Ecological assessment of the aftereffect of phosphogypsum on the stabilization of the carbon balance of the regenerated topsoil of degraded sod-podzolic soils

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Abstract. Against the background of global climate changes, agroecological problems of erosion and agrogenic degradation of intensively used arable soils have become more acute. This problem is most acute in the case of old-arable sod-podzolic soils with initially low humus content and small thickness of their sod horizons. Our research carried out with the support of project No. 075-15-2021-1030 of the Ministry of Science and Higher Education of Russia, provides investigation the influence of industrial waste in the production of phosphorous fertilizers - phosphogypsum on the stabilization of the carbon balance of the regenerated topsoil of degraded sod-podzolic soils. The research was carried out at the Agroecological Station of the Field Experimental Station of the Russian State Agrarian University - Moscow Timiryazev Agricultural Academy in fall of 2022 and in summer of 2023. The use of phosphogypsum in a dose of 1.5 t/ha contributed to the significant accumulation of organic carbon in the topsoil of the studied sod-podzolic soils – in comparison with the control. In combination with compost from bird dropping at a dose of 2.0 t/ha, the aftereffect of the use of phosphogypsum essentially increases, that indicates good prospects for the validation of this technology as a natural climate project.

1 Introduction

Against the background of global climate changes, agroecological problems of erosion and agrogenic degradation of intensively used arable soils have become more acute [1, 2].

The increased intensity and duration of less frequent spring and summer precipitation forms increased surface runoff and provokes accelerated erosion development with the loss of the most humus-rich fine-grained particles from topsoil [2]. The dry periods, that replace them, longer than before, [3] activate the processes of mineralization of soil organic matter and plant residues, further reducing humus reserves in topsoil [4]. Dishumification is usually accompanied by disaggregation and over-compaction of soil horizons with a decrease in their porosity and ability to quickly absorb precipitation, that often leads to further running of agrogenically accelerated erosion [5]. This problem is most acute in the case of old-arable sod-podzolic soils with initially low humus content and small thickness of their sod horizons [6]. The accelerated development of their erosion is often accompanied by a sharp drop in soil fertility and the need for bioremediation, as in the case of man-made disturbance of these soils in the zone of impact of construction and transport projects [7]. Lime-containing ameliorants are traditionally used to improve the structure and to stabilize the carbon balance of sod-podzolic soils [8]. Their principal disadvantages are the high cost of commercial ameliorants and the often-fixed increased content of heavy metals in using lime-containing industrial waste [9]. Our research provides investigation the influence of industrial waste in the production of phosphorous fertilizers - phosphogypsum on the stabilization of the carbon balance of the regenerated topsoil of degraded sod-podzolic soils.

Phosphogypsum is a by-product of the production of phosphorus fertilizers, which must be disposed of annually to reduce the negative impact on the environment at the place of its production and temporary storage [9, 10]. At the same time, phosphogypsum contains cations that contribute to the stabilization of humic compounds, and characterized by an increased concentration of macroelements of plant nutrition, including P and S [11], by the potential ability to regulate the reaction of the soil environment, plant nutrition conditions [12, 13] and microorganisms, the carbon state of soils and the mobility of pollutants.

Phosphogypsum is traditionally used for reclamation and neutralization of the alkaline reaction of saline soils [14-16], but there have been published papers with positive results of its application on podzolic soils - without significant acidification of their reaction [17].

Additional interest in such studies is caused by the problem of accelerated degradation of lawn ecosystems in conditions of increased recreational load on them at the

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megacities, where they play an important role in regulating the quality of the urban environment [18-21]. At the same time, most of the lawns artificially created on peat-sandy soils or overhauled with their use are characterized by increased instability of functioning in conditions of increased aeration of organic peat mass and high anthropogenic load [22-23], and therefore, they require regular updating of the soil material.

The usually increased instability and accelerated mineralization of organic matter of the most common lawn and regenerative soil-ground are associated with their peat-sand composition [24]. Peat in peat-sand mixtures, as a rule, decomposes rapidly with the formation of CO_2, increasing the total greenhouse gas emissions of urban ecosystems.

The addition of phosphogypsum to peat-sand soil substrates can contribute to the partial stabilization of their organic matter, neutralization of the soil pH and to the improvement the nutrition of lawn grass. This is important for prolonging the planned period of conservation of lawn and regenerative topsoil, reducing the cost of regeneration of eroded soils and lawn maintenance, as well as reducing the fluxes of greenhouse gases from the soil surface.

The goal of this paper is to give ecological assessment of the aftereffect of phosphogypsum on the stabilization of the carbon balance of the regenerated topsoil of degraded sod-podzolic soils in conditions of vegetation season with extremely high for Moscow region precipitation level in 2023.

2 Material and method

The research was carried out on the territory of the Agroecological Station of Field Experimental Station of the Russian State Agrarian University - Moscow Timiryazev Agricultural Academy (Fig. 1) in summer of 2023 with an extremely high precipitation (604 mm in May to August, that is 2 times more than the average long-term precipitation for this period - Table 1).

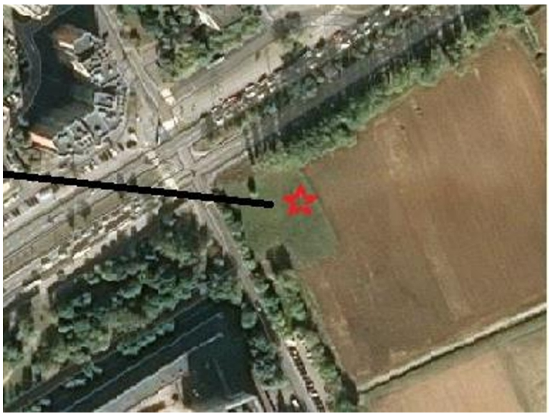


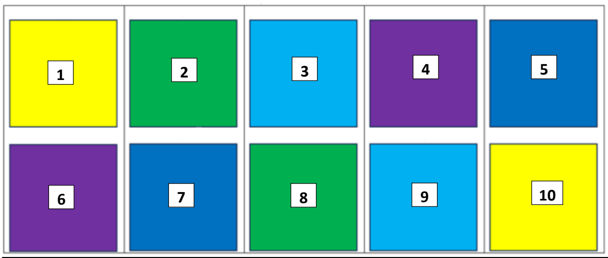
Fig. 1. The location of the Field demonstration experiment (55°50'24"N 37°33'02"E) at the Agroecological Station of the RSAU-MTAA.

Table 1. Weather conditions of the main growing season in 2023 in comparison with the average annual climatic data of the previous 12 years (2011-2022).

Month	De-cade	Average air temperature, °C			Precipitation amount, mm		
		2011-2022		2023	2011-2022		2023
May	1	13,6	8,6	13,9	61,0	10,6	73,3
	2		16,4			4,2	
	3		16,5			58,5	
June	1	17,3	15,8	18,1	77,0	35,1	140
	2		19,8			1,2	
	3		18,6			104	
July	1	19,7	21,7	19,4	84,0	6,1	305
	2		17,1			143	
	3		19,3			156	
August	1	17,6	24,1	20,6	78,0	0,2	126
	2		21,5			117	
	3		16,6			8,8	
May-August		17,1		18,0	300		644

The scheme of the micro-plot field experiment with plots of 4 m2 (2 m x 2 m - Fig. 2) included control variant (without the use of phosphogypsum), variants with an increasing doses of phosphogypsum (1.5, 3.0, 4.5 and 6.0 t/ha) and with the use of phosphogypsum in combination with compost from quail droppings (in doses of 4.5 t/ha + 2.0 t/ha and 6.0 t/ha + 2.0 t/ha), which were added to the peat-sand soil-ground (with a weight ratio peat to sand of 1 to 3) traditionally used in phytoremediation projects applied in a 15 cm layer to the surface of erosively degraded sod-podzolic soils.

In the seed method of lawn creation, a grass mixture was used with the following composition: pasture ryegrass (*Lolium perenne*) (40%), red Maxim 1 fescue (*Festuca rubra*) (40%), red Greenlight fescue (*Festuca rubra*) (10%), meadow bluegrass (*Poa pratensis*) (10%). Seeding rate: 200 g per plot.



Variant of the experiment	Phosphogypsum, t/ha	Compost, t/ha	Plot No.
I	-	-	1; 10
II	1,5	-	2; 8
III	3	-	3; 9
IV	4,5	2	4; 6
V	6	2	5; 7

Fig. 2. The location scheme of the micro-plot field experiment.

To carry out seasonal monitoring of CO_2 fluxes at all plots after the initial formation of the grass cover in

August 2022, the bases of the over-ground exposure chambers installed during the observation periods were installed (Fig. 3).

Fig. 3. The micro-plot field experiment with the bases of the over-ground exposure chambers.

Monitoring of organic carbon content in the topsoil, of soil regimes and of the dynamics of the growth of herbaceous biomass were carried out using traditional methods of agroecological monitoring [4, 5, 25] and land assessment [8, 27]. Monitoring of soil moisture and temperature conditions – using IoT sensors and portable electronic devices: a soil thermometer Checktemp 1 and a moisture meter Theratrobe HH2.

Determination of soil carbon dioxide emissions – using a portable gas analyzer LiCor-820 *in situ* [28]. Accounting of aboveground biomass and its growth rate – by the method of sequential mowing and IoT sensors CropTalker [5].

3 Results and discussion

The conducted studies have shown a relatively small, but statistically significant (even against the background of seasonal dynamics) decrease in comparison with the control variant of the bulk density of the turf topsoil (with a thickness of 6 cm) in 3 out of 4 variants of the phosphogypsum application (Fig. 4).

In the conditions of the summer season with a sharply increased amount of precipitation, changes in the soil moisture content of the turf topsoil are even more significant, but statistically significant only in case of phosphogypsum application without compost (Fig. 5).

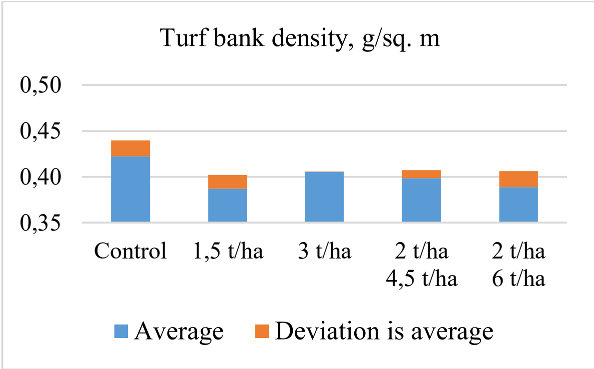


Fig. 4. Turf topsoil (0-6 cm) bulk density average for season values in the micro-plots of the field experiment with phosphogypsum (first line) and compost (second line).

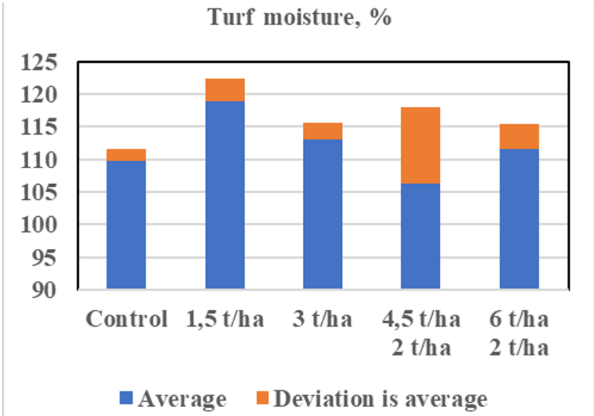


Fig. 5. Turf topsoil (0-6 cm) moisture average for season values in the micro-plots of the field experiment with phosphogypsum (first line) and compost (second line).

The initial content of organic matter at the beginning of the main growing season (Fig. 6, 04/28/2023) varies slightly and statistically insignificantly between the variants of the experiment.

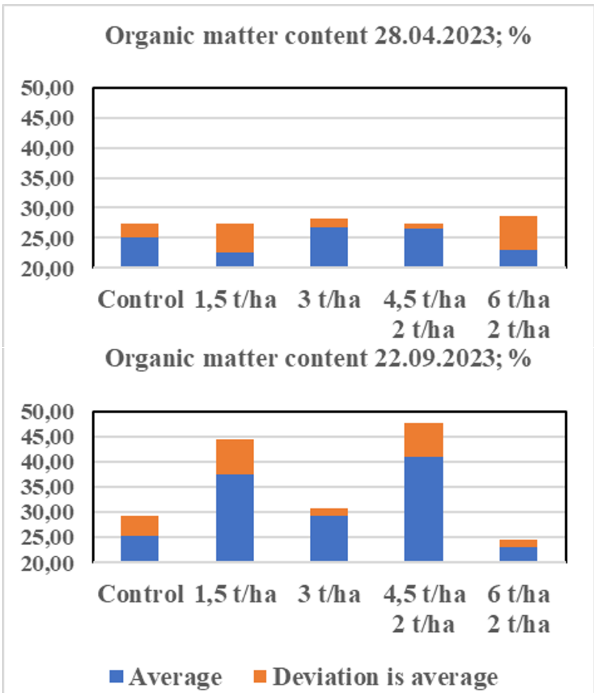


Fig. 6. Soil Organic matter content in the micro-plots of the field experiment with phosphogypsum (first line) and compost.

The maximum differences between their average values do not exceed 3.5% SOM (1.75% SOC), which is no more than 14 relative percent of the SOM content and is typical for peat-sandy soils [22, 23].

At the end of the main growing season (Fig. 6, 22.09.2023), 2 variants of the experiment (with 1.5 t/ha of phosphogypsum and with the phosphogypsum application in combination with compost from quail droppings in doses of 4.5 t/ha + 2.0 t/ha) showed statistically significant and pronounced even against the background of seasonal dynamics accumulation of organic matter in the turf topsoil (6 cm thick). At the same time, the content of organic matter in the control version remained almost unchanged.

In most of the studied variants of soil-grounds, the seasonal dynamics of soil CO_2 emission is pronounced (Fig. 7), measured during the daytime, in the period between 10 a.m. and 3 p.m.

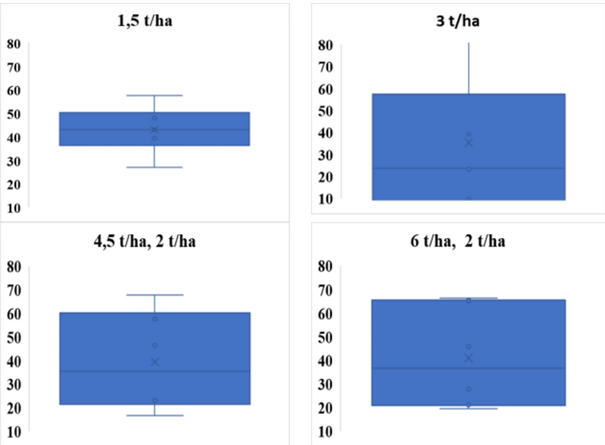


Fig. 7. Diagrams of the scope of seasonal dynamics of soil CO_2 emission by main variants of the micro-plot field experiment.

To a lesser extent, it is expressed in the variant of the experiment with 1.5 t/ha of phosphogypsum, which is characterized by a statistically significant increase in soil CO_2 emission (Fig. 8).

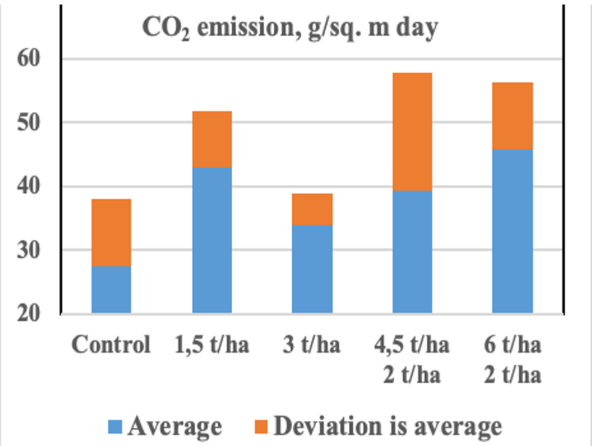


Fig. 8. Soil CO_2 emission average for season values in the micro-plots of the field experiment with phosphogypsum (first line) and compost (second line).

There are most pronounced between the experimental variants in the rate of formation of the above-ground grassy biomass (Fig. 9). In 3 variants of the experiment (with 1.5 t/ha of phosphogypsum and with the use of phosphogypsum in combination with compost from quail droppings in doses of 4.5 t/ha + 2.0 t/ha and of 6.0 t/ha + 2.0 t/ha), they are obviously statistically reliable and reach more than 4-multiple exceedances - with a relatively low variation between repetitions.

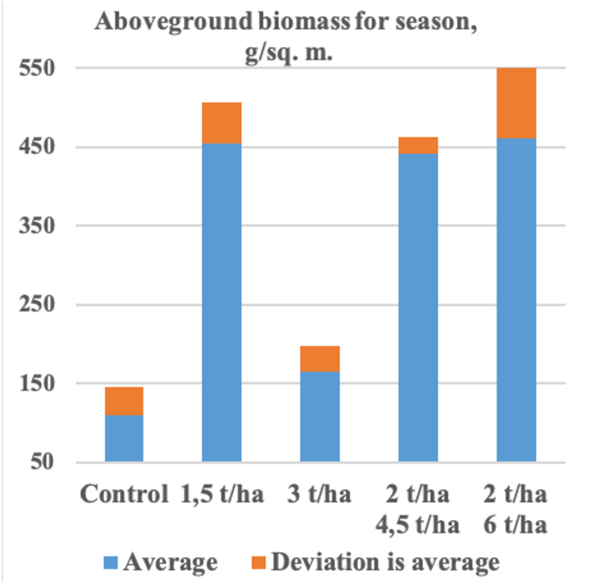


Fig. 9. Total for a season average values of the aboveground grass biomass in the micro-plots of the field experiment with phosphogypsum (first line) and compost (second line).

Summing up the seasonal accumulation of organic carbon in the turf topsoil (ΔCorg-s), in the aboveground grassy (∑Corg-gr) and its root biomass (∑Corg-r) minus the total carbon emissions for the season in the form of measured in situ soil CO_2 fluxes (∑C- CO_2) allows us to quantify integral carbon fluxes between the soil-plant systems studied in the field experiment and the surface layer of atmospheric air (Table 2).

Table 2. Assessment of the integral carbon fluxes between the soil-plant systems studied in the field experiment and the surface layer of atmospheric air.

Variant	ΔCorg-s, g/sq. m per season	∑Corg-gr, g/sq. m per season	∑Corg-gr, g/sq. m per season	∑C-CO_2, g/sq. m per season	Total carbon sink, g/sq. m per season
Control	11.5	55.2	16.6	903.1	-819.8
P-G 1,5 t/ha	1704.3	227.3	68.2	1409.8	590.0
P-G 3 t/ha	321.0	82.7	24.8	1109.8	-680.3
P-G 4,5 t/ha+ Comp 2 t/ha	1732.8	220.4	66.1	1288.8	730.5
P-G 6 t/ha + Comp 2 t/ha	3.8	230.9	69.3	1499.1	-1195.1

The analysis shows a pronounced change of the dominant soil CO_2 emission to the total atmospheric carbon sink in the experimental variants with 1.5 t/ha of phosphogypsum and with the use of phosphogypsum in combination with compost from quail droppings in doses of 4.5 t/ha + 2.0 t/ha.

This allows one to consider them as prototypes of the best available technologies for the regeneration of erosively degraded sod-podzolic soils, taking into account the phosphogypsum application aftereffect on the stabilization of carbon balance, the formation of large amount of herbaceous biomass and environmentally safe and profitable disposal of waste from the production of phosphorous mineral fertilizers.

4 Conclusion

The conducted studies have shown a relatively small, but statistically significant (even against the background of seasonal dynamics) decrease in comparison with the control variant of the bulk density of the turf topsoil (with a thickness of 6 cm) in 3 out of 4 variants of the phosphogypsum application for stabilization of the regenerated topsoil of degraded sod-podzolic soils in conditions of vegetation season with extremely high for Moscow region precipitation level in 2023. The study showed no signs of erosion and disturbances in the operation of the local hydrographic network, even during the most intense rains.

The use of phosphogypsum already in a dose of 1.5 t/ha contributed to the significant accumulation of organic carbon in the turf topsoil of the studied sod-podzolic soils – in comparison with the control. The use of a combination of phosphogypsum at a dose of 4.5 t/ha in combination with compost from the quail dropping (2.0 t/ha) additionally increased the intensity of carbon accumulation.

The positive balance in the soil-plant system was obviously adjusted too, that gives a significant positive assessment of the aftereffect of the use of phosphogypsum on the stabilization of the carbon balance of the regenerated topsoil of degraded sod-podzolic soils already at a dose of 1.5 t/ha.

In combination with compost from quail dropping at a dose of 2.0 t/ha, the aftereffect of the use of phosphogypsum essentially increases, that indicates good prospects for the validation of this technology as a natural climate project plus to формирования больших запасов травянистой биомассы и экологически безопасной утилизации отхода производства фосфорных минеральных удобрений.

Funding

The research carried out with the support of project No. 075-15-2021-1030 of the Ministry of Science and Higher Education of Russia.

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