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Establishment of an erosion-control plant cover in a sand pit under Arctic conditions using sewage sludge

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Abstract
This paper presents the findings of a prolonged field studies that aimed to assess the feasibility of using the sewage sludges (SS) form a regional water and wastewater services enterprise to expedite the establishment of a resilient erosion-control plant cover in sand pits located in the Arctic region of the Russian Federation. The study confirms the beneficial impact of the SS on the seed germination, subsequent growth, and development of plants. The study shows that SS can be used in two ways: first, by applying a continuous layer measuring 5 to 10 cm thick on the soil surface or by fragmentarily applying a layer 2–3 cm thick. Second, through early-winter sowing of seeds directly on the soil surface (under the SS layer) or on top of the sewage sludge. In both cases, an annual enhancement of the qualitative and quantitative parameters of the artificially formed stand of grass was observed. This included a significant increase in its height and density, biomass, foliage cover, and thickness of the formed sod, in contrast to the reference sample. The present study investigates the characteristics of the floristic composition of the phytocenoses formed in a sand pit. The findings demonstrate that the use of sewage sludge (SS), regardless of the quantity and application method, accelerates the restorative succession in the sand pit. The thick stand in the experimental variants, resulting from the attraction of pioneer vegetation, promotes the complexity of its structure and species composition, rapid vegetation of inner bare areas, and the emergence of natural phytocenoses elements that are specific to the zonal type of vegetation. Additionally, the use of SS stabilizes erosion processes in the study area. Consequently, the plant community formed in the experiment using SS can be classified as ecologically sustainable, with the potential for independent existence and further development. These results can serve as a foundation for monitoring efforts and the development of measures to optimize the vegetation of such ecotopes.

Keywords
sand pit, phytoremediation, sewage sludge (SS), ameliorant, grass mixture, plant cover

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ТЕХНОЛОГИЧЕСКАЯ БЕЗОПАСНОСТЬ В МИНЕРАЛЬНО-СЫРЬЕВОМ КОМПЛЕКСЕ И ОХРАНА ОКРУЖАЮЩЕЙ СРЕДЫ

Научная статья

Формирование противоэрозионного растительного покрова на песчаном карьере в условиях Арктики с помощью осадка сточных вод

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Аннотация

В настоящей работе представлены результаты многолетних полевых исследований по оценке возможности применения ОСВ регионального предприятия водопроводно-канализационного хозяйства для ускоренного формирования устойчивого противоэрозионного растительного покрова на песчаных карьерах в Арктической зоне РФ с подтверждением оказания им стимулирующего эффекта на прорастание семян, дальнейший рост и развитие растений. Показано, что ОСВ может применяться двумя способами: нанесением на поверхность грунта сплошным слоем высотой от 5 до 10 см, и фрагментарно – слоем 2–3 см, а подзимний посев семян – непосредственно по поверхности грунта (под слой ОСВ) либо поверх осадка сточных вод. В обоих случаях отмечено ежегодное улучшение качественных и количественных показателей искусственно созданного травостоя – многократное, по сравнению с контролем, увеличение его высоты и плотности, биомассы, проективного покрытия и мощности сформированной дернины. Исследованы особенности формирования флористического состава созданных в песчаном карьере фитоценозов. Установлено, что независимо от количества и способа нанесения применение ОСВ способствует ускорению восстановительной сукцессии на песчаном карьере, а мощный травостой опытных вариантов путем привлечения пионерной растительности – усложнению его структуры и видового состава, быстрому зарастанию внутренних оголенных участков и возникновению элементов естественных фитоценозов, свойственных зональному типу растительности, а также стабилизации процессов эрозии на объекте исследования. Все это позволяет характеризовать сформированное в эксперименте с помощью ОСВ растительное сообщество как экологически устойчивое, имеющее перспективы к самостоятельному существованию и дальнейшему развитию. Результаты таких исследований могут послужить основой для организации мониторинга и разработки мероприятий по оптимизации растительности подобных экотопов.

Ключевые слова

песчаный карьер, фиторекультивация, осадок сточных вод (ОСВ), мелиорант, травосмесь, растительный покров

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Introduction

The annual increase in mineral resource utilization, exploration and construction activities by mining companies for oil, gas and ore, as well as the construction of roads, power lines and other works, has resulted in the disturbance of natural ecosystems. These activities lead to the destruction of soil, plant cover and reduction of biodiversity, resulting in the emergence of new man-made forms of the landscape [1].

In the Murmansk Region, one of the most common forms of man-made change in the Arctic landscapes are pits that emerge after the removal of sand for construction and other purposes. Restoration of these areas requires measures to transform the disturbed lands into a state suitable for further use and prevent adverse impact on the environment [2].

One of way to rehabilitate such areas is to allocate a portion of them for self-organized vegetation [3]. However, due to the unfavorable forecast for natural vegetation and the complexity of revegetation on sand deposits due to individual and regional specifics, reclamation works are necessary to restore the productivity of disturbed lands by creating new, purposefully synthesized, artificial biogeocenoses [4][1].

When implementing reclamation measures to form a plant cover on sandy soil, one of the determining factors is the nutritive conditions of its surface layer. The structurelessness of such substrate, low water-holding capacity, lack of organic matter of biogenic origin (humus), and insufficient nutrient provision make it necessary to invest in expensive mineral fertilizers annually [5]. Sewage sludge (SS) treatment, a byproduct of regional municipal wastewater, can play a positive role in solving the problem of the low NPK status of sandy soils, creating a plant cover on them, and maintaining its stability [6–8]. SS has potentially useful properties due to its high content of easily accessible organic matter for microbiota [9], as well as the lability of nitrogen, phosphorus and potassium, which determines their rapid assimilation by plants [10, 11]. Although SS has a positive effect on the physical properties of sandy soils, optimizing the density and aggregation, it may contain a set of heavy metals and pathogens. Therefore, it is necessary to study each sediment in specific conditions of reclaimed areas [12].

The purpose of the study is to assess the feasibility of utilizing SS from a regional water and wastewater services (WWS) enterprise Apatityvodokanal JSC to expedite the development of a sustainable and effective erosion-control plant cover in sand pits located in the Arctic zone of the Russian Federation.

Research objectives:

1. To investigate the effects of SS on plant growth and quality of artificially formed seeded phytocenoses.
2. To evaluate the effectiveness of different methods of applying SS onto the surface of the sand pit soil during reclamation activities.

Objects and methods of research

The research was conducted between October 7, 2017, and October 10, 2020, in the Murmansk Region (Kola Peninsula, Russian Federation) on a local disturbed territory, which is a sand pit owned by Apatityvodokanal JSC.

The pit's depth ranges from 3 to 5 meters and is located in the northern taiga coniferous forests subzone, which has about 250 species of vascular plants [13]. Based on the research findings, the model site was identified as a secondary ecotope with a little number of plant germs in the soil surface layer. Examination of the plant communities growing in the pit area revealed the presence of small micro-groups consisting of one, two and perennial pioneer plant species with a low degree of surface coverage. Surrounding the pit, the plant cover comprises natural forest communities, primarily birch, lichen-grass and lichen-grass-moss fir wood, and meadow plants in open areas. In total, 56 species characteristics of dry and barren soils were recorded within the pit and its immediate vicinity. Under favorable growing conditions, these species could contribute to the natural vegetation of the pit's sandy soil, promoting biodiversity and the formation of a much more sustainable artificial phytocenosis [14].

The pit area shows clear indications of wind and water erosion, including soil sliding and rounded hilltops. The model site itself is was a 30° sandy slope facing northwest, with an area of 200 m^2 that has been cleared of vegetation, and prepared with surface flattening, terracing and levelling[2].

The objective of this study was to investigate sandy pit soil with an admixture of gravel and small boulders, which is classified as medium-grained according to State Standard 25100–2011[3], with a low proportion of clay particles.

[1] GOST R 57446–2017. Best available techniques. Disturbed lands reclamation. Restoration of biological diversity. Moscow: Standartinform; 2017.

[2] GOST 17.5.3.0483 (ST SEV 5302–85). Nature protection. Lands. Reclamation general requirements. Moscow: Standardinform; 1984.

[3] GOST 25100–2011. Interstate standard. Soils. Classification. 2013-01-01. Moscow: Standartinform; 2011.

Table 1

Diagram of field experiment

Variant	SS application technique
Variant 1 (*n* = 6)	SS was applied to the soil surface in a fragmentary manner, with a layer 2–3 cm high. The seeds were then sown directly on the soil surface, underneath the layer of SS
Variant 2 (*n* = 6)	SS was applied to the soil surface in a continuous layer, with a height of 5–10 cm. The seeds were then sown on top of the layer of SS
Variant 3 (*n* = 6)	No sludge was applied to the soil surface. The seeds were directly sown on the soil surface

The objective of this study was to investigate sandy pit soil with an admixture of gravel and small boulders, which is classified as medium-grained according to State Standard 25100-2011, with a low proportion of clay particles. To enhance the biogenesity of the soil, sludge from wastewater treatment plant (WTP-3) in Apatity (Murmansk Region) was used as an ameliorant. The sludge is a moist, plasticine-like mass with a black-brown color and a pungent specific smell. The sludge is classified as hazardous class V waste according to GOST R 54534–2011, and its total content of heavy metals is well below the standards [12] established by this regulation[4], At the WTP-3, sludge treatment involves drying and aging on sludge beds for three or more years[5].

The field experiment was designed with three variants, each with six replications, for a total of 18 experimental plots measuring 1×1 m and spaced 0.5 m apart at the model site. The experimental variants involved the application of sludge to the soil surface in two ways: fragmentarily and as a continuous layer, while the reference site did not receive any sludge application. The diagram of the field experiment is presented in Table 1.

No covering of the sandy surface with a fertile soil layer or additional fertilization of plants with mineral fertilizers was carried out during the experiment.

A complex sowing phytocenosis was formed using the early-winter method of direct sowing of the grass mixture, developed on the basis of biological characteristics of perennial herb species. The grass mixture comprised three species of grasses (red fescue (*Festuca rubra* L.), European dune wild ruttishness (*Leymus arenarius Hochst.*), and couch (*Elymus repens* (L.) *Gould*) and two species of legumes (*Washington lupine (Lupinus polyphyllus Lindl.*) and sweet vetch (Hedysarum alpinum L.) taken in the ratio of 5:1:1:0.1:0.1 (vol.), with a seed rate of 27.5 g/m^2. In variant 1, seeds were sown directly on the soil surface (under the sludge layer), and in variant 2, they were sown on top of a continuous layer of sludge. Additionally, six seeds of Scots pine (*Pinus sylvestris L.*) were sown separately from the grass mixture in the lower right corner of each plot.

Subsequent fieldwork involved regular monitoring of plant growth and development, as well as the formation of the grass stand. The effect of the ameliorant on the quality of the resulting phytocenosis was evaluated based on various parameters, such as plant height in the grass stand (cm), foliage cover (%) on the plots, changes in the structure and species composition of the phytocenosis [15, 16], and, at the end of the experiment, the sod thickness (cm), grass stand density (number of shoots per 1 m^2), and accumulation of raw biomass (g/m^2). Biometric measurements were taken simultaneously in all replications, and the biomass was determined in the laboratory using analytical scales.

The Latin names of plants are given according to the common international names of World Flora Online[6].

The collected data were processed using one-way analysis of variance (one-way ANOVA) in Excel.

Research results

2018. The first sprouts of seeded plants were observed in all three variants of the experiment simultaneously after the snow cover melted in May. However, the most vigorous and high-quality sprouts were noted in the variants with the use of SS (Table 2), which led to the assumption of a stimulating effect of this ameliorant on the seed germination process.

Over the next 1.5 months, primitive (one-tier) plant communities were formed on the experimental sites (Table 2), consisting of only two sown species – red fescue and couch as of July 2018. The quality of the grass stand on the experimental plots was significantly different from the reference plots. In both experimental variants, a dense and well-developed grass stand with high foliage cover of bright emerald green color was observed. The foliage cover was 100 % in plots with continuous application of SS

[4] GOST R 54534–2011. Resources saving. Sewage sludge. Requirements for recultivation of disturbed lands (official edition). Moscow: Standartinform, 2012.

[5] GOST R 54534–2011. Resources saving. Sewage sludge. Requirements for recultivation of disturbed lands. Moscow: Standartinform; 2013.

[6] The WFO Plant List. Snapshots of the taxonomy. URL: https://wfoplantlist.org/plant-list

and top sowing of the grass mixture (variant 2), and 87 % in the plots with fragmentary application of SS (variant 1). Seed germination was mainly observed in the areas of experimental plots free of the SS layer, and to a lesser extent in the areas covered with an ameliorant layer. In the reference area (without application of SS), the grass stand formed was sparse, yellow-red in color, covering only 15 % of the plot area. Plants within it were in a depressed state, and by the end of the growing season, they practically did not increase in height.

In the first vegetation period, an increase (up to five species) in the composition of the phytocenoses formed was observed only on the experimental plots (Table 2) due to the introduction of three new species from the nearby territories. These were native pioneer and weed plants – foalfoot (*Tussilago farfara* L.), fireweed (*Epilobium angustifolium* L.) and field sorrel (*Rumex acetosella* L.).

In **2019**, the grass stand at the reference sites remained low and sparse with the foliage cover of only 20 %, and the resulting community remained one-tiered (Table 2, Figure 1). The experimental plots were characterized by a dense grass stand of complex two-tier structure, with a height 4–5 times exceeding the height of plants at the reference site.

While the plants at the reference sites were only in the vegetative stage, the plants at the experimental sites had already entered the flowering phase. All six sown species, including Scots Pine seedlings, were only observed at the experimental plots. During this period, the species composition of the created plant community was augmented with four species from the main sowing grass mixture, namely European dune wild ruttishness (*Leymus arenarius Hochst.*), Washington lupine (*Lupinus polyphyllus Lindl.*), sweet vetch (*Hedysarum alpinum* L.) and Scots pine. Colonization of experimental plots, as well as their

Table 2

Average indicators of artificial phytocenosis in 2018–2019 in the sand pit of Apatityvodokanal JSC

Indicator	Variant and method of SS application					
	2018			2019		
	1*	2**	3 (reference)	1*	2**	3 (reference)
Number of tiers, pcs.	1	1	1	2	2	1
Average plant height (by dominant species), cm	27.4 ± 1.5	35.3 ± 1.2	8.1 ± 0.3	56.9 ± 1.7	69.7 ± 1.9	12.8 ± 0.5
Average number of species from the number of sown ones, pcs.	2	2	2	4.5	5.6	4,0
Average number of invaded species, pcs.	3	3	–	3.8	3.8	2.3
Foliage cover, %	87	100	15	100	100	20

* – fragmentary application of SS;
** – application of SS as a continuous layer.

Variant 1 *Variant 2* *Reference variant*

Fig. 1. Appearance of experimental plots in 2019

perimeter, continued with six new species of native plants: subarctic astragalus (*Astragalus norvegicus Grauer*), tufted hair grass (*Deschampsia caespitosa* (L.), *P. Beauv.*), marsh cress (*Rorippa palustris Besser*), fall dandelion (*Scorzoneroides autumnalis* (L.) *Moench*), colonial bent grass (*Agrostis capillaris* L.), and mountain sorrel (*Oxyria digyna Hill.*). At the reference sites, European dune wild ruttishness or Scots Pine were often not detected in the grass stand, which may be attributed to the quality of seeds collected from natural conditions and their low volume ratio during planting. Although Washington lupine is usually found in habitats with sandy soils and can thrive on nutrient-poor substrates [17], this species was only observed at experimental plots where sewage sludge was present.

2020. Over the course of three vegetation periods, plant communities with vigorous growth and development were formed on the model slope of the pit that lacked plant and soil cover, without the use of earthing or fertilizers, due to the application of SS. These communities were dominated by two species that determined their height: red fescue and couch.

The height of plants in the experimental variants reached 95.2 ± 1.4 cm (variant 2) and 86.7 ± 3.3 (variant 1), whereas at the reference sites, this measurement was six times lower (Table 3). In contrast to the reference sites, plants in the experimental variants retained an intense green color and a shiny surface of leaves and stems. The grass stand density in the experimental variants 1.7–4.4 times higher than the reference one. Only the experimental variants showed a 100 % foliage cover, whereas the reference site had an indicator of only 10 %, which was 5–10 % lower than the first and second vegetation periods. The roots of plants in the experimental variants effectively utilized the

Table 3

Results of variance analysis of the impact of SS application technique on the main qualitative indicators of artificial phytocenosis (2020)

Variant, sources of variation	Indicator		
	Height of plants (by dominant species), cm	Density of grass stand, number of stems/1 m^2	Green biomass, g/m^2
1	86.7 ± 3.3	12 830 ± 123.14	2952 ± 52.5
2	95.2 ± 1.4	32 589.7±546.7	5632 ± 28.9
3	13.7 ± 0.9	7431.7 ± 20.9	100 ± 3.2
SS	120 538	2 105 022 787	76 295 880.9
df	2	2	2
MS	60 269	1 052 511 394	38 147 940.5
F	13 452.6	10 040	39 119.4
p-value	< 0.001	< 0.001	< 0.001
*F critical**	7.4	3.7	3.9

* Critical *F* is a tabular value of the criterion of the adopted level – the reliability of differences between the variants was taken at the values of $p < 0.05$ ($n = 6$). Variants were considered unreliable at $p > 0.05$.

Table 4

Effect of SS application technique on qualitative indicators of artificial phytocenosis (2020)

Indicator	Variant		
	1*	2**	3 (reference)
Number of tiers, pcs.	2	3	1
Average number of species from the number of sown ones, pcs.	6,0	6,0	4,5
Average number of invaded species, pcs.	11.7	12.0	3.0
Foliage cover, %	100	100	10
Sod thickness (by core, $n = 3$), cm	3.6 ± 0.03	9.6 ± 0.02	2.6 ± 0.2

* – fragmentary application of SS;
** – application of SS as a continuous layer.

sandy substratum and formed a dense grass sod with a thickness of 3.6±0.03 cm (variant 1) and 9.6±0.02 cm (variant 2). In comparison this indicator was 1.4 and 3.7 times lower, respectively, at the reference site (Table 4). The high foliage cover and density of the grass stand in the variants with the use of SS resulted in a significant accumulation of biomass, which is notable for the northwest region of the Russian Federation [18]. The experimental variant 1 accumulated 2952.0±52.5 g/m^2, and in variant 2, it was 5632.0±28.9 g/m^2 (29 and 56.3 t/ha), which was 29 and 56 times higher than the reference site, which only accumulated 100.7±3.2 g/m^2) (1 t/ha) (Table 3).

The present study investigated the impact of SS on the qualitative indicators of the vegetation cover created over three vegetation periods (Table 3). The results demonstrated statistically significant differences ($p < 0.05$) in the average values of the three main quality indicators of the artificial phytocenosis. The calculated F statistic was greater than the critical F value, leading us to reject the null hypothesis that height, accumulation of green plant biomass, and grass stand density are not dependent on the use of SS. Instead, we accepted the alternative hypothesis that the main quality indicators are statistically influenced by the use of SS. These findings suggest that there is a 95 % probability that the use of SS has a positive effect on the quality indicators of the plant cover formed in the sand pit during the three vegetation periods.

The grass stand that formed at the experimental plots exhibited a complex two- and three-tiered structure, in contrast to the primitive, sparse, one-tiered structure of the reference site (Table 4). In 2020, two additional native plants, tea-leaved willow (*Salix phylicifolia* L.) and Kentucky bluegrass (*Poa pratensis* L.), were incorporated into the plant community; which accelerated the vegetation of bare inter-plot areas and the perimeter of the sites by pioneer plants, hastening the restoration succession of the pit. The total number of species at the model site, adapted to the specific conditions, increased to 21 in 2020, with seven of them completing a full cycle of development. The appearance of natural phytocenoses elements, typical of the zonal type of plant cover, allowed for the artificial plant community to be classified as ecologically sustainable, with potential for independent existence and further development [19].

Practical application

The value of research results for practice is evidenced by the proposal of an innovative and cost-effective method of creating high quality rehabilitative phytocenoses for environmental purposes.

This method is based on the use of a widely available and ow-cost high-absorbency component, which is also an additional source of nutrients from the product of regional municipal wastewater treatment – SS. This approach can play a positive role in addressing the problem of low productivity of sandy man-made soils. The proposed measures in this study could contribute to the growth of profit of wastewater treatment enterprises due to the reduction of penalties for the excessive waste discharge and the possibility of improving processes. Furthermore, it could allow for the involvement of a large volume of waste requiring utilization in the economic turnover, leading to a significant reduction of their adverse impact on the environment. The resulting economic effect of environmental protection is challenging to evaluate [20, 21].

Directions for future research

The results of this study require verification when implemented at the objects of accumulated environmental damage, specifically for fixing dusty surfaces of different types of tailings ponds in the Murmansk Region. This verification aims to recognize the proposed method as an alternative to traditional methods of reclamation of man-made soils.

Conclusion

Long-term field research was conducted to develop practical bases for an innovative method of bioreclamation of sandy soils without peating or earthing, and without use of mineral and organic fertilizers.

This method is based on the field observations of experimental irrigation of the man-made soil in a sand pit with the product of the regional municipal wastewater (SS) treatment, which confirmed the stimulating effect of its use on seed germination, further growth and development of plants, and improvement of the quality of artificially created sowing phytocenoses. This approach could partially contribute to the solution of important environmental problems such as the sound use of SS of regional WWS enterprises in the restoration of objects with accumulated environmental damage and environmental enhancement in the Extreme North.

The study showed that SS can be applied in two ways: as a continuous and fragmentary layer 2 to 10 cm thick on the man-made soil, and early-winter sowing of seeds – directly on the soil surface (under the SS layer) or on top of the sediment.

The method of ameliorant application significantly affects the quality of the sowing phytocenosis formed. Fragmentary application of SS on the soil surface increases the plant height in the created phytocenosis by 6.3 times, the grass stand density by 1.7 times, the biomass by 29.3 times, the foliage cover by 10 times, and the turf thickness by 1.4 times compared to the reference site (the variant without SS application). When applying the sediment as a continuous layer, these indicators increase even more compared to the reference site: the height of plants by 6.9 times, the density of the grass stand by 4.4 times, the biomass by 55.9 times, and the sod thickness by 3.7 times.

Regardless of the method of application, the application of SS contributes to the acceleration of restoration succession and an increase in biodiversity in a sand pit. A thick grass stand promotes the colonization of pioneer species, rapid vegetation of inner bare areas, the appearance of elements of natural phytocenoses typical of the vegetation zonal type, fixing, as well as stabilization of erosion processes.

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