing (self-consolidation of rocks redistribution of salts in the soil profiles, generation of sulfuric acid due to pyrite degradation, etc.). The process of mining rock oxidation (combustion) is intense rate due to physical and chemical weathering, under the exothermic reactions impact (Travleyev, Belova et al., 2005). The most common reactions are hydration, dehydration, hydrolysis, oxidation, dissolution and exchange. Pyrite in the interaction with oxygen and water is included in the following changes (Bilova et al. 2011) (formula 1):

$$
\begin{gathered}
2FeS_2\ (pyrite) + 7O_2 + 2H_2O = 2FeSO_4 + 2H2SO_4, \\
12FeSO_4 + 6H_2O + 3O_2 = 4Fe_2\ (SO_4)_3 + 4Fe(OH)_3, \\
2Fe_2(SO4)_3 + 9H_2O = 2Fe_2O_3 \times 3H_2O\ (limonite) + 6H_2SO_4.
\end{gathered} \tag{1}
$$

The results of research have revealed three main factors of toxicity in acid sulfide minesoils of Western Donbass are following: exchangeable Al, water-soluble Mn and Na (Kostenko, Opanasenko et al., 2012). The occurrence of these soil factors depends on the initial wastes' pyrite concentration, time since dumping, dumping technique, and relief. In the range of pH from 2.96 to 4.5, the mobile forms of Al suppress plant growth in the leached soils of depressions; the mobile

* Kontaktinis asmuo / Corresponding author

forms of Al and Mn suppress plant growth in the slopes of hillocks; the mobile forms of Al, Mn, and Na suppress plant growth in the soils of recently dumped and compacted mine wastes. Therefore transition from initially favorable rocks (in terms of forest substrate) to bad and all way around is possible.

Many authors consider the evaluation of the state of assimilation apparatus of the trees as environmental monitoring tool, as it is directly connected to their environmental stabilization role preventing spreading of the pollutants in the environment (Dulama, Popescu et al., 2012, Kabata-Pendias, 2011; Nik, Majid et al., 2011; Pietrzykowski, Socha et al., 2014).

The aim of this study was to evaluate the specialties of accumulation of heavy metals by leaves and tissues of trees growing on technosoils of “Pavlogradskaya mine” in the Dnipropetrovsk region.

Methods of the research

Experimental land reclamation station was established in spring 1976 in the minefield area of "Pavlogradskaya" mine. Rectangular shaped plot has total area of 3 hectares. The basis of the area was formed with thick layer (8–10 meters) of mine rock intercharged with various topsoil layers. Intensive deformations of the upper layers of the lithosphere and land subsidence with subsidy depth of 7–9 meters were registered.

Two variations of artificial soil profiles with different bulk thickness of mine rock and topsoil were created on the surface of mine dump site. The list of described hereinabove artificially created soil profiles (types) (stratigraphy downward) include:

- Type 1: mine rock;
- Type 2: 0.5 m – loess; 0.5 m – sand; mine rock.

The trees were strip planted across 2 different artificial soil profiles with width between rows 2.5 meters and distance between plants in row from 0.75 to 1.5 meters.

This paper presents investigational data on three plants: English oak, Silver birch and pear, which were planted on Type 1 and Type 2 soils. Samples of the plant which grew on the mine rock (techno soil).

The object of this study were the compartments of the silver birch (*Betula pendula* Roth.), English oak (*Quercus robur* L.) and European pear (*Pyrus communis* L.).

The determination of metals concentration in the technosoil was conducted employing method of the plasma Optical Emission Spectrometry (ICP-OES) on the spectrometer Technologist 5100 (Agilent) with inductively connected plasma. Samples of the plants were crushed to the powder state and after the batch of the plant material (0,3 g) was put into chemical flask and 10 ml of concentrated HNO_3 and 2 ml of 30 % H_2O_2 were added and mixture was resting for 1 hour. After that, acid solution was filtered and analyzed for the metal content. Analysis for the heavy metals was performed in the University of Girona, Spain.

Results and discussion

Mine rock was defined as unfavorable in their texture properties: with excessively large plasticity, significant shrinkage ability, high stickiness, significant coherence and low wear rate. Considerable variation of characteristic which are typical for artificial soil of remediation layer indicates the heterogenity of these substrates, diversity of properties that can be attributed to the time and place of coal mining, waste rocks storage conditions, etc.

Mine rocks water-physical properties. The data on mine rocks volumetric, specific mass density and porosity are shown in the table 1.

* Kontaktinis asmuo / Corresponding author

Table1. Mine rocks water-physical properties

№	Meaning	Volumetric density, g/cm^3	Specific density, g/cm^3	Porosity, %
1.	Average	1,64	2,52	34,78
2.	Min	1,55	2,43	33,20
3.	Max	1,75	2,69	36,21
4.	SD	0,1	0,15	1,23

It is obviously that mine rocks have high volumetric, specific mass density and porosity. Meantime, during intense oxidation and weathering of rocks, water-physical properties or those are improved. The surface of mine rock reclamation areas often forms water-retaining layer that optimizes significantly conditions for plants development on artificial topsoil of different types.

Artificial soil profile acidity and salinization. Analysis of the sulfur content in rocks on reclamation areas indicated that amount of pyrite in studied samples was changing from 1.8 to 3.3 %. The upper horizons of mine rocks contacting with atmosphere contained less pyrite compared to backfill horizons. Small portion of monitoring data to reflect the mining rocks pH and salinization profile distribution are shown in the table 2 and 3.

Table 2. The pH profile distribution

Depth, cm	Average	Min	Max	SD
		Type 1		
0–25	4.61	4.44	4.94	0.28
25–50	3.14	2.87	3.28	0.23
50–75	2.61	2.59	2.63	0.02
75–100	5.46	5.21	5.83	0.33
		Type 2		
0–25	8.16	7.93	8.53	0.33
25–50	8.14	7.98	8.23	0.14
50–75	6.92	6.77	7.02	0.13
75–100	7.59	7.24	7.83	0.31
100–125	6.64	6.38	6.84	0.24
125–150	6.42	6.03	7.09	0.59
150–175	6.17	5.91	6.42	0.26

Table 3. The salinization distribution in two artificial soil profiles

Depth, cm	Average	Min	Max	SD
		Type 1		
0–25	1071.0	948.00	1309.00	206.2
25–50	1924.7	1803.00	2090.00	148.4
50–75	2583.3	2310.00	2790.00	246.8
75–100	2170.0	2110.00	2280.00	95.4
		Type 2		
0–25	144.67	135.00	156.00	10.6
25–50	140.67	132.00	151.00	9.6
50–75	59.67	50.00	65.00	8.4
75–100	96.00	61.00	123.00	31.8
100–125	172.67	128.00	205.00	40.0
125–150	1828.67	1638.00	1956.00	168.2
150–175	1157.00	1021.00	1360.00	179.2

Acidity of mine rock (pH) in plot Type 1 along one meter profile was ranging from 2.61 to 5.46. Low pH levels were observed in the intergarged layer of rock with depth 50–75 cm. Creation of artificial soil profile allows to keep pH close as neutral or slightly alkaline in the stratum 1 meter. It was possible to fix pH within 6.17–6.64 due to geochemical barrier consisting of carbonated loess loam (0.5m) and sand (0.5m).

* Kontaktinis asmuo / Corresponding author

In comparison to type 1 (mine rock one meter profile) type 2 artificial profile taken characterized far less amount of salinization. By the other words during more then three decades weathering process led to pH and EC stabilization in reclaimed mine lands.

Plants vitality indicators. Features of trees and bushes development on the experimental forest restoration plots were defined according to vitality indicators, long-term dynamics of linear growth and above-ground phytomass. Significant difference in the rate of growth and vitality of plants on rock and topsoils was observed during the first years of the experiment. During the following years, the difference became even more noticeable. The vitality of trees and bushes on the mine rock was insufficient. Plants were poorly branched and had poor leaf covering. The annual increase in height was 5–30 times less, and average crown width was 16–25 times shorter compared to plant on other types of topsoil. Quantitative analysis of aboveground biomass fractions of experimental trees allowed to compare the productivity of different types of forest cultures depending on the particularities of this artificial topsoil and identified the most promising construction of artificial topsoils and types of forest crops (Travleyev et al., 2005). It was established that indicators of aboveground biomass development for experimental plants on the plot were close to those indicators for reclamation plants developing on undisturbed lands. Higher overall productivity for undisturbed lands was achieved due to higher planting density.

Evaluation of non-branching part of the trunk and heights of the crown of three tree species are given in the tables 4 and 5.

Table 4. Basal diameter of non-branching part of the stem of trees, cm

Type	English oak	Silver birch	European pear
1	11.62±0.83	8.44±3.9	8.73±3.7
2	12.44±1.39	12.1±6.6	14.69±9.31

Table 5. Height of the crown of three species of trees, cm

Type	English oak	Silver birch	European pear
1	527±29	630±17	412±15
2	813±68	827±27	789±41

In general studied tree species had bigger basal diameter of non-branching part of the trunk and crown height on the reclamation plot compared to plants growing on the mine dump on 40–50 %. English oak plants on the first type of topsoil (mine rock) had created a sustainable forestry plantation. Trees had closed in rows and between rows and trees give fruits, but linear growth rates are lower compared to other experimental groups.

Silver birch had spread around the site by itself, but mainly at the border between first and second topsoil type areas. Trees have well-developed crowns and a good vitality. Linear growth rates for border between first and second type of substrate.

European pear survived mainly on the second type of substrate. Main indication indexes of above ground phytomass for experimental cultures on the recultivation plots were better than for those growing on the mine rock.

The determination of heavy metals concentration in the leaves is essential in environmental studies. The trees accumulate heavy metals from soils in all seasons and transfer these elements, together with other nutrients, to leaves in the vegetation period. The minerals accumulation is strongly affected by the chemical composition of the soil from which trees get their nutrients (Dulama et al., 2012). The results of evaluation of heavy metals content in the leaves for both experimental types are given in the table 6.

* Kontaktinis asmuo / Corresponding author

Table 6. Heavy metals content in the leaves, ppm

Type	Cr	Cu	Mn	Ni	Sb	Sn	Zn
Betula pendula							
1	1.11±0.10	7.49±0.71	1077.93±51.6	5.09±0.28	3.52±0.25	3,38±0.18	75.44±3.4
2	2.51±0.18	5.70±0.27	588.43±15.0	9.76±0.01	0.8±0.02	3.42±0.21	279.78±2.59
Quercus robur							
1	2.53±0.16	5.96±0.08	1542.96±36.29	9.05±0.13	0.8±0.04	2,86±0.12	34.2±1.28
2	1.94±0.08	6.55±0.46	378.97±9.39	3.64±0.26	0.8±0.02	2.1±0.15	25.91±0.71
Pyrus communis							
1	1.7±0.07	5.17±0.22	194.49±9.74	10.01±0.48	1.33±0.10	1.7±0.03	44.17± 1.11
2	1.7±0.06	4.39±0.19	187.12±11.92	5.94±0.30	2.31±0.12	1.7±0.01	43.85±2.61

It was established that concentration of manganese in leaves decreased in reclamation type 2 comparing to trees that grew on the mine dump.

The results of evaluation of heavy metals content in the bark tissue for both experimental types are given in the table 7. The level of chromium, manganese and nickel in bark tissue had the same tendency to decrease in type 2 comparing to type 1.

Table 7. Heavy metals content in the bark, ppm

Type	Cr	Cu	Mn	Ni	Sb	Sn	Zn
Betula pendula							
1	2.30±0.15	4.60±0.16	301.75±4.7	1.77±0.13	0.8±0.02	3.03±0.11	107.00±1.76
2	1.39±0.10	5.42±0.12	292.10±3.8	1.30±0.01	0.8±0.03	2.08±0.07	104.46±1.9
Quercus robur							
1	2.49±0.14	5.97±0.32	200.0±3.2	1.49±0.01	1.49±0.01	3.11±0.10	28.02±2.15
2	1.86±0.05	6.33±0.12	170.7±2.75	1.34±0.03	1.34±0.03	2.12±0.12	35.44±0.69
Pyrus communis							
1	1.37±0.03	6.72±0.61	169.43±4.13	1.82±0.18	1.31±0.12	1.7±0.04	52.49±2.5
2	1.25±0.01	6.25±0.02	61.93±0.99	0.86±1.22	0.8±0.02	1.7±0.09	41.09±1.4

The results of evaluation of heavy metals content in the wood tissue for both experimental types are given in the table 8.

Table 8. Heavy metals content in the wood, ppm

Type	Cr	Cu	Mn	Ni	Sb	Sn	Zn
Betula pendula							
1	2.72 ± 0.10	2.95± 0.09	86.87±5.50	1.10±0.04	3.52±0.25	2.46± 0.10	42.37± 1.25
2	4.19±0.12	3.67±0.05	160.66±5.72	0.8±0.01	0.8± 0.02	2.93± 0.05	53.89 ±4.00
Quercus robur							
1	1.62± 0.14	4.78±0.04	10.03±0.04	1.10 ± 0.03	1.49±0.10	1.98±0.04	28.37±2.54
2	1.73±0.91	4.06±0.33	39.76±1.78	0.8±0.02	1.37±0.10	2.19±0.1	19.49±0.69
Pyrus communis							
1	9.74±0.13	3.51±0.10	156.33±2.20	0.8±0.01	0.8±0.02	6.48±0.55	32.07±2.13
2	1.27± 0.05	4.02±0.11	11.83±0.05	0.8±0.03	0.8±0.01	1.7±0.08	16.66±0.78

Analysis of the data indicates the opposite trends of distribution of heavy metals in the wood of two trials.

Conclusion

It was established, that main indicators of aboveground phytomass for experimental cultures on the reclaimed plots were better than for those growing on the mine dump. Studied tree species had bigger basal diameter of non-branching part of the trunk and crown height on the reclamation plot compared to plants growing on the mine dump on 40–50 %. English oak plants on the first type of topsoil (mine rock) had created a sustainable forestry plantation. Silver birch had spread around

* Kontaktinis asmuo / Corresponding author

the site by itself, but mainly at the border between first and second topsoil type areas. Main indication indexes of above ground phytomass for experimental cultures on the recultivation plots were better than for those growing on the mine rock.

In the same environmental conditions, accumulation of heavy metals by functional parts of plants heavily depends on soil or substrate contamination rate. Concentration of manganese in leaves decreased in reclamation type compared to trees that grew on the mine dump. The level of chromium, manganese and nickel variation in bark tissue had the same tendency. The opposite trends of distribution of heavy metals in the wood of two trials were fixed.

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Экологическая целесообразность лесовосстановления на отвалах шахт Западного Донбасса

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Резюме

Западный Донбасс является мощным угледобывающим регионом Украины. Высокие темпы промышленного и экономического развития обусловили антропогенную трансформацию окружающей среды на площади более 12 тысяч гектаров.

Отработанные горные породы угольного региона Днепропетровской области часто содержат токсичные неорганические контаминанты. Складируемые отходы горных разработок подвергаются непрерывным эрозионным процессам и химическому выщелачиванию, которые приводят к освобождению растворимых соединений металлов, легко поглощаемых биотой.

В связи с этим, использование отработанных горных пород для биологической рекультивации является актуальной экологической проблемой. Многие виды деревьев способны накапливать тяжелые металлы из техноземов круглогодично и поглощать эти элементы вместе с другими питательными веществами в надземную фитомассу в течение вегетационного периода.

Многие годы создание лесных насаждений в сложных почвенно-гидрологических степных условиях было связано с антропогенной трансформацией в районах Западного Донбасса. Принципы лесной рекультивации были реализованы на антропогенных ландшафтах, которые возникли в результате оседания

* Kontaktinis asmuo / Corresponding author

грунта, изменения гидрологического режима или подтопления, деградации почв и аборигенной растительности, интенсивного формирования промышленных свалок.

Цель данного исследования – оценивание особенностей к накоплению тяжелых металлов фракциями надземной фитомассы (листья, кора и древесина ствола) древесных растений, произрастающих на техноземах шахты «Павлоградская» в Днепропетровской области.

Участок экспериментальной рекультивации был создан в 1976 году, площадь которого - 3 га. Для участка характерны интенсивные деформации верхних слоев литосферы и оседание поверхности. На участке были созданы две вариации искусственных профилей почвы с различной объемной толщиной горной породы и верхнего слоя почвы: Тип 1 – горная порода; Тип 2 – 0,5 м –лёсс; 0,5 м – песок; горная порода.

Объекты исследования – структурные компоненты надземной фитомассы березы повислой (*Betula pendula* Roth.), дуба обыкновенного (*Quercus robur* L.) и груши обыкновенной (*Pyrus communis* L.).

Определение концентрации тяжелых металлов в горной породе и растительных образцах проводилось с использованием метода плазменной оптической эмиссионной спектрометрии (ICP-OES) на спектрометре Technologist 5100 (Agilent) с использованием индуктивно связанной плазмы.

Были определены водно-физические свойства горной породы: удельная плотность – 2,52 г/см³; объемная плотность – 1,64 г/см³. Кислотность горной породы (pH) 2,61–5,46. Анализ содержания серы в горной породе на участке лесной рекультивации показал, что количество пирита в исследуемом образце находится в диапазоне от 1,8 до 3,3 %.

Особенности развития деревьев на экспериментальном участке лесной рекультивации определялись по показателям жизнеспособности, динамике линейного роста и надземной фитомассы.

Отмечена значительная разница в темпах роста древесных растений, произрастающих на опытном участке с горной породой. Растения были слабо разветвленными и имели более низкое развитие фракций листьев в структуре надземной фитомассы. Годовой прирост в высоту и средняя ширина кроны были в 5–30 и 16–25 раз, соответственно, меньше данных показателей растений, выросших на горной породе с добавлением лёсса и песка.

При определении тяжелых металлов установлено, что концентрация марганца уменьшалась в листьях деревьев, культивируемых на участке с добавлением лёсса и песка, по сравнению с деревьями, которые росли на горной породе. Уровень хрома, марганца и никеля в коре экспериментальных растений имел идентичную тенденцию.

* Kontaktinis asmuo / Corresponding author