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The possibilities of using biochar for the reclamation of anthropogenic-disturbed soils Using the example of Russky island

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Abstract

As a result of the construction, the soil is degraded, losing horizons and fertility. Recultivation of urban soils is important for the formation of agroecosystems. Biochar can be used to improve the quality of urban soil. This study examines the effect of biochar on the restoration of anthropogenic soils. The study was conducted on the soils of Russian Island (Russia), where horizon A and partly B were removed because of the construction of the Far Eastern Federal University campus. Biochar from birch was introduced into the soil in 2023 in doses of 0 kg/m², 1 kg/m² and 3 kg/m² in three repetitions. The study was conducted for three years. During the three years of the field experiment, the formation of a humus horizon up to 1.5 cm thick, an increase in the content of organic carbon and the formation of a humate-fulvate type of humus were recorded. In 2023, CO₂ fluxes in areas with biochar decreased compared to control, and in 2024, carbon dioxide fluxes in areas with biochar were higher compared to the control. Measurement of CO₂ fluxes at sites confirms the formation of a root-habitable layer, which increases the contribution of roots to soil respiration.

Keywords: Biochar, Carbon dioxide, Soil reclamation, Soil restoration, Soil degradation.

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1. Introduction

Anthropogenic-altered soils play an important role in urban ecosystems and have global ecological significance. These soils typically differ from natural soils in terms of their morphological structures and chemical properties [1]. Natural soils generally have an isotropic soil profile, where properties change evenly along the vertical axis [2]. Anthropogenic-altered

soils, on the other hand, often have an anisotropic profile. This means that properties may change unevenly or in specific patterns, such as the appearance of intermediate horizons or changes in the distribution of chemical elements [3].

Since urban soils form the foundation of urban ecosystems, understanding how urbanization impacts their condition is crucial for developing effective strategies for environmental remediation and sustainable urban management [1].

A common form of anthropogenic soil degradation is the absence of upper soil layers, as changing the landscape and removing the fertile topsoil is the initial stage of construction [4]. Based on a study of soil samples from 11 cities, Herrmann et al. found that 50% of urban soils lack upper soil layers [5]. In addition, horizons often become separated from the surface, with horizon B being absent and horizon A buried [1].

In addition to the reduction in the number of soil layers due to construction, the soil also faces several other technical impacts. These include the destruction of vegetation, compaction of the soil, backfilling, pollution from heavy metals, and construction waste [6-8]. These actions lead to a loss of the soil's structure, decreased filtration capacity, reduced biodiversity, erosion, diminished soil functions, lower productivity, loss of organic matter, and overall decreased fertility [9, 10].

The level of human interference can vary from being insignificant to leading to the complete destruction of the soil and loss of its fertile layer. Therefore, based on the degree and type of soil degradation, it is essential to select appropriate remediation measures [11].

The use of biochar for soil cover remediation is attributed to physical soil remediation [12].

According to research, biochar is an effective tool for soil remediation and can help solve various problems, such as reducing erosion, improving physical and chemical properties, and restoring soil biological functions [13-15].

The wide range of benefits that biochar can provide for soils is due to its porous and high-carbon structure [13]. This has led to its use in various fields such as agriculture, ecology, and industry [14-17].

When solving the problems of degraded soils, it has been noted that, depending on the soil and climatic conditions, biochar can reduce the effects of water and wind erosion by 16-61% [18-20]. Soil erosion with the use of biochar is reduced due to: improving the aggregative stability of the soil, which prevents erosion and destruction of the soil surface; improving infiltration, which prevents the appearance of surface runoff; increasing water retention, which prevents rapid drying and wind transport of soil particles; maintaining the development of the root system of plants [19]. However, there is currently no clear understanding of the relationship between the dose, type of biochar, and type of soil in terms of the degree of erosion reduction [21]. It has been observed that the use of biochar in clay soils tends to contribute more to improving soil aggregative stability [22, 23].

By stimulating the formation of soil aggregates, biochar effectively counters soil over-compaction, increasing the volume density and porosity by 29% and 59%, respectively, as demonstrated in the study conducted by Singh, et al. [24].

The formation of pores in the soil, especially macropores, contributes to an increase in organic carbon content. As established, this indicator can reach up to 58% [20, 23, 24].

The pore space of the soil and the biochar itself provide a favourable habitat for microorganisms [25] therefore, biochar potentially contributes to the restoration of the biological function of the soil by increasing microbial biomass and enzyme activity [26].

By improving the physical properties of the soil, such as its surface area and structure, and the biological activity of microorganisms, biochar facilitates the faster transformation of nutrients and their easier access to plant roots [13, 26, 27]. This, in turn, promotes plant growth and increases agricultural productivity [14].

Biochar has the ability to reduce greenhouse gas emissions from soil. The effect of this reduction, depending on the conditions of biochar use, is noted to decrease N₂O, CH₄ and CO₂ emissions [28]. The impact of biochar on greenhouse gas reduction is associated with its effect on functional genes involved in the formation and cycling of N₂O, CH₄ and CO₂ [26, 28]. Most studies show a decrease in N₂O and CH₄ emissions [26, 29, 30] while the impact on CO₂ emissions is more variable: an increase in CO₂ emissions has been recorded in some cases, but the simultaneous reduction in N₂O and CH₄ ensures a positive overall climate balance [29, 31].

The current study focuses on the analysis of soil parameters, which were altered as a result of construction work, when the upper soil layer was removed and several doses of biochar were added in order to enhance the soil properties.

2. Materials and Methods

The study was conducted at a plot located in the Ajax settlement of Vladivostok on Russky Island. The plot is located 20 meters away from the road at coordinates 43.131 degrees north and 131.00 east in Primorsky Krai, Russia. The laboratory building used for the study belongs to the Far Eastern Federal University (FEFU) Figure 1.

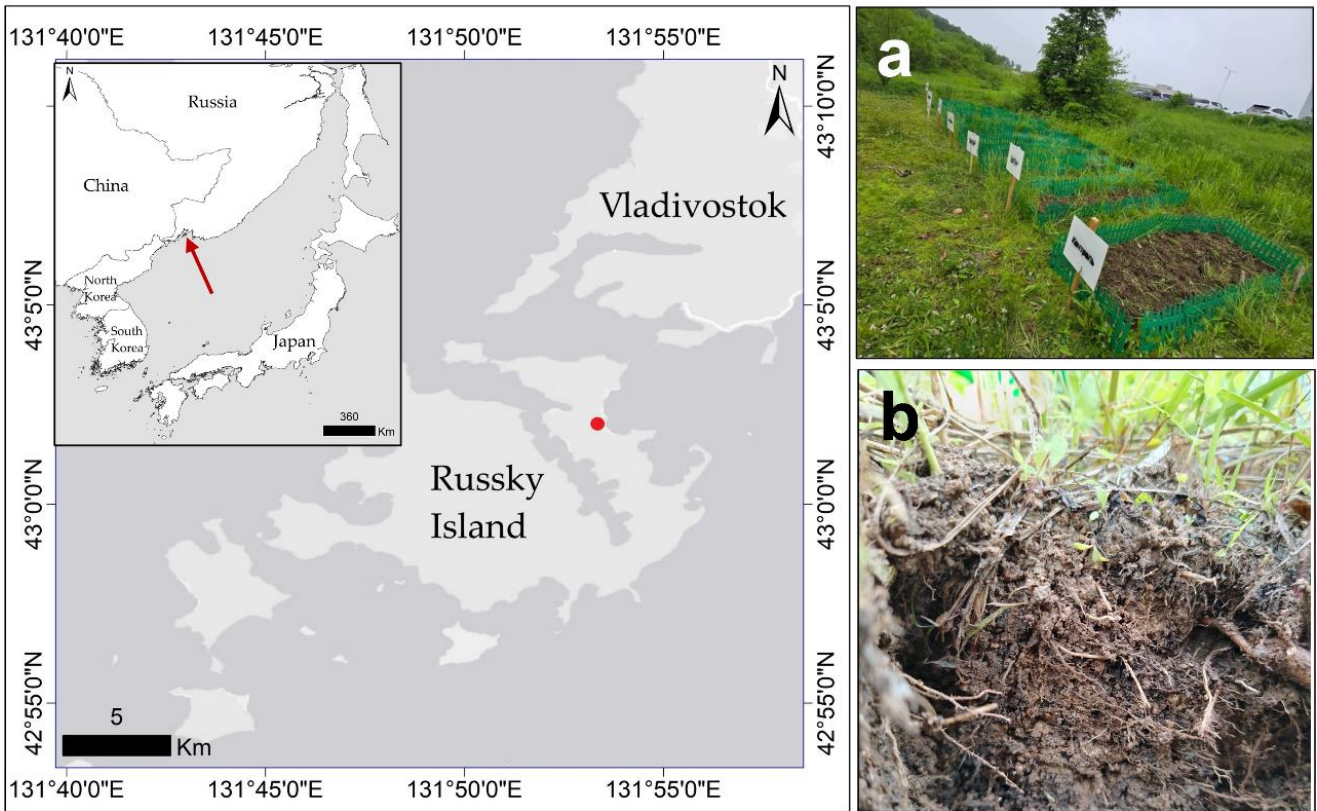


Figure 1. The map-diagram shows the location of the studied soils in the Primorsky Krai of Russia. A) The experimental plots are indicated. B) The upper horizon of the soils under study is shown.

The FEFU campus was built on Russky Island, near Ajax Bay, in the Primorsky Krai region, close to Vladivostok (see Figure 1). Construction began in 2009 and finished in 2012.

During the construction process, the topsoil was completely removed, as well as a significant portion of the subsoil. As a result, the plot underwent a transformation from typical borehole soil (Haplic Cambisols) to structurally modified abrasive soils (Urbic Technosols) according to the World Reference Base of Soil Resources.

After the completion of construction, the restoration of the topsoil did not take place, and the plot naturally revegetated until 2023, becoming a degraded type of structurally modified abrasives (Urban Technosols). Over time, this soil gradually transformed into an underdeveloped type with increased surface horizon (humus petrozems) (Pretic Anthric Cambisols).

Since 2012, the soil has been underdeveloped in terms of its humus content. Therefore, in July 2023, an experiment was conducted to test the effect of biochar at doses of 1 and 3 kg/m² on the formation of a humus layer. The design of the experiment is shown in Figure 2.

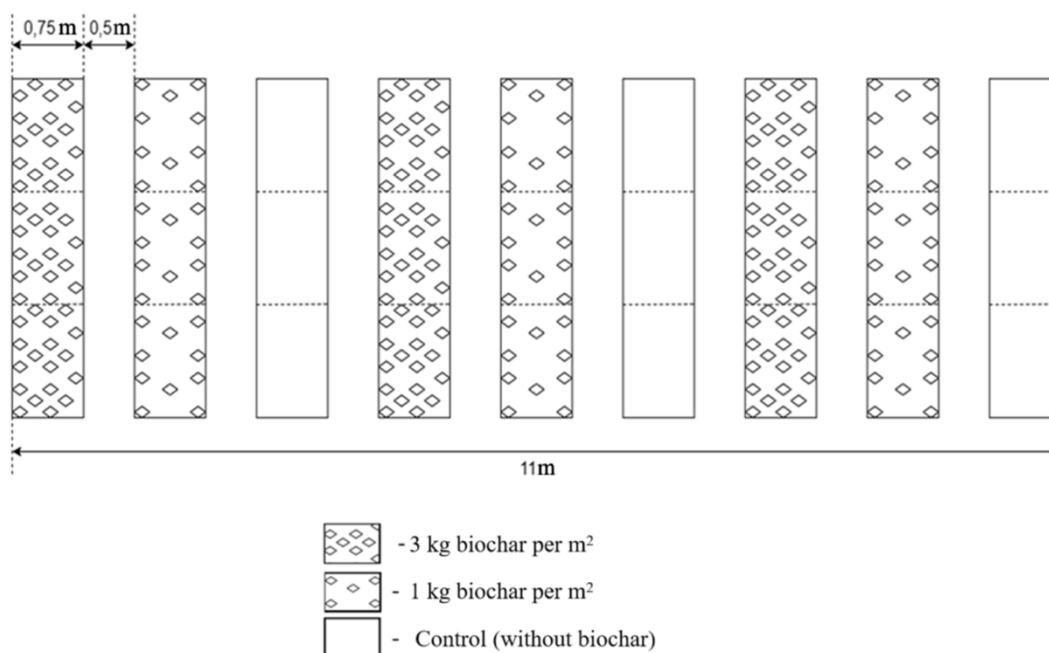


Figure 2.
The layout of the experimental plots and the doses of biochar application.

For the experiment, we selected a plot with a total plot of 11 x 3 meters, which was divided into nine plots measuring 0.75 x 3 m each. The surface horizon was formed by loosening and mixing the remains of the original horizon, and its thickness was approximately 1 centimeter. In 2023, we applied biochar in doses of 1 and 3 kg/m² to the study plot at one time. Each experimental plot included a control option (no biochar added), an option with biochar at 1 kg/m², and an option with with biochar at 3 kg/m². After that, we sowed oats on the plots. In 2024, we planted a grass mixture containing seeds of meadow timothy, alfalfa, and red clover on the experimental plot.

In 2025, no new materials were added to the soil or any plants were planted. Instead, soil samples were collected for analysis in 2025.

The biochar used in the experiment was derived from birch (*Betula alba*). Biochar was produced through slow pyrolysis at temperatures ranging from 360°C to 380°C. Before using it in the field, the properties of the biochar were assessed in accordance with the requirements of the IBI international standard.

Biochar had a very low metal content, making it a safe product. It had a surface area of 73.25 m²/g, a pore volume of 0.048 cm³/g, and good water absorption properties. It also had a high carbon content (78%), a H/C and H/O ratio of 0.0518 and 0.1452 respectively, pH 8.09, and EC 186.3 mmol/cm³. The ash content ranged from 5.4% to 7.3%, and the volatile compounds ranged from 29% to 31.2% [32].

Standard soil analyses were used to determine various parameters. For example, soil pH was measured potentiometrically using a Five Easy Plus FP20 device from Mettler Toledo in Russia [33]. Soil organic carbon content (Corg) was determined by wet burning, which involves oxidizing soil organic matter with a mixture of H₂SO₄ and K₂Cr₂O₇ followed by titration with Mohr’s salt [34-36]. The qualitative composition of soil humus was analyzed using the Kononova and Belchikova method, which was developed by M.I. Dergacheva and adapted for different types and subtypes of mineral soil [37]. With the help of this method, three main groups of humic substances can be identified: humic acids, fulvic acids, and the insoluble residue of humic substances. It also helps to characterize the mobility of humus and the nature of humic acids.

Humic substances are extracted using a mixture of sodium pyrophosphate solution and alkali, according to the method described by Dergacheva, et al. [37]. The total nitrogen content is determined using the standard method described by Mathieu and Pieltain [38].

All analyses were repeated using the same methods. To confirm microbial activity, CO₂ flux measurements were taken during 2023 and 2024. In addition to the nine experimental plots (three control plots, three plots with 1 kg/m² of biochar, and three plots with 3 kg/m²) indicated in the study objectives, CO₂ flux was also measured at three additional plots under the forest canopy, which was located near reclaimed plots and under the influence of anthropogenic activity.

A linear relationship between gas concentration and time was used to calculate gas exchange in the soil-atmosphere carbon dioxide system. Gas exchange calculation formula 1:

$$F_{gas} = \frac{[Gas]}{t} \times 10^6 \times V \times 3600 \times M[Gas] \quad (1)$$

where F_{gas} = linear flow of the test gas in (mg (Gas)/m² h); $\Delta [Gas]/\Delta t$ —the number of gas particles at time t , expressed in ppm/s; V —is the total volume of the chamber, m³; A —is the area of the investigated surface, m²; ρ —the molar density of

air (mol/m^3), defined as P/RT , where P is the air pressure, Pa; R —the universal gas constant, equal to $8.31 \text{ Pa m}^3/\text{mol}^1 \times \text{K}^1$; T —is the air temperature, K; 3600—coefficient for converting seconds to hours; $M[\text{Gas}]$ —is the molar mass of gas.

The reliability of the data was assessed in accordance with the value of the coefficient of determination R^2 .

The air pressure and temperature required to calculate emissions were determined simultaneously with on-site carbon dioxide measurements using a Vaisala Weather Transmitter WXT520 (Vaisala, Helsinki, Finland).

3. Results and Discussion

The natural soils in Vladivostok are typically brown soils (Haplic Cambisols) on gentle slopes, eluvial brown soils (Albic Cambisols) with surface horizons AYe (A) on leveled surfaces, and gleam brown soils (Gleyic Cambisols) with surface horizon AY(A).

The superficially anthropogenically transformed soils of Vladivostok include urban stratified subtypes of borezems (urban borezems, Novic Cambisols), with surface horizons Ayur (Au), structurally metamorphic urbanized agrozems as soils of urban gardens (Anthric Cambisols), with surface horizon Pur (Apu), and lithozems of gray humus urbanized (Anthric Leptosols) with surface horizon Ayur (Au).

Deeply anthropogenically-transformed soils include urbanozems as soils of residential territories (Urban Technosols) with horizon U (Au) and cultural ecosystems as soils of old abandoned vegetable gardens and orchards (Petic Anthrosols) with horizon AY (Apu); Rekreazems are soils of flower beds, lawns, and squares with reusable fillings of organomineral substrates (Terric Anthrosols). Replantozems are soils of reclaimed blackened slopes with a low-power organic horizon (Petic Anthric Cambisols). Necrosems are soils of urban cemeteries (Urban Cambic Technosols). Technozems are soil-like bodies (Cambic Technosols) under asphalt or concrete pavement (Novic Cambisols). Among the soils of forest and park areas in Vladivostok, typical borozems, slightly transformed urban borozems, and heavily transformed urbanozems and ekranezems were identified [39].

Urban soils are often contaminated with heavy metals and organic toxins, which poses a threat to the health of ecosystems and necessitates the development of effective methods for their remediation. In this regard, the use of biochar presents a promising avenue for enhancing the properties of these soils [40].

As a general rule, urban soils differ from natural soils in terms of their composition and the properties of organic matter. Specifically, they lack organic matter or have increased concentrations of it due to the use of fertilizers and other soil reclamation agents.

Soil organic matter plays a crucial role in maintaining the fertility and sustainability of soil ecosystems. It is a source of nutrients, helps improve soil structure, enhances moisture retention and aeration, and affects the biological activity in the soil. This concept is closely related to the idea of humus, which contributes to the long-term accumulation of nutrients and enhances the physico-chemical properties of the soil [41].

The humus content in the surface layers of urban soil varies and is estimated to be around 4-6% [42]. The highest humus levels are found in replantozems and rekreazems, while the lowest levels are in urbanozems and ekranezems. Other soils in urban areas have relatively higher humus content compared to background zonal soils. As the depth increases, the humus level in borer soils and replantozems decreases significantly, while in other soils, the distribution along the soil profile is uneven. The type of humus found in the surface layers of urban soils is predominantly fulvate-humate or humate [43].

To assess the effect of biochar on the formation of the surface horizon in recultivated soils, samples were collected from all experimental plots in the fall of 2025. The data presented in Table 1 shows that the content of organic carbon and humus in the soil increased with the addition of biochar doses. Analysis of the data indicates that in 2025, maximum values for organic carbon and humus were observed in plots where biochar was applied at a dose of 3 kg/m^2 . The difference in organic carbon content between control and biochar-treated plots ranged from 5-27% for a dose of 1 kg/m^2 and 29-45% for a dose of 3 kg/m^2 , respectively. This variation can be attributed to the uneven distribution of plants and planting density, which affects the amount of organic matter formed in the root zone. It should be noted that during the process of preparing soil samples, any biochar particles present in the soil were removed.

Table 1.

The content of organic carbon and nitrogen, as well as the conversion to humus and the humus reserves in the anthropogenic disturbed soils on Russky Island.

The object of research	Corg. %	Humus. %	Humus reserves. t/ha	N. %	C/N	Assessment of humus reserves Biryukova and Orlov [42]
Control 1 repetition	2.0±0.1	3.4±0.1	39.8±0.5	0.5±0.1	4.6±0.1	Very low
Biochar 1 kg/m ² 1 repetition	2.1±0.1	3.6±0.2	45.4±0.3	0.5±0.1	6.8±0.1	Very low
Biochar 3 kg/m ² 1 repetition	2.9±0.1	5.0±0.2	62.4±0.4	0.6±0.1	6.0±0.2	Low
Control 2 repetition	1.8±0.2	3.0±0.3	30.5±0.2	0.5±0.1	5.1±0.2	Very low
Biochar 1 kg/m ² 2 repetition	2.3±0.2	3.9±0.2	51.7±0.3	0.6±0.1	6.5±0.3	Low
Biochar 3 kg/m ² 2 repetition	2.6±0.1	4.5±0.2	58.2±0.4	0.6±0.1	5.1±0.2	Low
Control 3 repetition	2.1±0.1	3.5±0.1	44.1±0.3	0.5±0.1	6.4±0.3	Very low
Biochar 1 kg/m ² 3 repetition	2.5±0.1	4.3±0.2	52.7±0.2	0.6±0.1	6.1±0.1	Low
Biochar 3 kg/m ² 3 repetition	2.7±0.1	4.5±0.2	61.7±0.3	0.6±0.1		Low

Despite a significant increase in the organic carbon content in the surface horizon, the carbon reserves remain low. This is not a negative result, as it has been almost three years since the reclamation process with biochar.

One of the important characteristics of soil humus is the type of humus. This is determined by the ratio of carbon from humic acids to that from fulvic acids. All the plots belong to the humate-fulvate type, as the ratio of Cha (humic acid carbon) to Cfa (fulvic acid carbon) lies between 0.5 and 1.0 (see Table 2).

Table 2.

The type of humus in anthropogenic-altered soils.

The object of research	Cha/Cfa	Humus type Orlov Biryukova and Orlov [42] and Bezuglova, et al. [44]
Control 1 repetition	0.62±0.2	humate-fulvate
Biochar 1 kg/m ² 1 repetition	0.79±0.1	
Biochar 3 kg/m ² 1 repetition	0.86±0.1	
Control 2 repetition	0.96±0.2	
Biochar 1 kg/m ² 2 repetition	0.95±0.2	
Biochar 3 kg/m ² 2 repetition	0.99±0.1	
Control 3 repetition	0.61±0.1	
Biochar 1 kg/m ² 3 repetition	0.89±0.2	
Biochar 3 kg/m ² 3 repetition	0.91±0.2	

The humate-fulvate type of humus is characterized by more stable forms of organic matter, indicating better carbon conservation and higher quality organic material when using biochar [41]. Table 2 shows that the ratio of carbon from humic acids to carbon from fulvic acids averages close to 0.6. When 1 kg/m² of biochar is added, this value increases, indicating an increase in the proportion of humic acids in the humus. When 3 kg/m² is applied, the humus type becomes closer to the fulvate-humate type (Table 2), indicating that biochar helps increase the stable carbon content in the soil humus, confirming its positive effect on organic carbon conservation.

In addition to organic carbon, humus also contains nitrogen, which is one of the essential elements for the vital activity of plants and microorganisms in soil. Nitrogen is a component of amino acids, proteins, and nucleic acids, ensuring the growth and development of plants.

Nitrogen in soil exists in both organic and mineral forms, and its availability for plants depends on processes such as mineralization and immobilization, which are related to the amount and quality of organic matter in the soil [41].

The ratio of carbon to nitrogen in soil is an important indicator of its nutrient balance and biological activity. Optimal C/N ratios ensure the decomposition of organic matter and the availability of nitrogen for plant growth. A high C/N ratio may indicate delayed decomposition and potential nitrogen deficiency, while a low ratio suggests a faster nitrogen cycle and increased availability [41].

The total nitrogen content in the soils under study varies slightly, ranging from 0.5% to 0.6%. The C/N ratio also varies, ranging from 4.6 to 6.9, indicating a moderate balance between carbon and nitrogen. On average, the nitrogen content is 0.6% in the control plots, and 0.5% in plots with biochar doses of 1 and 3 kg/m².

We see that biochar primarily affects the carbon content of the soil, which in turn affects the availability and assimilation of organic matter by microbial and plant communities at the tested plots.

The soil acidity index is an important parameter that affects plant growth and development. Most plants prefer a neutral pH, and the most active transition of macro- and micronutrients into an accessible form occurs at pH between 6.0 and 7.5. Therefore, the acid-base properties of soil are a key factor in determining the chemical, biological, and physical characteristics of the soil [45].

An important factor for the formation and accumulation of organic matter in soil is the pH of the environment. This affects the composition and abundance of microbial communities and the availability of nutrients for plants. The brown soils of the southern Far East, for example, are traditionally characterized by an acidic environment [43]. It has been noted that adding alkaline biochars to these acidic soils can increase pH levels [46, 47].

Studies have shown that the actual soil acidity measurements in all experimental variants did not show any significant deviations during the observation period. The values ranged from 6.29 to 6.49, corresponding to a slightly acidic medium. In plots without biochar, the average acidity was 6.42. In plots with biochar applied at a dose of 1 kg/m², the average was 6.41. And in plots with a higher dose of biochar (3 kg/m²), the average was slightly lower, at 6.38. These results indicate that biochar did not significantly affect the pH of the soil.

In addition to assessing the chemical properties of soils in plots undergoing reclamation, we also recorded morphological changes in soil parameters, indicating the formation of a humus horizon. Before the start of the reclamation experiment, the surface humus horizon was completely absent. After the formation of the surface horizon and the sowing of grasses in 2023 and 2024, the average thickness of the humus layer in all plots was approximately 1.5 centimeters (Figure 3).

The initial formed surface horizon had a lumpy structure with aggregates ranging in size from 10 to 50 millimeters and a medium loamy composition inherited from the underlying median horizon of natural soils. By 2025, the structure of the surface horizon had begun to include smaller aggregates, approximately 5-10 millimeters in size. The granulometric composition had not changed significantly during the course of the experiment, indicating that a longer period of time may be needed for the accumulation of fine particles.



Figure 3.
Anthropogenic disturbed soil of Russky Island.

An assessment of carbon dioxide gas exchange in the soil-atmosphere system at the plots studied in 2023 revealed that the introduction of biochar reduces carbon dioxide fluxes from the soil. The greatest reduction in carbon dioxide flux was observed in August at the plot where biochar was applied at a dose of 3 kg/m^2 , with a decrease of 71.1% compared to the control. The smallest reduction in carbon dioxide emissions occurred in November at the plot treated with biochar at a dose of 1 kg/m^2 , resulting in a reduction of 12.1% compared with the untreated control. These findings indicate that biochar application reduces carbon dioxide emissions, which can be seen as an indicator of increased binding potential in the soil. This is positive for soil restoration, as it indirectly indicates increased soil fertility [48].

According to the results of measurements of carbon dioxide gas exchange in the soil-atmosphere system in reclaimed plots in 2024, the effect of biochar on the joint cultivation of grass mixtures (18% blue alfalfa, 67% red clover, 15% black hedgehog) has increased the flow of CO_2 . On average, from May to November 2024, the CO_2 flux in plots with biochar was 36.7% higher than in the control plot, and 56% higher in the canopy of a forest under anthropogenic influence. There was no significant difference in the CO_2 flux between the plots with 1 kg/m^2 of biochar addition and the plots with 3 kg/m^2 addition. The average CO_2 flux value in the plot with 1 kg/m^2 biochar addition was $726.2 \text{ mg (CO}_2\text{) m}^2\text{/h}$ and $714 \text{ mg (CO}_2\text{) m}^2\text{/h}$ in the plot with 3 kg/m^2 .

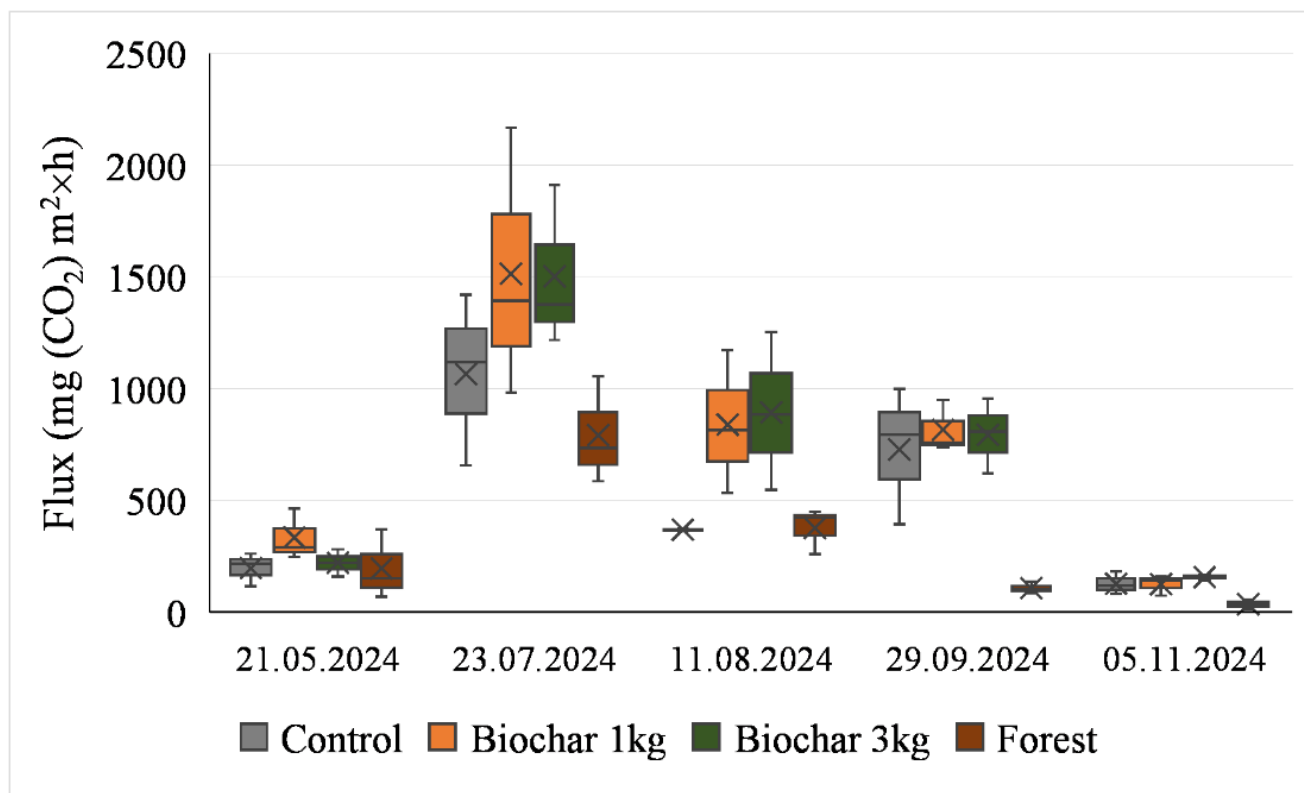


Figure 4. CO₂ fluxes at remediation plots from May to November 2024. Experimental options: without biochar (Control), with 1 kg/m² of biochar (1 kg/m²) and 3 kg/m² (3 kg/m²), forest under anthropogenic load (Forest).

CO₂ fluxes are positively correlated with soil temperature and humidity. The highest values of CO₂ flux were observed in July, when soil temperatures and humidity were at their highest levels. The lowest CO₂ flux values were recorded in November.

The correlation between CO₂ flux and soil temperature and humidity is more significant in plots under forest canopies. During the study period, CO₂ flux under forest canopies had the lowest values, ranging from 36.4 to 792.8 mg (CO₂) m²/h. There was no significant difference in CO₂ flux between the control plot and under forest canopies in May, July, and August. However, in September and November, CO₂ flux was significantly lower under forest canopies, likely due to lower soil temperatures.

According to the results of measurements taken in 2023, the use of biochar in degraded plots, combined with the cultivation of oats, led to a reduction in CO₂ emissions in those plots. This was measured by comparing the CO₂ flux at the treatment plots with that of control plots, which had similar flux values. The resulting difference in the results between 2023 and 2024 may be due to the development of microbiological processes and the type of vegetation grown. In 2024, grass mixtures were planted at the plots, which had a larger amount of biomass and more robust root systems than oats.

4. Conclusion

Studies have shown that prior to the start of the reclamation experiment, the surface humus horizon was completely absent. In 2025, the average capacity of the humus horizon in all plots was approximately 1.5 centimeters. A positive increase in humus horizon capacity was observed in variants with biochar addition.

Regarding acid-base properties, the addition of biochar did not significantly affect the pH of the soil environment. The organic carbon content on experimental plots with biochar was higher compared to control plots.

The Cha/Cfa ratio increased with the introduction of biochar, indicating that it contributes to an increase in stable carbon content in the soil humus layer, confirming the positive effect of biochar on organic carbon conservation. Additionally, the type of humus shifted towards a more stable humate-fulvate composition, further confirming the positive impact of biochar.

The average nitrogen content varied slightly. According to the results of measuring soil respiration in reclaimed plots in 2024, the effect of biochar on the flow of CO₂ increased during joint cultivation of a grass mixture. On average, from May to November 2024, CO₂ flux in plots with biochar was 36.7% higher than in the control plot, and 56% higher under the canopy of a forest under anthropogenic influence. There was no significant difference in CO₂ flux between the plot with 1 kg/m² of biochar addition and the plot with 3 kg/m² addition. The difference in results between 2023 and 2024 measurements could be due to the development of microbiological processes and type of vegetation (the grass mixture in 2024 plots had more biomass and a stronger root system than oats).

References

- [1] M. Chaurasia, K. Patel, R. Bhadouria, and K. Rao, "Spatial variability in soil physicochemical parameters across land use classes in the peri-urban landscape: M. Chaurasia et al.," *Environment, Development and Sustainability*, vol. 26, no. 10, pp. 24791-24815, 2024, <https://doi.org/10.1007/s10668-023-03653-8>.
- [2] D. L. Herrmann, L. A. Schiffman, and W. D. Shuster, "Urbanization drives convergence in soil profile texture and carbon content," *Environmental Research Letters*, vol. 15, no. 11, p. 114001, 2020, <https://doi.org/10.1088/1748-9326/abb00>.
- [3] B. Minasny, U. Stockmann, A. E. Hartemink, and M. A. B., *Digital soil morphometrics measuring and modelling soil depth functions*. Berlin: Springer, 2016.
- [4] M. McDaniel, G. L. Thompson, and P. Sauer, "Decompaction and organic amendments provide short-term improvements in soil health during urban, residential development," *Journal of Soil and Water Conservation*, vol. 79, no. 4, pp. 169-179, 2024, <https://doi.org/10.2489/jswc.2024.00111>.
- [5] D. L. Herrmann, L. A. Schiffman, and W. D. Shuster, "Widespread loss of intermediate soil horizons in urban landscapes," *Proceedings of the National Academy of Sciences*, vol. 115, no. 26, pp. 6751-6755, 2018, <https://doi.org/10.1073/pnas.1800305115>.
- [6] S. DeVilleneuve, A. Kelly, N. Miyanaka, T. Shanmuhasundaram, P. Murphree, and B. M. Wyatt, "Impacts of vegetation and topsoil removal on soil erosion, soil moisture, and infiltration," *Agrosystems, Geosciences & Environment*, vol. 6, no. 3, p. e20402, 2023, <https://doi.org/10.1002/agg2.20402>.
- [7] N. Mamehpour, S. Rezapour, and N. Ghaemian, "Quantitative assessment of soil quality indices for urban croplands in a calcareous semi-arid ecosystem," *Geoderma*, vol. 382, p. 114781, 2021, <https://doi.org/10.1016/j.geoderma.2020.114781>.
- [8] S. Sandil and R. Kumar, *Ecological and health effects of building materials soil contamination from construction projects*. Cham: Springer, 2021.
- [9] O. Gordienko and A. Kulik, "Effects of recreational and residential functional land use on urban soils," *Hungarian Geographical Bulletin*, vol. 73, no. 2, pp. 131-146, 2024, <https://doi.org/10.15201/hungeobull.73.2.2>.
- [10] Y. Gao et al., "Influence of highway construction of alpine grassland area in Gannan on soil properties and microbiota," *Scientific Reports*, vol. 15, no. 1, p. 22964, 2025, <https://doi.org/10.1038/s41598-025-06867-0>.
- [11] P. Raupp, Y. Carrillo, and U. N. Nielsen, "Soil health to enhance ecological restoration and conservation," *Journal of Sustainable Agriculture and Environment*, vol. 3, no. 4, p. e70022, 2024, <https://doi.org/10.1002/sae2.70022>.
- [12] G. C. Percival, S. Graham, C. Percival, and D. Challice, "Evaluation of nature-based and traditional solutions for urban soil decompaction," *Arboriculture & Urban Forestry*, vol. 51, no. 4, pp. 297-313, 2025, <https://doi.org/10.48044/jauf.2025.012>.
- [13] S. Joseph et al., "How biochar works, and when it doesn't: A review of mechanisms controlling soil and plant responses to biochar," *Gcb Bioenergy*, vol. 13, no. 11, pp. 1731-1764, 2021, <https://doi.org/10.1111/gcbb.12885>.
- [14] Z. Zou et al., "Response of plant root growth to biochar amendment: A meta-analysis," *Agronomy*, vol. 11, no. 12, p. 2442, 2021, <https://doi.org/10.3390/agronomy11122442>.
- [15] Y. Dai, H. Zheng, Z. Jiang, and B. Xing, "Combined effects of biochar properties and soil conditions on plant growth: A meta-analysis," *Science of The Total Environment*, vol. 713, p. 136635, 2020, <https://doi.org/10.1016/j.scitotenv.2020.136635>.
- [16] S. Ravinuthala, R. Nithya, and S. P. Das, "Application of biochar for wastewater treatment," *BioChar: Applications for Bioremediation of Contaminated Systems*, vol. 185, 2022.
- [17] S.-H. Jien and C.-S. Wang, "Effects of biochar on soil properties and erosion potential in a highly weathered soil," *Catena*, vol. 110, pp. 225-233, 2013, <https://doi.org/10.1016/j.catena.2013.06.021>.
- [18] B. Gholamhadi et al., "Biochar impacts on runoff and soil erosion by water: A systematic global scale meta-analysis," *Science of the Total Environment*, vol. 871, p. 161860, 2023, <https://doi.org/10.1016/j.scitotenv.2023.161860>.
- [19] D. P. Kushwaha and A. Kumar, "A review on biochar-based restoration of degraded soils through effective preparation and application," *International Journal of Plant & Soil Science*, vol. 37, no. 6, pp. 526-537, 2025.
- [20] Y. Li, J. Yang, M. Yang, and F. Zhang, "Exploring biochar addition impacts on soil erosion under natural rainfall: A study based on four years of field observations on the Loess Plateau," *Soil and Tillage Research*, vol. 236, p. 105935, 2024, <https://doi.org/10.1016/j.still.2023.105935>.
- [21] P. Conte, C. Librici, A. Nicosia, V. Palmeri, V. Pampalone, and V. Ferro, "Wood-biochar influence on rill erosion processes and hydrological connectivity in amended soils," *Hydrological Processes*, vol. 39, no. 2, p. e70093, 2025, <https://doi.org/10.1002/hyp.70093>.
- [22] X. Yuan et al., "Biochar effects on aggregation and carbon-nitrogen retention in different-sized aggregates of clay and loam soils: A meta-analysis," *Soil and Tillage Research*, vol. 247, p. 106365, 2025, <https://doi.org/10.1016/j.still.2024.106365>.
- [23] M. Ghorbani and E. Amirahmadi, "Insights into soil and biochar variations and their contribution to soil aggregate status—A meta-analysis," *Soil and Tillage Research*, vol. 244, p. 106282, 2024, <https://doi.org/10.1016/j.still.2024.106282>.
- [24] H. Singh, B. K. Northup, C. W. Rice, and P. V. Prasad, "Biochar applications influence soil physical and chemical properties, microbial diversity, and crop productivity: A meta-analysis," *Biochar*, vol. 4, no. 1, p. 8, 2022, <https://doi.org/10.1007/s42773-022-00138-1>.
- [25] C. J. Ennis, A. G. Evans, M. Islam, T. K. Ralebitso-Senior, and E. Senior, "Biochar: Carbon sequestration, land remediation, and impacts on soil microbiology," *Critical Reviews in Environmental Science and Technology*, vol. 42, no. 22, pp. 2311-2364, 2012, <https://doi.org/10.1080/10643389.2011.574115>.
- [26] J. Bai, B. R. D. A. Moreira, Y. Bai, C. G. Nadar, Y. Feng, and S. Yadav, "Assessing biochar's impact on greenhouse gas emissions, microbial biomass, and enzyme activities in agricultural soils through meta-analysis and machine learning," *Science of the Total Environment*, vol. 963, p. 178541, 2025, <https://doi.org/10.1016/j.scitotenv.2025.178541>.
- [27] M. J. Vahidi, M. H. S. Zahan, F. A. Atajan, and Z. Parsa, "The effect of biochars produced from barberry and jujube on erosion, nutrient, and properties of soil in laboratory conditions," *Soil and Tillage Research*, vol. 219, p. 105345, 2022, <https://doi.org/10.1016/j.still.2022.105345>.
- [28] H. Lyu et al., "Biochar affects greenhouse gas emissions in various environments: A critical review," *Land Degradation & Development*, vol. 33, no. 17, pp. 3327-3342, 2022, <https://doi.org/10.1002/ldr.4405>.
- [29] R. Zhang, X. Zhao, C. Zhang, and J. Li, "Impact of rapid and intensive land use/land cover change on soil properties in arid regions: a case study of Lanzhou new area, China," *Sustainability*, vol. 12, no. 21, p. 9226, 2020, <https://doi.org/10.3390/su12219226>.

- [30] Y. Zhao *et al.*, "Comparative biotic and abiotic effects on greenhouse gas emissions from agricultural ecosystems: application of straw or biochar?," *Environmental Science and Pollution Research*, vol. 30, no. 52, pp. 112307-112320, 2023, <https://doi.org/10.1007/s11356-023-30099-2>.
- [31] Y. He *et al.*, "Effects of biochar application on soil greenhouse gas fluxes: A meta-analysis," *Gcb Bioenergy*, vol. 9, no. 4, pp. 743-755, 2017, <https://doi.org/10.1111/gcbb.12376>.
- [32] M. A. Bovsun *et al.*, "Effect of biochar on soil CO₂ fluxes from agricultural field experiments in Russian Far East," *Agronomy*, vol. 11, no. 8, p. 1559, 2021, <https://doi.org/10.3390/agronomy11081559>.
- [33] G. W. Thomas, *Soil pH and soil acidity. Methods of soil analysis. SSSA book series*. Hoboken: John Wiley & Sons. Ltd, 1996.
- [34] A. Walkley, "An examination of methods for determining organic carbon and nitrogen in Soils1.(With one text-figure.)," *The Journal of Agricultural Science*, vol. 25, no. 4, pp. 598-609, 1935.
- [35] A. Walkley and I. A. Black, "An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method," *Soil Science*, vol. 37, no. 1, pp. 29-38, 1934, <http://dx.doi.org/10.1097/00010694-193401000-00003>.
- [36] I. Bashour and A. Sayegh, *Methods of analysis for soils of arid and semi-arid regions*. Beirut: FAO, 2007.
- [37] M. Dergacheva, E. Kovaleva, and N. Ryabova, "Humus of soils of the Altai Mountains," *Eurasian Soil Science*, vol. 40, no. 12, pp. 1264-1269, 2007, <https://doi.org/10.1134/S1064229307120022>.
- [38] C. I. Mathieu and F. Pieltain, *Physical analysis of soils. Methods chosen*. Paris: TEC et DOC Lavoisier, 1998.
- [39] E. A. Zharikova, "Heavy metals in urban soils: Assessment of content and environmental risk," *Bulletin of the Tomsk Polytechnic University. Geo Assets Engineering*, vol. 332, no. 1, pp. 164-173, 2021.
- [40] M. Ahmad *et al.*, "Biochar as a sorbent for contaminant management in soil and water: a review," *Chemosphere*, vol. 99, pp. 19-33, 2014, <https://doi.org/10.1016/j.chemosphere.2013.10.07>.
- [41] E. V. Arinushkina, *Guide to chemical analysis of soils*. Moscow: Moscow State University Publishing House, 1970.
- [42] O. Biryukova and D. Orlov, "Content and composition of humus in the main soil types of Russia," *Eurasian Soil Science*, vol. 37, pp. 143-158, 2004.
- [43] E. A. Zharikova, "Soils of Vladivostok: Main characteristics and properties," *Bulletin of the Far Eastern Branch of the Russian Academy of Sciences*, vol. 3, pp. 67-73, 2012.
- [44] O. Bezuglova, A. Komarov, and A. Komarov, "Identification of humic substances on the transformation of an organic substrate," *Eurasian Journal of Soil Science*, vol. 11, no. 1, pp. 10-16, 2022, <https://doi.org/10.18393/ejss.974224>.
- [45] V. D. Mukha, N. I. Kartamyshv, and D. V. Mukha, *Agrosoil science: Textbook for universities*. Moscow, Russia: KolosS, 2003.
- [46] N. Wang, Z. Cui, L. Xu, J. Ma, R. Yu, and Y. Wang, "Effects and mechanisms of biochar derived from different biomass sources on mitigating soil acidification," *Agronomy*, vol. 15, no. 11, p. 2523, 2025, <https://doi.org/10.3390/agronomy15112523>.
- [47] F. Sui, Y. Qi, J. Ma, L. Cui, G. Quan, and J. Yan, "S-Rich biochar enhances cd immobilization by boosting fe transformation under decreasing pe+ pH conditions," *Agronomy*, vol. 15, no. 10, p. 2423, 2025, <https://doi.org/10.3390/agronomy15102423>.
- [48] O. V. Nesterova, V. V. Nesterov, M. A. Bovsun, and A. V. Brikmans, "Reclamation of disturbed soils through the application of biochar," in *Scientific Research of the SCO Countries: Synergy and Integration: Proceedings of the International Conference (pp. 99-102)*. Beijing, China, 2023.