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ОЦЕНКА ПРИМЕНИМОСТИ ОСАДКА СТОЧНЫХ ВОД В КАЧЕСТВЕ ДОБАВКИ К ПОЧВЕ ДЛЯ РЕКУЛЬТИВАЦИИ ЗЕМЕЛЬ, ОБРАЗОВАННЫХ ПРИ ДОБЫЧЕ ПОЛЕЗНЫХ ИСКОПАЕМЫХ

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Аннотация: дефицит органического вещества является одним из ключевых препятствий при рекультивации техногенно нарушенных земель, образованных в результате разработки месторождений твердых полезных ископаемых. В качестве эффективного эколого-экономического решения предлагается рекультивировать отработанные земли с применением органической добавки к почве — осадка сточных вод целлюлозно-бумажной промышленности. В статье представлены результаты первичной оценки почвенных субстратов, улучшенных внесением осадка сточных вод и торфосмесью путем анализа воздействия на растительный покров (в лабораторных условиях при контролируемых микроклиматических параметрах). Кроме того, в статье представлены методы оценки роста и развития растений и предложен альтернативный подход к оценке роста растений (биомассы) путем анализа цифровых изображений при сохранении анализируемого растительного материала.

Ключевые слова: мелиорант, биомасса, растительный покров, анализ изображений, индекс листовой поверхности, техноземы.

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The evaluation of sewage sludge as soil amendment for post-mining land rehabilitation

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Abstract: The lack of organic matter is one of the key difficulties in the reclamation of technogenically disturbed lands formed in the mineral deposits' development areas. As a solution, it is proposed to reclaim post-mining lands with the use of organic soil additive — sewage sludge of the pulp and paper industry. The article presents the results of the primary assessment of soil substrates improved with pulp and paper mill sewage sludge and peat moss (in comparison) by analysing the effect on the vegetation cover (pot experiments under controlled microclimate conditions). Additionally, this article presents primary methods for assessing plant growth and development and digital image analysis as a non-destructive sampling method for assessing plant growth (biomass).

Key words: Amendment, Biomass, Green cover, Image analysis, Leaf area index, Technosols.

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The largest group (by origin) of disturbed lands belongs to industrial lands (over 40%); by 2020, about 437 thousand hectares of technologically disturbed lands have been accumulated in the Russian Federation.[1, 2]. Post-mining lands are mostly large-scale and hard-to-recover objects, primarily quarries, dumps, tailings containment and waste storage facilities, and others lands contaminated by industrial waste [3, 4].

Initially, it is necessary to obtain information about the ecological state of the land [4.1].The function of natural recovery of disturbed ecosystems (lands) is highly debilitated. Reclamation of disturbed lands is often complicated by various obstacles, particularly: unsuitable natural and climatic conditions, unique features of local abiotic factors, abnormal values of physical and chemical or biological properties.

Lands disturbed by open-pit mining are characterised by increased labour-intensity of reclamation works associated with the need to form the previously removed fertile soil layer. Measures to restore the soil-ground horizons include relief recreation, ground and soil layers application, melioration, fertilisation, irrigation, and drainage. However, despite the measures taken, the organic matter deficiency remains in these lands[5].

Organic matter is one of the crucial soil factors of humus formation, increasing soil fertility and sustainable functioning of soil and vegetation complexes [6]. Therefore, when reclaiming technologically disturbed and polluted lands it is necessary to restore the optimal content of organic matter by introducing soil additives, various fertilisers, and ameliorants [7,8].

Sewage sludge-based soil additive is proposed as a solution. Municipal sewage sludge is actively used for rehabilitation of disturbed lands, reforestation, and as fertiliser on agricultural lands [7, 9, 10]. However, municipal sewage sludge poses a high environmental risk due to pathogens (bacteria, viruses, and parasites). Mandatory treatment to reduce the biological hazard is required.

Sludge from industrial wastewater treatment systems has different properties and composition due to the specifics of production. In this regard, chemical stabilization treatment is required; the applicability of which is assessed separately by the characteristics of the reclamation potential and environmental safety (in terms of the content of heavy metals and harmful chemicals).

One of the options for assessing soil amendments (reclamation potential and environmental safety) is to analyse their impact on plant communities by modelling soil-vegetation complexes [11]. Assessment of plants' response to changes in the growing environment is carried out by analysing the growth and reproductive development of plants using two methods: time-response and dose-response [10]. Measured parameters of plants can be physical quantities of plant growth and reproductive development (germination, growth dynamics, stem height, leaf length, flower diameter, biomass, etc.), and external signs of damage (visual indicators — plant pigmentation, chlorosis, and necrosis, etc.).

Analysis of physical values and visual indicators can be processed at all stages of the growing season [12].

A pot experiment under controlled microclimate conditions was conducted based on the assessment method of plants' response to the growth environment. The experiment included: the dynamics of growth and the total terrestrial biomass assessment.

The results of an earlier study (simulation of soil reclamation treatment) showed the probable presence of ameliorative (fertilising) potential of the proposed soil additive (sewage sludge) without phytotoxicity effects [13].

Assessment of vegetation biomass growth. The analysis of total biomass in the primary simulations was carried out by measuring the green mass of the aboveground part of the grass cover from each model at the end of the exponential period of plant growth. The analysis method used with the destruction of plant material is low-informative, material- and time-consuming, and requires many models to validate the results [12,14, 15].

A similar method of analysing plant growth and reproductive development is Digital Image Analysis (DIA) [16–19]. DIA is carried out without destroying the sample (plant material) and can reflect on an increase in biomass over time [14, 15]. This method is widely used in agriculture, agrochemistry, biology, etc. [20].

The method is based on the processing RGB (Red, Green, Blue) images of vegetation cover and consists of the following steps:

— removal of background (soil, stones, various inclusions, etc.) [21–23],

— recalculation [23] and classification [20],

— information processing based on color correction [14, 22],

— measurements of physical quantities to be determined (e. g., line length — for roots, plant growth height, roundness — crop or seed quality, number of pixels, roundness and lines — for biomass, seeds, and shoots counts) [22,24].

Materials and methods

The experimental scheme includes: (1) creating models with different compositions selected from previous studies [13] and (2) assessing the effect on herbaceous plants –to determine the optimal application rates and assess the potential effect of the soil additive. The experiment was conducted with two types of soil additives: pulp and paper mill sewage sludge and peat moss (as an alternative additive).

Materials

1. Sewage sludge from the pulp and paper industry. The sludge was taken from the biological wastewater treatment system (from the sulfite pulping process). Sewage sludge is a grey mass, consisting mainly of excess activated sludge with various possible inclusions: lignin substances, alumina, cellulose fibre, etc. [13].

2. Peat. Peat mixture as one of the most common soil was taken as an alternative experimental unit for comparison.

The peat moss used is a commercial product (of natural origin) — sphagnum peat with a medium degree of decomposition, and with modification to improve the characteristics of the substrate — with the addition of lime (100–180 mg/l — N (NO_3 + NH_4), 135–255 mg/l — P (P_2O_5), 115–215 mg/l — K (K_2O) and pH ~ 5,0–6,0).

3. Soil. Control group –natural soil (> 80% 0.05–2 mm — sandy soil), which was sampled in the field-protecting area of agricultural land in the Leningrad Region (N60.2811, E30.2342).

4. Plant material. The effect of various soil additives was assessed on two plant species (Poaceae family): ryegrass *Lolium perenne* and meadow fescue *Festuca*

pratensis with the rate of seeding grass mixture — 20 centner/ha.

Experimental setup

Experimental setup was a set of soil and plant models (in perforated seedling bags 15x15 cm and 40 cm high) with phytolamps of light (full spectrum illumination — 35W) to provide the necessary lighting conditions.

Based on initial modeling results, optimal microclimatic parameters were determined as T>20ºC; W (atm.) <50%, W (soil) <80%. Each experimental model of soil-plant complex was formed in a perforated seedling bag (15x15 cm and 40 cm high). Soil additives were in three ratios (by volume) — 1:1, 1:2, 1:3 (sediment / peat: soil). Ratios were established based on: (1) recommendations for peat moss addition, (2) recommendations for optimum soil density for herbaceous plants, (3) literature review, and (4) results of preliminary substrate analyses. After the soil complexes were stabilised (within a week), grass seeds were sown in each model.

Method 1. Measurement of biomass (with the destruction of plant material). On the 14th day (after the seeding), the grass cover was cut (5 cm from the ground) in each model of soil-vegetation complex, and then the wet grass mass was measured.

Method 2. DIA (without destruction of plant material). Biomass indicator* estimation by digital image analyses was carried out using ImageJ software (Java-based open-source software ImageJ 1.40g). The DIA method for calculating biomass* consists of processing and differentiating grass cover images into two colour groups corresponding to "green" ground cover and "non-green" ground cover, with the calculation of "green" coverage units [14]. An example of the images resulting from DIA preparation is shown in Fig. 1.

*Biomass was estimated based on the Leaf Area Index (LAI). The index

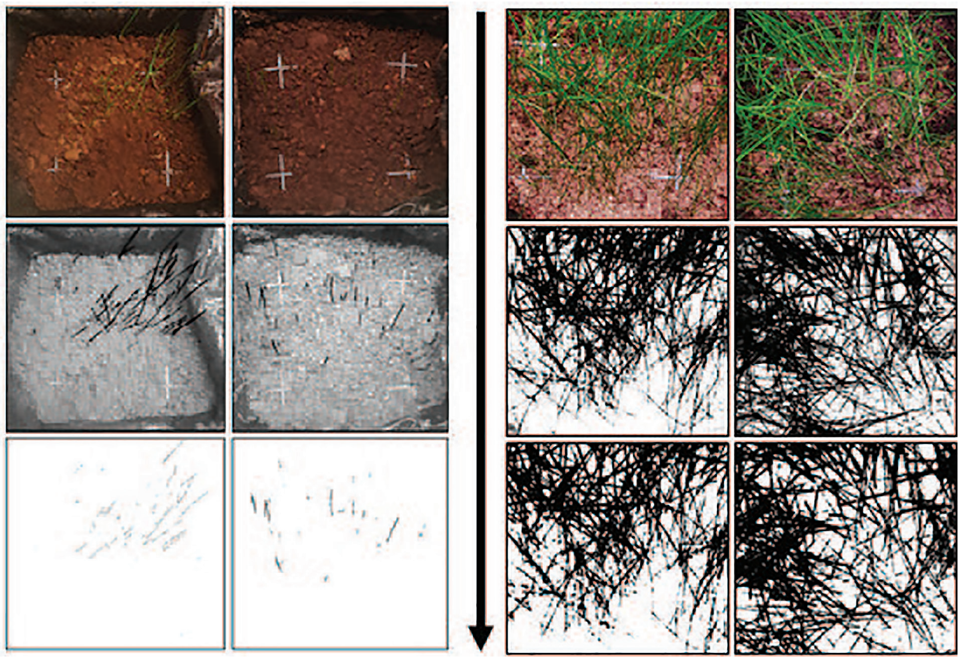

Fig. 1. Examples of image processing results (for DIA)

characterises vegetation cover as the area of vegetation cover per unit surface area (land). This value is dimensionless, reflecting the projected area of the vegetation unit (LAI = leaf area/land area, m^2/m^2) [14, 22]

Results and discussion

1. Results of biomass measurements (with destruction of plant material). The results of the biomass estimation based on the first cut showed that the ratio in the growth medium (soil and additive) plays a more critical role than the type of substrate used as a soil additive (peat moss or sewage sludge). Nevertheless, sewage sludge mixtures are several times inferior to soil-plant complexes with peat moss with equal substrate ratios. The values of control biomass (wet plant mass from control models) were able to approach the results of models with the following ratios:

— Soil models supplemented with peat moss (ratios 1: 2 and 1: 3)

— Soil models supplemented with sewage sludge (ratio 1: 3).

The measurement results are shown in Fig. 2.

2. DIA results (without plant material destruction). Biomass estimation* analysis with DIA is based on LAI. This method gave a similar result — a stronger dependence of biomass on the ratio of soil additives applied, which could potentially be associated with a better soil layer density. The closest values of biomass* (to control) were achieved in models with ratios of:

— Soil models with the addition of peat moss (ratios 1: 2 and 1: 3);

— Soil models with the addition of sewage sludge (ratio 1: 3).

A graphical representation of the results is shown in Fig. 3.

Comparison of two methods of plant biomass estimation: (1) method with plant material destruction (measurement of cut biomass) and (2) method without material destruction (using DIA) — to evaluate the effectiveness of the DIA method was carried out in MS Excel software using Pearson correlation analysis (Fig. 4).

The results of the study showed a high correlation between these two methods. Significant deviations were noted in the samples with an increase in the biomass of the grass cover. This again indicates that the accuracy of the analysis results is lost with increasing vegetation units [14,15,22, 25].

Conclusions

Sewage sludge is an available alternative soil supplement with a high organic matter content. Municipal sewage sludge is actively

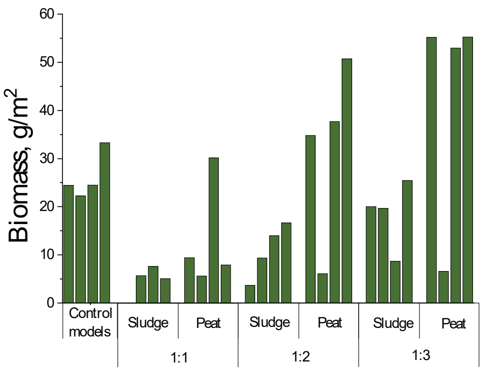

Fig. 2. Graph of biomass measurement results, g/m2 (with destruction of plant material)

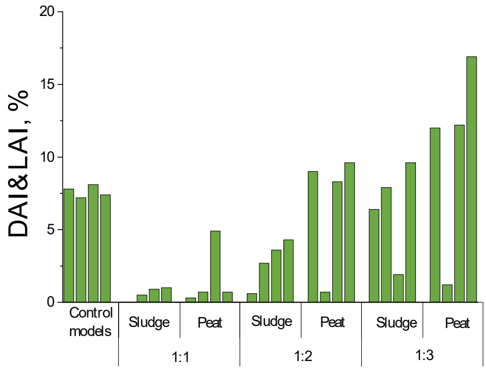

Fig. 3. Graph of DIA results (without plant material destruction)

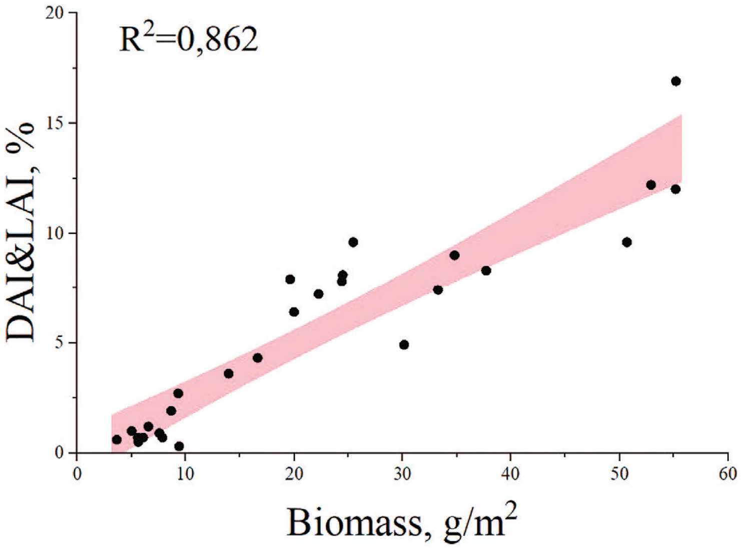

Fig. 4. Relationship between wet plant weight (biomass) and projected plant area (DIA & LAI)

used in the national economy and meets the principles of sustainable development and the circular economy model. Industrial sewage sludge differs in composition and property characteristics, and therefore it is more complicated to implement into economic use.

This research workproposes to use sewage sludge in technologically disturbed lands of post-mining areas to compensate the deficit of organic matter and restore the soil and vegetation complex.

At this stage, the potential of sewage sludge as an organic soil additive is considered in comparison with a commercial additive based on peat moss. In the primary results of comparing soil additives and their effect on the formed soil cover, when plants enter the exponential growth stage, the ratio of the soil substrate (soil + peat / sewage sludge) plays a more critical role than the selected soil additives.

Biomass was chosen as the main parameter for soil additive effect assessment. The indicator (biomass) was analyzed by two methods: (1) method with destruction of plant material (measurement of cut wet biomass) and (2) method without destruction of material (using DIA & LAI). Both methods showed similar results ($R^2 > 0.85$) — the closest values of biomass* in comparison with the control model (soil) were achieved in models with ratios: 1:2 and 1:3 — peat moss additive and 1:3 sewage sludge additive.

No signs of phytotoxic effects from the used additives (chlorosis, necrosis, and plant death) were found.

Additional studies are needed to assess the impact of sewage sludge additives on soil physicochemical characteristics, plant growth and development of plants throughout the growing season, and the soil micro- and mesofauna.

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