Chapter 3

SCIENTIFIC BASE OF FORMING CLIMATE-SMART CROP ROTATIONS ON IRRIGATED SOILS

Vozhehova R. A.

DOI https://doi.org/10.30525/978-9934-26-389-7-3

INTRODUCTION

The process of forming climate-smart crop rotations and achieving stable yields of agricultural crops is closely linked to the presence of specific external conditions and relevant influencing factors affecting the ability of plants to utilize soil-climatic conditions and withstand adverse climate changes. Creating optimal conditions for each crop in the crop rotation is a significant task, the solution of which requires in-depth scientific justification. One of the crucial factors in ensuring effective agricultural activities on irrigated soils is a scientifically substantiated system of primary soil tillage tailored to specific conditions. The tillage system should create optimal conditions for root system development by regulating soil's agrophysical parameters, protecting the soil from various forms of degradation, balancing water and nutrient regimes, and providing favorable conditions for seed germination, the utilization of plant residues, and fertilizers[1]. Through numerous scientific works by domestic and foreign researchers[2, 3, 4, 5, 6] he key parameters of the physical properties of soils affecting the efficiency of primary tillage systems without plowing have been identified. In contrast to this, most Ukrainian scientists present the results of research on a

---

[1] Гамаюнова В. В. Сучасний стан та проблеми родючості ґрунтів південного регіону України. *Таврійський науковий вісник*. Херсон : Айлант, 2005. Вип. 40. С. 130–135.

[2] Наукові основи агропромислового виробництва в зоні Степу України / за ред. М. В.Зубця та ін. Київ : Аграрна наука, 2004. 844 с.

[3] Земельні ресурси України / під ред. В. В. Медведєва, Т. М. Лактіонової. Київ : Аграрна наука, 1998. 150 с.

[4] Сайко В. Ф., Малієнко А. М. Системи обробітку ґрунту в Україні. Київ : ЕКМО, 2007. 44 с.

[5] Петриченко В. Ф., Безуглий М. Д., Жук В. М., О. О. Іващенко О. О. Нова стратегія виробництва зернових та олійних культур в Україні. Київ : Аграр. Наука, 2012. 48 с.

[6] Islam R., Reeder R. No-till and conservation agriculture in the United States: An example from the David Brandt farm, Carroll, Ohio : ScienceDirect, 2014. P. 31–35.

differentiated approach to the application of tillage systems[7, 8, 9, 10]. The diversity of views on this matter necessitates a more detailed and in-depth experimental study of the impact of various tillage systems, not only on the productivity of agricultural crops but also on soil-forming processes, ecological balance in agroecosystems, and the climate-oriented functionality of these systems.

Since 2008, research has been conducted on irrigated lands at the Askania State Agricultural Research Station of the Institute of Climate-Oriented Agriculture of the National Academy of Agrarian Sciences of Ukraine, using high-performance tools of plow, chisel, disc types, and seeders for sowing in previously untilled soil. The aim of the research was to develop elements of an intensive climate-adapted farming system for irrigated lands, utilizing intermediate crops after post-harvest cover crops to improve and stabilize soil fertility indicators and the ecological balance of agroecosystems.

To achieve this goal, the following tasks were carried out step by step: investigate the impact of post-harvest cover crops under different primary tillage systems on soil fertility and the ecological ameliorative state in irrigated crop rotations; scientifically substantiate the influence of cover crop fertilizers under different primary tillage systems on the productivity of agricultural crops and the ecological balance of agroecosystems, as well as the climate-oriented functionality of these systems under irrigation.

In terms of soil and climate, the Askania State Agricultural Research Station is located in the dry steppe soil-ecological zone within the Kahovka irrigation massif. The climate is characterized by significant heat resources and insufficient natural moisture. The annual average air temperature is 9.8 °C, and the sum of effective temperatures above 10 °C ranges from 3200 to 3400 °C. The duration of the frost-free period varies from 180 to 200 days, and the growing season lasts 225–230 days on average. The annual atmospheric precipitation is about 440 mm, with a hydrothermal coefficient

---

[7] Ресурсозберігаючі технології механічного обробітку ґрунту в сучасному землеробстві України / І. Д. Примак, В. О. Єщенко, Ю. П. Манько, М. І. Трегуб, О. І. Примак. Київ : «КВІЦ», 2007. 272 с.

[8] Сайко В. Ф., Малієнко А. М. Мінімальний та нульовий обробітки ґрунту, стан і перспективи їх запроваджень в Україні. *Посібник українського хлібороба*. Київ : Урожай, 2009. С. 178–188.

[9] Кроветто Карлос К. NO-TILL. Взаимосвязь между No-Till, растительными остатками, питанием растений и почвы. Днепропетровск, 2007. 235 с.

[10] Косолап М. П., Кротінов О. П. Система землеробства No-till. Київ : Логос, 2011. 352 с.

of 0.5. Rainfall distribution during the growing season is uneven, and the utilization coefficient of these rains is very low. Groundwater is located at a depth greater than 10 meters. The soil of the research plot is dark chestnut, weakly saline, and of medium-loamy texture. The topsoil layer (0–22 cm) contains 2.82 % humus, and the gross forms of nitrogen, phosphorus, and potassium are 0.18 %, 0.16 %, and 2.7 %, respectively, with a pH of the soil water extract ranging from 7.0 to 7.2. The lowest moisture content in the soil layer of 0–100 cm is 21.3 %, wilting moisture is 9.5 %, water-stable aggregates account for 34.1 %, equilibrium bulk density is 1.29 g/cm^3, porosity is 49.2 %, and water permeability is 1.25 mm/h.

The research was conducted on irrigated lands as part of a two-factor field experiment within a four-year crop rotation, both spatially and temporally. The crop rotation included the following crop sequences: winter barley with post-harvest mustard cover crop – soybean – winter wheat with post-harvest mustard cover crop – grain maize. Various varieties and hybrids of agricultural crops were used for planting: soft winter wheat (Askaniiska variety, originator Askaniia DSDS IKSAG NASC), winter barley (Dostoinyi variety, originator Selection and Genetics Institute NASC), soybean (Diona variety, originator IKSAG NASC), and maize (DKS 4541 hybrid, originator Monsanto).

Four different primary soil tillage systems were investigated. The control system consisted of a differentiated primary tillage system, alternating deep plowing with moldboard plowing and shallow tillage without plowing. The second variant utilized a shallow single-depth moldboardless primary tillage system. The third variant involved deep chisel plowing with depth ranging from 23–25 cm to 28–30 cm. The fourth variant involved direct seeding into untilled soil.

The research was conducted under three mineral nutrition backgrounds: the application of fertilizer to the cover crop sown after the harvest of winter wheat and winter barley, involving the addition of three doses of nitrogen fertilizer per hectare in the crop rotation area in addition to 40 kg of phosphorus fertilizer, and a control treatment without a cover crop, applying recommended doses of mineral fertilizers for crops in the rotation. The cover crop used in the study was spring mustard of the Mriya variety, registered in Ukraine in 2000.

Field experiments and related studies followed established methodologies and guidelines[11, 12, 13, 14, 15, 16].

Based on the results of the research analysis, it was determined that at the beginning of the crop's vegetation period, the soil bulk density in the 0–40 cm layer under the control system (differentiated primary tillage) and variants without the use of post-harvest cover crops and fertilizers in the crop rotation averaged 1.26 g/cm^3. Under the shallow single-depth tillage system, the bulk density was similar to the control, and under the shallow tillage system, it was 0.8 % higher than the control. The highest soil density (1.31 g/cm^3) was observed in the no-till variants, exceeding the control by 3.9 %.

On the research variants where the effectiveness of cover crop application was studied, the bulk density in the 0–40 cm soil layer was slightly lower. The greatest impact of the cover crop was observed in the deep no-till system with incorporation of the green mass to a depth of 28–30 cm, where the bulk density was 2.3 % lower than the control. The lowest bulk density was observed for the long-term use of shallow no-till soil tillage. Under no-till conditions with cover crop, the bulk density was 2.2 % lower than the control and averaged 1.28 g/cm^3 over the two years of research.

During the crop harvest period, the bulk density of the soil under the variants without cover crops was in the range of 1.24–1.31 g/cm^3. In the variants where the effectiveness of cover crop application was studied, the bulk density was 2.3 % lower for the differentiated primary tillage system, 3.0 % lower for shallow no-till, 1.6 % lower for deep no-till, and 2.2 % lower for no-till seeding into untilled soil. Additionally, soil compaction during the crop's vegetation period was less intensive on the variants with cover crop application than on the variants without cover crops.

One of the characteristics of the soil's physical properties is its total porosity, which depends on the structural state of the soil and its mechanical composition. As the research results indicate, at the beginning of the crop's vegetation period, the total porosity of the soil layer in the 0–40 cm range on the research variants without cover crop application averaged 49.93–51.78 %.

---

[11] Єщенко В. О., Копитко П. Г., Опришко В. П., Костогриз П. В. Основи наукових досліджень в агрономії. Київ : Дія, 2005. 288 с.

[12] Вожегова Р. А., Лавриненко Ю. О., Малярчук М. П. та ін. Методика польових і лабораторних досліджень на зрошуваних землях. Херсон : Грінь Д. С. 2014. 286 с.

[13] Ушкаренко В. О., Вожегова Р. А., Голобородько С. П., Коковіхін С. В. Статистичний аналіз результатів польових дослідів у землеробстві : монографія. Херсон : Айлант, 2013. 403 с.

[14] Ушкаренко В. О., Нікішенко В. Л., Голобородько С. П., Коковіхін С. В. Дисперсійний і кореляційний аналіз у землеробстві та рослинництві. Херсон : Айлант, 2008. 272 с.

[15] ДСТУ 4729:2007 «Якість ґрунту. Визначенння нітратного та амонійного азоту в модифікації ННЦ ІГА ім. І. Н. Соколовського».

[16] ДСТУ 4114:2002 «Грунти. Визначення рухомих сполук фосфору і калію за модифікованим методом Мачигіна».

The highest soil porosity in the 0–40 cm layer was observed for the deep differentiated and deep no-till systems with chisel tillage, reaching 51.78 % and 51.68 %, respectively. It was slightly lower for the shallow single-depth no-till system at 51.19 %. The lowest porosity (49.93 %) was observed for the untilled soil.

On the variants where the effectiveness of cover crop application was studied, porosity was generally higher for all tillage systems, ranging from 50.79 % for no-till seeding into untilled soil to 52.69 % for deep tillage with a chisel implement. There was a slight increase in total porosity in the 0–40 cm soil layer on the variants with cover crop application: 0.72 % for the differentiated primary tillage system, 0.28 % for the shallow no-till system, 1.0 % for deep chisel tillage, and 0.86 % for no-till seeding into untilled soil.

During the crop's vegetation period, the soil compaction increased due to weather conditions, irrigation, and agronomic practices, resulting in a slight reduction in soil porosity, averaging 1.0–1.4 % on average.

Water infiltration rate into the soil depends not only on the soil type and its moisture content but also on the soil cultivation system, which significantly influences the rate of permeability. Research results indicate that soil cultivation methods leading to lower soil compaction and higher porosity promote better water infiltration into the soil.

Depending on the primary soil cultivation systems in crop rotations, soil permeability at the beginning of crop vegetation (in variants without catch crops) was as follows: for corn crops, it ranged from 0.63 to 3.14 mm/h; for soybean crops, it ranged from 1.25 to 4.19 mm/h; for winter wheat crops, it ranged from 2.77 to 4.82 mm/h; and for winter barley crops, it ranged from 2.15 to 4.10 mm/h. On average across the crop rotation, the best soil permeability (4.03 mm/h) was achieved with non-plow cultivation to a depth of 23–25 cm for winter crops and 28–30 cm for spring crops, using chisel-type tools. The slowest water absorption rate was observed in variants with direct planting of crops in untilled soil (average 1.95 mm/h). This can be attributed to higher compaction, lower overall porosity, and the ability of untilled soil to retain moisture for a longer period.

In variants using catch crops, an increase in soil permeability was noted. Under a differentiated system, the water infiltration rate was 0.75 mm/h higher, under shallow non-plow system it was 0.45 mm/h higher, under deep non-plow system, it was 0.55 mm/h higher, and under direct planting into untilled soil, it was 0.59 mm/h higher.

By the end of the crop rotation, the soil permeability under all cultivation systems became more uniform, ranging from 3.69 to 4.12 mm/h for control variants (without catch crops). The use of catch crops in intercropping led to increased water absorption rates in the differentiated system by 1.02 mm/h, in the deep non-plow system by 0.6 mm/h, and under no-tillage cultivation by

0.84 mm/h. In the shallow non-plow cultivation system, soil permeability was similar to the control.

1. Impact of Primary Soil Cultivation Systems on the Accumulation of Effective Soil Moisture

In order to study the impact of various factors on the accumulation of effective soil moisture during the autumn-winter period and its utilization by crop rotations, the total water consumption and water consumption for crop yield formation were determined.

The total water consumption of crop rotations significantly depended on agrotechnical measures. According to research results, the lowest total water consumption was observed in winter cereal crops, depending on the primary soil cultivation method. In winter barley, it ranged from 3364 to 3629 m^3/ha, and in winter wheat, it ranged from 3772 to 4070 m3/ha (variants where catch crops were not applied). The total water consumption of spring crops in the crop rotation was higher, with soybeans ranging from 4992 to 5144 m^3/ha and corn from 4941 to 5392 m^3/ha. This is due not only to increased irrigation frequency for these crops during their vegetation but also to higher water consumption for yield formation. The lowest total water consumption for winter crops was observed in variants with no-tillage soil cultivation, specifically chisel plowing to a depth of 23–25 cm for winter barley and disc plowing to a depth of 12–14 cm for winter wheat. The highest total water consumption for spring crops was observed when planting directly into untilled soil, while for winter cereals, it occurred in the control group (under differentiated soil cultivation with disc treatment for barley and wheat).

In variants where catch crops were used as a fertilization source, the total water consumption for soybean crops was lower by 54–129 m^3/ha, and for corn crops, it was lower by 70–154 m^3/ha. The significant impact of catch crop utilization in intercropping on the total water consumption of winter crops was only observed under differentiated primary soil cultivation with disc tillage, where water consumption for winter wheat was lower by 330 m^3/ha and for winter barley by 247 m^3/ha.

An essential indicator that characterizes the efficiency of water use by crops for yield formation is the water use coefficient. This coefficient depends on various factors, such as crop variety, cultivation techniques, and soil and meteorological conditions. It is inversely related to the crop yield level, meaning that the higher the yield, the less water is required for each ton of production.

Based on research results, the water use coefficient for cereal crops in the crop rotation ranged from 544 to 669 m^3, while for soybeans, it was higher, ranging from 1793 to 1915 m^3. The highest water use coefficient for all crop rotations was observed when planting crops directly into untilled soil. Under these conditions, 638 m^3 of water was required to produce a ton of winter wheat, 667 m^3 for corn, 669 m3 for winter barley, and 1915 m^3 for soybeans.

The best conditions for winter crop yield formation in the crop rotation were created under disc plowing to a depth of 12–14 cm, where the water use coefficient was the lowest. For winter wheat, it was 545 m^3/ton, and for winter barley, it was 591 m^3/ton. The lowest water use coefficient for corn (544 m^3/ton) was observed under chisel plowing to a depth of 28–30 cm, while for soybeans, it was under conventional plowing to the same depth, requiring 1793 m3 of water to produce one ton of yield.

In variants where catch crops were used as a source of fertilization, water consumption for winter wheat yield formation was reduced by 5.5–16.0 %, corn by 6.1–15.4 %, winter barley by 11.5–20.5 %, and soybeans by 12.5–19.9 %.

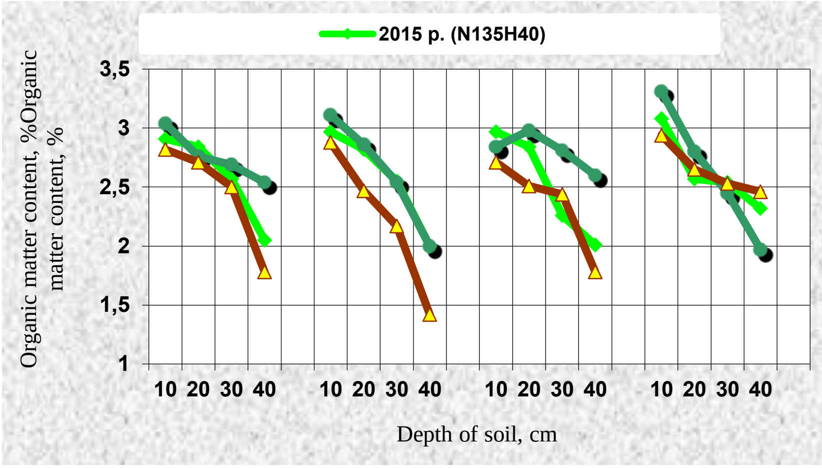
2. The impact of research factors on soil humus

The impact of research factors on soil humus content was assessed by measuring humus content in the 0–40 cm soil layer at the beginning (2015) and after the completion of a full crop rotation (2020). For comparison, experimental variants were selected where, against the background of applying mineral fertilizers at a rate of N120P40 (per 1 ha of crop rotation area) and agricultural crop by-products, mustard was used as a cover crop/siderat, and variants with the same amount of fertilizers and agricultural crop by-products were applied without a cover crop. Soil samples for laboratory analysis were collected in the autumn after the harvest of agricultural crops.

The source of humus consists of organic residues from higher plants, microorganisms, and animals living in the soil. Green plant residues enter the soil in the form of above-ground litter and the dead root system of plants. The amount of organic matter entering the soil varies and depends on the composition, age, and density of crops, as well as the degree of development of the plant cover.

Most of the organic residues are oxidized to carbon dioxide and water. A smaller portion undergoes a second stage of transformation, called humification, which involves the synthesis of humic substances. The rate and direction of humification depend on various factors, including the quantity and chemical composition of plant residues, soil moisture and aeration, soil microorganism composition, soil solution pH, soil particle size distribution, and more.

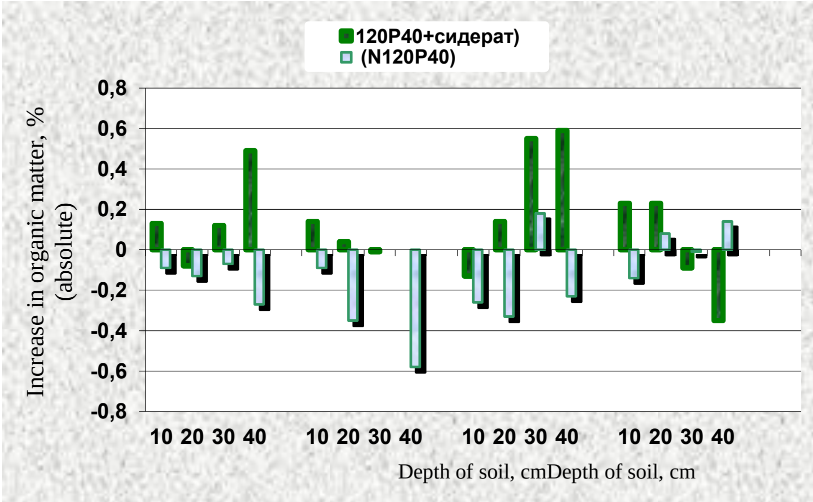
Figure 1 presents the results of soil samples' analysis for humus content in the 0–40 cm soil layer under different primary tillage systems, direct seeding of crops into untilled soil, and fertilization at the beginning and end of the crop rotation.



Differentiated / Shallow one-depth / Variable-depth / No-till

Fig. 1. Humus Content in the 0–40 cm Soil Layer, %

Analyzing changes in humus content in the 0–40 cm soil layer under different primary tillage systems, direct seeding of crops into untilled soil, and fertilization at the beginning and end of the crop rotation, conclusions can be drawn. At the start of the crop rotation (data from 2015), the humus content in the upper (0–10 cm) soil layer was relatively high under all primary tillage systems and direct seeding into previously untilled soil, ranging from 2.9 % to 3.1 %. As the depth increased, the amount of humic compounds decreased, and in the 40 cm soil layer, it was 2.0 % in variants with mechanical soil tillage and 2.35 % in the variant where such tillage was not performed. A higher quantity of humic compounds in the experimental variants where soil tillage was not conducted can be explained by the fact that, under aerobic conditions created by mechanical tillage, in the presence of sufficient moisture and warmth, mineralization processes of plant residues prevail over humification processes in the upper root-containing layer. After the completion of the crop rotation, the humus content in the soil samples was lower by 0.1–0.3 % in the upper (0–10 cm) soil layer and by 0.3–0.6 % at a depth of 40 cm. Only in the variants where a cover crop/siderat was used as fertilizer, there was an increase in humus content throughout the depth of the root-containing soil layer, which averaged 0.2–0.6 %. The most significant increase in humic compounds was observed under the variable-depth differentiated and variable-depth no-till primary tillage systems in the 20–40 cm soil layers (Figure 2).



Differentiated / Shallow one-depth / Variable-depth / No-till

Fig. 2. Changes in Humus Stock in the 0–40 cm Soil Layer During the Crop Rotation Period (2015–2019)

An important condition for preserving soil fertility is the activity of microorganisms. Soil biological activity depends on various factors, including soil type and fertility, acidity, agrophysical properties, weather conditions, the presence of organic matter, and others.

3. The activity of soil microorganisms depends on the tillage systems

The activity of soil microorganisms was determined by the intensity of flax straw decomposition in the 0–30 cm layer over a period of 90 days (Figures 3–4). The intensity of flax straw decomposition provides insights into the rates of decomposition of plant residues, which contain a significant amount of cellulose[17].

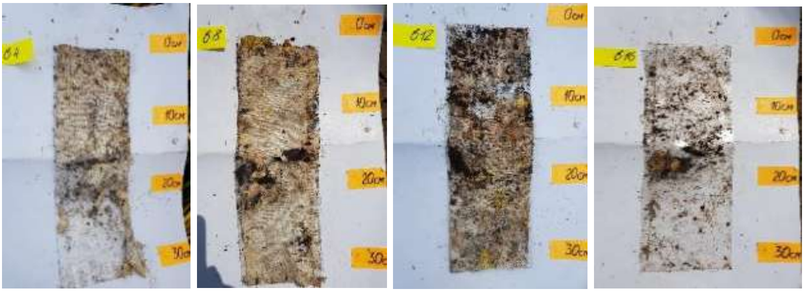
---

[17] Пахомов О. Є., Дідур О. О., Кульбачко Ю. Л., Лоза І. М. Екохімічні аспекти існування безхребетних тварин у ґрунті: методи визначення : навч. посіб. Д. : РВВ ДНУ, 2010. 176 с.

Winter Barley Crops: Fertilization System III (after the green manure)

Differentiated / Shallow one-depth / Variable-depth / No-till
Tillage System / Tillage System / Zero-tillage System

Fertilization System IV (without the use of green manure)



Differentiated / Shallow one-depth / Variable-depth / No-till
Tillage System / Tillage System / Zero-tillage System

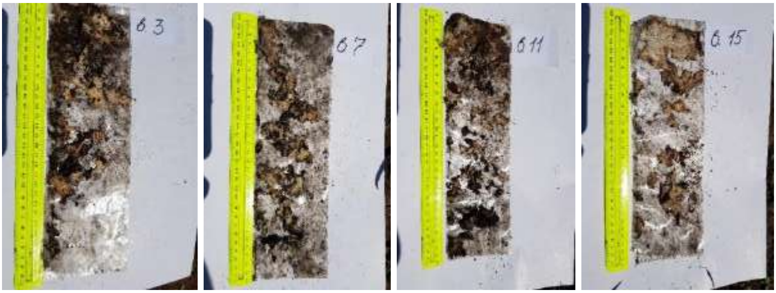
Fig. 3. Intensity of Flax Decomposition in Winter Barley Crops under Different Soil Tillage Systems and Green Manuring

One of the main factors affecting the activity of soil microorganisms is the mechanical tillage, or its absence. Soil tillage affects not only the physical properties of the soil and its water regime but also the nature and direction of biological processes within it, including the decomposition of organic matter and the rate of mineralization of plant residues[18].

---

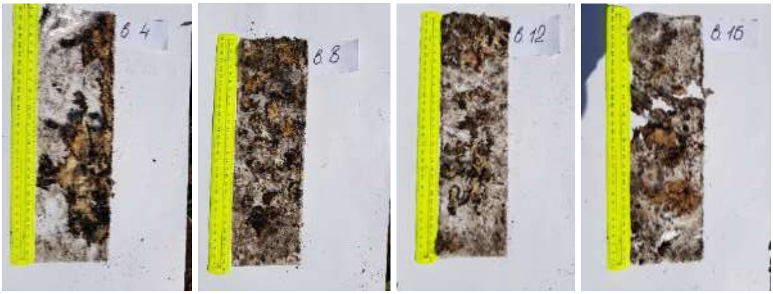
[18] Бітюкова Л. Б., Драч Ю. О., Малієнко А. М. Вплив тривалого застосування способів обробітку на мікробний ценоз і гумусний стан дерново-підзолистого ґрунту. *Вісник аграрної науки*. 1999. № 9. С. 12–17.

Soybean Crops: Fertilization System III (with the use of green manure)



Differentiated / Shallow one-depth / Variable-depth / No-till
Tillage System / Tillage System / Zero-tillage System

Fertilization System IV (without the use of green manure)



Differentiated / Shallow one-depth / Variable-depth / No-till
Tillage System / Tillage System / Zero-tillage System

Fig. 4. Intensity of Flax Decomposition in Soybean Crops under Different Soil Tillage Systems and Green Manuring

One of the main factors affecting the activity of soil microorganisms is the mechanical tillage, or its absence. Soil tillage affects not only the physical properties of the soil and its water regime but also the nature and direction of biological processes within it, including the decomposition of organic matter and the rate of mineralization of plant residues[19].

---

[19] Бітюкова Л. Б., Драч Ю. О., Малієнко А. М. Вплив тривалого застосування способів обробітку на мікробний ценоз і гумусний стан дерново-підзолистого ґрунту. *Вісник аграрної науки*. 1999. № 9. С. 12–17.

Research results indicate that microbiological activity was lower in shallow no-tillage variants of soil management, characterized by an increase in zero-tillage variants where the intensity of flax decomposition in the soil ranged from 85 % to 90 %. Unbroken structure of the upper root-inhabited soil layer, preserved when crops are sown directly into untilled soil, and the ability to retain moisture for a longer time, contributes to better conditions for the development and functioning of the soil microbiota and the intensity of metabolic processes.

Soil waters that fill the capillaries of the soil mass effectively become solutions. All changes in them occur in accordance with the conditions of the soil environment as a three-component system, subject to sharp fluctuations of hydrotrophic factors. In the soil solution, processes of humus substances decomposition and synthesis, formation of secondary minerals, and organo-mineral compounds occur. Plants obtain necessary nutrients and water from the soil solution.

4. Influence of Soil Tillage Systems on Soil Salinity and Alkalization

The presence of soluble salts in soil enhances plant growth but can also increase the content of toxic substances. The primary salts responsible for soil salinity include sodium, calcium, and magnesium cations, along with sulfate and chloride anions. Additionally, potassium, bicarbonate, carbonate, and nitrate ions may be present in smaller quantities in soils. High sodium concentrations in soil can lead to increased soil dispersion, hindering water and air movement.

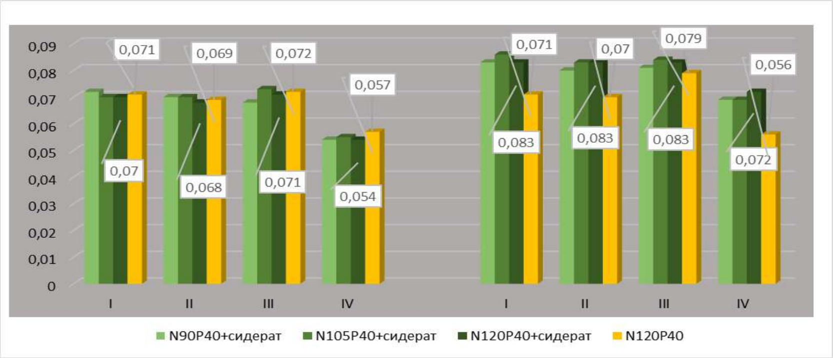
It has been demonstrated that salts accumulate in the soil profile primarily due to the capillary rise of groundwater into the upper horizons and subsequent evaporation from the soil surface[20]. In nature, there is an annual cycle of moisture and temperature fluctuations in the upper soil layers, where the initial stage of increasing moisture in the upper soil horizons during the autumn results from atmospheric precipitation absorption and insufficient evaporation. This is followed by the freezing stage, characterized by the movement of moisture from the lower layers to the upper layers. Finally, the spring thaw stage, associated with maximum soil saturation, occurs. After positive temperatures and increased evaporation, a drying phase of the upper soil layers follows. Such a cycle can also affect the saturation of soil horizons with soluble salts. The less water in the soil, the more concentrated the salt solution in it becomes.

---

[20] Назаренко І. І., Польчина С. М. Нікорич В. А. Грунтознавство : підручник. Чернівці : Книги – XXI, 2004. 400 с.

The results of the conducted research indicate that, in terms of the dominant anions, all experimental variants in the arable layer of the soil exhibit a chloride-sulfate salinity type. Based on the content of total and toxic water-soluble salts, the soil is classified as non-saline.

It should be noted that at the beginning of the growing season for agricultural crops in the crop rotation, there is no distinct trend of increasing or decreasing the total amount of soluble salts in the arable soil layer depending on the primary tillage methods. The exceptions are the variants where crops were sown in untilled soil, where a reduction of soluble salts in the soil by 18.5–22.8 % was observed (Figure 5).



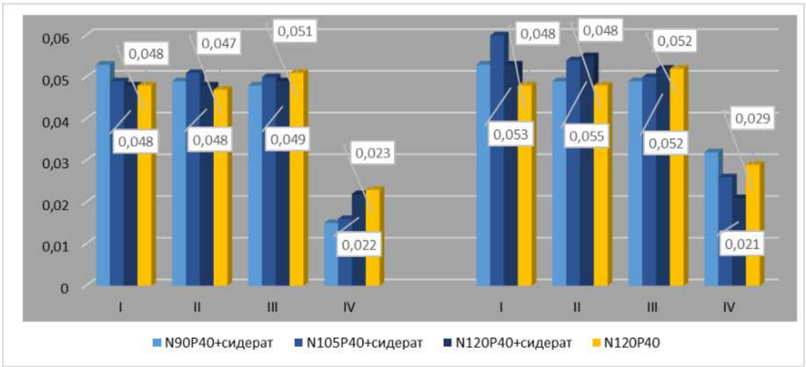
Beginning of Vegetation End of Vegetation

Note: Soil tillage systems: I – differentiated; II – shallow no-till; III – deep no-till; IV – planting crops in untilled soil.

Fig. 5. Total soluble salt content in soil samples in the experimental variants at the beginning and at the end of the crop vegetation period, % (average for the crop rotation of 2019–2020)

By the end of the crop vegetation period, the soluble salt content in the 0–30 cm soil layer remained almost unchanged in the variants where cover crops were not used and increased by 18.5–33.3 % in the variants where post-harvest cover crops were sown.

In all variants involving mechanical soil tillage, there was an observed nearly twofold increase in the amount of toxic salts (Figure 6).



Beginning of Vegetation End of Vegetation

Note: Soil tillage systems: I – differential; II – shallow no-till; III – deep no-till; IV – sowing crops into untilled soil.

Fig. 6. Sum of toxic salts in soil samples in the research variants at the beginning and end of the crop vegetation, % (average for the crop rotation 2019–2020)

The lowest content of toxic salts, which include sodium ions, was observed both at the beginning and at the end of the crop vegetation period in the variants where crops were sown into untilled soil. Overall, the content of toxic salts in the studied soil layer was insufficient to indicate the soil salinization process[21].

5. Formation of crop yield depending on the researched factors

As a result of the conducted research, it was noted that the best conditions for the formation of corn yield, both in 2020 and on average over the two years of the study, were achieved through deep chisel tillage of the soil. In comparison to the control (plowing), the average yield increase in 2019–2020, depending on the fertilization system, ranged from 0.02 to 0.86 tons per hectare with NPK (nitrogen-phosphorus-potassium) ratio of 0.6 tons per hectare. The highest crop yield of 10.83 tons per hectare was obtained with the application of fertilizers at a rate of N180P40 and the use of a cover crop (see Table 1).

---

[21] Інструкція з проведення ґрунтово-сольової зйомки на зрошуваних землях України. ВНД 33-5.5-11-2002 / С. А. Балюк, В. Я. Ладних, В. Г. Новікова, Н. Ю. Гаврилович, О. А. Носоненко, М. І. Ромащенко та ін. Київ : Державний комітет України по водному господарству, 2002. 32 с.

The yield of corn on the variants without cover crop was lower by 0.85–1.26 tons per hectare for all soil tillage systems (NPK_{05} = 0.31 t/ha).

On the research variants with the application of cover crops and a dose of mineral fertilizers of 90 kg/ha, soybean yield was higher compared to the non-cover crop background by 0.21–0.58 t/ha, with an NPK_{05} of 0.13 t/ha. However, the highest soybean yield in the conditions of 2020 (3.14 t/ha) was obtained with an $NPK_{60}P_{40}$ fertilizer dose on a cover crop background with chisel plowing to a depth of 28–30 cm (see Table 2).

Based on the results of the two-year research, no significant impact of soil tillage methods on soybean yield was found. On variants with deep (28–30 cm) and shallow (12–14 cm) chisel plowing and $NPK_{60}P_{40}$ fertilization with the application of cover crops, soybean yield was higher than the control by 0.32–0.35 t/ha, with an NPK_{05} of 0.22 t/ha.

Table 1

Corn yield under different soil tillage methods and fertilization

Tillage System	**Tillage Method and Depth (A)**	**Fertilization System (B)***	**Yield, t/ha**			**+,– compared to Control**	
			2019	**2020**	**2019–2020**	**(A)**	**(B)**
Differential	28–30	1	10,06	7,91	8,99	–	0,08
		2	10,42	8,48	9,45	–	0,55
		3	10,53	9,42	9,98	–	1,08
		4	9,23	8,57	8,90	–	–
Shallow no-till	12–14	1	9,86	6,88	8,37	–0,62	–0,84
		2	10,26	7,39	8,83	–0,63	–0,38
		3	10,36	9,76	10,06	0,08	0,85
		4	9,10	9,31	9,21	0,31	–
Deep no-till	28–30	1	10,19	7,81	9,00	0,02	–0,60
		2	10,35	9,04	9,70	0,25	0,09
		3	**10,95**	**10,71**	**10,83**	0,86	1,23
		4	9,23	9,97	9,60	0,70	–
No-till	No-till	1	9,68	8,41	9,05	0,06	0,86
		2	9,77	8,54	9,16	–0,30	0,97
		3	9,91	8,98	9,45	–0,53	1,26
		4	9,16	7,21	8,19	–0,72	–
HIP_{05}	(A)		**0,48**	**1,2**	**0,6**		
	(B)		**0,14**	**0,63**	**0,31**		

Note: * 1 – cover crop + $N_{120}P_{40}$; 2 – cover crop + $N_{150}P_{40}$; 3 – cover crop + $N_{180}P_{40}$; 4 – $N_{180}P_{40}$ (control).

Table 2

Soybean Yield for Different Soil Tillage Methods and Fertilization

Tillage System	**Tillage Method and Depth (A)**	**Fertilization System (B)***	**Yield, t/ha**			**+,– compared to Control**	
			2019	**2020**	**2019–2020**	**(A)**	**(B)**
Differential	28–30	1	3,66	2,71	3,19	–	0,36
		2	3,73	2,81	3,27	–	0,44
		3	3,55	3,02	3,29	–	0,46
		4	3,15	2,51	2,83	–	–
Shallow no-till	12–14	1	3,75	2,90	3,33	0,14	0,56
		2	**4,27**	2,97	**3,62**	0,35	0,86
		3	3,68	2,64	3,16	–0,13	0,40
		4	3,10	2,43	2,77	–0,06	–
Deep no-till	28–30	1	3,43	2,91	3,17	–0,02	0,37
		2	4,03	**3,14**	3,59	0,32	0,79
		3	3,6	3,01	3,31	0,02	0,51
		4	3,13	2,47	2,80	–0,03	–
No-till	No–till	1	3,48	2,60	3,04	–0,15	0,30
		2	3,58	2,68	3,13	–0,14	0,39
		3	3,70	2,96	3,33	0,04	0,59
		4	3,10	2,38	2,74	–0,09	–
HIP_{05}	(A)		**0,35**	**0,2**	**0,22**		
	(B)		**0,14**	**0,13**	**0,08**		

Note. * 1 – cover crop + $N_{30}P_{40}$; 2 – cover crop + $N_{60}P_{40}$; 3 – cover crop + $N_{90}P_{40}$; 4 – $N_{90}P_{40}$ (control);

On other variants, the difference in yield levels did not exceed the experimental error. A decrease in soybean yield compared to the control by 0.09–0.18 t/ha was recorded under conditions of planting in untreated soil. The highest soybean yield of 3.62 t/ha was observed with shallow (12–14 cm) chisel plowing and the application of cover crops in conjunction with $NPK_{60}P_{40}$ fertilizer. Further increasing the fertilizer dose to $NPK_{90}P_{40}$ did not result in a yield increase. The yield increase from the use of cover crops was observed for all soil tillage systems and ranged from 0.4 to 0.59 t/ha.

When mineral fertilizers $N_{90}P_{40}$ were applied as a precursor (after soybeans) in combination with cover crop use and chisel plowing to a depth of 23–25 cm, the highest winter wheat yield was observed. Over the two years of research, it averaged 7.53 t/ha, which was higher than the control (disk tillage in a differentiated system) by 0.43 t/ha, with a LSD_{05} of 0.26 t/ha (Table 3). Under disk tillage to a depth of 12–14 cm in the long-term application of this system in crop rotation under the same fertilization system, a slight decrease in yield of 0.12 t/ha compared to the chisel plowing option was observed. Yield reduction compared to the control was noted for no-till variants and ranged from 0.24 to 0.82 t/ha. In variants without cover crops, the yield was lower by 0.28–1.26 t/ha with an LSD$_{05}$ of 0.11 t/ha.

The highest yield of winter barley was achieved with chisel plowing and fertilization systems using cover crops, combined with applying a dose of mineral fertilizers N$_{180}$P$_{40}$ after the precursor crop (corn) – 7.25 t/ha (Table 4).

Overall, the fertilization systems had a greater impact on the yield of winter barley than the soil tillage methods. Under the same fertilization systems, the difference in winter barley yield between various soil tillage methods was not significant, except for no-till variants where a yield reduction relative to the control (differentiated soil tillage system) of 0.27–0.53 t/ha was observed, with an LSD$_{05}$ of 0.36 t/ha.

Table 3

Winter Wheat Yield for Different Soil Tillage Methods and Fertilization, t/ha

Tillage System	**Tillage Method and Depth (A)**	**Fertilization System (B)***	**Yield, t/ha**			**+,– compared to Control**	
			2019	**2020**	**2019–2020**	**(A)**	**(B)**
Differential	12–14	1	6,1	7,20	6,65	–	0,13
		2	6,35	7,33	6,84	–	0,32
		3	6,83	7,37	7,10	–	0,58
		4	5,87	7,17	6,52	–	–
Shallow no-till	12–14	1	6,04	7,49	6,77	0,12	–0,16
		2	6,16	7,67	6,92	0,08	–0,01
		3	7,0	7,81	**7,41**	0,31	0,48
		4	6,42	7,43	6,93	0,41	–
Deep no-till	23–25	1	5,85	7,17	6,51	–0,14	0,24
		2	6	7,65	6,83	–0,01	0,56
		3	**7,01**	**8,05**	**7,53**	0,43	1,26
		4	5,45	7,09	6,27	–0,25	–
No-till	No-till	1	4,51	7,16	5,84	–0,82	–0,44
		2	5,19	7,24	6,22	–0,63	–0,06
		3	5,85	7,26	6,56	–0,55	0,28
		4	5,59	6,97	6,28	–0,24	–
HIP$_{05}$	(A)		**0,37**	**0,5**	**0,26**		
	(B)		**0,21**	**0,16**	**0,11**		

Note. * – N$_{90}$P$_{40}$ applied after a precursor, with the following mineral fertilization rates: 1 – cover crop + N$_{30}$P$_{40}$; 2 – cover crop + N$_{60}$P$_{40}$; 3 – cover crop + N$_{90}$P$_{40}$; 4 – N$_{90}$P$_{40}$

Under different primary soil tillage systems, the increase in winter barley yield on variants using cover crops as precursors was 0.85–1.06 t/ha (LSD_{05}=0.38 t/ha).

In general, the nutrient and water regime of the soil in crop rotations under differentiated and shallow no-tillage systems ensured the formation of high crop yields and crop productivity. A decrease in productivity was observed when crops were sown directly into untilled soil.

Based on the results of the two-year study, under control conditions (with differentiated soil tillage and fertilization without the use of post-harvest cover crops), the productivity of crop rotations was at the level of 6.44 grain units (Table 5).

Table 4

Winter Barley Yield for Different Soil Tillage Methods and Fertilization, t/ha

Tillage System	**Tillage Method and Depth (A)**	**Fertilization System (B)***	**Yield, t/ha**			**+,– compared to Control**	
			2019	**2020**	**2019–2020**	**(A)**	**(B)**
Differential	12–14	1	5,77	4,30	5,04	–	–0,82
		2	5,68	5,55	5,62	–	–0,23
		3	6,18	**7,21**	6,70	–	0,85
		4	5,05	6,65	5,85	–	–
Shallow no-till	12–14	1	5,94	4,78	5,36	0,33	–0,54
		2	6,01	5,44	5,73	0,11	–0,18
		3	**6,84**	7,07	**6,96**	0,26	1,06
		4	5,42	6,38	5,90	0,05	–
Deep no-till	23–25	1	5,85	5,28	5,57	0,53	–0,17
		2	5,97	5,82	5,90	0,28	0,16
		3	6,31	**7,25**	6,78	0,08	1,05
		4	4,93	6,54	5,74	–0,12	–
No-till	No-till	1	5,18	4,20	4,69	–0,35	–0,63
		2	5,23	5,46	5,35	–0,27	0,03
		3	5,84	6,81	6,33	–0,37	1,01
		4	4,68	5,96	5,32	–0,53	–
HIP_{05}	(A)		**0,35**	**0,48**	**0,36**		
	(B)		**0,40**	**0,6**	**0,38**		

Note. * – $N_{120}P_{40}$ applied after a precursor, with the following mineral fertilization rates: 1 – cover crop + $N_{120}P_{40}$; 2 – cover crop + $N_{150}P_{40}$; 3 – cover crop + $N_{180}P_{40}$; 4 – $N_{180}P_{40}$

Table 5

Crop Rotation Productivity in an Irrigated System under Different Primary Soil Tillage Systems and Fertilization, t/ha grain units (2019–2020)

Tillage System	Fertilization System			
	$N_{90}P_{40}$+ cover crop (I)	**$N_{105}P_{40}$+ cover crop (II)**	**$N_{120}P_{40}$+ cover crop(III)**	**$N_{120}P_{40}$ (IV)**
Differential	6,47	6,81	7,25	6,44
Shallow no-till	6,49	6,85	7,35	**6,60**
Deep no-till	**6,56**	**7,07**	**7,60**	6,52
No-till	6,14	6,45	6,92	6,05

Under shallow no-tillage soil loosening, productivity was higher than the control by 2.5 %, under deep no-tillage soil loosening, it was higher by 1.2 %, while sowing crops in untilled soil resulted in a 6.0 % decrease in crop rotation productivity.

The inclusion of post-harvest cover crops in intermediate crop rotations contributed to an increase in the productivity of the crop rotation under all primary soil tillage systems: under the differentiated system by 12.5 %, under shallow no-tillage by 11.4 %, under deep no-tillage by 16.5 %, and when sowing crops directly into untilled soil by 14.3 %. According to the study results, the highest productivity, reaching 7.60 t/ha of grain units per hectare of crop rotation area, was achieved by crop rotation under the deep no-tillage system with chisel soil loosening to a depth of 23–25 cm to 28–30 cm and the use of post-harvest cover crops as a fertilizer.

6. The economic efficiency assessment of climate-smart crop cultivation technologies in crop rotations under irrigation

The economic efficiency assessment of climate-smat crop cultivation technologies in crop rotations under irrigation indicates that the highest profit and level of profitability per hectare of crop rotation area are achieved with the use of cover crops and the deep no-tillage soil preparation system (see Table 6).

In variants without a cover crop, the best economic performance was observed in cases of shallow subsoil tillage systems with chisel and disc plowing to a depth of 12–14 cm. The highest profit of 40,364 UAH per hectare with a profitability level of 202.8 % was achieved with N120P40 fertilization per hectare of crop rotation area and the use of cover crops as fertilizers.

Table 6

Economic Efficiency of Crop Cultivation Technologies under Different Soil Tillage and Fertilization Systems (average for the crop rotation, 2019–2020)

Efficiency indicator	**Tillage System**	**Fertilization System**			
		$N_{90}P_{40}$+ cover crop (I)	**$N_{105}P_{40}$+ cover crop (II)**	**$N_{120}P_{40}$+ cover crop (III)**	**$N_{120}P_{40}$ (IV)**
Production costs, UAH/ha	Differential	19218	19507	19800	19086
	Shallow no-till	19029	19319	19615	18993
	Deep no-till	**19324**	**19613**	**19908**	**19246**
	No-till	19010	19301	19594	19013
Received profit, UAH/ha	Differential	32241	34559	37742	32040
	Shallow no-till	32591	35218	38701	**33387**
	Deep no-till	**32748**	**36559**	**40364**	32384
	No-till	29745	31926	35345	28997
Profitability level, %	Differential	167,8	177,2	190,6	167,9
	Shallow no-till	**171,3**	182,3	197,3	**175,8**
	Deep no-till	169,5	**186,4**	**202,8**	168,3
	No-till	156,5	165,4	180,4	152,5

CONCLUSIONS

Based on the research results, it has been determined that the use of cover crops (specifically, spring mustard) as fertilizer and the incorporation of preceding crop by-products alongside recommended mineral fertilizer doses under different primary soil tillage methods in a four-field crop rotation under irrigation provide several advantages:

- Reduces soil bulk density in the 0–40 cm layer by 1.6–2.3 % and increases soil porosity with less intensive compaction during crop growth, resulting in improved soil water permeability by an average of 0.45–0.75 mm/hr.
- Reduces the total water consumption of the crop rotation: 54–129 m^3/ha for soybeans and 70–154 m^3/ha for corn.
- Decreases water usage for the formation of winter wheat yields by 5.5–16.0 %, corn by 6.1–15.4 %, winter barley by 11.5–20.5 %, and soybeans by 12.5–19.9 %.
- Increases the content of humus in the 0–40 cm soil layer by an average of 0.2–0.6 % (absolute values), with the greatest increase observed in the 20–40 cm soil layer under deep differentiated and deep no-tillage soil preparation systems.
- Enhances microbiological activity in cases where primary soil tillage is not performed.

- Reduces the quantity of soluble salts in the soil, particularly toxic salts containing sodium, when crops are sown directly into untilled soil.
- Increases the yields of corn by an average of 1.11 t/ha, soybeans by 0.49 t/ha, winter wheat by 0.65 t/ha, and winter barley by 0.99 t/ha.

The best conditions for achieving high corn yields, up to 10.83 t/ha, were found when deep chisel plowing (28–30 cm) was performed, along with the use of cover crops as fertilizers (N180P40).

The highest soybean yield, at 3.62 t/ha, was achieved with shallow chisel subsoil tillage (12–14 cm) combined with N60P40 fertilization and the use of cover crops.

The highest yield for winter wheat, reaching 7.53 t/ha, was obtained with chisel soil preparation to a depth of 23–25 cm and N90P40 fertilization, including the incorporation of the by-products of the preceding crop (soybeans).

The highest winter barley yield, at 6.96 t/ha, was achieved with disc soil preparation (12–14 cm depth) and N120P40 fertilization, using cover crops and incorporating the by-products of the preceding crop (corn).

The most productive technology, yielding 7.60 t of grain per hectare of crop rotation area and the highest profit of 40,364 UAH/ha with a profitability level of 202.8 %, was achieved through the combination of deep no-tillage soil preparation (23–25 to 28–30 cm) and N120P40 fertilization, including the incorporation of cover crops in intermediate sowings.

SUMMARY

The paper addresses the scientific justification of designing climate-smart crop rotations on irrigated soils, depending on the primary soil cultivation systems and the utilization of catch crops in intercropping to enhance and stabilize soil fertility and ecological balance in agroecosystems. The impact of catch crops under various primary soil cultivation systems on soil fertility and environmental amelioration in irrigated crop rotations was investigated. It was established that the use of catch crops as fertilizers results in reducing soil compaction in the 0–40 cm soil layer under different primary soil cultivation systems by 1.6–2.3 % and increasing its porosity compared to variants without catch crops, reducing compaction during the crop's vegetation period. This leads to an average increase in soil permeability by 0.45–0.75 mm/h, a reduction in the total water consumption of crops in the rotation, and an increase in humus accumulation in the 0–40 cm soil layer by an average of 0.2–0.6 %. It also enhances microbiological activity in variants where primary soil cultivation was not performed and decreases the concentration of soluble salts in the soil. The highest productivity was achieved with the cultivation of crops in a system of deep non-plow primary

soil cultivation with chiseling to a depth of 23–25 to 28–30 cm and fertilization with N120P40, including the use of catch crops in intercropping.

Bibliography

1. Гамаюнова В. В. Сучасний стан та проблеми родючості ґрунтів південного регіону України. *Таврійський науковий вісник*. Херсон : Айлант, 2005. Вип. 40. С. 130–135.
2. Наукові основи агропромислового виробництва в зоні Степу України / за ред. М. В. Зубця та ін. Київ : Аграрна наука, 2004. 844с.
3. Земельні ресурси України / під ред. В. В. Медведєва, Т. М. Лактіонової. Київ : Аграрна наука, 1998. 150 с.
4. Сайко В. Ф., Малієнко А. М. Системи обробітку ґрунту в Україні. Київ : ЕКМО, 2007. 44 с.
5. Петриченко В. Ф., Безуглий М. Д., Жук В. М., Іващенко О. О. Нова стратегія виробництва зернових та олійних культур в Україні. Київ : Аграр. Наука, 2012. 48 с.
6. Islam R., Reeder R. No-till and conservation agriculture in the United States: An example from the David Brandt farm, Carroll, Ohio. ScienceDirect, 2014. P. 31–35.
7. Ресурсозберігаючі технології механічного обробітку ґрунту в сучасному землеробстві України / І. Д. Примак, В. О. Єщенко, Ю. П. Манько, М. І. Трегуб, О. І. Примак. Київ : КВІЦ, 2007. 272 с.
8. Сайко В. Ф., Малієнко А. М. Мінімальний та нульовий обробітки ґрунту, стан і перспективи їх запроваджень в Україні. *Посібник українського хлібороба*. Київ : Урожай, 2009. С. 178–188.
9. Кроветто Карлос К. NO-TILL. Взаимосвязь между No-Till, растительными остатками, питанием растений и почвы. Днепропетровск, 2007. 235 с.
10. Косолап М. П., Кротінов О. П. Система землеробства No-till. Київ : Логос, 2011. 352 с.
11. Єщенко В. О., Копитко П. Г., Опришко В. П., Костогриз П. В. Основи наукових досліджень в агрономії. Київ : Дія, 2005. 288 с.
12. Вожегова Р. А., Лавриненко Ю. О., Малярчук М. П. та ін. Методика польових і лабораторних досліджень на зрошуваних землях. Херсон : Грінь Д. С. 2014. 286 с.
13. Ушкаренко В. О., Вожегова Р. А., Голобородько С. П., Коковіхін С. В. Статистичний аналіз результатів польових дослідів у землеробстві: монографія**.** Херсон : Айлант, 2013. 403 с.
14. Ушкаренко В. О., Нікішенко В. Л., Голобородько С. П., Коковіхін С. В. Дисперсійний і кореляційний аналіз у землеробстві та рослинництві. Херсон : Айлант, 2008. 272 с.

15. ДСТУ 4729:2007 «Якість ґрунту. Визначенння нітратного та амонійного азоту в модифікації ННЦ ІГА ім. І. Н. Соколовського».

16. ДСТУ 4114:2002 «Грунти. Визначення рухомих сполук фосфору і калію за модифікованим методом Мачигіна».

17. Пахомов О. Є., Дідур О. О., Кульбачко Ю. Л., Лоза І. М. Екохімічні аспекти існування безхребетних тварин у ґрунті: методи визначення: навч. посіб. Донецьк : РВВ ДНУ, 2010. 176 с.

18. Бітюкова Л. Б., Драч Ю. О., Малієнко А. М. Вплив тривалого застосування способів обробітку на мікробний ценоз і гумусний стан дерново-підзолистого ґрунту. *Вісник аграрної науки*. 1999. № 9. С. 12–17.

19. Назаренко І. І., Польчина С. М. Нікорич В. А. Грунтознавство: Підручник. Чернівці : Книги – XXI, 2004. 400 с.

20. Інструкція з проведення ґрунтово-сольової зйомки на зрошуваних землях України. ВНД 33-5.5-11-2002 / С. А. Балюк, В. Я. Ладних, В. Г. Новікова, Н. Ю. Гаврилович, О. А. Носоненко, М. І. Ромащенко та ін. Київ : Державний комітет України по водному господарству, 2002. 32 с.

Information about the author:
Vozhehova Rayisa Anatoliivna,
Doctor of Agricultural Sciences, Professor,
Academician of National Academy of Sciences,
Institute of Climate-Smart Agriculture
of the National Agrarian Academy of Agrarian Sciences of Ukraine,
24, Maiatska doroha str., Khlibodarske, Odesa region, 67667, Ukraine