Soil development processes under different tree species at afforested post-mining sites

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Abstract. The studied plantation is a post-mining sites of Kursk magnetic anomaly located in the northeastern part of Belgorod region in a iron-mining district of European part of Russia. The objects of this study are afforested external slope heaps produced by iron open-pit mine in Gubkin. Research work focused on 13-years old pure stands of birch (Betula pendula), sea buckthorn (Hippóphae rhamnoídes), locust tree (Robinia pseudoacacia), oleaster (Elaéagnus angustifólia) and grey alder (Alnus incana) growing on the different substrates. Soil physical and chemicals properties of substrates were analyzed and forest litter stocks were calculated in different slope parts. Substrate quality varied considerably. Forest litter stock depends on site characteristics, tree species and substrate. Study results show that vegetation is the important factor facilitating soil development, the impact of forest litter stock that the surface structure determined is higher with such N-fixing tree species as alder, locust tree and oleaster.

1. Introduction

More than 1 million hectares have been surface mined in the Russia Federation by 2016 [1]. Reclamation of post-mining sites aim at restoration of ecosystem biodiversity and soil play a vital role in this process. Soils developing on reclaimed sites are highly modified, as compared to native soils, in terms of their physical, chemical, and biological properties and their vertical arrangement into distinct horizons; indeed a new classification system has been developed for such soils, termed Anthroposols in Canada, Udorthents in the USA, and Technosols in the world reference base for soil resources [2].

Overburden rock types that are used as topsoil include weathered and unweathered sandstones, siltstones, and shales [3]. When placed on the surface these materials will weather and transform over time into a variety of mine soil materials with vastly different physical and chemical properties [4]. Overburden materials have lower nutrients than native topsoils [5].

Akala and Lal [6] estimate that up to 70% of soil organic carbon is lost during drastic land disturbance. Soil organic matter decline in drastically disturbed land occurs through the following mechanisms: erosion of soil during stripping, storing, respreading and seeding; water and wind erosion; reduced inputs from vegetation in the form of above-ground and below-ground litter; dilution as surface soils with higher soil organic carbon concentrations become mixed with soils from deeper in the profile [7].

Shrestha and Lal [8] defines drastically disturbed soils as those where native vegetation and annual communities have been removed with most of the topsoil lost, altered or buried.
Restoration and reclamation of post-mining and post-industrial sites aim at mitigating the adverse impacts of mining on the environment and human health. Regeneration is, however, a long process, as affected ecosystems have lost their biodiversity and most of their ecosystem functions and services [9].

Brevik et al. [10] emphasized that rates of pedogenesis in reclaimed soils are not higher than in natural soils; however, soil amendments used during the reclamation process likely create parent material conditions that are ideal to support vegetative growth and start reclamation pedogenesis at an advanced stage.

Tree plantations remain to be a viable option for reclamation of abandoned mine lands, either as a use-only method or as a polishing procedure to be used as an add-up technology at already restored sites. It permits restoration of sites by conserving and improving basic soil biological and physical properties. At the same time it is cost-effective and can even bring some economical return through commercial valorization of obtained biomass and both aesthetic and environmental recovery of the landscape [11].

Moreover, tree plantations and forest ecosystems play an important role in global carbon balance by accumulating carbon in plants, soil and litter. In the framework of mitigation measures of GHG emissions, the restoration of degraded lands has significant potential for C-sequestration, by increasing photosynthetic storage [12].

Tree species selection on poor mine soils are important for reclamation and afforestation success. For example, Black alder (Alnus glutinosa), locust tree (Robinia Pseudoacacia) as N-fixing species, are often planted on afforested post-mining barrens as an admixture to improve soil properties crucial for their biological activity and fertility [13-16]. Common birch (Betula pendula Roth) is important deciduous species used in afforestation of post-mine sites in Russia and Eastern Europe.

At the same time, afforested post-mining sites provide a unique opportunity to study the early development of ecosystems and soils [17].

The aim of the current study was to determine vegetation, substrate (parent material) and slope effect on developing soils of post-mining sites.

2. Methods and materials
The studied plantation is a post-mining sites located in the northeastern part of Belgorod region in an iron-mining district of European part of Russia, called The Kursk magnetic anomaly (KMA). KMA is one of the largest territories rich in iron ores on Earth. Reserves of iron ores are presently estimated at 200-210 billion tons about 50% of iron reserves on the planet. The boundaries of reserves extend to 160 thousand square km. Underground ore mining methods are used. The iron ores extraction determined a considerable removal of sands, aleurites, clays, shales, chalk, marl and phosphorite and the consequent transport of this materials to neighbouring areas.

The objects of this study are afforested external slope heaps produced by iron open-pit mine in Gubkin. The slopes degree varies from 25° to 38°. The height of heaps reached 50 m, and in recent years, according to technological plans, heaps are formed with an actual height of more than 100 m with 3-4 terraces. The studied heaps are mainly consisted of cenomanian and aptian sands. The admixture of neocomian silts, jurassic and devonian clays give the sandy loams or loams texture. Sometimes heaps are almost entirely consisted of mesozoic carbonate rocks, forming so-called chalk and marlheaps.

Sampling was performed in pure stands of birch (Betula pendula), sea buckthorn (Hippophae rhamnoïdes), locust tree (Robinia pseudoacacia), oleaster (Elaéagnus angustifólia) and grey alder (Alnus incana) growing on the following substrates: sands, mixed sands and clays, clays and mixed chalk and marl. The studied plantations were created at 2005.

For each tree type, substrate and slope three replicates of soil samples were taken from the top 5 cm bellow the litter layer. Soil samples were crushed, transported to the laboratory and after that sieved, air-dried and analyzed.

The pH of a 1:2.5 water suspension was determined potentiometrically. Extraction of labile fractions of soil phosphorus and potassium was carried out by Machigin’s method by solution of carbonate ammonium (NH₄)₂CO₃ (1% (w/w) concentration) at ratio of soil to solution 1:20. Cations and anions contents of water soluble compounds were determined in water extract from the soils. Exchangeable
cations composition was investigated in 0.1 N NH₄Cl-ethanol extract after leaching of water-soluble compounds. Total nitrogen content was determined by Kornfeld method with hydrolysis of organic compounds of the soil with 1N NaOH solution. The content of organic carbon was determined using the modification of the Tyurin method (dichromate oxidation). Hydrolytic acidity was determined by Kappen method. Particle size distribution was determined by the Kachinskii method with sodium pyrophosphate. Forest litter stocks were measured from weighting dry biomass [18].

3. Results and discussion

3.1. Soil physical and chemical properties

The basis of any soil is parent material and its chemical and physical properties directly effects on such important soil formation processes as species biodiversity, vegetation productivity, decomposition of organic residue, humus formation and interaction between mineral and organic part of the soil.

In term of mine site reclamation, composition and properties of parent material effects on fixing surface of the slope and developing soil formation. Type of vegetation and productivity of above- and below ground biomass are also key factors of surface stability and soil formation.

One of the most important substrate (parent material) properties is soil particle size distribution. According to our data, technogenic substrates consists of various fractions with domination of sand particles – 0.05-1.0 mm. In clay and sand loamy substrates, the content of small particles (0.005-0.05 mm) sharply increases. Chalk and marl substrates contain a significant percentage of dust particles – 0.005-0.001 mm (table 1).

Table 1. Particle size distribution in substrates at post-mining sites

| Substrate                  | 1-0.25 | 0.25-0.05 | 0.05-0.01 | 0.01-0.005 | 0.005-0.001 | 0.001 | 0.01 | 0.005 |
|----------------------------|--------|-----------|-----------|------------|-------------|-------|------|-------|
| Clay (light clay silt)     | 6.35   | 15.74     | 13.78     | 8.46       | 11.45       | 44.20 | 64.11| 55.6  |
| Chalk and marl (light clay)| 2.70   | 23.89     | 9.23      | 10.04      | 44.50       | 9.64  | 64.18| 54.14 |
| Sand (coarse sand)         | 43.00  | 44.83     | 4.44      | 0.81       | 0.08        | 4.84  | 7.73 | 6.92  |
| Sandy loam (sand)          | 43.86  | 7.14      | 2.60      | 12.60      | 4.80        | 20.00 | 27.01|       |

Analysis of water soluble compounds shows that all studied substrates of slope heaps are completely suitable for afforestation. The salinity is insignificant (dry matter not exceed 0.05-0.1%) and salts are mainly represented by bicarbonates and calcium and magnesium sulphates (table 2). With presence of chalk and marl admixture in substrate the percentage of dry matter sharply increase (0.77%) and salinity of such sites is very high and represented by HCO₃⁻ and SO₄²⁻ anions.

Table 2. Water-soluble compounds in substrates at post-mining sites

| Substrate          | Dry matter | Alkalinity | HCO₃⁻ | SO₄²⁻ | Total | Ca²⁺ | Mg²⁺ | Na⁺  | K⁺  | Total |
|--------------------|------------|------------|-------|-------|-------|------|------|------|------|-------|
| Clay               | 0.15       | 0.90       | 0.20  | 0.20  | 1.30  | 0.90 | 0.30 | 0.14 | 0.02 | 1.36  |
| Loamy clay         | 0.10       | 0.80       | 0.15  | 0.40  | 1.35  | 0.70 | 0.30 | 0.40 | 0.01 | 1.42  |
| Chalk and marl     | 0.77       | 1.15       | 0.20  | 6.80  | 8.15  | 7.60 | 0.40 | 0.11 | 0.10 | 8.21  |
| Sand               | 0.05       | 0.90       | 0.20  | 0.20  | 1.30  | 0.70 | 0.30 | 0.09 | 0.12 | 1.21  |
| Sandy loam         | 0.10       | 0.85       | 0.25  | 0.20  | 1.30  | 0.80 | 0.40 | 0.08 | 0.02 | 1.30  |
Sand substrates are characterized by lack of vital chemical elements. Sands more than 96% consist of silicon dioxide (SiO₂), just in case of admixture loams, clay loams or carbonates in sands increase the content of such biologically important elements as calcium, phosphorus and manganese.

Soil physical and chemical properties of substrates strongly vary, because of different parent material, fragmentation of overburden rock materials and topographic features. pH ranged between 7.2 and 7.7. Soil exchangeable capacity ranged between 2.5 and 21 cmol (+) / kg, with Ca²⁺ predominating among the exchangeable cations. Mixed overburdened rocks have some fertility elements accumulated during long-term period of pedogenesis processes. In all substrates there is an organic matter; it content differed greatly among substrates, i.e., the highest rate in clay (0.4-0.8%), then sandy loam (0.35-0.58%) and lowest in chalk and marl (0.09-0.11%). NKP content significantly higher in clay (0.6; 16.0 and 1.85 mg/100 g respectively) as well, at the same time there is no significant difference between other substrates (table 3).

### Table 3. Soil physical and chemical properties of substrates

| Substrate             | C_or % | cmol (+) /kg  | pH | mg/100 g |
|-----------------------|--------|---------------|----|----------|
|                       |        | Ca²⁺ | Mg²⁺ | Total | N  | K  | P  |
| Clay                  | 0.4-0.8| 49   | 2    | 51    | 7.1 | 0.6 | 16.0 | 1.85 |
| Chalk and marl        | 0.09-0.11| 29  | 7    | 36    | 7.8 | 0.02 | 4.0  | 2.0  |
| Sand                  | 0.19-0.30| 1.50| 1.0  | 2.5   | 7.2 | 0.03 | 5.0  | 0.75 |
| Sandy loam            | 0.35-0.58| 5.0 | 1.0  | 6.0   | 7.6 | 0.2  | 8.0  | 1.50 |

### 3.2. Relationships between tree species, substrates and different slope part

The studied forest plantation has significant effect on structure and properties of substrates. The main trend was the organic layer formation, on loamy clay substrate it thickness ranged from 1.5 to 2.5 cm, and forest litter stock ranged between 2.9 and 7.8 t ha⁻¹. The litter stock was significantly higher under pure stands of grey alder (Alnus incana), 3-5 times more than in others tree type, the lowest stock was in birch (Betula pendula) and oleaster (Elaeagnus angustifolia) plantations (2.8-4.0 t ha⁻¹) (table 4).

### Table 4. Forest litter stock in different tree type on loamy clay substrate

| Tree type | Part of slope | Litter stock t ha⁻¹ | N % | Ash content % |
|-----------|---------------|---------------------|-----|---------------|
| Locust tree | top          | 4.6                | 2.05 | 62.14        |
|           | middle        | 5.5                | 2.16 | 61.88        |
|           | bottom        | 3.9                | 1.94 | 66.05        |
| Sea buckthorn | top      | 3.4                | 1.98 | 49.82        |
|           | middle        | 4.0                | 2.13 | 47.53        |
|           | bottom        | 3.7                | 2.40 | 51.61        |
| Grey alder | top          | 7.3                | 3.06 | 64.13        |
|           | middle        | 7.8                | 3.14 | 60.08        |
|           | bottom        | 7.1                | 3.40 | 69.81        |
| Oleaster     | top          | 2.9                | 1.6  | 50.40        |
|           | middle        | 3.6                | 2.00 | 44.10        |
|           | bottom        | 2.8                | 1.89 | 48.17        |
| Birch       | top          | 3.4                | 1.54 | 59.17        |
|           | middle        | 4.0                | 1.3  | 58.42        |
|           | bottom        | 2.9                | 2.65 | 51.62        |

The chemical composition of forest litter varies slightly. The highest ash content was in grey alder, locust tree and birch stands, lowest in oleaster and sea buckthorn stands. There was no significant
difference in nitrogen content. It ranged from 1.3 to 3.6%. The highest content was with grey alder and locust tree stands, intermediate with sea buckthorn and oleaster stands and the lowest with birch stands.

The distribution of forest litter stock according to the part of slope varies as well. There is trend of increasing litter biomass in the middle part of the slope, and decreasing biomass in top and bottom parts. One possible explanation for this is that at bottom, in the conditions of better moistening, there is a more intensive decomposition of the litter, and at top there is high rate of litter removal by the wind and precipitations.

On chalk and marl substrates in all vegetation types was observed soil organic layer formation. Forest litter stock on chalk and marl heaps were two times lower than at the same plantations on loamy clay substrates. Only exception was in oleaster stands, under it canopy forest litter stock was 4.0-5.3 t ha⁻¹, i.e. 1.4-1.6 times higher than in same plantations on clay loamy substrate. The lowest forest litter stock was in sea-buckthorn stands, it ranged from 0.9 to 1.7 t ha⁻¹.

Ash content of forest litter in all plantations on chalk and marl substrate was less than on loamy clay heaps. However, on the carbonate substrates, the percentage of nitrogen in the organic layer had significantly decreased. It was not possible to establish any reason why there is a difference between ash and nitrogen content according to different part of slope heaps, but there is a trend of increasing ash content in the litter formed at the bottom part of the slope, due to the presence here mixed herbaceous species, the admixture of which can decrease nitrogen content (table 5).

### Table 5. Forest litter stock in different tree type on chalk and marl substrate

| Tree type   | Part of slope | Litter stock t ha⁻¹ | N %  | Ash content % |
|-------------|---------------|---------------------|------|---------------|
| Locust tree | top           | 2.9                 | 1.90 | 44.13         |
|             | middle        | 2.6                 | 1.97 | 42.00         |
|             | bottom        | 2.2                 | 2.16 | 47.18         |
| Sea buckthorn | top         | 1.1                 | 2.14 | 40.00         |
|              | middle       | 1.7                 | 2.30 | 41.19         |
|              | bottom       | 0.9                 | 2.58 | 47.80         |
| Grey alder  | top           | 2.9                 | 2.47 | 49.14         |
|             | middle        | 3.7                 | 2.09 | 48.00         |
|             | bottom        | 3.4                 | 2.14 | 42.50         |
| Oleaster    | top           | 4.8                 | 2.56 | 38.50         |
|             | middle        | 5.3                 | 2.39 | 41.94         |
|             | bottom        | 4.0                 | 2.30 | 42.11         |
| Birch       | top           | 3.0                 | 1.12 | 35.44         |
|             | middle        | 3.8                 | 1.44 | 37.19         |
|             | bottom        | 3.2                 | 1.60 | 39.10         |

On sandy loam substrates forest litter stocks were higher than on chalk and marl substrates and approximately the same in comparison to loamy clay. It should be noticed the significant input of sea buckthorns, under it canopy forest litter stock reached 7.7-9.1 t ha⁻¹(table 6). Consequently it accumulates more nitrogen and ash elements.

Locust tree litter stocks were almost two times lower in comparison with sea buckthorn and it had less nitrogen and ash elements content. And, finally, in birch stands forest litter stock were significant only at the bottom part of slope heap. As for top and middle parts birch trees had poor quality and were concentrated mainly in small depressions.

The development of topsoil depends on the part of slope heaps. Topography has a significant influence on the soil formation, especially at reclaimed sites. On heaps with a high slope degree the surface structure determined soil moisture and organic residues distribution. On the lower half of slopes, in the conditions of better moistening, there is a more intensive decomposition of the litter, and on upper
slopes there is high rate of litter removal by the wind and precipitations. This is confirmed by Zipper et al. (2011) who recommend for upper slope drought tolerant species [19].

Table 6. Forest litter stock in different tree type on sandy loam substrate

| Tree type       | Part of slope | Litter stock t ha\(^{-1}\) | N % | Ash content % |
|-----------------|---------------|-----------------------------|-----|---------------|
| Locust tree     | top           | 3.4                         | 1.80| 50.00         |
|                 | middle        | 5.0                         | 2.00| 47.56         |
|                 | bottom        | 4.6                         | 1.70| 43.11         |
| Sea buckthorn   | top           | 7.7                         | 2.48| 45.75         |
|                 | middle        | 9.1                         | 2.39| 54.43         |
|                 | bottom        | 8.2                         | 3.00| 48.74         |
| Grey alder      | top           | 2.0                         | 1.94| 56.15         |
|                 | middle        | 2.9                         | 1.96| 50.11         |
|                 | bottom        | 3.3                         | 2.13| 48.60         |
| Birch           | top           | 1.4                         | 0.99| 40.00         |
|                 | middle        | 1.9                         | 1.14| 41.14         |
|                 | bottom        | 2.7                         | 1.43| 72.77         |

Soil formation process directly depends on the nature of the overburden material (substrate). Our findings show that loamy clay substrate provides for developing soil better physical and chemical properties in comparison with sandy loam and chalk and marl, in turn influencing successful vegetation establishment.

Vegetation is the important factor facilitating soil development. In agreement with Wos B et al. (2015), the impact of litter decomposition on chemical substrate properties and element leaching during early soil formation in afforested post-mine sites and the influence of different tree species are key issues in new ecosystem development [20]. Our analysis show that nitrogen-fixing species like alder, locust tree and oleaster more perspective for reclaimed soils. This is consistent with the findings of Chilti T et al. (2007) that the presence only in the mixed stand of patches of a darker A material, indicate an effective role of the N-fixer species on both pedogenic processes and C cycle in this human-made environment.

4. Conclusions
This study shows that soil development process at afforested post-mining sites needs complex approach. The studied plantations is only 13-years after planting confirming that soil formation proceeds in different way due to tree species, substrate and site characteristics.

Our findings for reforested post-mining soil of Kursk magnetic anomaly that differed in tree species and parent material indicate that: 1) on heaps with a high slope degree the surface structure determined organic residues distribution. Upper slopes have less forest litter stock; 2)loamy clay substrate provides for developing soil better physical and chemical properties; 3) the soil development at afforested post-mining sites is better with N-fixing species like alder (Alnus incana), locust tree (Robinia pseudoacacia) and oleaster (Elaeágnus angustifólia).

Also it should be noticed that on early stages of soil development the formation of labile humus (i.e., humus readily metabolized by microbes) are not significant. That’s why we are planning to determine soil organic matter content in our further investigations.

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