

RESEARCH OF INDICATORS OF HUMUS CONTENT IN SOILS OF POLTAVA REGION (UKRAINE) AND TECHNOLOGIES OF ITS RESTORATION AND INCREASE

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Abstract. The paper presents the results of long-term research and analyzes the current state and prospects for the development of organic farming in the Poltava region (Ukraine). The dynamics of humus content in soils during 2011-2020 were studied. It has been established that the humus balance in the surface layer remains predominantly deficient and unstable. Most soils are characterized by moderate humus content (2.1-3.0%), while the share of soils with high humus content decreased significantly (from 10.9% to 2% between 2013 and 2019), indicating gradual soil fertility depletion. The reduction in livestock numbers has led to a decrease in organic fertilizer application (to $1.0 \text{ t} \cdot \text{ha}^{-1}$ compared to the required $9-10 \text{ t} \cdot \text{ha}^{-1}$), which is one of the key factors of humus loss. It has been proven that intensive and unbalanced tillage accelerates degradation processes in the upper soil layer. The study confirms that green manure crops, incorporated into the soil, are an effective alternative source of organic matter. Their use provides an agronomic effect comparable to applying $20-30 \text{ t} \cdot \text{ha}^{-1}$ of organic fertilizers at significantly lower cost. A technological approach for improving the process of shredding and incorporation of green manure biomass has been developed. The incorporation of plant material improves soil aeration and moisture conditions and increases microbial activity by 2.5-3.2 times within 30-40 days, enhancing organic matter mineralization. An innovative technical solution is proposed in the form of a needle-type cutting disc integrated into a combined tillage unit, which performs shredding, mixing, incorporation of plant residues, and soil loosening to a depth of 10-15 cm. Experimental results showed an incorporation efficiency of 74.5%, exceeding agrotechnical requirements (65%). Technical and economic evaluation confirmed that the proposed technology reduces the cost of soil fertility restoration. The use of green manure on 10% of the area allows obtaining $200-350 \text{ cwt} \cdot \text{ha}^{-1}$ of biomass, equivalent to $20-35 \text{ t} \cdot \text{ha}^{-1}$ of organic fertilizers.

Keywords: humus balance, green manure, agroengineering technology, tillage machinery, needle cutting disc, sustainable agriculture.

Introduction

Under the conditions of intensification of production, expansion of agricultural activity, there has recently been an increase in the negative impact of human activity on the cultivation of agricultural crops. A global environmental problem resulting from human production management is the destructive impact on natural ecosystems [1]. It is the microbiological component of the soil ecosystem that suffers from the accelerated development of agricultural production. A person involved in agricultural production is not able to control natural phenomena. But nature has given us the knowledge to control microorganisms. Studies have shown that in a 20-centimeter surface layer of the soil, the weight of microorganisms can reach up to 42 kg per one hundred square metres. The presence and diversity of microorganisms are the most important arguments for considering the soil alive. Without plants, the microbiological component of the soil ecosystem will have nothing to feed on.

The main task of the Agricultural Engineering Service is to develop modern technologies and use innovative tools to increase the organic substrate in the surface layer of the soil [2].

At present, the main causes of humus loss in the soils of the Poltava region are:

- tilling with heavy machinery, which significantly compacts the soil;
- irrational and ill-considered use of large quantities of mineral fertilizers;
- almost complete absence of organic fertilizers (manure, humus, compost);
- absence of green manure crops and the low proportion of legumes and perennial grasses in crop rotation;
- increasing use of pesticides, which accumulate in the soil and disrupt the normal functioning of the microbiological component of the soil ecosystem;
- failure to observe crop rotations. Monoculture and monotonous crop rotation, along with an unchanging structure of cropland, deplete the soil and alter its original structure.

In European countries, plant matter is widely used as green manure. An analysis of literature indicates that more than 60 different crops are used for green manure. They perform the main task of enriching the soil with nutrients, improving its structure, water, air and thermal regimes, ensuring phytosanitary safety and protecting against erosion. Fertilizer from green manure is a renewable source of organic matter. According to the results of scientific research by Pisarenko Victor, Antonets Semen, incorporating 15-20 t·ha⁻¹ of green manure into the soil is equivalent to applying 20 t·ha⁻¹ of manure. It should be noted that the energy costs for fertilizing one hectare at the rate of 30 t of manure exceed the costs of growing green manure crops by more than 2,5 times [3].

Consequently, the cost savings are significant, and the benefits for the microbiological component of ecosystem of the humus layer of the soil are priceless. As in recent years there has been a decrease in the number of animals in farms of the agro-industrial complex, it can be assumed that in the coming years agricultural production will have a shortage of organic fertilizers for application to the fields. Therefore, the use of green manure crops as green fertilizer is the direction of development of ecological and organic farming that needs to be studied, popularized and used, as it happens in the unique agricultural enterprise of Ukraine Private Enterprise Agroecology of the Mirgorod District of the Poltava region (Ukraine) [4].

The recommended techniques for restoring and increasing the humus content in the soil of the region under study are:

- to establish a route for machinery movement across the field in order to reduce the number of passes and ensure that vehicles follow the same tracks;
- use combined and wide-coverage implements, and combine operational tasks to reduce the number of passes;
- it is recommended to use direct-drill seeders, as this significantly reduces the load on the soil;
- use green manure crops and perennial grasses, and refine and develop practices for managing plant residues. Adjust shredders and monitor the size of the shredded green manure crops and crop residues. Use commercially available products that promote the biotransformation of plant residues into humus and activate the microbial activity of the soil ecosystem;
- it is recommended to implement controlled farming and direct-drilling technologies. These are components of a comprehensive strategy for energy-efficient and environmentally balanced soil cultivation, where the developed unit acts as an adaptive element of the technological process, aimed at minimizing degradation processes and preserving the humus content of the topsoil;
- draw on the experience and study the technologies of successful farms that promote organic farming.

Uncontrolled and scientifically unsubstantiated human impact on the soil cover inevitably leads to adverse changes in its condition. In particular, there is a deterioration in water-physical properties, a reduction in humus content (degumification), acidification, waterlogging and the accumulation of pollutants, which together are characterized as soil degradation. Water and wind erosion, which are global natural and anthropogenic processes, have a particularly destructive impact on soil resources. They lead to washing away and blowing away of the upper fertile horizon, the restoration of which takes a long time – from several decades to hundreds of years. As a result of erosive destruction, annual losses of the most valuable soil layer average around 15 t·ha⁻¹, which significantly reduces its natural fertility and productive potential [5]. An analysis of research results by Łabaz [6] showed that soil with clear signs of degradation can be observed in profiles where erosion has caused a reduction in horizon thickness and a loss of the dark colour of the topsoil. This profile also has the lowest HA and FA content among all the samples analyzed. Such results, characteristic of heavily eroded chernozems, are confirmed by the research of Turski [7], who established a decrease in humic acid content with increasing erosion intensity on the slope.

The authors therefore concluded that, for erosion-prone soils in the Poltava region, it would be advisable to develop a tillage implement that would minimize mechanical disturbance to degraded soil horizons whilst effectively shredding green manure crops and ensuring their subsequent uniform incorporation into the soil. The combination of simultaneous soil degradation and restoration scenarios using various mechanization methods in a long-term experiment with different tillage practices under steady-state conditions, similar particle size distribution and climate makes the Highfield land-use

change experiment at Rothamsted Research unique. The Highfield-LUCE experiment enabled a quantitative assessment of the rate of change in organic matter (OM) fractions and soil structural stability (SSS) six years after land-use change for soils subjected to different long-term tillage options [8]. The available studies provide a general overview of the soils and clay content in two macroaggregate size fractions (DispClay 1–2 mm and DispClay 8–16 mm), however, they do not fully reveal the cause-and-effect relationships between the impact of mechanization implements on the fractional composition of macroaggregates and do not allow for the formulation of targeted, regionally adapted technological solutions.

Therefore, it is necessary to conduct a more in-depth and systematic study with the following objectives:

- to identify the main factors (agrotechnical, technological, climatic, landscape, socio-economic) that determine changes in humus content in various agroecosystems of the Poltava region;
- establish the spatial and temporal differentiation of degumification and humus formation processes;
- evaluate the effectiveness of existing and promising technologies and technical means for humus reproduction, taking into account local conditions.
- Taking into account a more in-depth analysis of previous studies, the authors outlined areas for further study:
 - insufficient experimental data on integrated farming systems (combinations of green manure, organic fertilisers and minimum tillage);
 - the role of microbiota and its interaction with various land use practices in the context of humus stabilisation has not been studied;
 - there is a lack of data on the long-term effects of the implementation of specific agricultural technologies and technical means on stable humus content;
 - the economic attractiveness of humus restoration measures for different types of farms is uncertain.

The results of the study are of significant scientific and practical importance for the development of modern approaches to assessing soil fertility in the Poltava region and for the development of effective technologies and technical methods for restoring humus potential. An analysis of the results of studies on the impact of tillage techniques on humus content showed that the use of minimum tillage systems contributes to an increase in organic matter content by 0.8-22.1% and an increase in the proportion of water-stable soil aggregates by 1.3-13.6% in the 0-30 cm layer compared to the traditional tillage system [9]. The data obtained on the dynamics of humus content in the topsoil layer make it possible to identify trends in degumification processes and determine the main factors influencing the reduction or stabilisation of humus levels. In studies by Boincean [10], conducted as part of long-term field experiments with various tillage systems (excluding no-till), no statistically significant differences were found in soil moisture reserves during the spring period, soil bulk density, or yield levels. At the same time, it was noted that losses of soil organic matter under conditions of ploughing with a mouldboard plough exceeded similar indicators for disc tillage by a factor of 1.6. It was established that the retention of plant residues on the soil surface contributes to its protection against erosion processes and ensures stable functioning of the soil biota, which, under favourable conditions, is capable of self-sustainment. It has been found that when the soil surface is covered with plant residues to a level of about 70%, erosion processes cease almost entirely [10].

Consequently, with a view to developing organic farming in the Poltava region, as well as to preserve and restore the humus content in the topsoil, the authors have proposed a structurally novel working body – a needle-type cutting disc – integrated into a combined soil cultivation unit. This working body enables a range of agricultural operations, including the shredding, mixing and incorporation of plant residues, whilst simultaneously loosening the soil to a depth of 10-15 cm and levelling its surface.

From a scientific perspective, the work deepens our understanding of the mechanisms of humus formation in the agricultural landscapes of the Forest-Steppe zone of Ukraine and justifies the need to transition to balanced farming systems based on a combination of organic and mineral nutrition, the

implementation of soil-conserving tillage technologies, green manure crops, and monitoring of humus balance.

From a practical perspective, the results can be utilised:

- by agricultural enterprises and farms to develop programmes for improving soil fertility and monitoring changes in humus status;
- by government bodies responsible for agricultural policy and land protection – to improve methodologies for assessing the ecological condition of agricultural land;
- in research institutions and higher education establishments – as a methodological basis for further research into regeneration of soil organic matter.

Thus, this study provides a scientific basis for improving the efficiency of land resource use in the Poltava region, promotes the implementation of sustainable agriculture principles, and contributes to food security through the preservation and restoration of soil fertility.

As part of the research work aimed at studying humus content in the soils of the Poltava region and developing technologies for its restoration and enhancement, the main focus is on improving the process of incorporating green matter from green manure crops into the soil. The aim of the research is to improve the efficiency of mechanised equipment for shredding, mixing and incorporating plant residues into the topsoil to create favourable conditions for humus formation.

Achieving this objective involved improving the design and spatial arrangement of the working parts of the combined tillage unit, as well as optimising the technological scheme of their interaction with the soil environment during incorporation of green manure plant matter.

Experimental studies of the working bodies designed for shredding and incorporating green manure crops were conducted by physically modelling the technological process under laboratory conditions using a specialised setup to simulate the movement of the working bodies of soil cultivation machines [11]. This approach made it possible to reproduce the real-world conditions of interaction between the working bodies and the soil and plant models, whilst allowing for control of the process parameters.

In the course of the study, the authors carried out the following main tasks:

- developed a design for a tillage implement for shredding and incorporating green manure crops into the soil;
- carried out laboratory modelling of the process of shredding and incorporating plant models;
- performed mathematical analysis of the experimental data to determine the proportion of unincorporated plant models, assessed the efficiency of the developed working body, and established the accuracy of the operational procedure.

The results obtained were used for a technical-technological and technical-economic assessment of the feasibility of introducing the developed combined tillage unit for incorporating green manure crops into the soil as part of a technology to increase humus content.

Materials and methods

The research program included:

- to analyze the state of the humus layer of the soil in the Poltava region (Ukraine);
- to assess the resource potential of providing the studied region with organic fertilizers;
- to study the features of the main technologies for using green manure crops as a green fertilizer;
- to analyze technologies for embedding the green mass of green manure crops in the soil;
- to study agro-technical requirements for assessing the quality of embedding the green manure crops in the soil;
- to justify the technical specifications of the needle-type cutting disc for a combined soil cultivation unit designed to shred and incorporate green manure crops into the soil;
- to study the technology of chopping and embedding green manure crops in the soil by modeling the process in laboratory conditions using the unit for modeling the movement of working bodies of tillage machines;

- to perform mathematical calculations on determination of the percentage value of unembedded plant models based on the statistical data in order to determine the error in the efficiency of the proposed working body in laboratory conditions;
- the scope of the presented research consists in conducting a technical, technological and technical-economic assessment of the use of the developed soil-cultivating combined unit as a technological operation for incorporating green manure plants into the soil.

During the research carried out between 2013 and 2020 at the Poltava State Agrarian University, using equipment from the Faculty of Engineering and Technology, a set of interrelated methods was applied, aimed at assessing the effectiveness of incorporating plant models into the soil and analysing the operation of the working parts of soil-tilling machines.

1. Experimental-laboratory method. The research was carried out using a laboratory setup, developed in-house, for modelling the movement of the working bodies of soil-tilling machines [11], which allowed the technological process to be reproduced under controlled conditions and ensured adjustable parameters for the interaction of the working bodies with the soil and plant models.
2. Field and laboratory modelling method. Standard test plots with an area of 0.25 m² were used to replicate the operating conditions of the needle-type cutting disc of a combined tillage unit. This allowed the process of incorporating plant matter to be modelled and ensured the comparability of results between different research variants.
3. Photogrammetric (visual recording) method. The condition of the control plots was recorded by means of digital photography before and after the implementation of the technical operation. The photographs were taken using a digital camera positioned at a fixed point relative to the plot, which ensured consistent observation conditions, minimized errors and enabled subsequent comparative analysis.
4. Digital and graphical analysis method. The images obtained were processed by superimposing a measurement grid or using graphical software. On this basis, the percentage ratio of the area of unwrapped plant models to the total area of the control plot (0.25 m²) was determined, which allowed for a quantitative assessment of effectiveness of the technological process.
5. Statistical data processing method. To ensure the reliability of the results, each experiment was repeated 10 times in accordance with the methodological recommendations of B.A. Dospekhov. The data obtained were subjected to mathematical processing to determine the mean values, standard deviation and coefficient of variation, which ensured an assessment of the accuracy and stability of the results.
6. Comparative analysis method. A comparison was carried out of the effectiveness of mulching plant models for different design and technological variants of working bodies, which made it possible to establish the influence of their parameters on the quality of the technological operation.

The set of methods employed ensured an objective assessment of the process of plant biomass incorporation and enabled the identification of quantitative patterns regarding the influence of structural and technological factors on the efficiency of soil organic matter formation.

Results and discussion

After analysing data on humus content in soils in the Poltava region for 2011-2020, it was found that its balance in the surface layer remains deficient. The results of the analysis by year show that in 2011 the humus balance was 0.37 t·ha⁻¹, in 2012 – 0.36 t·ha⁻¹, 0.13 t·ha⁻¹ in 2013, 0.20 t·ha⁻¹ in 2014, 0.30 t·ha⁻¹ in 2015, 0.34 t·ha⁻¹ in 2016, -0.07 t·ha⁻¹ in 2017, 0.40 t·ha⁻¹ in 2018, 2019 – 0.35 t·ha⁻¹, 2020 – 0.03 t·ha⁻¹. It should be noted that the best humus balance indicators were obtained in 2012, 2016 and 2018, which was caused by the introduction of a larger amount of organic matter into the soil. However, the worst humus balance indicators were obtained in 2017 and 2020, which indicates soil depletion (Fig. 1) [12; 13].

According to the latest data of the General Administration of State Service of Ukraine for Geodesy, Cartography and State Cadastre in the Poltava region (2015) of the total area of the Poltava region of 2875,068 thousand hectares, agricultural lands were 2223.198 thousand hectares – 77.3%, plantations were 2165,381 thousand hectares, or 75.31%. From them arable land was 1774,686 thousand hectares, or 61.7% of the total territory (82% of plantations).

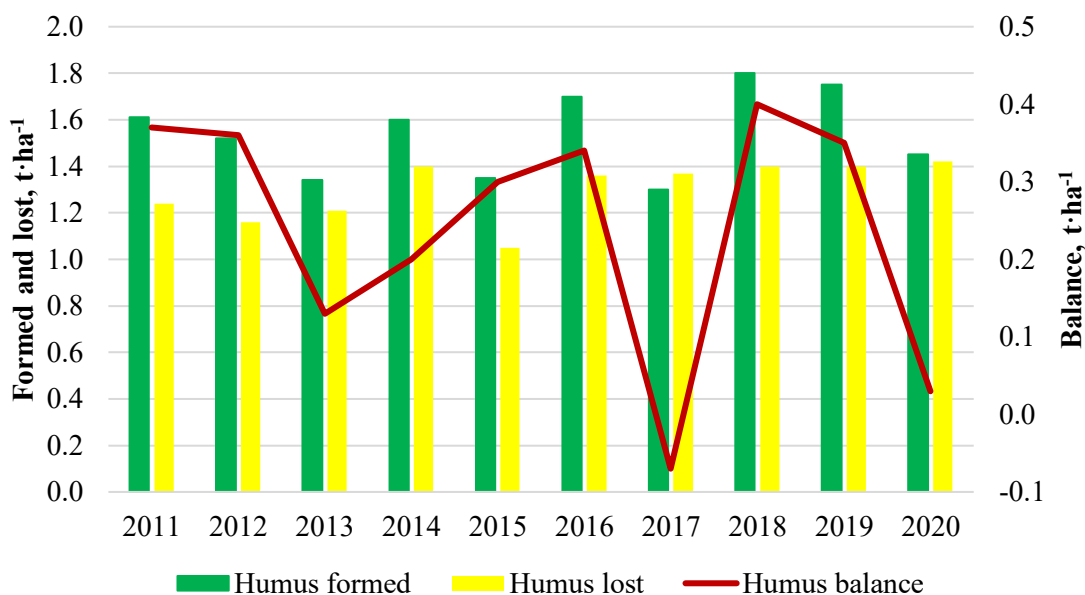


Fig. 1. Humus balance in the soils of the Poltava region (Ukraine) for 2011-2020

An analysis of the dynamics of humus balance in the soils of the Poltava region for 2011-2020 shows that the deficit trend in organic matter content continues. Despite isolated periods of improvement (2012, 2016, 2018), the humus balance is generally unstable due to insufficient restoration of organic matter reserves as a result of intensive land use. The lowest values in 2017 and 2020 confirm the processes of degumification and indicate the need to implement measures to improve soil fertility. The structure of the Land Fund of the Poltava region is shown in Fig. 2 [7]. Fig. 2 shows how land resources are distributed in the Poltava region [14].

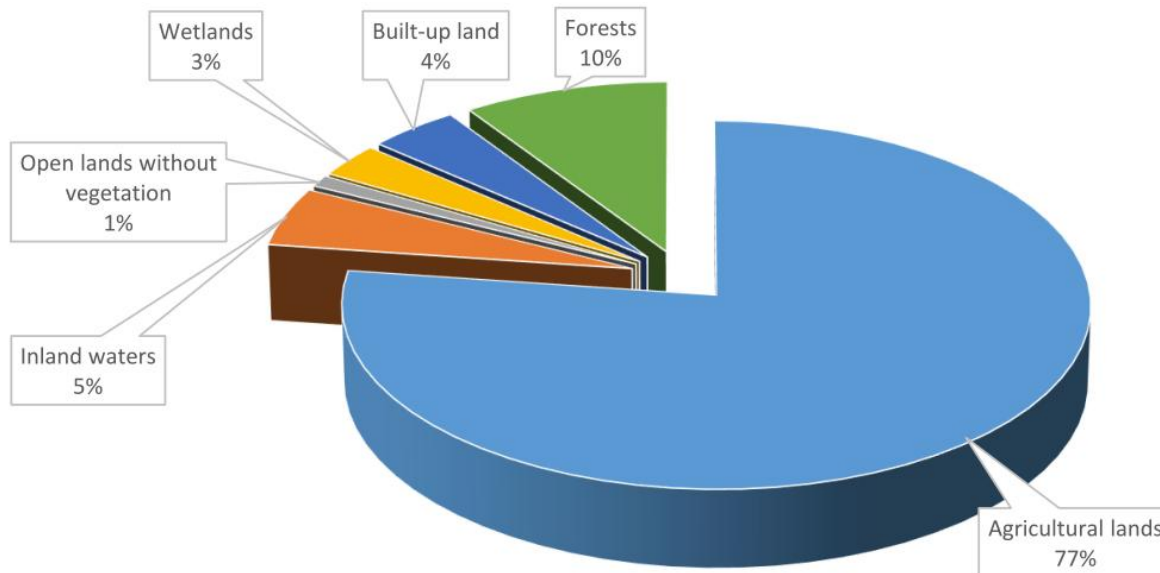


Fig. 2. Structure of the Land Fund of the Poltava region (Ukraine)

According to observations, starting from the 1960s, there has been a gradual decrease in humus content in the soils of the Poltava region. The results of research in 2013-2020, characterizing the soils of the studied region by humus content, are presented in Fig. 3 [14].

Analyzing the data in Fig. 3, we can conclude that the humus content in the studied soils is not stable and changes every year. According to the established data, the soils of the Poltava region can be classified as with an average humus content of 2.1-3.0%. But we are concerned about statistical data on the decrease in the percentage value of soils with a high humus content of 4.1-5.0% in recent years from

10,9% of all arable land areas in 2013 to 2% in 2019. This indicator indicates the relevance of the research topic and focuses the authors' attention on the development of a technology for reproducing humus in the soil and improving mechanization tools adapted to the proposed technology for the conditions of the Poltava region.

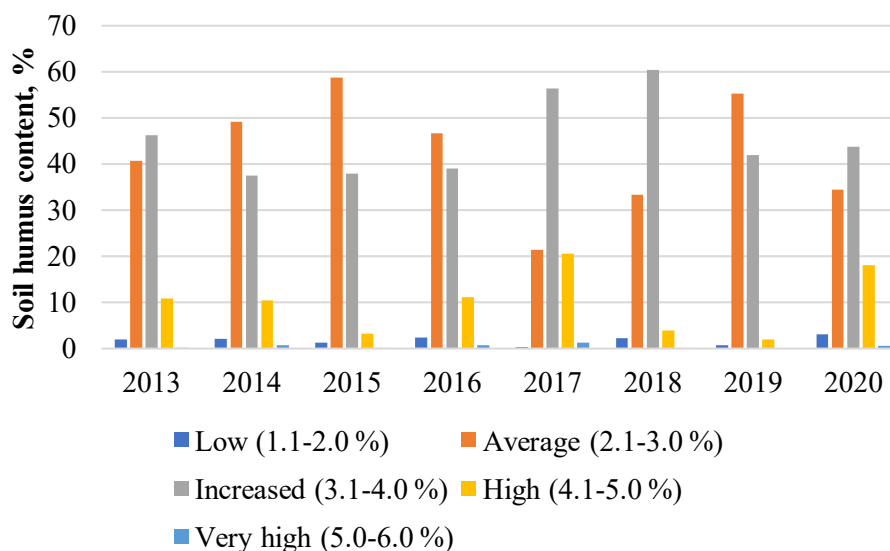


Fig. 3. Dynamics of soil humus content (%) in the Poltava region during 2013-2020

According to calculations in 2019, the balance of humus in the soils of the Poltava region is deficient and ranges from -0.13 to $-0.20 \text{ t}\cdot\text{ha}^{-1}$. In comparison with previous years, there is a tendency to reduce the reserves of humus in soils, its content, and, accordingly, soil fertility, which indicates the soil depletion in Table 1.

Table 1

Average data on humus content in soils of Poltava region

Year	Weighted average (%)
2013	3.26%
2014	–
2015	3.0%
2016	3.18%
2017	3.55%
2018	3.19%
2019	3.01%
2020	3.29%

Studies of recent years have shown that organic fertilizers are the main resource for ensuring the restoration of humus in the soils. The volumes of organic fertilizer application in the Poltava region is decreasing every year with the average dynamics of about 4,99% per year, with the maximum indicator in 2011 – 23%. If in 1996 each hectare of the sown area received 8,8 tons of organic fertilizers, then in 1997 – only 3,7, in 2010 only 1,3 tons, and in 2011 – 1,0 tons, while to ensure a deficit-free balance of humus, $9-10 \text{ tons}\cdot\text{ha}^{-1}$ should be applied. The sharp decrease in the rates of organic fertilizer application is associated with a decrease in the volume of its production by animals due to a decrease in the number of farm animals kept in agricultural enterprises of the region in recent years [15].

However, at the same time, there is a positive trend in increasing the volume of plowing of plant residues (straw, green manure, etc.). Studies have established that the replenishment of organic matter reserves in the soil is also carried out by growing green mass (green manure crops) with subsequent embedding in the soil. The incorporation of special plant crops into the soil (according to agrotechnical requirements up to 65%) is called “green manuring”, and the crop itself is called siderate [16]. By the degree of influence on crop yields green manure crops are close to litter manure in the norm of $20-30 \text{ t}\cdot\text{ha}^{-1}$, and the cost of their production and use is 2-4 times lower. In general, in 2020, individual

farms of the Poltava region, in the recalculation of fertilized area, introduced $4 \text{ t} \cdot \text{ha}^{-1}$ of straw and 11.6 tons per hectare of green manure crops, which directly indicates the strategy of using an additional resource to ensure the restoration of humus in the soils. According to the team of the authors, the use of green manure crops as an alternative to organic fertilizers is explained by the fact that a new tillage equipment on subsoil tillage came to the Poltava region, which made it possible to chop and mix and embed the plant residues in the soil better. In recent years, technologies that provide for the use of postharvest and postcut plantings for green fertilizers enable agricultural enterprises of the Poltava region to move to biological methods of increasing the soil fertility.

The chopping of green manure mass accelerates biochemical processes by increasing the surface area of these materials and improving the contact of microorganisms with the substrate. At the yield of green manure crop biomass of more than $150 \text{ centners} \cdot \text{ha}^{-1}$, firstly it is chopped by disc harrows or mulching machines, and only then it is plowed. In addition, the chopped green manure mass is evenly moistened, supplied with oxygen, and therefore decomposes faster. It retains moisture well due to the capillary disruption and prevents heat loss by organic mass. As a result of accelerating the organic matter degradation processes due to the chopping, their consumption for the vital activity of cellulose-destroying microorganisms increases. Green manure crop with the yield of up to $150 \text{ centners} \cdot \text{ha}^{-1}$ is chopped and embedded into the soil before the soil freezes in the autumn. Assessment of the quality of embedding the green manure crops after disking is determined by applying special frames to the field and counting the number of plants left unembedded, followed by determining their percentage value (Fig. 4).

The percentage of green manure crop plants during the technological operation of soil disking should be no less than 65%. The stems of green manure crops should be well chopped with the disc harrow or shelling machines and embedded to the depth of not less than 12-15 cm by unpolished tillage tools of the type - heavy disc harrow (HDH – 7). Insufficient embedding of the chopped green mass can be caused by incorrect setting the angle of attack of disk tools, the presence of flaws, low speed of movement of aggregates, etc. All these reasons must be eliminated. For better embedding of the remains of green manure crops in the soil, they should be previously chopped with a heavy disc harrow of the type HDH – 7 in one or two passes (in two or four tracks) to the depth of 10-12 cm [17].

As a result of the conducted research, it was found that the technological operation of harvesting green mass of green manure crops in compliance with agrotechnical requirements is a rather complex task, which requires repeated passes of the tillage unit to ensure qualitative indicators of cultivation.



Fig. 4. Special frame for determining the quality of embedding green manure crops

The key to success, according to the authors, is the improvement of the tillage working bodies of the unit and training to improve the qualified skills of the worker. The authors proposed to use in the technological operation of chopping and embedding green manure crops in the soil the combined unit that is equipped with a developed tillage working body. This application that is installed on a combined tillage unit (position 7, Fig. 5), efficiently chops and embeds the organic component of green manure crops left on the field surface.

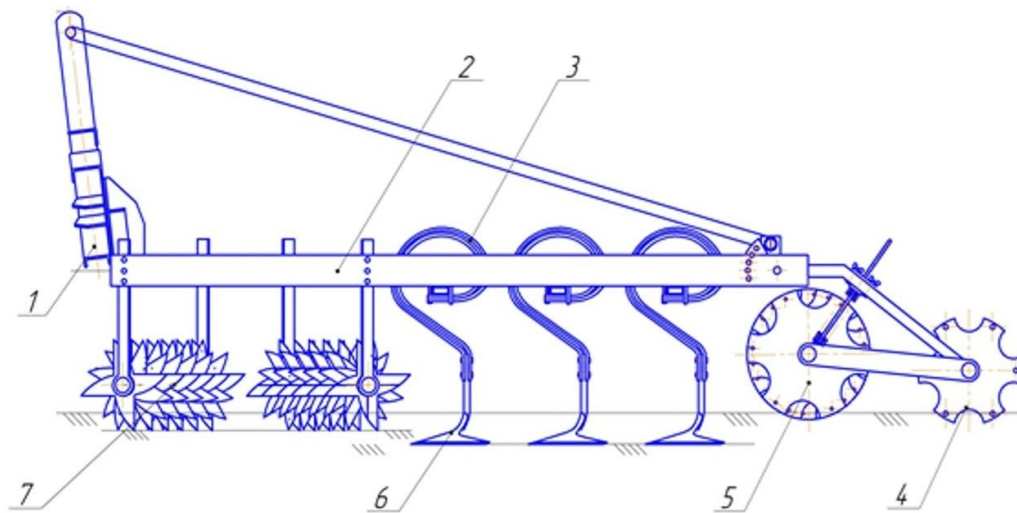


Fig. 5. **Structural and technological diagram of a combined tillage unit:** 1 – frame; 2 – frame; 3 – flexible stand; 4 – crushing roller; 5 – compaction roller; 6 – arrow cultivator paw; 7 – needle cutting disc

As can be seen from Fig. 5, in the front part two batteries of needle cutting discs, each installed with a certain angle of attack, are mounted on the frame of the combined unit. After the battery of disks, cultivator paws that hoe the soil are installed by the three-row scheme, with elastic racks. Going deeper into the soil, cultivator paws hoe the soil and open the soil layer.

In order to level the cultivated surface of the soil and to form an additional dense surface layer, rollers of various designs and diameters are provided in the unit. The technological operation of crushing and processing green manure plants takes place in the following stages: chopping of green manure crops and mixing them with the soil, hoeing of the soil to a given depth and embedding of plant residues, leveling the soil surface and forming the surface with the required density. Laboratory studies of needle cutting discs for cutting and wrapping green manure crop plants in the soil were carried out at the installation for modeling the movement of working bodies of soil tillage machines at the Faculty of Engineering and Technology of the Poltava State Agrarian University [11]. The general view of the installation is shown in Fig. 6.



Fig. 6. **Photo of the installation for modeling the movement of working bodies of soil tillage machines**

The installation is made in the form of a cut cylinder (with a rectangular cross-section of the tray) with an internal diameter of 2.6 m, an external diameter of 3.6 m, and the wall height of 0.5 m. The tray with a width of 0.5 m is filled with soil. The tray rotates around the vertical axis. In the installation the needle cutting disc (Fig. 5, on the right) was fixed on the support frame.

Preparation of the installation for operation included the following operations.

1. The first stage of preparation provided for filling the installation tray with the soil with the thickness of 0.5 m, distributing it evenly over the tray and compacting it with rollers (see Fig. 5, on the left). At the end of the first stage of soil preparation, the following indicators were determined: bulk density of soil; structural composition of soil; soil moisture; soil hardness.
2. The second stage involved placing plant models in a tray with the soil, distributing them evenly along the length of the tray (Fig. 7, a). Plant models made of green paper are usually rectangular, round, and square in shape with a pre-calculated area located on the soil surface (Fig. 7, a). At the end of the second stage of preparation of the study, the analytical indicators were determined that indicated the calculated area of plant models located on the soil surface of the installation. At the end of the second stage of preparation, the research protocol was filled out.
3. The third stage, the final one, involved marking the test control areas for measurements with an area of 0.25 m², distributed evenly along the length of the tray, monitoring and fixing the area of plant models for each site separately (Fig. 6, the yellow frame in the centre). At the end of the third stage of preparation, the research protocol was filled out.

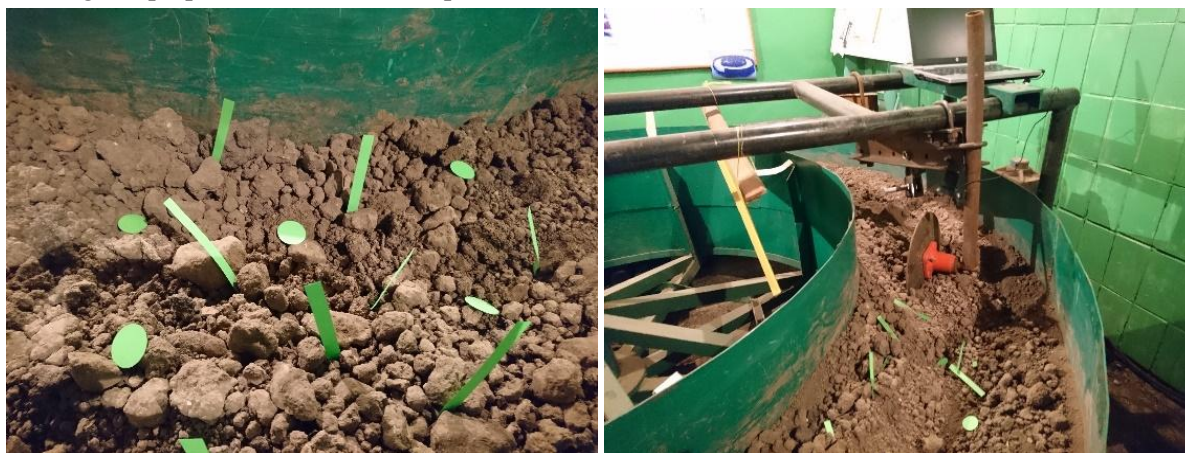


Fig. 7. **Photos of conducting the research:** a – placement of plant models before the experiment; b – embedded plant models after the experiment

The experiment was performed according to the following algorithm.

A needle cutting disc was installed at a certain angle and fixed motionless to the frame of the laboratory installation. The lower part of the studied working body was buried to a given depth of processing. During the rotation of the tray with soil, the needle cutting disc, while rotating performed the technological operation of chopping the plant models with their simultaneous embedding.

During the research, at the first stage, the test control areas were photographed. At the second stage, the degree of incorporation of plant models into the soil was determined. The percentage ratio of the area of plant models not embedded in soil to the area of the test control area was determined, it is equal to 0.25 m². The required number of repetitions was determined according to the recommendations of B.A. Dospekhov, the experiment was conducted with a repeatability of 10 times. To assess accuracy, the following statistical characteristics of the sample were used: mean: $\approx 74.45\%$; standard deviation: $\approx 2.04\%$; coefficient of variation: $\approx 2.7\%$. The low coefficient of variation obtained ($<5\%$) indicates high reproducibility and stability of the experimental results. The criteria for establishing a relationship between the parameters under study were: statistical homogeneity of the sample of results; minimisation of random error through multiple repetitions; analysis of mean values and variation; comparison of the results obtained with agrotechnical standards for the efficiency of plant mass incorporation. The results of experimental laboratory studies are presented in Fig. 8.

Results of the percentage value of unembedded plant models based on statistical data (Fig. 8) indicate the efficiency of the needle cutting disc when performing the technological operation of chopping and embedding plant models in laboratory conditions. The degree of embedding of models of green manure crops under laboratory conditions of tillage was 74.5%, (in accordance with agro-technical requirements – not less than 65%).

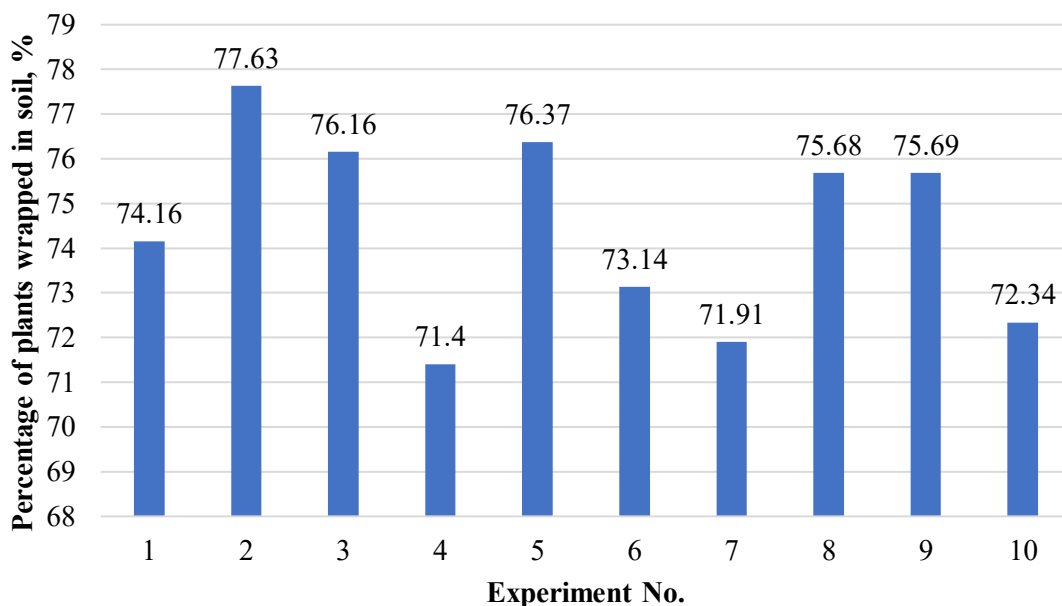


Fig. 8. Diagram of the results of the percentage values of plant model uptake into soil determined in laboratory conditions

The technical and economic assessment of the conducted studies indicates the following: if you sow 5-10 hectares of mustard or oilseed radish, you can save money on purchasing the seeds of these crops. But it can also be purchased in the summer for a small amount of money. From 10 hectares, you can collect 10 tons of seeds (not necessarily of high reproductions) and sow it after harvesting 500-700 hectares of green manure (the seeding rate of green manure is from 15 to 20 kg·ha⁻¹). If you annually sow 10% of the total land structure with green manure crops, you can get 200-350 centners·ha⁻¹ of green mass, which will replace precious and already inaccessible organic fertilizers in the equivalent of 20-35 t·ha⁻¹.

The results of the study are consistent with the scientific findings of Novakovska [18], which indicate that under conditions of minimum tillage (5-10 cm), an increase in humus content was observed. Consequently, agricultural systems should be geared towards increasing and preserving organic matter by optimizing their technical components, thereby ensuring that the soil maintains an adequate humus content. At the same time, further research and implementation of effective monitoring, assessment and reporting systems are required for an objective evaluation of organic matter growth.

In order to enhance the scientific rigour of the research, the authors propose that future scientific studies should focus on a comprehensive, multi-level monitoring programme covering the “region – farm – plot” levels and involving the use of standardized sampling and laboratory analysis methods. To ensure the reliability and reproducibility of the results, it is necessary to organize a series of replicated field experiments using a needle-type cutting disc integrated into a combined tillage unit under various soil and climatic conditions in the Poltava region.

Improvements to the technological process of shredding, mixing and incorporating green manure plant matter – which is a source of sugars, starch, protein compounds and nitrogen – into the soil are aimed at enhancing the efficiency of its mineralization and agronomic yield. The authors have established that the incorporation of green manure crops as an alternative organic fertilizer significantly improves the water-air regime of humus-accumulating soil horizons. During the first 30-40 days after incorporation, a 2.5-3.2-fold increase in the biological activity of the soil microbiota is observed, which intensifies the processes of transforming organic matter into mineral compounds available to plants. The results obtained are consistent with the findings of Bulgakov [19], who established that the maximum reduction in soil nitrogen immobilization is achieved precisely after the incorporation of organic residues into the soil.

An important area for future work is the integration of research into soil microbiota – in particular, metagenomic analysis methods and indicators of microbiological activity – into a comprehensive system

for assessing humus quality. This is consistent with the research by Dudek [20] on soil transformations based on organic matter composition, which, according to him, should be supplemented by the use of spectroscopic methods to analyze isolated humic compounds, thereby providing more detailed information on the qualitative characteristics of soil organic matter.

In addition, it is necessary to develop scientifically sound economic and organizational recommendations for agricultural enterprises regarding the phased introduction of humus restoration technologies, taking into account the possibilities for attracting financial resources, in particular through state support programmes or carbon credit markets.

The scientific significance and practical value of the research results lie in the following. Implementation of the proposed research system will help establish causal and strategic relationships between farming technologies and the dynamics of soil humus status. In line with the research conducted by Masilionytė [21], experiments on soil humus dynamics were carried out between 2006 and 2017. It was found that the application of manure together with white mustard biomass results in a lower degree of humification compared to the use of green manure alone, green manure in combination with mineral nitrogen, and manure and green manure together with mineral nitrogen. The results obtained will be of practical value in developing technologies and technical methods adapted to local conditions for the purpose of humus restoration for various categories of farms in the Poltava region. Furthermore, it is expected that a scientific and information base will be established to improve the state policy in the field of soil monitoring and the preservation of soil fertility.

Consequently, the further conduct of comprehensive field, laboratory and modelling studies, based on an in-depth analysis of previous results, is a key prerequisite for identifying the mechanisms of humus loss and developing effective, region-specific measures for the restoration and conservation of humus in the agricultural landscapes of the Poltava region (Ukraine).

Conclusions

As a result of the research conducted, the authors have obtained a set of scientifically substantiated findings that have enabled them to assess the current state of the humus balance in the soils of the Poltava region and to propose effective ways of restoring it.

1. It has been established that during the period 2011-2020, the humus balance in the arable soil layer of the region remained predominantly deficient and was characterised by significant year-to-year variability. Despite isolated periods of improvement (2012, 2016, 2018), the overall trend indicates the instability of organic matter regeneration processes and the progression of degumification, which was particularly evident in 2017 and 2020. Furthermore, the long-term trend of declining humus content, which has been observed since the second half of the 20th century, has been confirmed.
2. The authors have determined that the soils of the Poltava region, in terms of humus content, are predominantly of medium fertility (2.1-3.0%), however, a significant reduction in areas with high humus content has been recorded (from 10.9% to 2% between 2013 and 2019), indicating a gradual depletion of soil fertility. The key causes of this situation have been identified, the most significant of which are intensive land use and a critical reduction in the application of organic fertilisers (to $1.0 \text{ t} \cdot \text{ha}^{-1}$, compared to the required $9-10 \text{ t} \cdot \text{ha}^{-1}$).
3. At the same time, the authors have demonstrated the potential of using alternative sources of organic matter, in particular green manure crops and crop residues. It has been demonstrated that ploughing in green manure and crop by-products is an effective means of restoring humus, which, in terms of agronomic effect, is comparable to applying $20-30 \text{ t} \cdot \text{ha}^{-1}$ of organic fertilisers, but at a significantly lower cost. The technological features of the green manure process have been identified, in particular the need for high-quality shredding and incorporation of plant matter to intensify biochemical processes in the soil.
4. In the course of the research, the authors established that existing technologies for incorporating green manure are insufficiently effective and require improvement. To this end, a structurally new working body has been proposed – a needle-type cutting disc integrated into a combined tillage unit. A technological scheme has been developed for the operation of shredding, mixing and incorporating plant matter whilst simultaneously loosening the soil to a depth of 10-15 cm and levelling the surface.

5. The authors have experimentally confirmed the effectiveness of the proposed technical solution under laboratory conditions. According to the test results, the degree of incorporation of plant residues was 74.5%, which exceeds the minimum permissible agronomic requirements (65%) by 9-14% and confirms the effectiveness of the improved technology. This indicates the high quality of the technological operation and the feasibility of implementing the development in production.
6. Furthermore, a technical and economic assessment has shown that the use of green manure crops, combined with improved mechanization, can significantly reduce the costs of restoring soil fertility. It has been established that when green manuring is implemented on 10% of the area, it is possible to obtain 200-350 cwt·ha⁻¹ of green mass, which is equivalent to applying 20-35 t·ha⁻¹ of organic fertilizers.
7. Thus, the authors have not only confirmed the existence of the problem of humus degradation in the soils of the Poltava region, but have also proposed a scientifically sound set of technological and technical solutions to address it. The results obtained are of practical value and can be used to implement resource-efficient and environmentally safe technologies for improving soil fertility.

Therefore, it is necessary to take the above steps today to preserve soil fertility. Future generations will be grateful to us. The right decision, but one that is taken too late, is considered wrong.

Author contributions:

Conceptualization, S.L.; methodology, S.L. and O.B.; software, A.K.; validation, S.L. and A.K.; formal analysis, O.B. and A.L.; investigation, S.L., A.K., O.B. and A.L.; data curation, S.L. and A.K.; writing – original draft preparation, S.L.; writing – review and editing, A.K. and O.B.; visualization, S.L., A.L.; project administration, A.K.; funding acquisition, A.K. All authors have read and agreed to the published version of the manuscript.

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