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Structural Amelioration of Soils for Sustainable Land Management

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Abstract: The aim of this study is to determine the effects of structural soil restoration on the buffering capacities of these soils, their productivity, and the efficiency of their use as a basis for sustainable management. Based on a review of literature sources and our own experimental research, the proposed article shows the possibility of improving the buffering capacities of sod-podzolic cohesive sandy soils through the use of structural amelioration as an effective measure to protect them from degradation and ensure their resilience to climate change. The use of structural ameliorants (clay and peat) in the studied soils improves the granulometric composition, has a positive effect on the pH-buffering capacities, and contributes to optimizing the moisture capacity of soil. It was found that the efficiency of the application of structural amelioration on sod-podzolic cohesive sandy soils increases significantly with the local application method (e.g., clay in a dose of 10 t/ha or a combined application of clay in a dose of 2 t/ha with lowland peat in a dose of 3 t/ha). The largest yield increase in winter wheat (27.2%) was achieved by the local application of 2 t/ha of clay combined with peat in a dose of 3 t/ha.

Keywords: sod-podzolic cohesive sandy soil; productivity; buffer capacity; acidic soils; economic efficiency; sustainable soil management

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1. Introduction

The relevance of this study is based on the fact that in Ukraine, relatively large areas are occupied by low-yielding soils, in particular acidic soils, which are very difficult to farm effectively without taking corrective measures. Acidic soils are those in which acidity dominates, among other problems that determine the effectiveness of using them for agricultural purposes [1,2]. In the country, soils with excessive acidity, limiting normal crop development and growth, occupy an area of about 8.5 million hectares (5.5 million hectares arable), or almost 21% of total agricultural land. Sod-podzolic soils of light granulometric composition, characterized by acid reactions of the soil environment, deficiency in nutrients and organic substances, and low buffering capacity, are widespread in the territory of Ukraine's Polissia. They were formed in rather humid climatic conditions, mainly in sandy and sandy-loamy soils. In recent years, due to the dominance of short crop rotations (winter wheat, maize, and rape), a reduction in the amount of organic fertilizer, and a lack of mineral fertilizers and calcium-containing ameliorants, the agroecological condition of the sod-podzolic soils has deteriorated significantly. Acidification, leaching of absorbed bases, and deterioration of buffering capacities are leading to the rapid degradation of these soils. This is further exacerbated by climate change, with sharp temperature shifts and contrasting precipitation patterns, where long dry spells give way to incessant downpours [3,4]. It is dangerous that the degradation processes in the sod-podzolic soils, due to their weak buffering capacity, develop very rapidly and that the traditional measures of improvement (liming) are not able to effectively counteract the degradation. This makes the need to find management solutions to sustainably manage unproductive acidic soils even more urgent.

The results of the analysis of scientific sources on soil reclamation indexed in the Scopus database shows that a total of 159 publications in the world for the period of 1975–2022 are presented in this database. The main search query was performed using the keyword "soil improvement". The first publication in the Scopus database was in 1975, and the largest number of publications (18) was in 2021 (Figure 1).

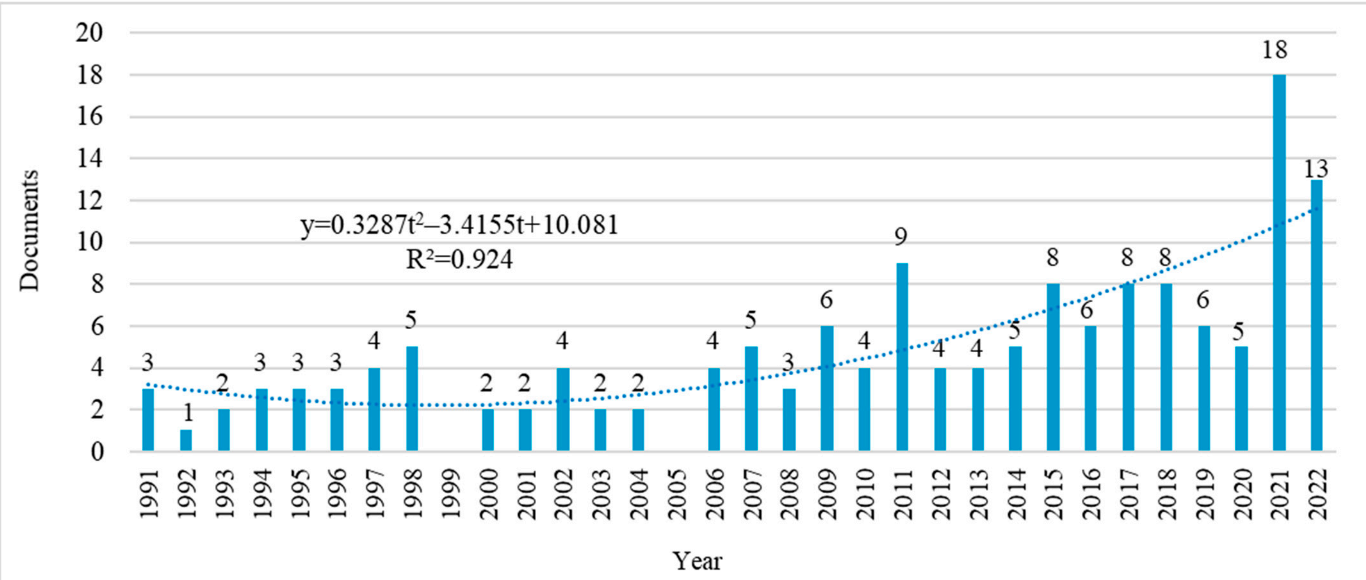

Figure 1. Global chronology of scientific publication activity on soil amelioration. Source: authors' compilation based on the Scopus database.

In general, there has been an increase in the number of publications on soil improvement in the world during the last 10 years, which is an indication of the relevance of this problem to the scientific community.

Scientists from China, Australia, the United States, India, and the United Kingdom are the most actively involved in improving soil (see Figure 2). As of 2022, Ukrainian scientists had only one article indexed in the Scopus database that contained the term "soil amelioration" in the title, in the abstract, and in the keywords.

Sectoral analysis revealed that agricultural and biological sciences, environmental sciences, and earth and planetary sciences were most prevalent at 37.1%, 23.6%, and 9.8%, respectively. Recent publications have focused on the following topics:

- The impact of acidic soil amendment on soil health and rhizosphere microbial communities, based on which it was found that the regulation of rhizosphere microbial formation in the soil microbiome–plant–pathogen system can support soil health [5];
- The desirability of expanding the use of biochar to improve soil physical (porosity, ion exchange, and water holding capacity) and chemical (pH, nutrient exchange, functional groups, and carbon uptake) properties to enhance plant nutrient

assimilation and growth, reduce greenhouse gas emissions, and minimize plant infectious diseases [6];

- The effect of soil liming on the spread of antibiotic resistance genes (ARGs) in acidic chernozem, based on which it was established that lime application reduced the amount and prevalence of ARGs and slowed the spread of manure-derived ARGs in the soil–plant system [7];
- The effectiveness of specific management practices for improving soil acidity in the humid tropics, specifically finding that applications of lime, dolomite, and gypsum improved soil pH, reduced exchangeable Al, and exchangeable acidity in sandy and lateritic soils, with more pronounced effects in sandy soils [8];
- Identifying characteristics of the effect of biochar on microbial biomass and activity in boreal soils, which are that the application of typical boreal biochar may not have the same stimulatory effect on microbial biomass and activity as has been recorded in some other ecosystems, and that the enhanced plant growth in response to biochar addition sometimes observed in boreal environments is likely to occur through other mechanisms, such as direct nutrient supply from biochar or improved soil pH [9];
- The efficacy of food waste compost and palm-kernel biochar as ameliorators of acidic soils, the use of which (compost) showed an improvement in soil quality due to an increase in soil pH, an improvement in soil macromolecules, and an improvement in trace elements compared to the control [10];
- The possibility of using biochar from rice straw for the reclamation and improvement of soils contaminated with vanadium in areas that are subject to leaching by acid rain [11].

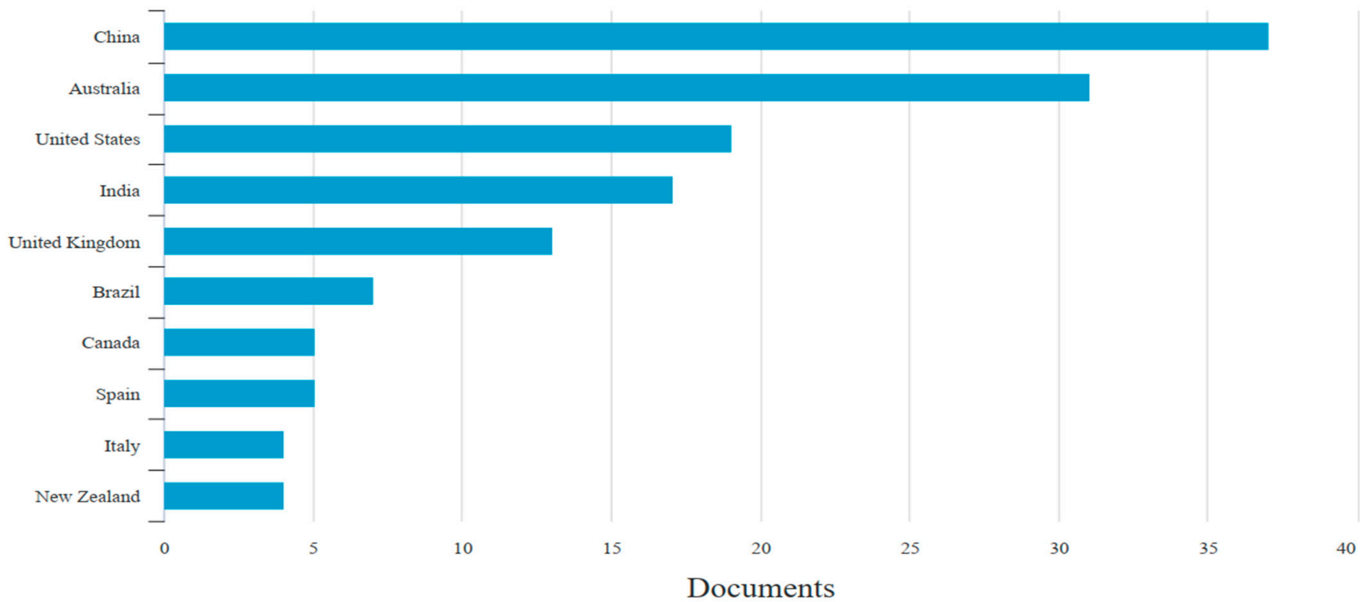

Figure 2. TOP 10 countries represented by scientific publications on soil amelioration. Source: authors' compilation based on the Scopus database.

Analyzing the current state of the problem of improving acidic soils at the global level, it is reasonable to say that there is insufficient scientific justification for solving it, taking into account the national and regional peculiarities of soil and climatic conditions. Studying sod-podzolic soils, Ukrainian scientists have recently focused on evaluating the effectiveness of short rotations with economically attractive crops [12] and the influence of fertilization systems on nitrogen-compound stocks in these soils [13]. At the same time, soil acidity is one of the critical limitations for the productivity of agricultural crops in sod-podzolic soils; therefore, there is a need to study the effectiveness of methods of management of physicochemical properties, water-physical properties, and the granulometric composition of these soils.

Preservation and improvement of physicochemical properties, water-physical properties, and the granulometric composition of sod-podzolic soils can be achieved with the application of calcium-containing ameliorants, both separately and together with organic matter, traditionally by surface spreading and subsequent ploughing into the arable layer, as well as local bands with application into the subsoil layer [14–17]. At the same time, improving the structure of sodic soils by increasing their buffering capacity is the fundamental basis for maintaining their fertility, improving the water regime, and optimizing self-regulating functions [18].

The purpose of this study was to evaluate, based on experimental data, the impact of this reclamation on the buffering capacities of sod-podzolic cohesive sandy soil and the productivity and efficiency of their use as a basis for sustainable land management, given the insufficient level of attention to the issue of agronomic, environmental, and economic effectiveness of structural soil reclamation.

2. Materials and Methods

A theoretical analysis of the state of scientific support for soil improvement in the world was carried out on the basis of data on publication activity based on the Scopus database. The experimental part of this study was carried out within the framework of the research theme of the National Scientific Center "Institute of Soil Science and Agrochemical Research named after O.N. Sokolovsky" for the period of 2016–2018. The object of this research was the sod-podzolic cohesive sandy soil of the Kolkiv Higher Vocational School (Volyn region, Lutsky district, village of Kolky). The studied sod-podzolic soil is cohesive sandy with a physical clay content of 8.8% according to the granulometric composition. It has the following physical and chemical parameters: In the arable layer, the pH of the saline water is 4.0 units, and the pH of the water is 5.1 units. The carbon content of the organic matter is 1.04%, which characterizes the soil studied as a soil with low humus content and moderate acidity.

A laboratory model experiment was carried out to study the effect of clay and peat structural amendments on the physicochemical, agrochemical, and agrophysical indicators of sod-podzolic cohesive sandy soils and on the mass of barley seedlings. The following variants were included in the experimental design: (1) without ameliorants (control); (2) lowland peat (15 t/ha); (3) clay (5 t/ha); and (4) clay (5 t/ha + peat, 15 t/ha). The experiments were carried out in glass containers and were replicated three times; the soil weighed 0.5 kg. The test crop was barley of the variety "Phoenix". At the beginning of the experiment, after one week of composting and after four weeks at the end of the experiment, pH and Ca-ion activity were measured.

The small-scale field experiment was designed according to the following scheme:

1. No ameliorants (control);
2. Clay, 10 t/ha (spread across the plot);
3. Clay, 2 t/ha (applied locally);
4. Clay, 50 t/ha (spread across the plot);
5. Clay, 10 t/ha (applied locally);
6. Peat, 15 t/ha (spread across the plot);
7. Peat, 3 t/ha (applied locally);
8. Clay, 10 t/ha + peat, 15 t/ha (spread across the plot);
9. Clay, 2 t/ha + peat, 3 t/ha (applied locally).

In the field trial, the structural ameliorants were applied to the soil, both separately and in combination, and were spread over the surface of the soil, with subsequent ploughing into the crop layer and locally into the subsoil layer to a depth of 25–30 cm. The size of the plots was 1 m^2, and the distance between variants and replicates was 0.5 m. The pattern was repeated 4 times. At the beginning and end of each growing season, soil samples were taken from the 0–20 cm layer to determine soil agrochemical and agrophysical parameters. Oats, triticale, and winter wheat were the crops grown in the experiment.

The following were used as structural ameliorants: montmorillonite clay—pH_{H2O} —8.5; content—calcium 2.27%, calcium and magnesium carbonates 5.76 and 17.77%, and lowland eutrophic peat; moisture content—64%; ash content—22.3%; water pH—5.3 units (weakly acidic); degree of decomposition—86%. Note that the clay used in this study contains the clay minerals montmorillonite, mica, and glauconite, and is alkaline due to its significant levels of calcium and magnesium carbonates.

The method from Dospekhov [19] was used for the field research. Soil samples were taken and prepared for analysis according to acting standards in Ukraine: DSTU 4287:2004 [20] and DSTU ISO 11464:2007 [21]. The soil samples were analyzed for agrophysical parameters (granulometric composition by pipette method, according to DSTU 4730:2007 [22], and field moisture by thermostatic weight method) and physicochemical parameters (calcium ion activity by potentiometric method, according to DSTU 4725:2007 [23]; pH_{H2O}, according to DSTU 7862:2015 [24]; acid–base buffering capacity of soil, according to DSTU 4456:2005 [25]; and potassium buffering, according to DSTU 4375:2005 [26]). The assessment of the economic efficiency of the application of structural improvements was carried out on the basis of separate static and dynamic indicators, in accordance with the methodology from Kucher et al. [27,28].

3. Results

3.1. Impact of Structural Amelioration of Soils on Their Buffer Capacities as a Basis for Sustainable Management

The main idea of this research was the assumption that the structural amelioration of soils with light granulometric compositions will improve their buffer capacities and also have a positive effect on soil parameters through the optimization of acidity, lime potential, and calcium ion activity.

The key factor that significantly affects the solubility and mobility of nutrients in the soil, microbial activity, and, in general, the development and growth of agricultural crops is certainly active acidity, which is determined by the indicator pH_{H2O} [17,29]. Therefore, we determined the nature of the change in this indicator under the influence of structural ameliorants.

The results of our research, carried out in a laboratory model experiment on sod-podzolic cohesive sandy gleyed soils, showed that the reaction of the soil solution (active acidity) is improved depending on the application of clay and clay together with lowland peat (Table 1).

Table 1. Changes in physical and chemical parameters of sod-podzolic cohesive sandy gleyed soil under the influence of claying (laboratory model experiment).

Variants	pH_{H2O}	pCa	Lime Potential, pH—0.5 pCa	Calcium Activity, aCa, mmol/dm^3
1. No ameliorants (control)	5.1	2.6	3.9	5.0
2. Clay, 5 t/ha	5.4	2.4	4.5	9.9
3. Peat, 15 t/ha	5.3	2.3	4.6	8.5
4. Clay, 5 t/ha + peat, 15 t/ha	5.4	2.3	4.7	10.1
LSD_{05} (Least Significant Difference)	-	-	-	0.17

Source: authors' research results.

In all the experimental variants, the pH indicator increased by 0.2–0.3 units, which is a sign of neutralization of the soil solution due to the rather high carbonate content of the ameliorants used. According to the variants of the experiment, the calcium activity ranged from 5.0 mmol/dm^3 in the control variant to 10.1 mmol/dm^3 in the fourth variant, using clay at a dose of 5 t/ha together with peat at a dose of 15 t/ha. Neutralizing the acidity and improving the calcium activity contributed to optimizing the lime potential, the optimal values of which are 4.2–4.8 for sod-podzolic soils [30].

In the experiment carried out, the lime-potential index was below the optimal values only in the control variant. In the variants with the application of structural ameliorants, it was within the optimal limits, which is a positive result.

The effect of structural ameliorants on the mass of barley seedlings in sod-podzolic cohesive sandy soil (Table 2) indicated their positive impact on plant growth, which was determined by the improvement in the functioning of the buffer mechanisms of the soil. It was found that the mass of barley seedlings in sod-podzolic cohesive sandy soil increased in all variants in comparison with the control. However, the most positive influence on the growth of the plants was the application of peat, both in ploughing and in its combined application together with clay. In these variants, the increase in the mass of the seedlings was 56.10 and 60.98%, respectively.

Table 2. Effects of structural ameliorants on the mass of barley seedlings on a sod-podzolic cohesive sandy soil (laboratory model experiment).

Variants	Seedling Mass, g/vessel	Growth	
		g/vessel	%
1. No ameliorants (control)	2.7	-	-
2. Clay, 5 t/ha	4.0	1.3	45.12
3. Peat, 15 t/ha	4.3	1.6	56.10
4. Clay, 5 t/ha + peat, 15 t/ha	4.4	1.7	60.98
LSD_{05}	0.32	-	-

Source: authors' research.

Thus, it can be assumed that the established increase in the mass of seedlings during claying of sod-podzolic cohesive sandy soil, compared to the control, is related to the improvement of its buffer capacities and quality characteristics.

An important component of the buffering mechanisms of the soil is the granulometric composition of the soil. The optimal granulometric composition of the soil contributes to the formation of the best buffer capacity of the soil and improvement in the air–water regime and has a positive effect on the productive function. If the physical clay content is less than 10%, such soil is cohesive sandy, and with values from 10 to 20%, it is sandy loamy—with better buffering than cohesive sandy. The influence of claying on changing the parameters of the granulometric composition of sod-podzolic cohesive sandy gleyed soils is shown in Table 3.

The method of local soil improvement, developed at NSC ISSAR [31,32], allows for the achievement of optimal soil indicators and buffering capacities by creating local zones that are heterogeneous in terms of trophic regime in the root layer, while using a much smaller amount of fertilizer and ameliorant compared to traditional spreading. Significant saving of material and energy resources (fertilizers and amendments, fuel, and lubricants) can be achieved through local soil amelioration.

Table 3. Changes in the granulometric composition of sod-podzolic cohesive sandy soil under the influence of claying (field experiment).

Variants	Content of Granulometric Fractions, %							Granulometric Composition
	1–0.25 mm	0.25–0.05 mm	0.05–0.01 mm	0.01–0.005 mm	0.005–0.001 mm	<0.001 mm	Sum of Fractions < 0.01	
1. Control (no ameliorants)	53.48	24.87	13.68	0.71	0.85	6.41	7.97	cohesive sandy
2. Clay, 10 t/ha (spread)	49.17	32.66	8.79	1.36	2.27	5.75	9.38	cohesive sandy
3. Clay, 2 t/ha (local)	23.34	30.83	34.88	2.25	1.91	6.79	10.95	sandy loamy
4. Clay, 50 t/ha (spread)	39.90	37.13	8.75	2.40	5.10	6.72	14.22	sandy loamy
5. Clay, 10 t/ha (local)	20.89	24.76	37.04	5.02	5.46	6.83	17.31	sandy loamy
6. Peat, 15 t/ha (spread)	50.41	33.40	8.03	1.06	1.56	5.54	8.16	cohesive sandy
7. Peat, 3 t/ha (local)	51.20	30.08	10.49	1.12	1.02	6.09	8.23	cohesive sandy
8. Clay, 10 t/ha + peat, 15 t/ha (spread)	22.74	34.94	28.50	4.40	3.15	6.27	13.82	sandy loamy
9. Clay, 2 t/ha + peat, 3 t/ha (local)	21.23	25.45	37.07	8.53	1.16	6.56	16.25	sandy loamy
LSD_{05}	0.67	-	0.83	0.12	0.09	0.23	-	-

Source: authors' research results.

It was found that the application of clay (fourth, fifth, and sixth variants) to the sod-podzolic cohesive sandy soil helps to increase the content of physical clay in the soil to the amount at which it is characterized as sandy loamy, and improves its buffering capacity. In the second variant, due to the low dose of clay, the application of 10 t/ha on the surface, with subsequent ploughing into the top layer of the soil, was ineffective. The physical clay content was about 14.22%, much higher than in the control variant, when 50 t/ha clay was applied. However, with the local application of clay at a dose of 10 t/ha, the physical clay content indicator increased even more in the local areas and reached a value of 17.31%, even though much less clay had been applied. The use of lowland peat combined with clay also contributed to increasing the physical clay content of the soil, thus improving the buffering mechanisms of the sod-podzolic cohesive sandy soil.

Thus, it has been found that the application of clay to sod-podzolic cohesive sandy soil, both by surface application with subsequent ploughing into the arable layer and locally by strips (clay mixed with peat) into the subsoil layer, contributes to the increase in the physical clay content, which is an encouraging positive result.

The buffering capacity of a soils is considered to be an objective criterion of its qualitative state since it is an integral function of all chemical components of the soil, including the products of plants and microorganisms, as well as applied fertilizers, pesticides, and amendments [31,32]. In this work, on the basis of graphs and indicators of acid–base buffering (pH buffering), we propose carrying out a fundamentally new method of assessing changes in buffering capacities of soils. Graphs showing the pH buffering of sod-podzolic cohesive sandy soils as a function of various added amounts of clay are shown in Figure 3.

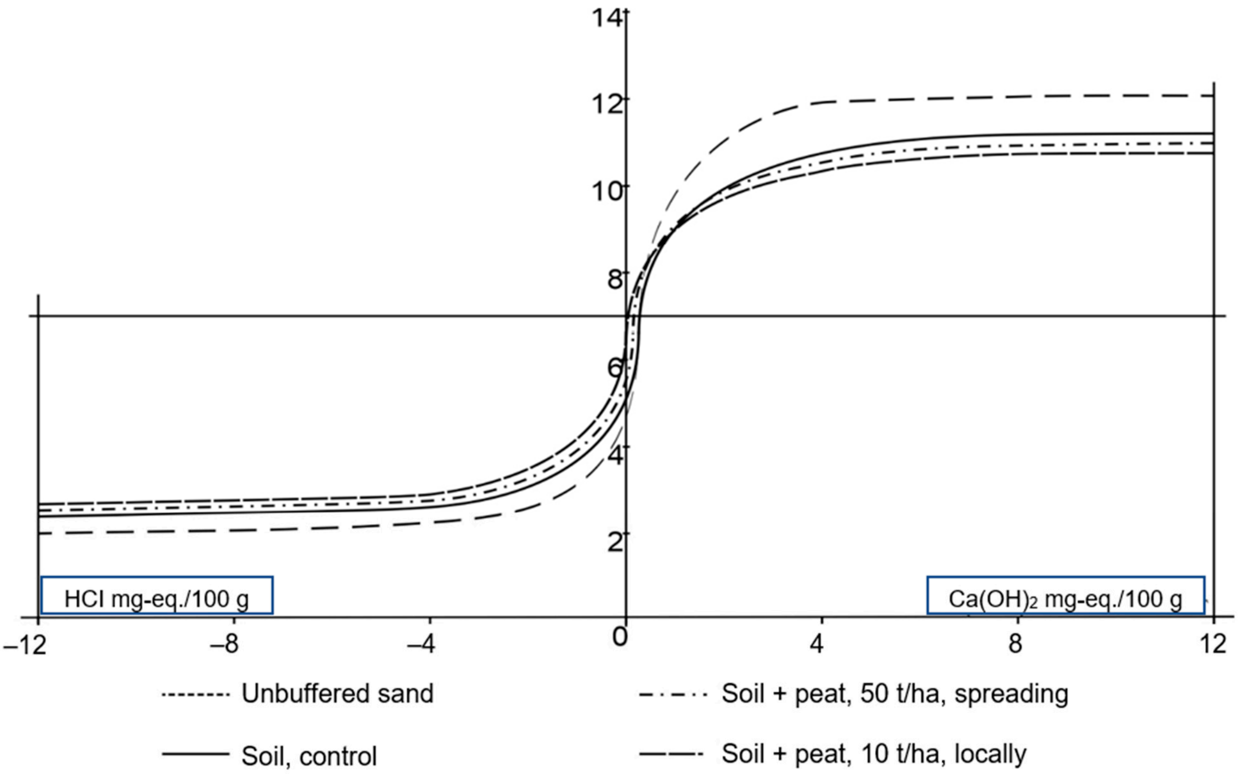

Figure 3. Graphs of pH buffering of sod-podzolic cohesive sandy soil depending on the method of applying doses of clay. Source: authors' research results.

In the given figure, attention is drawn to the growth of the buffer capacities (the area between the lines of unbuffered sand and soil) in the alkaline and acidic interval of the loads in the series: control → clay 50 t/ha (spread) → clay 10 t/ha (locally applied), i.e., an obvious dependence of pH buffering of the studied soil on the number of clay particles per unit of soil mass. As has been mentioned above, the amount of clay minerals was higher in the local zones than it was in the case of the application of clay.

The initial pH values of the soil solution, the depth of carbonates, the humus content, the cation exchange capacity, the degree of base saturation, etc., are obligatory components of the traditional method of soil quality assessment. Only their compatible (integral) use makes it possible to diagnose soil fertility and assess the agroecological condition of the soil. Buffer indicators directly consider all the mentioned criteria and also significantly extend these through the introduction of estimated indicators of buffering [31,33].

The advantages of local application of structural ameliorants compared to surface application followed by ploughing are clearly illustrated by the graphs of pH buffering of sod-podzolic cohesive sandy soils depending on the application method of clay doses in Figure 3.

It was found that in the control variant, the pH indicator at the reflecting point or active acidity was equal to 5.1 units, and the general estimated buffering index was quite low, only 10.09 points. These indicators increased in all experimental variants, i.e., the pH buffering capacity improved with the introduction of structural ameliorants. Thus, the pH indicator at the reflecting point or active acidity was equal to 5.2 units, and the general estimated buffering index was 13.68 points when 50 t/ha of clay was spread over the surface of the studied soil and then ploughed into the arable layer. However, these indicators not only do not deteriorate, but even improved to 5.4 pH units and 17.26 points, respectively, with the local application of clay at a dose of 10 t/ha.

The results of this study show that an increase in the proportion of physical clay in sod-podzolic cohesive sandy soil under the influence of structural land reclamation and the increase in its buffering capacity ensure the improvement of the moisture capacity of this soil.

Studies on the effect of clay, peat, and clay together with peat on the moisture content of the field, applied both separately and locally on the soil surface, showed that when clay was applied at a dose of 50 t/ha, the soil moisture content was 13.2%, while in the control variant it was only 11.6% (Table 4). When smaller doses of clay were applied, the soil moisture remained slightly lower, but was higher than the control.

Table 4. Effects of structural land reclamation on the field moisture capacity of sod-podzolic cohesive sandy gleyed soil.

Variants	Mass of Moisture, g/kg of Soil	Moisture Content, %
1. No ameliorants (control)	103.4	11.6
2. Clay, 10 t/ha (spread)	103.8	11.9
3. Clay, 2 t/ha (local)	89.7	12.3
4. Clay, 50 t/ha (spread)	92.9	13.2
5. Clay, 10 t/ha (local)	118.4	13.3
6. Peat, 15 t/ha (spread)	119.5	13.6
7. Peat, 3 t/ha (local)	119.1	13.7
8. Clay, 10 t/ha + peat, 15 t/ha (spread)	118.2	13.4
9. Clay, 2 t/ha + peat, 3 t/ha (local)	119.1	13.9
LSD_{05}	0.5	-

Source: authors' research results.

The combined application of clay together with peat, with their local application in doses of 2 and 3 t/ha (variant nine), had the greatest influence on the field moisture capacity of the sod-podzolic cohesive sandy soil. In this variant, the moisture content increased to 13.9%. The soil moisture content was slightly lower in the variants with peat application;

the soil moisture content was 13.6% when it was applied in the amount of 15 t/ha by spreading and 13.7% under the condition of only 3 t/ha of peat applied locally.

In spite of a significant reduction in the amount of ameliorant per hectare, in the local zones, the moisture content of the field was almost at the same level as that of a similar indicator at the time of its application, and this indicator had a fivefold increase. The latter reflects the economic feasibility of local amelioration, which means a significant saving of ameliorant and soil resources compared to the traditional technology of spreading ameliorants on the soil surface followed by ploughing into the arable layer.

Mathematical processing of our research results (Figure 4) made it possible to establish a significant correlation between the increase in the physical clay content in soil due to structural amelioration and soil moisture. The correlation coefficient was found to be 0.68.

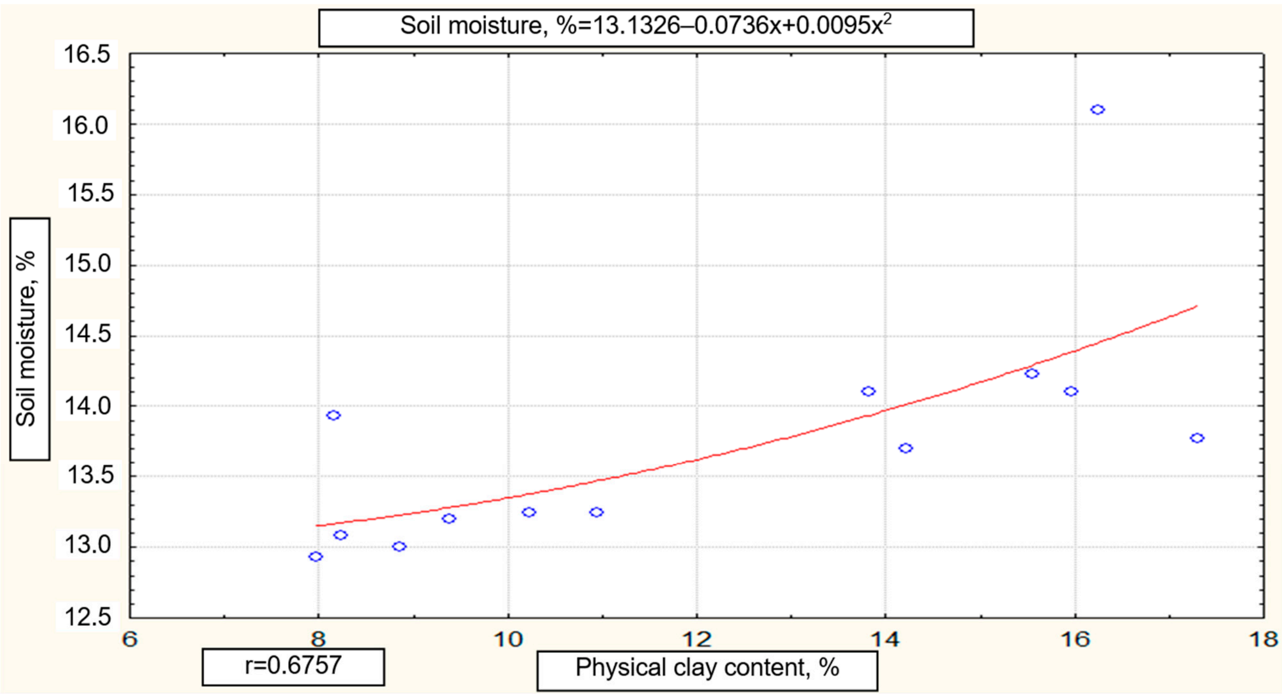

Figure 4. The relationship between soil moisture and the physical content of clay. Source: authors' research results.

In our opinion, the increase in the amount of physical clay in the sod-podzolic cohesive sandy soil under the influence of structural amelioration contributes to the increase in its buffering capacity, which ensures the improvement of the moisture capacity of this soil.

The obtained results confirm the fact that, for the weakly structured sod-podzolic soils, the water permeability is almost functionally dependent on the granulometric composition of the soil. The above is important for the development of agricultural measures aimed at mitigating the catastrophic effects of climatic adversities in the sense of preventing and suspending the already initiated processes of aridifying the hydromorphic soils of the Polissia zone.

On the basis of literary sources, it can be predicted with a high degree of probability that the improvement of the moisture retention capacity and saturation with important nutrients in local zones also contributes to the intensification of the self-regulating functions in sod-podzolic soils of light granulometric composition. As stated in [32,33], the strengthening of self-regulating processes determines the heterogeneity of local cells. Due to their own biology, the roots of cultivated plants find the most favorable ecological niche for their growth in the soil environment through the phenomenon of chemotropism.

In turn, plant roots secrete enzymes, phytohormones, vitamins, and other organic compounds into the soil, which activate the activity of soil microflora. This contributes to the mineralization of soil organic matter and fertilizers, releasing mineral compounds that nourish plants. Thus, a higher mass of root residue is accumulated in local cells that, after their death, together with microbial biomass, are a powerful source of organic matter accumulation. That is, the precise local application of structural ameliorants, improving soil conditions for the "living" part of the soil, determines the activation of self-reproduction processes of soil fertility.

Improving the buffering properties and field moisture capacity of sod-podzolic soils becomes important under modern, often arid, climatic conditions, when structural land reclamation can become an effective measure to combat the effects of drought in the cultivation of agricultural crops. It should also be noted that structural land reclamation is an effective measure to improve soil quality and, in the context of ecosystem services, directly improves the regulation and maintenance of physical and chemical soil conditions and indirectly influences yield increase as indicators of ecosystem service regulation and provision [34].

3.2. Impact of Structural Amelioration of Soils on Agricultural Productivity

The positive effect of applying structural amelioration to sod-podzolic cohesive sandy soils was established, which is also confirmed by the obtained results of crop yields: oats for grain, triticale for sillage, and winter wheat. In all variants of the field experiment, an increase in crop yield was observed with localized application of structural ameliorants compared to those variants in which increased doses of these ameliorants were applied in spread manner. The high efficiency of their combined use in organomineral mixtures compared to separate application was also demonstrated (Table 5).

Table 5. The influence of structural ameliorants on the yield of agricultural crops in sod-podzolic cohesive sandy soil (field experiment).

Variants	1st Year Oats for Grain			2nd Year Triticale for Sillage			3rd Year Winter Wheat		
	Yield, t/ha	Growth		Yield, t/ha	Growth		Yield, t/ha	Growth	
		t/ha	%		t/ha	%		t/ha	%
1. No ameliorants (control)	2.31	-	-	25.52	-	-	1.77	-	-
2. Clay, 10 t/ha (spread)	2.75	0.44	19.1	27.75	2.23	8.7	1.92	0.15	8.5
3. Clay, 2 t/ha (local)	2.66	0.35	15.2	27.81	2.29	8.9	1.95	0.18	9.9
4. Clay, 50 t/ha (spread)	2.84	0.53	22.9	28.03	2.51	9.8	2.02	0.25	14.2
5. Clay, 10 t/ha (local)	2.93	0.62	26.8	29.19	3.67	14.4	2.08	0.31	17.4
6. Peat, 15 t/ha (spread)	2.91	0.60	26.0	29.46	3.94	15.4	2.12	0.35	19.5
7. Peat, 3 t/ha (local)	3.09	0.78	33.8	30.35	4.83	18.9	2.20	0.43	24.1
8. Clay, 10 t/ha + peat, 15 t/ha (spread)	3.05	0.74	32.0	30.50	4.98	19.5	2.28	0.51	26.0
9. Clay, 2 t/ha + peat, 3 t/ha (local)	3.42	1.11	48.1	32.66	7.14	28.0	2.32	0.55	27.2
LSD_{05}	0.03	-	-	2.21	-	-	0.04	-	-

Source: authors' research results.

According to the results of the dispersion analysis, in the first year of the improvement of the sod-podzolic cohesive sandy soil, the application of structural ameliorants of clay, peat, and clay in combination with peat usually had a positive effect on the oat plants. The highest yield of 3.42 t/ha of oat grains was obtained within the variant with the 2 t/ha use of clay in combination with peat at the local dose of 3 t/ha, where the yield increase compared to the control variant was 1.1 t/ha, which equals 48.1%.

The yield results obtained for the second year of cultivation of triticale for sillage indicate that, in almost all variants of the experiment, a noticeable difference in yield growth was observed in comparison with the control. The highest increases in yield of triticale sillage were obtained in the variants with combined application of clay and peat, while again we observed a pattern of increasing indicators with the local application of ameliorants in the variants with high absorbing properties.

In the third year, the tendency of winter wheat to increase its yield in variants with the application of structural ameliorants, especially when applied locally, remained even compared to the spreading method with increased ameliorant doses. Significant increases in yield of winter wheat were recorded in variants with local applications of clay with peat, reaching 27.2%. The latter proves the high efficiency of the combined use of ameliorants with high absorption properties in organomineral mixtures compared to their separate application.

Therefore, the above proves the effectiveness and expediency of using the local melioration method to increase the productivity of sod-podzolic cohesive sandy soil.

3.3. Economic Viability of Applying Structural Soil Amelioration: Moving towards Sustainable Management Solutions

The analysis of the economic efficiency of applications of structural ameliorants on sod-podzolic cohesive sandy soils carried out over three years shows that, at the end of the second year of after-effect, the conditional cost–recovery ratios increased significantly for all experimental variants (Table 6). This is due to the fact that there is no cost for applying the amendments in the aftermath, and the value of the additional products obtained significantly exceeds the costs of their collection and transport.

Table 6. Static indicators of economic efficiency of application of structural amelioration (considering the after-effect) on sod-podzolic cohesive sandy soil.

Variants	Total Costs for the Application of Ameliorants, Collection and Delivery of Additional Produce within the Three Years, USD/ha	The Total Costs of Additional Produce within the Three Years, USD/ha	Conditional Cost–Recovery Ratio (Cp), Coef.	Conditional Profitability Level, %
1. No ameliorants (control)	–	–	–	–
2. Clay, 10 t/ha (spreading)	53.3	80.5	1.509	50.9
3. Clay, 2 t/ha (locally)	10.7	73.8	6.922	592.2
4. Clay, 50 t/ha (spreading)	266.7	104.2	0.391	−60.9
5. Clay, 10 t/ha (locally)	45.7	127.8	2.795	179.5
6. Peat, 15 t/ha (spreading)	74.3	131.6	1.771	77.1
7. Peat, 3 t/ha (locally)	14.9	166.6	11.212	1021.2
8. Clay, 10 t/ha + peat, 15 t/ha (spreading)	127.6	172.1	1.349	34.9
9. Clay, 2 t/ha + peat, 3 t/ha (locally)	25.5	231.1	9.055	805.5

Source: authors' research results.

In the second year of after-effect, the application of ameliorants contributed to the increase in the conditional cost recovery ratios in comparison with the similar indicator during the direct action. For example, with local application of 10 t/ha clay (variant 5) and its simultaneous application in a dose of 2 t/ha with lowland peat in a dose of 3 t/ha (variant 9), the conditional payback coefficients increased by 0.5 and 3.0, respectively.

It should be noted that the local application of ameliorants with high absorption properties into the soil in the after-effect period continues to be more beneficial compared to the spreading technique. Thus, high indicators of the cost–recovery ratio were achieved with the local application of 3 t/ha of peat (Cp = 11.2), 2 t/ha of clay with 3 t/ha of peat (Cp = 9.1), as well as 2 t/ha clay (Cp = 6.9). Along with this, spreading of 50 t/ha of clay turned out to be economically inefficient since the conditional cost–recovery ratio equals 0.4.

Therefore, according to the relative static indicators of economic efficiency of the application of structural ameliorants (taking into account the after-effect) on sod-podzolic cohesive sandy soil, variant seven (local application of peat in the dose of 3 t/ha), variant nine (local application of clay (2 t/ha) + peat (3 t/ha)), and variant three (local application of clay in the dose of 3 t/ha) have proven to be most efficient. This conclusion is, to a certain extent, confirmed by the results of the discounted economic efficiency indicators (Table 7), verified at 5% discount rate.

Table 7. Discounted indicators of economic efficiency of the application of structural amelioration (taking into account the after-effect) on sod-podzolic cohesive sandy soil.

Variants	Net Present Value within the Three Years, USD/ha	Profitability Index, Coef.	Discounted Payback Period, Years
1. No ameliorants (control)	–	–	–
2. Clay, 10 t/ha (spread)	25	0.479	6.3
3. Clay, 2 t/ha (local)	61	5.736	0.5
4. Clay, 50 t/ha (spread)	−164	−0.619	–
5. Clay, 10 t/ha (local)	78	1.721	1.7
6. Peat, 15 t/ha (spread)	53	0.719	4.2
7. Peat, 3 t/ha (local)	146	9.895	0.3
8. Clay, 10 t/ha + peat, 15 t/ha (spread)	39	0.305	9.8
9. Clay, 2 t/ha + peat, 3 t/ha (local)	198	7.816	0.4

Source: authors' research results.

According to the net present value indicator, spreading 50 t/ha of clay is economically inefficient; other variants can be considered to be relatively acceptable. However, according to the profitability index, variants two, six, and eight also have a low (inadequate) level of economic efficiency, since in those cases the index is less than one. Other variants (three, five, seven, and nine) are acceptable for implementation according to the profitability index. This conclusion is also confirmed by the discounted payback period, which varies from 0.3 to 1.7 years depending on the four variants in question. In fact, taking into account the specifics of agricultural production, it can be assumed that the funds invested in structural reclamation (considering the after-effect) on sod-podzolic cohesive sandy soils according to the specified variants pay off in one or two production cycles. As for variants two, six, and eight, the discounted payback period of the funds invested in structural amelioration is in the range of 4.2 to 9.8 years, i.e., indicating insufficient economic efficiency of such solutions. While the discounted payback period at the level of 4.3 years can be acceptable for an agricultural producer (provided that the after-effect of the structural improvement will uphold during the specified period), the variant with 9.8 years of payback period could hardly be considered a satisfactory indicator from the economic point of view.

4. Discussion

In connection with the discussion of the obtained experimental results of this study, it should be noted that they confirm and develop previous scientific achievements [18,31–33] regarding the sustainable management of the fertility of acidic soils, taking into account the positive impact of their structural improvement on the properties of buffer soils, productivity and efficiency of their use.

The use of the ameliorants considered in this study can generally be considered ecologically safe, but there are different opinions in the literature on the extent to which they comply with the principles of sustainability and circular economy, especially regarding the use of peat. For example, sustainability assessment results (through LCA modeling) showed that peat has the least negative environmental impact compared to alternatives (coconut pith and rock wool) [35]. At the same time, it should be noted that, although peat use may affect the quality of cultivated soils, the ecological hazards of developing and commercializing peat also deserve attention and require further research and discussion in the future. For example, according to Vincevica-Gaile et al. [36], peat is considered to be ecologically dangerous and unsustainable due to its fossil origin.

Finding materials to replace peat is critical on a global scale and may prove to be a vital challenge for future generations. The need for peat-free soil is also driven by the goals of circular economy and environmental sustainability, leading to the reduction in or elimination of the use of fossil resources and attention to the use of waste as a secondary resource [36–39]. At this stage of our scientific research, we should probably agree that using peat as an ameliorating agent can be considered expedient, provided that it is environmentally safe and economically efficient. For this purpose, not only the traditional approaches should be used, but also the new approaches based on the results of the determination of the activity of biological processes in the soil [40].

Since in recent decades there has been a trend of deteriorating soil quality in Ukraine, i.e., today the natural fertility of the soil is being used, which needs to be preserved for future generations [41], it is necessary to improve the principles of rational use of agricultural land in order to ensure sustainable management of soils, including acidic and low-productivity soils.

In general, the conclusions about the economic efficiency of the application of structural amelioration (considering the after-effects) on sod-podzolic cohesive sandy soils, drawn on the basis of discounted indicators, are consistent with the results of previous research [27,28] and indicate that without additional economic leverage, many ecologically and agronomically effective types of land improvement will remain economically ineffective and nonattractive for agricultural producers. The full establishment of private property through the functioning of the agricultural land market could motivate landowners to invest in structural amelioration, but as some studies show, land ownership does not always increase agricultural investment [42]. Therefore, an important priority is to improve the organizational and economic conditions and institutional environment towards achieving land degradation neutrality, which involves taking into account the assets of agronomic, soil, environmental and economic sciences [43]. At the same time, the effectiveness of sustainable management of acidic soils should primarily consist of efforts to anticipate, reduce vulnerability and increase resilience of agricultural land use to climate change [44]. Our interdisciplinary research findings can be used to develop new business models based on combining environmental, social and economic interests. Such business models should facilitate the transition to integrated solutions with the aim of achieving land degradation neutrality by 2030 [45].

Thus, structural improvement of sod-podzolic soils allows to effectively manage buffer mechanisms, soil solution reaction, increase productivity of these soils and improve the quality of ecosystem services of regulation due to improvement of soil quality, and supply—due to increase in crop yields. Thus, in order to increase the level of interest of agricultural producers in the implementation of effective methods of structural improvement of sod-podzolic soils, various methods of economic incentives should be applied.

5. Conclusions

This article presents possible variants for the sustainable management of low-yielding acidic soils through structural restoration in order to preserve their fertility and ecosystem services and to ensure their resilience to climate change. It was found that applications of structural ameliorants (clay, peat) to sod-podzolic cohesive sandy soils improves granulometric composition, positively affects pH-buffering properties and contributes to the optimization of field moisture capacity.

The high efficiency of structural soil improvement on the sod-podzolic cohesive sandy soil has been proven. The efficiency of structural soil amelioration significantly increases under the conditions of local application of amelioration agents, e.g., clay in the dose of 10 t/ha, or combined application of clay in the dose of 2 t/ha with lowland peat in the dose of 3 t/ha. It was shown that cultivating the sod-podzolic cohesive sandy soils by using structural amelioration is an effective way to improve their productivity, while the greatest increase in winter wheat yield of 27.2% was obtained with the local application of 2 t/ha of clay together with peat at a dose of 3 t/ha. The key to preserving the fertility of these soils, improving their water regime and optimizing their self-regulating functions, is to improve their buffering properties through structural reclamation. In addition, the positive changes in the soil contribute to the improvement of the ecosystem services of the agrolandscape: by increasing the yields and making the soil more resistant to acidification.

The analysis of the results of the evaluation of the economic efficiency of applying structural improvement confirmed the regularity of the advantages of the local application of amelioration agents with high absorbing properties in the soil compared to the spreading method of their application. Thus, according to the relative indicators of economic efficiency of application of structural improvement (taking into account the after-effect) on the sod-podzolic cohesive sandy soil, the variant seven (local application of peat in the dose of 3 tones/ha), variant nine (local application of clay (2 tones/ha) + peat (3 tones/ha)) and variant three (local application of clay in the dose of 3 tones/ha) are the most efficient. According to the profitability index and the discounted payback period, the variants three, five, seven, and nine turned out to be economically viable for implementation.

Therefore, it is recommended to the agricultural entities carrying out economic activities on the sod-podzolic soils of light granulometric composition to carry out local application of ameliorants with ploughing into the subsoil, in particular clay in the dose of 10 t/ha of soil, as well as application of clay for optimization of production processes in the dose of 2 t/ha together with lowland peat in the dose of 3 t/ha. Obtained results of research on structural soil improvement can serve as a basis for relevant subjects to make effective decisions on the system of sustainable acidic soil management. At the same time, the need to find innovative solutions for the sustainable management of such soils, which can be one of the promising directions of research, is indicated by the insufficient level of economic efficiency of some variants of structural improvement of sod-podzolic cohesive sandy soil.

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