ISSN 2411-3336; e-ISSN 2541-9404

JOURNAL OF MINING INSTITUTE

Zapiski Gornogo instituta

Journal homepage: pmi.spmi.ru

Research article

Assessing the effectiveness of sewage sludge in the reclamation of disturbed areas in the Kola subarctic zone (a case study of a sand quarry)

Lyubov A. Ivanova[1,2], **Marina V. Slukovskaya**[3,4], **Evgeniya A. Krasavtseva**[2,3]✉

[1] *N.A.Avrorin Polar-Alpine Botanical Garden-Institute, Kola Science Centre of the RAS, Kirovsk, Russia*

[2] *Institute of North Industrial Ecology Problems, Kola Science Centre of the RAS, Apatity, Russia*

[3] *Laboratory of Nature-Inspired Technologies and Environmental Safety of the Arctic NMC, Kola Science Centre of the RAS, Apatity, Russia*

[4] *Institute of Chemistry and Technology of Rare Elements and Mineral Raw Materials, Kola Science Centre of the RAS, Apatity, Russia*

How to cite this article: Ivanova L.A., Slukovskaya M.V., Krasavtseva E.A. Assessing the effectiveness of sewage sludge in the reclamation of disturbed areas in the Kola subarctic zone (a case study of a sand quarry). Journal of Mining Institute. 2024. Vol. 267, p. 444-452.

Abstract. An assessment was made of the effectiveness of reclamation using sewage sludge for the accelerated formation of a stable erosion-proof vegetation cover on the unproductive anthropogenic soil of a sand quarry in the context of the Kola North. The experiment, launched in 2017, included three treatments: control – no treatment, experiment 1 – fragmentary (50 %) application of sewage sludge, experiment 2 – continuous application. In the sixth growing season, anthropogenic soil samples were examined, and measurements of CO_2 emissions were carried out. It was shown that the application of sewage sludge had a positive effect on the physicochemical and agrochemical properties of the soils: *in situ* pH and density decreased, hygroscopicity increased, available phosphorus and potassium increased. Significant differences ($p < 0.05$) were found between CO_2 emissions in the control and experimental treatments. The content of organic carbon in the control treatment was lower than in the experimental ones; under fragmentary application of sewage sludge, it was three times lower, and under continuous application, it was nine times lower. Significant ($p < 0.05$) differences in the content of carbon and nitrogen in cold and hot water extracts between control and treatment samples were found under continuous application of sewage sludge. At the same time, by calculating the C/N ratio, a very low level of nitrogen was found in the humus. The main factors behind the variability of the estimated parameters were identified – the treatment itself and the method of its application, the contribution of the treatment alone was 60 %, the contribution of the application method was 14 %. Taking into account the economic factors, fragmentary application of sewage sludge onto the anthropogenic sand quarry soil is recommended to support the establishment of a stable erosion-proof phytocenosis.

***Keywords*:** landscape; sand quarry; anthropogenic soil; ameliorant; sewage sludge; CO_2 emissions

***Acknowledgments*.** The study was carried out within the framework of research topics FMEZ-2022-0022, FMEZ-2022-0010.

Received: 28.03.2024 ***Accepted: 03.06.2024*** ***Online: 04.07.2024*** ***Published: 04.07.2024***

Introduction. Mining operations in Russia's Murmansk region involving open-pit mining of sand, crushed stone, block stone, and others mineral resources widely used in the construction and production of construction materials industry has led to the emergence of numerous small and large quarries. This approach optimizes the economics of the region's construction industry but involves a number of environmental problems associated with the emergence of new anthropogenic landscape forms with low biological productivity and distinct geomorphological, hydrophysical, and geochemical properties. The mineral reserves of Murmansk region include 68 deposits of sand and gravel mixture with estimated reserves of 92,690 thousand m^3 in categories A + B + C1, while the reserves under active development amount to 48,721 thousand m^3. [1]

[1] Current state of the mineral resource base of the Murmansk region. URL: https://mpr.gov-murman.ru/activities/napravleniya/10.mineral/00.current/ (accessed 28.03.2024).

This is an open access article under the CC BY 4.0 license

Quarry mining is in greatest demand close to urban areas, but lead to air pollution, soil disturbance, and upset surface and groundwater and biota balance, which also negatively affects human health [1-3].

In Russia, in accordance with the Law on Subsoil[2], upon completion of the development of a deposit in areas disturbed by mining operations, mandatory reclamation measures are required to prevent negative environmental impacts and bring the area to a condition suitable for further use. However, unproductive anthropogenic soils typical of former quarries are unsuitable for reclamation both in terms of physical properties and chemical composition (GOST 17.5.1.03-86) [4-6], especially in the harsh climatic conditions of the Far North. Reclamation is problematic without additional investment in expensive materials and fertilizers, therefore it is necessary to search and develop non-conventional, science-based methods adapted to the region's environment and economics involving the use of alternative ameliorants that improve the biogenicity of human-modified soils [7, 8].

In this context, the products of regional water and sewerage treatment facilities – sewage sludge (SS) – are of great relevance [9, 10]. Many Russian and international researchers are studying the possibilities of using SS as ameliorants to restore vegetation cover at tailings storage facilities of bauxite [11], copper [12, 13] and rare metal mines [14, 15]. The introduction of SS, characterized by a high content of organic matter and nutrients in bioavailable forms, helps to improve the edaphic factors of reclaimed soils [16-18]. However, the material needs to be carefully studied on a case-by-case basis due to the potential presence of heavy metals and pathogenic microorganisms [19].

The use of organic ameliorants for the establishment of erosion-proof phytocenoses on the sandy soils of quarries in the Arctic context without conventional land cultivation can help solve the dusting problem. A number of indicators should be studied – available forms of nutrients (nitrogen, phosphorus, potassium), organic carbon, dissolved organic matter, soil respiration (CO_2 emissions from the soil) – widely used to assess the state and productivity of the resulting ecosystems [20].

The purpose of this study is to assess the effectiveness of soil reclamation using SS for the accelerated establishment of stable erosion-proof vegetation cover in sand quarries. The practical goal of the research is to develop a cost-effective ecotechnology for reclaiming disturbed landscapes using an unconventional organomineral ameliorant that otherwise requires disposal.

Methods. *Description of experimental sites and experimental design*. In 2017, at the model site of a sand quarry operated by the regional water utility AO Apatityvodokanal, staff of the Federal Research Center KSC RAS laid out a small-plot field experiment on the establishment of erosion-proof grass cover by applying SS. The ameliorant was provided by the indicated utility. According to earlier studies, SS of AO Apatityvodokanal was considered waste of hazard class 5 fully compliant with the requirements of GOST R 54534-2011 for SS when used as engineered soils for biological or engineering reclamation (Table 1) [8, 21, 22]. The content of organic matter was 62 %, of potassium 0.38 %. The approximate age of the applied SS was 3 to 5 years of storage in aeration tanks.

The experiment was carried out on 18 plots measuring 1 m^2 each, laid at a distance of 0.5 m from each other. The experimental design included three treatments (n = 6): control plot (no SS applied), experimental treatment 1 – fragmentary application of SS (50 % of the area – pointwise, in a checkerboard pattern on each of the plots), experimental treatment 2 – continuous application of SS (100 % of the area). The thickness of the applied SS layer was about 5 cm. The SS had a creamy texture, eliminating the possibility of sediment spreading beyond the treatment area. The humidity of the

[2] Law of the Russian Federation "On Subsoil" dated February 21, 1992 N 2395-1. Article 22. Basic rights and obligations of the subsoil user. URL: https://www.consultant.ru/document/cons_doc_LAW_343/ed644f2f2ff8ea426789b6895057ff6ddd4807d3/ (accessed 28.03.2024).

This is an open access article under the CC BY 4.0 license

Journal of Mining Institute. 2024. Vol. 267. P. 444-452
© Lyubov A. Ivanova, Marina V. Slukovskaya, Evgeniya A. Krasavtseva, 2024

applied material was 95-97 %. A grass seed mixture was used as seed material, including zoned seeds of cereal and legume plant species. During the first three years, the quality of the established phytocenoses was assessed annually: height of plants, projected area of cover, density of the grass cover, above-ground phytomass, thickness of the grass turf, increase in plant biodiversity in the established phytocenoses, and later, photosynthetic efficiency [8, 21, 22]. Condition of vegetation in the experimental plots from 2019 to 2023 is presented in Fig.1.

Table 1

Comparative analysis of the chemical composition of the SS of AO Apatityvodokanal compared to GOST R 54534-2011

Parameter	SS	Terms of use	
		Technical reclamation	Biological remediation
Environmental hazard class	V	IV, V	IV, V
Pb, mg/kg	< 30	1000	500
Zn, mg/kg	186	7000	3500
Ni, mg/kg	< 30	800	400
Cu, mg/kg	< 30	1500	750
pH_{KCl}	5.50	5.0-8.5	5.0-8.5
N_{total}, %	0.19	Not standardized	0.5
P_{total}, %	0.02	Not standardized	1.5

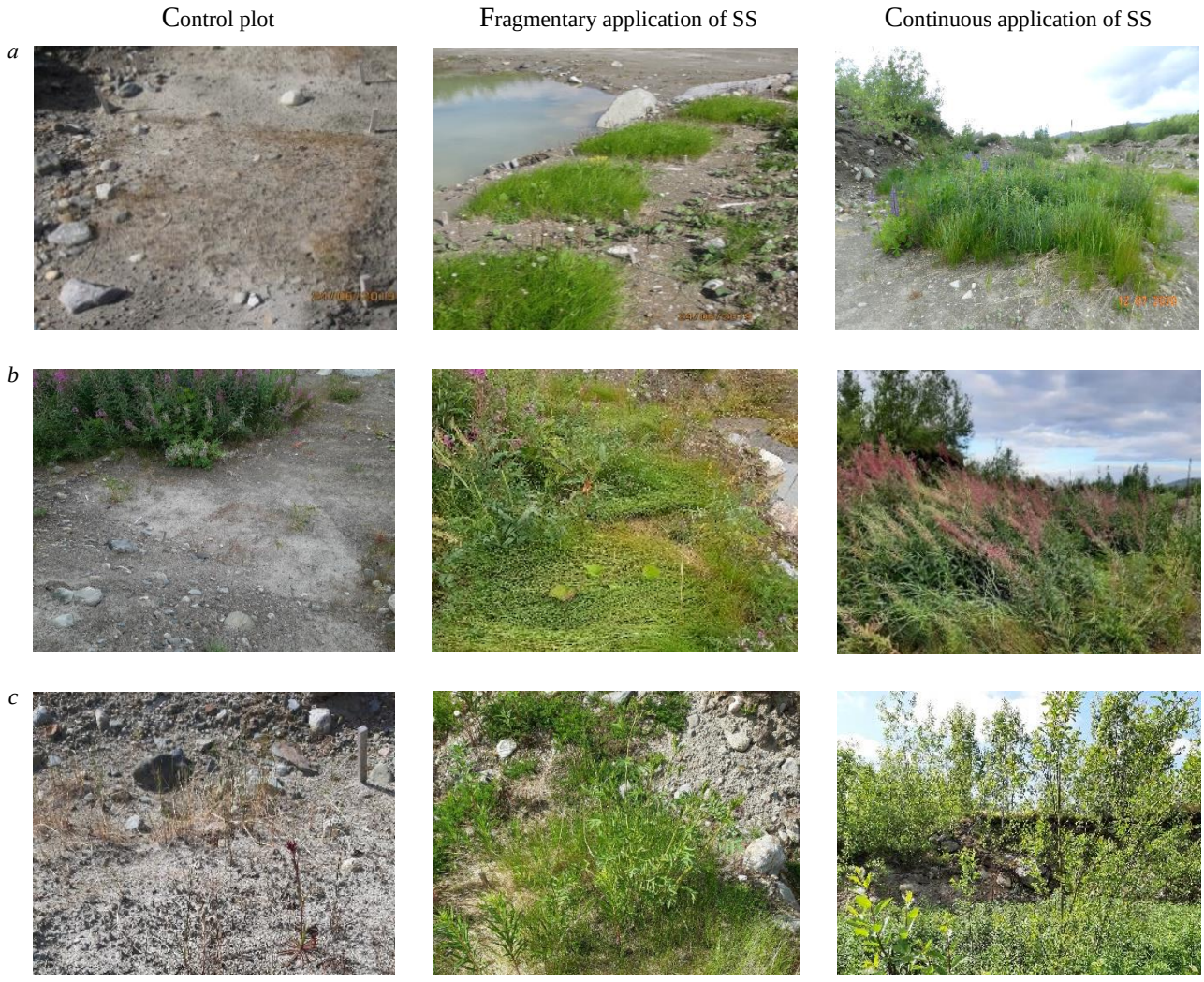


Fig.1. State of vegetation on experimental plots in 2019 (*a*), 2020 (*b*) and 2023 (*c*)

This is an open access article under the CC BY 4.0 license

Sampling and analysis. Samples of soil and anthropogenic soils at the experimental site in the quarry were taken in the sixth growing season using a cutting ring with a diameter of 10 cm and a height of 5 cm. Samples were taken one at a time in each sampling round, i.e. for each treatment, six samples were collected, $n = 6$. Soil density was calculated as the ratio of the dry mass of the sample to the volume of the sampler.

Laboratory ion meter I-160MI fitted with glass laboratory electrode ES-10603 and reference electrode ESr-10103 was used to measure the pH of the aqueous and salt (KCl) extracts. The extract for measuring pH_{H2O} was prepared at a solid to liquid ratio (S : L) of 1 : 5, stirred for three minutes, settled for five minutes in accordance with GOST 26423-85.

The extract for measuring pH_{KCl} was prepared at an S : L ratio of 1 : 25, stirred in a laboratory shaker for one hour in accordance with GOST 26490-85. The determination of the hygroscopicity coefficient of the samples was carried out at the Shared Resource Center, INEP KSC RAS, in accordance with GOST 28268-89.

Mobile phosphorus and exchangeable potassium were determined using the Kirsanov method as modified by TsINAO (GOST P 54650-2011). 0.2 N HCl solution was added to the soil sample (S : L 1 : 5), the mixture was stirred in a laboratory shaker for 15 minutes, then filtered through a blue ribbon paper filter. The resulting solutions were analyzed at the Shared Resource Center, INEP KSC RAS, using atomic absorption spectrometry (atomic absorption spectrometer Quantum-2mt) and photometry (photoelectric photometer KFK 3-01).

Organic carbon in solid samples was determined using the Tyurin method (GOST 26213-91). The content of labile forms of carbon and nitrogen was analyzed after extraction with cold and hot water [23]. Extraction with cold water was carried out at room temperature (distilled water as extractant, S : L ratio 1 : 10, extraction time 30 min), the solutions were centrifuged (universal laboratory centrifuge Dlab DM0636, 3500 rpm, 30 min) and filtered through a Vladipor membrane filter with a pore size of 0.45 μm. For hot water extraction, a fresh portion of distilled water was added to the remaining solid phase and kept in a thermostat at 80 °C for 16 h. The resulting extracts were centrifuged and filtered as described. The concentrations of nitrogen and carbon in the resulting filtrates were determined using an elemental composition analyzer Topaz NC.

Measurements of CO_2 emissions from soils were carried out twice during the growing season using a portable gas analyzer EGM-5 with an SRC-2 camera (PP Systems). One hour before the measurement, the open chambers were deepened into the soil by 3-4 cm with the preliminary removal of living biomass. At the same time, soil temperature was measured at a depth of 1 and 10 cm with a thermometer Checktemp-1 (Hanna Instruments) and soil moisture was measured at a depth of 10 cm with a moisture meter SM-150 (Delta-T Devices) [24].

Statistical processing of the results was carried out in MS Excel 2016, StatPlus suite (v7, AnalystSoft Inc.). The statistical significance of differences in measured parameters among the treatments was assessed using one-way analysis of variance ANOVA ($p < 0.05$).

Results and discussion. The results of measuring the basic physicochemical and agrochemical properties of soil samples taken from the experimental plots and their statistical processing are presented in Table 2.

Table 2

Physicochemical and agrochemical properties of samples

Parameter	Control sample	Sample with fragmentary application of SS	Sample with continuous application of SS
Density, g/cm^3	1.48 ± 0.07^a	1.11 ± 0.04^b	0.99 ± 0.04^b
Hygroscopicity coefficient	1.006 ± 0.0001^a	1.008 ± 0.001^{ab}	1.012 ± 0.002^b
pH_{H_2O}	6.37 ± 0.05^a	6.40 ± 0.03^a	6.20 ± 0.04^b
pH_{KCl}	5.84 ± 0.08^a	5.36 ± 0.03^b	5.03 ± 0.10^c
K, mg/kg	15.60 ± 0.89^a	38.01 ± 2.85^{ab}	59.35 ± 11.12^b
P, mg/kg	81.28 ± 15.32^a	72.13 ± 1.50^{ab}	229.92 ± 63.46^b

Note. Means ± standard errors are shown; letters in superscripts mean the reliable presence (letters are different) or absence (letters are the same) of differences between the experimental options at $p < 0.05$.

This is an open access article under the CC BY 4.0 license

© Lyubov A. Ivanova, Marina V. Slukovskaya, Evgeniya A. Krasavtseva, 2024

The application of SS and its long-term deposition led to a significant decrease in soil density and an increase in its hygroscopicity on the experimental plots. The density of anthropogenic soil samples in comparison with the control area decreased by 1.3 and 1.5 times on the experimental plots with fragmentary and continuous application of SS, respectively. Significant differences were found ($p < 0.05$) in soil density between the experimental and control treatments without a significant difference between the treatment methods. The hygroscopicity coefficient was statistically significantly different for samples from control plots and continuous application plots. Previous research [19, 25, 26] noted the positive effect of SS on the physicochemical properties of soils, in particular density and water-air exchange.

According to the pH of the aqueous extract, all samples are classified as slightly acidic, close to neutral. The application of SS significantly reduced ($p < 0.05$) the actual acidity in the continuous application samples. The pH values of the salt extract changed significantly: the quarry soil was close to neutral, while the soil from the experimental plots was close to being slightly acidic. Not only the fact of treatment, but also the area exposed to the SS treatment did affect the potential acidity level.

Chemical analysis showed a natural increase in the content of mobile potassium along the gradient control treatment < fragmentary application of SS < continuous application of SS. Similar results were obtained during an experiment on apatite-nepheline tailings [21]. However, the content of available phosphorus was significantly higher than in the control only in the continuous application treatment.

When comparing the content of mobile phosphorus and potassium in the soil with the scale of soil nutrient supply presented in the guidelines[3], it was found that anthropogenic soils belonged invariably to the very high phosphorus supply class. In terms of potassium content, the soil of the continuous application plots showed a very high level, while that of the fragmentary application plots demonstrated an elevated level, and the control plots – an average level. Thus, the content of mobile nutrients in the soil six years after a single application of SS allows one to judge the prolonged action of the treatment.

Levels of carbon and nitrogen in various fractions and the statistical processing results are presented in Table 3. The amount of organic carbon naturally increased along the gradient control treatment < fragmentary application of SS < continuous application of SS. Significant differences were found between the control and experimental treatments involving continuous application of SS ($p < 0.05$).

Table 3

Carbon and nitrogen content in various fractions

Parameter	Control sample	Sample with fragmentary application of SS	Sample with continuous application of SS
C_{org}, %	0.29 ± 0.05^{a}	0.90 ± 0.20^{ab}	2.89 ± 0.93^{b}
C_{cold}, mg/kg	199.7 ± 54.7^{a}	358.8 ± 119.1^{ab}	556.1 ± 60.5^{b}
N_{cold}, mg/kg	4.64 ± 0.71^{a}	12.6 ± 1.6^{ab}	27.4 ± 10.1^{b}
C/N_{cold}	46.1 ± 22.0^{a}	26.7 ± 8.1^{a}	26.83 ± 9.4^{a}
C_{hot}, mg/kg	811.5 ± 92.2^{a}	1675.1 ± 425.2^{ab}	2420.3 ± 476.2^{b}
N_{hot}, mg/kg	19.9 ± 4.3^{a}	36.4 ± 1.1^{ab}	227.6 ± 102.3^{b}
C/N_{hot}	51.0 ± 12.7^{a}	45.1 ± 10.3^{a}	21.0 ± 7.2^{a}

The fraction of carbon extracted by distilled water at room temperature characterizes the content of water-soluble organic matter, which is a substrate for soil microflora and vegetation [27-29]. As expected, the content of carbon and nitrogen increased with increasing amount of added SS. Significant ($p < 0.05$) differences in the content of water-soluble carbon and nitrogen were found between the control and experimental samples with continuous application of SS.

[3] Guidelines for conducting comprehensive monitoring of soil fertility in agricultural lands. Moscow: FGNU "Rosinformagrotech", 2003, p. 241.

This is an open access article under the CC BY 4.0 license

The carbon and nitrogen content in the extract prepared using hot water as an extractant characterizes the carbon and nitrogen content of microbial biomass [30-32]. Similarly to the cold-water extracts, the content of carbon and nitrogen in the hot-water extracts increased along the gradient control treatment < fragmentary application of SS < continuous application of SS. Significant differences were also found in the carbon and nitrogen content in the experimental treatment involving continuous application of SS when compared to the control.

An additional indicator of the humus status of soils is the C/N ratio. As found in [33], soils whose C/N ratio exceeds 14 correspond to a very low level of nitrogen in the humus. The C/N ratio of water-soluble varieties in the cold-water extract of the studied samples was significantly higher than the indicated value. At the same time, in both experimental treatments using SS, this indicator is two times lower than in the control one, which may be due to an increase in the nitrogen content together with carbon and correlated with the treatment method. The value of the C/N ratio in the hot-water extract decreased along the gradient control treatment – fragmentary application of SS – conti-nuous application of SS.

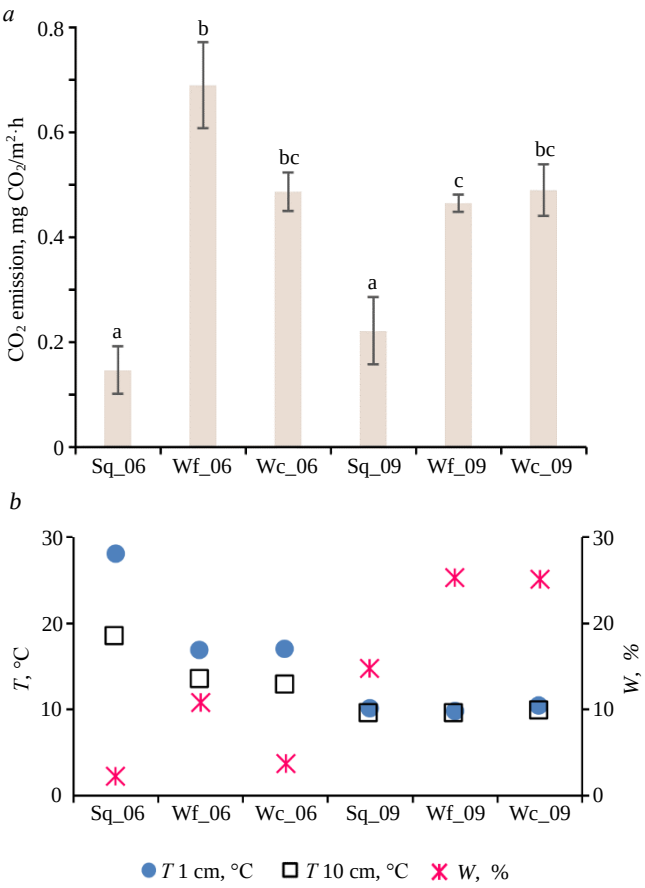


Fig.2. CO_2 emission from soil (*a*), soil moisture and temperature in the surface layer and at a depth of 10 cm (*b*) in June and September

Sq – control; Wf – fragmentary application of SS; Wc – continuous application of SS; 06 – June; 09 – September
Letters above the columns – reliable presence (letters are different), no differences (letters are the same) between experimental variants at $p < 0.05$

The lowest values of CO_2 emission in June were observed on the control plots at 0.15 ± ± 0.05 mg $CO_2/m^2 \cdot h$ at an average humidity of 2,2 % (Fig.2). On the fragmentary treatment plots, this figure was significantly higher at 0.69 ± 0.08 mg $CO_2/m^2 \cdot h$ at an average humidity of 10.7 %, and on the continuous treatment plots, 0.49 ± 0.04 mg $CO_2/m^2 \cdot h$ at an average humidity of 3.8 %.

At the end of the vegetation season, CO_2 emission was 0.22 ± 0.06 mg $CO_2/m^2 \cdot h$ (at a humidity of 14.7 %) from the control plot; 0.47 ± 0.02 mg $CO_2/m^2 \cdot h$ (at a humidity of 25.3 %) from the fragmentary treatment plots; 0.49 ± 0.05 mg $CO_2/m^2 \cdot h$ (at a humidity of 25.2 %) from the continuous treatment plots. In the control plots, no significant difference was found between the results obtained in different measurement periods. At the same time, emissions from the control plots were significantly ($p < 0.05$) lower compared to the experimental treatments both in June and September. On the fragmentary treatment plots, CO_2 emissions in June were statistically significantly higher than at the end of the season, whereas on the continuous treatment plots, no such trend was found. High values of CO_2 emissions in June from the fragmentary treatment plots were due to increased soil moisture at the beginning of the growing season [34, 35].

Our analysis of the correlations between CO_2 emissions and other labile soil parameters showed a high level of correlation between soil respiration, humidity, and the content of carbon and nitrogen in the hot-water extract (Table 4). A similar pattern was reported in [36].

This is an open access article under the CC BY 4.0 license

Table 4

Pearson correlation coefficients for some parameters (n = 18)

Parameter	CO_2 emission, mg $CO_2/m^2 \cdot h$	Humidity W, %	Content of nitrogen in hot-water extract N_{hot}, mg/kg
W, %	**0.7147**	–	–
p	0.0013	–	–
N_{hot}, mg/kg	**0.5165**	**0.6712**	–
p	0.0338	0.0023	–
C_{hot}, mg/kg	**0.6145**	**0.6539**	**0.7814**
p	0.0087	0.0032	0.0001

Our analysis revealed two main factors that explain over 74 % of the variability in the parameters being examined – the application of SS and the treatment method (Fig.3, Table 5). The contribution of the first factor – the application of SS – was 60 %. The greatest effect on this factor was exerted by the content of bioavailable phosphorus, potassium, carbon, nitrogen, CO_2 emission from the soil, potential acidity, density, humidity, and hygroscopicity coefficient. Nearly all parameters had a direct relationship, and only soil density and pH of the salt extract had an inverse relationship [35].

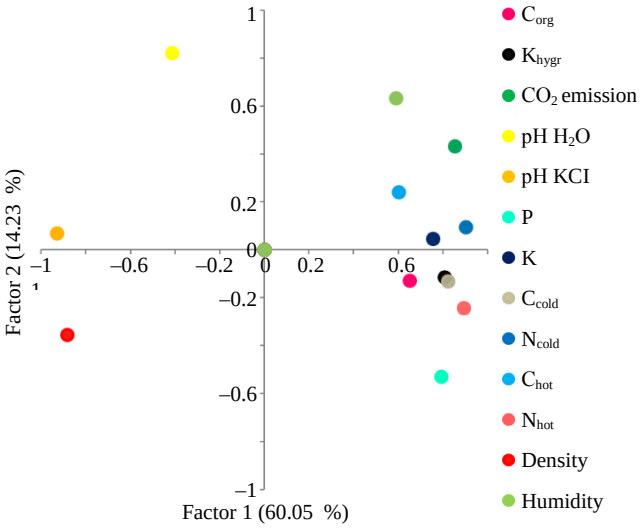


Fig.3. Diagram of factor analysis results

Table 5

Contributions of individual components to the factor analysis

Variable	Factor 1	Factor 2
C_{org}, %	**0.65**	–0.13
K_{hygr}	**0.81**	–0.11
CO_2 emission, mg $CO_2/m^2 \cdot h$	**0.85**	0.43
pH H_2O	–0.41	**0.82**
pH KCl	**–0.93**	0.07
P, mg/kg	**0.79**	**–0.53**
K, mg/kg	**0.75**	0.05
C_{cold}, mg/kg	**0.82**	–0.13
N_{cold}, mg/kg	**0.90**	0.09
C_{hot}, mg/kg	**0.60**	0.24
N_{hot}, mg/kg	**0.89**	–0.24
Density, g/cm^3	**–0.88**	–0.35
Humidity, %	**0.59**	**0.63**

The second factor – the treatment method, whose contribution is 14.2 % – was driven by the pH of the water extract, volumetric humidity, and the content of mobile phosphorus. An inverse relationship was found only for the content of the mobile factor.

The most important condition is the presence of a layer of ameliorant, which leads to loosening of the soil and an increase in its hygroscopicity, a decrease in the pH of the salt extract, an increase in the content of bioavailable phosphorus, potassium, carbon, nitrogen, and an increase in CO_2 emissions from the soil. The second factor is the area of application of SS.

Analysis of the study results indicates that SS can be recommended as a promising ameliorant promoting the accelerated establishment of a stable erosion-proof vegetation cover in sand quarries. Taking into account the economic effect, we find it reasonable to recommend fragmentary application of SS to increase the biogenicity of the soil and create a stable erosion-proof phytocenosis in sand quarries

Conclusion. Adding SS had a positive effect on the physicochemical and agrochemical properties of the sand quarry soil, expressed in a decrease in its *in situ* density, a slight increase in hygroscopicity, a decrease in the pH of aqueous and salt extracts, and an increase in the content of available phosphorus and potassium even after six years after the treatment.

This is an open access article under the CC BY 4.0 license

The average carbon content in the soil samples of the control treatment was 0.29 ± 0.05 %, which is three times lower than in the experimental fragmentary treatment with SS and nine times lower than in the continuous treatment. An increase in the content of carbon and nitrogen in cold- and hot-water extracts was observed along the gradient control treatment – fragmentary treatment – continuous treatment. At the same time, the estimated values of the C/N ratio correspond to a very low level of nitrogen in the humus.

Significant differences were found ($p < 0.05$) between CO_2 emissions in the control and experimental treatments in both measurement periods. A high level of correlation was revealed between soil respiration, moisture, and the content of carbon and nitrogen in the hot-water extract.

Our factor analysis identified two main factors controlling the change in the estimated parameters – the application of SS and the method of application. Moreover, 60 % of the variability in physicochemical, agrochemical, and labile soil parameters is explained by the first factor.

The authors express their gratitude to the staff of the Center for Collective Use of INEP KSC RAS for conducting chemical analysis of extracts and samples, S.E.Krasavtsev and A.V.Timokhin for assistance in collecting soil samples.

REFERENCES

1. Dabbagh A. A study on Moscow region sand pits' plants properties for the restoration of sand pits vegetation. *RUDN Journal of Ecology and Life Safety*. 2018. Vol. 26. N 3, p. 299-308. DOI: 10.22363/2313-2310-2018-26-3-299-308

2. Gentili R., Casati E., Ferrario A. et al. Vegetation cover and biodiversity levels are driven by backfilling material in quarry restoration. *CATENA*. 2020. Vol. 195. N 104839. DOI: 10.1016/j.catena.2020.104839

3. Moseykin V.V., Galperin A.M., Ermolov V.A., Krupoderov V.S. The analysis of the situation with mining and industrial wastes (geo-ecological aspects). *Mining Informational and Analytical Bulletin*. 2013. N S1, p. 7-23 (in Russian).

4. Li Wang, Bin Ji, Yuehua Hu et al. A review on in situ phytoremediation of mine tailings. *Chemosphere*. 2017. Vol. 184, p. 594-600. DOI: 10.1016/j.chemosphere.2017.06.025

5. Ivanova N.A. Biological reclamation of sand quarries in the Mari Trans-Volga region by the establishment of Scots pine forest plantations (Pinus sylvestris L.): Avtoref. dis. … kand. s.-kh. nauk. Ioshkar-Ola: Povolzhskii gosudarstvennyi tekhnologicheskii universitet, 2020, p. 21 (in Russian).

6. Osipenko R.A., Zaripov Yu.V., Belov L.A., Morozov A.E. Experience of sand pit recultivation in the northern taiga subzone. *Forests of Russia and economy in them*. 2020. N 4 (75), p. 12-19 (in Russian). DOI: 10.51318/FRET.2020.40.90.002

7. Koptsik G.N., Koptsik S.V., Smirnova I.E. Alternative technologies for remediation of technogenic barrens in the Kola Subarctic. *Eurasian Soil Science*. 2016. Vol. 49. N 11, p. 1294-1309. DOI: 10.1134/S1064229316090088

8. Lusis A.V., Ivanova L.A., Gorbachyova T.T., Rumyantseva A.V. Establishment of an erosion-control plant cover in a sand pit under Arctic conditions using sewage sludge. *Mining Science and Technology* (*Russia*). 2023. Vol. 8. N 3, p. 223-231. DOI: 10.17073/2500-0632-2023-01-73

9. Garbini G.L., Caracciolo A.B., Rolando L. et al. Effects of municipal waste compost on microbial biodiversity and energy production in terrestrial microbial fuel cells. *New Biotechnology*. 2023. Vol. 78, p. 131-140. DOI: 10.1016/j.nbt.2023.10.009

10. Asemaninejad A., Langley S., Mackinnon T. et al. Blended municipal compost and biosolids materials for mine reclamation: Long-term field studies to explore metal mobility, soil fertility and microbial communities. *Science of the Total Environment*. 2021. Vol. 760. N 143393. DOI: 10.1016/j.scitotenv.2020.143393

11. Shengguo Xue, Feng Zhu, Xiangfeng Kong et al. A review of the characterization and revegetation of bauxite residues (Red mud). *Environmental Science and Pollution Research*. 2016. Vol. 23. Iss. 2, p. 1120-1132. DOI: 10.1007/s11356-015-4558-8

12. Asensio V., Covelo E.F., Kandeler E. Soil management of copper mine tailing soils – Sludge amendment and tree vegetation could improve biological soil quality. *Science of the Total Environment*. 2013. Vol. 456-457, p. 82-90. DOI: 10.1016/j.scitotenv.2013.03.061

13. Novo L.A.B., Covelo E.F., González L. The use of waste-derived amendments to promote the growth of Indian mustard in copper mine tailings. *Minerals Engineering*. 2013. Vol. 53, p. 24-30. DOI: 10.1016/j.mineng.2013.07.004

14. Lingyan Zhou, Zhaolong Li, Wen Liu et al. Restoration of rare earth mine areas: organic amendments and phytoremediation. *Environmental Science and Pollution Research*. 2015. Vol. 22. Iss. 21, p. 17151-17160. DOI: 10.1007/s11356-015-4875-y

15. Lin Zhang, Wen Liu, Shenghong Liu et al. Revegetation of a barren rare earth mine using native plant species in reciprocal plantation: effect of phytoremediation on soil microbiological communities. *Environmental Science and Pollution Research*. 2020. Vol. 27. Iss. 2, p. 2107-2119. DOI: 10.1007/s11356-019-06645-2

16. Koptsik G.N., Smirnova I.E., Koptsik S.V. et al. Efficiency of remediation of technogenic barrens around the "Severonikel" works in the Kola peninsula. *Moscow University Soil Science Bulletin*. 2015. Vol. 70. N 2, p. 78-84. DOI: 10.3103/S0147687415020052

17. Vinogradov D.V., Vasileva V.M., Makarova M.P. Agroecological effect of sewage sludge and its mixtures with zeolite on the agrocenoses of oilseeds. *Theoretical and Applied Ecology*. 2019. N 3, p. 127-133 (in Russian). DOI: 10.25750/1995-4301-2019-3-127-133

This is an open access article under the CC BY 4.0 license

18. Asensio V., Vega F.A., Andrade M.L., Covelo E.F. Technosols Made of Wastes to Improve Physico-Chemical Characteristics of a Copper Mine Soil. *Pedosphere*. 2013. Vol. 23. Iss. 1, p. 1-9. DOI: 10.1016/S1002-0160(12)60074-5

19. Petrova T.A., Rudzisha E. Utilization of sewage sludge as an ameliorant for reclamation of technogenically disturbed lands. *Journal of Mining Institute*. 2021. Vol. 251, p. 767-776. DOI: 10.31897/PMI.2021.5.16

20. Purtova L.N., Kostenkov N.M., Semal V.A., Komachkova I.V. Carbon dioxide emissions from soils of natural and anthropogenic landscapes in the south of Primorye region. *Fundamentalnye issledovaniya*. 2013. N 1. Part 3, p. 585-589 (in Russian).

21. Ivanova L.A., Lusis A.V., Gorbacheva T.T., Krasavtseva E.A. It's time to reclaim the Arctic landscapes. Use of production and consumption waste from regional water and sewerage utilities for the reclamation of disturbed landscapes. Apatity: Kolskii nauchnyi tsentr RAN, 2023, p. 77 (in Russian). DOI: 10.37614/978.5.91137.494.5

22. Shmakova N.Ju., Ivanova L.A., Ermolaeva O.V., Lusis A.V. Photosynthetic productivity of artificially created phytocoenosis using sewage sludge. *Mine Surveying and Subsurface Use*. 2023. N 3 (125), p. 60-68 (in Russian). DOI: 10.56195/20793332_2023_3_60_68

23. Hamkalo Z., Bedernichek T. Total, cold and hot water extractable organic carbon in soil profile: impact of land-use change. *Zemdirbyste-Agriculture*. 2014. Vol. 101. N 2, p. 125-132. DOI: 10.13080/z-a.2014.101.016

24. Korneykova M.V., Vasenev V.I., Saltan N.V. et al. Analysis of CO_2 Emission from Urban Soils of the Kola Peninsula (European Arctic). *Eurasian Soil Science*. 2023. Vol. 56. N 11, p. 1653-1666. DOI: 10.1134/S1064229323601749

25. Mikha M.M., Benjamin J.G., Stahlman P.W., Geier P.W. Remediation/Restoration of Degraded Soil: I. Impact on Soil Chemical Properties. *Agronomy Journal*. 2014. Vol. 106. Iss. 1, p. 252-260. DOI: 10.2134/AGRONJ2013.0278

26. Jordán M.M., Bech J., García-Sánchez E., García-Orenes F. Bulk density and aggregate stability assays in percolation columns. *Journal of Mining Institute*. 2016. Vol. 222, p. 877-881. DOI: 10.18454/PMI.2016.6.877

27. Matiasek S.J., Pellerin B.A., Spencer R.G.M. et al. Water-soluble organic carbon release from mineral soils and sediments in an irrigated agricultural system. *Journal of Environmental Management*. 2023. Vol. 343. N 118184. DOI: 10.1016/j.jenvman.2023.118184

28. Bobrik A.A. Patterns of greenhouse gas emissions from the soils of northern taiga and forest-tundra ecosystems of Western Siberia: Avtoref. dis. … kand. biol. nauk. Moscow: Moskovskii gosudarstvennyi universitet im. M.V.Lomonosova, 2016, p. 26 (in Russian).

29. Singh A.K., Kumar S., Kalambukattu J.G. Assessing aggregate stability of soils under various land use/land cover in a watershed of Mid-Himalayan Landscape. *Eurasian Journal of Soil Science*. 2019. Vol. 8. Iss. 2, p. 131-143. DOI: 10.18393/ejss.514319

30. Khlystov I.A. Carbon and nitrogen of organic soil compounds in the conditions of the pollution by the copper smelting plant emissions. *Bulletin of KSAU*. 2015. N 5, p. 17-22 (in Russian).

31. Šeremešić S., Milošev D., Sekulić P. et al. Total and hot-water extractable carbon relationship in chernozem soil under different cropping systems and land use. *Journal of Central European Agriculture*. 2013. Vol. 14. Iss. 4, p. 1496-1504. DOI: 10.5513/JCEA01/14.4.1382

32. Ortner M., Seidel M., Semella S. et al. Content of soil organic carbon and labile fractions depend on local combinations of mineral-phase characteristics. *SOIL*. 2022. Vol. 8. Iss. 1, p. 113-131. DOI: 10.5194/soil-8-113-2022

33. Shamrikova E.V., Kubik O.S., Deneva S.V., Punegov V.V. Composition of the Water-Soluble Soil Fraction on the Barents Sea Coast: Organic Carbon and Nitrogen, Low-Molecular Weight Components. *Eurasian Soil Science*. 2019. Vol. 52. Iss. 11, p. 1347-1362. DOI: 10.1134/S1064229319110103

34. Karelin D.V., Zamolodchikov D.G., Zukert N.V. Interannual changes in PAR and soil moisture during the warm season may be more important for directing of annual carbon balance in tundra than temperature fluctuations. *Biology Bulletin Reviews*. 2013. Vol. 3. N 5, p. 371-387. DOI: 10.1134/S2079086413050058

35. Goncharova O.Yu., Semenyuk O.V., Matyshak G.V., Bogatyrev L.G. Biological Activity of Urban Soils: Spatial Variability and Control Factors. *Eurasian Soil Science*. 2022. Vol. 55. N 8, p. 1009-1022. DOI: 10.1134/S1064229322080038

36. Xiaomei Chen, Muying Liu, Zhanying Xu, Hui Wei. Influences of temperature and moisture on abiotic and biotic soil CO_2 emission from a subtropical forest. *Carbon Balance and Management*. 2021. Vol. 16. N 18. DOI: 10.1186/s13021-021-00181-8

***Authors*: Lyubov A. Ivanova,** *Doctor of Biology Sciences, Chief Researcher, Leading Researcher, https://orcid.org/0000-0002-7994-5431 (N.A.Avrorin Polar-Alpine Botanical Garden-Institute, Kola Science Centre of the RAS, Kirovsk, Russia; Institute of North Industrial Ecology Problems, Kola Science Centre of the RAS, Apatity, Russia),* **Marina V. Slukovskaya,** *Candidate of Biology Sciences, Senior Researcher, https://orcid.org/ 0000-0002-5406-5569 (Laboratory of Nature-Inspired Technologies and Environmental Safety of the Arctic NMC, Kola Science Centre of the RAS, Apatity, Russia; Institute of Chemistry and Technology of Rare Elements and Mineral Raw Materials, Kola Science Centre of the RAS, Apatity, Russia),* **Evgeniya A. Krasavtseva,** *Candidate of Engineering Sciences, Researcher, vandeleur2012@yandex.ru, https://orcid.org/0000-0002-8821-4446 (Institute of North Industrial Ecology Problems, Kola Science Centre of the RAS, Apatity, Russia; Laboratory of Nature-Inspired Technologies and Environmental Safety of the Arctic NMC, Kola Science Centre of the RAS, Apatity, Russia).*

The authors declare no conflict of interests.

This is an open access article under the CC BY 4.0 license