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AGROPHYSICAL PROPERTIES OF SOIL IN THE IRRIGATED CROPS OF WINTER BARLEY UNDER THE INFLUENCE OF BASIC TILLAGE AND ORGANIC-MINERAL FERTILIZATION IN THE SOUTHERN STEPPE OF UKRAINE

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Abstract

The study was performed in Askanian State Agricultural Research Station of the Institute of Climate-Smart Agriculture of the National Academy of Agrarian Sciences of Ukraine, located in the Southern Steppe zone of the country. The experiments were carried out in a stationary field in the period 2015-2020 within a four-field crop rotation (winter barley with post-harvest sowing of green manure crop-soybean- winter wheat with post-harvest sowing of green manure crop-grain maize) and resulted in scientific substantiation of the influence of different systems of basic tillage and organic-mineral fertilization systems on the agrophysical parameters of dark-chestnut soil and formation of winter barley yields. It was determined that the no-till variations, which outperformed the bulk density in the control (under the conduct of mechanical tillage) by 4.0%, are responsible for the soil's maximum bulk density (1.30 g/cm^3). The bulk density of the dark-chestnut soil was decreased by 1.6% when post-harvest green manure was used, and by 2.3% when continuous no-till farming was used. The bulk density of the arable layer of dark-chestnut soil in the range of 1.22-1.26 g/cm^3 produces the maximum productivity of winter barley. Crop yields are impacted by a reduction in bulk density brought on by excessive soil loosening as well as soil compaction.

Key words: *water permeability, soil porosity, soil tillage systems, green manure crop, bulk density of the soil, winter barley*

INTRODUCTION

Processes of soil degradation are observed in many countries of the world, including Ukraine. Among the factors affecting the intensity of soil degradation processes are their natural salinity and sodification, the natural aridity of the land, which is accompanied by insufficient rainfall, a negative water balance, and the related conditions of soil formation. For example, the erosion area of the Ukrainian lands currently reaches approximately 17.0 million hectares, with a share of 41% to the total agricultural land area and is annually increased by 80,000 hectares [1]. This is especially relevant to the most fertile and over-ploughed black-earth soils, which occupy 60% of the arable land in Ukraine.

The harmful impacts of natural and anthropogenic factors on soil resources cause, first, deterioration of soil structure, mechanical destruction and compaction of soil, permanent depletion of humus and nutrients, water and wind erosion, soil contamination with mineral fertilisers and chemicals. Agrophysical degradation associated with soil compaction, is a wide-scale problem. Bulk density is an important component of soil fertility, the main indicator of its physical conditions, on which the water, air, and thermal regimes of the soil depend. Therefore, the main reasons for the decrease in fertility in over-compacted soils are insufficient or poor water permeability and deterioration of the water regime in general, and on too loose soils – a low concentration of moisture and nutrients in the upper layer and unproductive water uptake for evaporation.

In the soil-ecological zone of the Southern steppe of Ukraine, Southern chernozems, dark chestnut and chestnut soils, which were formed under a significant natural moisture deficit, are common. A feature of these soils is a compact transition horizon and low water permeability. The upper layers of the soil have physical characteristics favourable for the development of plants, in contrast to the deeper layers of the subsoil horizon. Therefore, the question of ensuring optimal bulk density of the soil during the growing season, which will contribute to the most efficient water use, better development of the root system and vegetative mass, and as a result – an increase in productivity, is relevant.

Among numerous agricultural measures that affect soil agrophysical parameters, tillage is of greatest importance, because in the vast majority cases the bulk density and structure of the soil are regulated by the way and depth of tillage.

Mechanical tillage, together with crop rotation and fertilisers, is an important link in the systems of intensive farming. Under the influence of rational soil tillage, its agronomic properties change, favourable parameters of the structure and density of the arable layer are created, the water-air, heat and nutrient regime improves, which in its turn leads to an increase in the yield of cultivated crops [7].

Tillage systems, which are currently used in Ukraine, are one of the most actively discussed questions of modern agriculture and have always received special attention of the scientists. The development of tillage systems is closely related to the general organisational and economic changes in the agricultural sector, the nature of land resource use, the structure of cultivated areas, crop rotations, social and demographic processes, trends in climate change, and reclamation measures. To study the influence of different tillage systems, ways, and depth of loosening on the processes of soil formation and crop yields in different soil and climatic zones of Ukraine, stationary experiments were carried out. A significant contribution to the study of the mentioned problems was made by domestic scientists V. F. Saiko, A. M. Malienko, V. M. Polovyi, M. P. Maliarchuk, etc., who proved that soil tillage systems should rationally combine multi-depth ploughing with the operations conducted using sub-surface tiller [12, 19, 20, 28].

Thus, according to the results of the long-term study by I. D. Primak and O. B. Panchenko, conducted on black-earth soils, which are typical for the Central Forest-Steppe of Ukraine, it was established that under sub-surface, differentiated, and continuous shallow tillage, the bulk density of the arable layer of the soil, compared to ploughing, is greater by 0.10, 0.06 and 0.04 g/cm^3, respectively. A significant increase in the volume of non-capillary pores is observed only under continuous shallow tillage with the application of 12 tons of manure + $N_{83}P_{116}$ [18].

On the dark grey podzol slightly-loamy soils of the Western Forest Steppe, the application of different methods of basic tillage for winter wheat (namely, ploughing at 20–22 cm, harrowing at 10–12 cm and 6–8 cm) ensured a favourable bulk density of the soil for the crop in the layers 0–10 and 10–20 cm, respectively, 1.14–1.27 and 1.24–1.36 g/cm^3. However, in the layer 20–30 cm, a sub-plough compaction occurred in all the variants, especially where shallow tillage was applied. The use of by-products for fertilisation contributed to a certain decrease in soil compaction, but led to an increase in weediness, which increased with a decrease in the depth of tillage [17].

In the Precarpathia sod-podzolic surface gley soils, ploughing at 20–22 cm with loosening of the subsoil layer at 12–14 cm ensures a decrease in the bulk density of the soil of 0.01–0.04 g/cm^3, which has a positive effect on the growth and development of winter rye [2].

On the irrigated lands of the Southern Steppe of Ukraine, more favourable agrophysical properties of the soil are created when the mouldboard tillage at the depth of 25–27 is interchanged with tillage at 14–16 cm in the systems of multi-depth and differentiated tillage in crop rotation, which ensures the formation of higher productivity of spring rapeseed with the lowest production cost of seeds and the best profitability [3]. Against the background of shallow mulching tillage, as a result of reducing the loosening depth to

12–14 and 14–16 cm, there is some compaction of the 0–30 cm soil layer, but the optimal density parameters are not exceeded [22].

In modern agriculture, the specialisation of farms, crop rotations, and the amount of minimal tillage (shallow, surface) is increasing.

The no-till system, which is considered by scientists and agricultural producers the main factor in preserving soil fertility, increases soil resistance to wind and water erosion, and is increasingly widespread [10, 14, 15]. There is a recent study, which proves high economic efficiency and technological rationality of no-till implementation in the cultivation of grain corn in the South of Ukraine [5]. At the same time, scientists have proven several drawbacks of this technology, among which the bulk density of soils under crops is greater than under conventional tillage systems. Therefore, continuous investigation of tillage in crop rotations, conducted in the Southern Steppe zone of Ukraine, showed that the highest benefits both for the cultivated crops and soil conditions are recorded under the systems of differentiated tillage, which foresees changing of shallow plough less tillage and deep chisel loosening of the soil [13].

A significant contribution to the development of the theoretical foundations of minimal tillage was made by US scientists, who in the middle of the twentieth century started the world's first research project on conservation (zero) tillage and are developing it as a main strategy of modern agriculture. Furthermore, the central component of the concept when applying zero-tillage technology are cover crops, which can be used both in single species crops and in the form of crop mixtures. The results of US scientists testified that soil compaction in no-till systems was significantly reduced by cover crop mixtures, and the use of radish oilseeds in crop mixtures provides an average improvement effect of approximately 40% [8, 16, 21].

Therefore, the diversity of views on this problem led to a more detailed and in-depth study of the influence of various tillage technologies in combination with the use of cover crops (namely, post-harvest green manure crops) in the fertilisation system on the agrophysical parameters of the soil and the formation of the crop yield under irrigated conditions of the Southern Steppe of Ukraine.

MATERIALS AND METHODS

The study was carried out on the irrigated lands of the Askanian State Agricultural Research Station of the Institute of Irrigated Agriculture of the National Academy of Agrarian Sciences of Ukraine. The stationary field experiment has been performing since 2007. Experiments are carried out in a four-field crop rotation, namely: winter barley with post-harvest sowing of green manure crop - soybean - winter wheat with post-harvest sowing of green manure crop - grain maize. The study assessed the influence of different systems of basic tillage and organic-mineral fertilization systems on agrophysical properties of the dark-chestnut soil and yields of winter barley.

The soil of the experimental field is represented by dark-chestnut middle-loamy residually slightly saline soil. Soil-forming rock is represented by loess enriched with lime and gypsum, which is at a depth of approximately 2 metres from the surface. High yields of crops can be obtained on dark-chestnut soils in the years with enough precipitation or under irrigation [4].

The arable soil layer is 0–22 cm deep, and contains 2.3% of humus, 0.18%, 0.16, and 2.7% of the gross forms of nitrogen, phosphorus, and potassium, respectively. The pH of the aqueous soil extract is 7.0–7.2 points. The field water-holding capacity of the soil layer 0–100 cm is 21.3%, wilting point is 9.5%, the content of water-resistant aggregates is 34.1%, the equilibrium bulk density is 1.29 g/cm^3, the porosity is 49.2%, water permeability – 1.25 mm/min. The groundwater is located deeper than 10 m.

Because, due to its biological features, winter barley has the shortest vegetation period among cereal crops, it vacates the field earlier and acts as a good fore crop for the use of post-harvest green manure crops in the structure of the sown areas of irrigated crop rotations.

The study on the optimal agrotechnological complex for the cultivation of winter barley in a stationary field experiment, conducted in the period 2016–2020, included the following factors and options.

Factor A – four systems of basic soil tillage used for winter barley applying different methods and depths: disk tillage to the depth of 12–14 cm within a differentiated system of tillage in the crop rotation (control 1); disk tillage to the depth of 12–14 cm within the system of shallow tillage (no plough used) in the crop rotation; chisel tillage to the depth of 23–25 cm within the system of multi-depth tillage with no plough in the crop rotation; continuous (exceeding 10 years period) no tillage in the crop rotation.

Factor B – four systems of fertilisation: application of mineral fertilisers $N_{120}P_{40}$ for winter barley in all experimental variants on the background of the after-action of different fertilisers, applied in the field of a fore crop (grain maize): 1 – green manure + $N_{120}P_{40}$; 2 – green manure + $N_{150}P_{40}$; 3 – green manure + $N_{180}P_{40}$; 4 – $N_{180}P_{40}$ (control 2) and by-products, used as fertiliser.

Disk tillage was performed using a heavy disk harrow BDVP-4.2; chisel loosening was performed using a CASE-7300 ripper. In the no-till variant, the leaves and stems of the fore crop were shredded using the Schulte machine.

Winter barley was seeded in the first ten-day period of October using a Great Plains drill, which is used to sow in uncultivated soil. The sowing rate was 4.5 million of seeds per hectare.

The field experiments were conducted in four replications. The plots were systematically located by the tillage options with further division by the fertilisation rates. The total area of the experiment was 3.0 ha. The plot area – 450 m^2, the accounted area – 50 m^2.

The crop was cultivated with accordance to common cultivation technology for the South of Ukraine, in exception of the studied factors. Irrigation was performed by the machine «Zimmatik».

Spring mustard *var. Mriya* (included in the State Register of Plant Varieties Suitable for Dissemination in Ukraine since 2000) was sown as a green manure crop after the harvest of winter cereals. The crop has a short growing season; therefore, it could be used in intermediate crops in the grain-row crop rotation. The green manure crop was mown in the flowering stage - the first ten-day period of September. In the non-till variants, the green mass of the crop was left on the field surface as mulch, and in the variants with conventional tillage it was wrapped in the soil. The green mass of mustard at the time of mowing reached 9.4–10.7 t/ha.

The study was carried out using field, weighing, calculation, comparison, mathematical, and statistical methods, which were carried out according to the corresponding methodologies. Statistical data processing was performed to evaluate the significance of the differences between the experimental variants using the two-way ANOVA algorithm with the calculation of Fisher's least significant difference at $p<0.05$ (LSD_{05}) [11, 23, 24, 26, 27].

RESULTS AND DISCUSSIONS

The study's findings showed that the bulk density of the soil in the 0-40 cm layer in the control (with a differentiated system of basic tillage) and the variants without the use of post-harvest green manure was, on average, 1.25 g/cm^3 at the start of the winter barley growing season. The bulk density was 2.4% lower under the plough-less multi-depth system with chisel tillage than it was under the control, whereas it was 0.8% higher under the shallow ploughing method. The no-till choices had the highest bulk density of the soil (1.30 g/cm^3), which was 4.0% higher than the bulk density of the control (Fig. 1). These results are supported by the work of other scientific groups tested the effects of no-till options on the soil compaction [6].

The bulk density in the 0–40 cm soil layer was somewhat lower in the experimental versions where the effectiveness of green manure was investigated. When the green mass of the crop was wrapped to a depth of 28–30 cm, and the soil bulk density was reduced by 1.6%, the green manure crop had the largest impact on the multi-depth plough-less system.

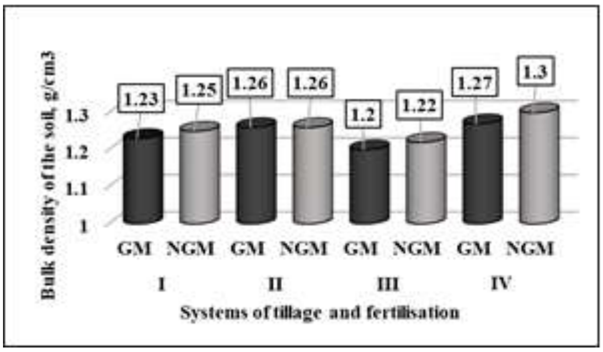

Fig.1. Bulk density of the soil in 0–40 cm layer at the beginning of winter barley growing season under different basic tillage and fertilisation systems, g/cm^3 (averaged for 2016–2020)

Notes. I – differentiated multi-depth system of soil tillage in the crop rotation; II – system of shallow plough-less tillage; III– system of differentiated plough-less tillage; IV – no-till; GM – green manure crop sown as the intermediate crop; NGM – no green manure crop sown.

Source: Own calculation and graphical work based on data from the conducted research

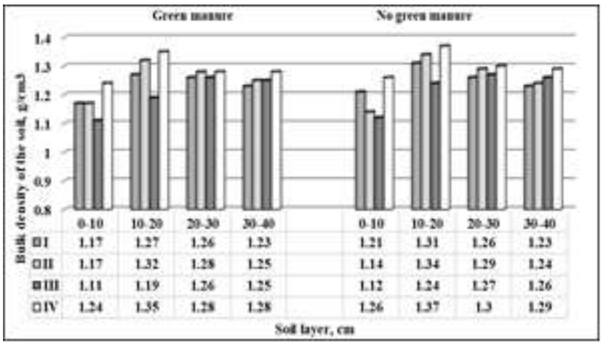

Fig. 2. Bulk density of the soil in the layers 0–10 cm, 10–20 cm, 20–30 cm and 30–40 cm at the beginning of winter barley's growing season under the different systems of basic tillage and fertilisation, g/cm^3 (averaged for 2016-2020)

Notes. I – differentiated multi-depth system of soil tillage in the crop rotation; II – system of shallow plough-less tillage; III– system of differentiated plough-less tillage; IV – no-till; GM – green manure crop sown as the intermediate crop; NGM – no green manure crop sown.

Source: Own calculation and graphical work based on data from the conducted research.

The slightest effect of green manure was on the variant with continuous shallow plough-less tillage. No-till, on average, resulted in a decrease in the bulk density of the soil by 2.3% (it was 1.27 g/cm^3).

The highest (0–10 cm) layer of the soil was the least compacted for all basic tillage and no-till systems; the examined parameter's value was 1.11–1.24 g/cm^3 for variants with green manure crop seeded and 1.12-1.26 g/cm^3 for variations without. (Fig. 2). The established fact is in agreement with other studies on this subject [6].

Soil compaction was seen beginning at a depth of 10 cm in the disk tillage and no-till variations at a depth of 12–14 cm. The soil layer 10–20 cm on these variants had the maximum bulk density, ranging between 1.31 and 1.37 g/cm^3 for the variants without a green manure crop and 1.27 to 1.35 g/cm^3 for the variants with a green manure crop seeded.

Soil compaction under the plough-less tillage approach with chisel loosening was measured up to 1.26 and 1.27 g/cm^3 in the layer 20–30 cm.

The bulk density of the soil was found to be lower in all the basic tillage variants investigated, ranging from 1.23-1.29 g/cm^3 in the versions without the green manure crop to 1.23-1.28 g/cm^3 in the variants when the green manure crop was seeded.

The study's findings also demonstrate that, when grown on dark-chestnut soil, winter barley yields are highest when the bulk density of the soil's arable layer is between 1.20 and 1.26 g/cm^3. Crop production is decreased by both an increase in the indicator under study and a drop in bulk density brought on by excessive soil loosening.

Among the physical properties of the soil, which are important to characterise its structure and mechanical composition, is total porosity. Soil porosity is influenced by the nature of the soil-forming process and tillage. Bulk density and soil porosity are inter-related values: the lower the soil density is, the greater its porosity is.

According to the study's findings, at the start of the winter barley growing season, the total porosity of the soil layer 0-40 cm in the versions without green manure use was at a level of 50.2-53.2%.

The highest soil porosity in the 0–40 cm layer was observed for the systems of multi-depth plough-less tillage with chisel loosening, where it was 53.2%. It was somewhat lower for the differentiated and shallow single-depth tillage systems with disk loosening – 52.0 and 51.9%, respectively. The no-till variants provided the lowest porosity of the soil – 50.2% (Fig. 3).

The variants with green manure crop had higher porosity was all the tillage systems, and it reached 51.5% for no-till, and up to 53.9% for deep chisel tillage. A slight increase in the total porosity of the soil layer 0–40 cm was recorded in the variants with the green manure crop: for the differentiated system with disk tillage and deep chisel tillage without ploughing – by 0.7%, for no-till – by 1.3 %.

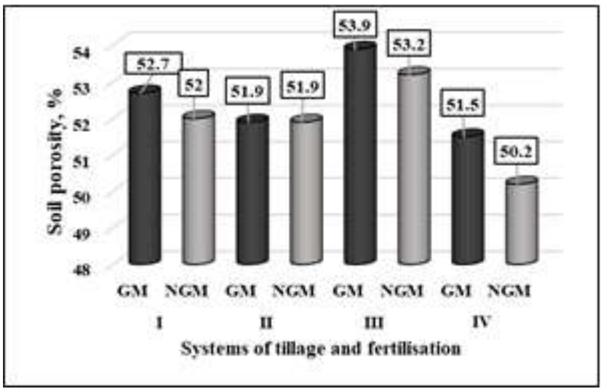

Fig. 3. Soil porosity in the 0–40 cm at the beginning of winter barley's growing season under the different systems of basic tillage and fertilisation, % (averaged for 2016-2020)

Notes. I – differentiated multi-depth system of soil tillage in the crop rotation; II – system of shallow plough-less tillage; III– system of differentiated plough-less tillage; IV – no-till; GM – green manure crop sown as the intermediate crop; NGM – no green manure crop sown.

Source: Own calculation and graphical work based on data from the conducted research.

During the growing season, crop rotation under the influence of weather conditions, irrigation, and agrotechnical measures increased the bulk density of the soil, leading to a slight decrease in its porosity by an average of 1.0–1.4%.

The value of soil water permeability depends not only on the type of soil and its moisture storage, but also on tillage.

As evidenced by the results of the current study, the methods of tillage that provide a lower bulk density of the soil and its greater porosity contribute to better absorption of water into the soil.

Depending on the basic tillage systems in crop rotation, the water permeability of the soil at the beginning of the winter barley growing season in the control (variants without a green manure crop) was 2.33–4.08 mm/min.

On average, during the study years, the best soil water permeability (4.08 mm/min) was provided by plough-less tillage to a depth of 23–25 cm using chisel tools.

The lowest rate of water absorption was recorded in the no-till variants (2.33 mm/min) (Fig. 4).

Among the reasons are higher bulk density, lower total porosity and the ability of untreated soil to retain moisture for a longer period.

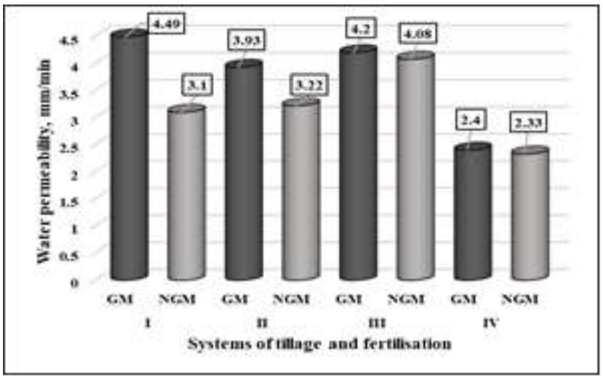

Fig. 4. Soil water permeability in the period of spring growth renovation of winter barley under the different systems of basic tillage and fertilisation, mm/min (averaged for 2016–2020)

Notes. I – differentiated multi-depth system of soil tillage in the crop rotation; II – system of shallow plough-less tillage; III– system of differentiated plough-less tillage; IV – no-till; GM – green manure crop sown as the intermediate crop; NGM – no green manure crop sown.

Source: Own calculation and graphical work based on data from the conducted research.

An increase in the water permeability of the soil was recorded in the variants with green manure crop.

With the differentiated tillage system, the rate of water permeability was higher by 1.39 mm/min, with a shallow plough-less system – by 0.71 mm/min, with a multi-depth plough-less system – by 0.12 mm/min, with no-till – by 0.07 mm/min, respectively.

The study's findings show that winter barley is a good fore crop for post-harvest green manure crops and efficiently exploits the yield-forming effects of green manure application.

It was found that in the differentiated basic tillage system (control 1), the winter barley yield was on average 5.93 t/ha, and increased from 5.46 to 6.50 t/ha with an increase in the dose of mineral fertilisers applied under the fore crop (Table 1).

Under the shallow single-depth and multi-depth plough-less basic tillage systems, barley formed a slightly higher average yield - 0.15 and 0.19 t/ha, respectively.

Table 1. Yields of winter barley grain depending on under the different systems of basic tillage and fertilization, t/ha (averaged for 2016-2020)

Soil tillage system (Factor A)					**Average by the Factor A**
	$N_{120}P_{40}$ +green manure	$N_{150}P_{40}$ +green manure	$N_{180}P_{40}$ +green manure	$N_{180}P_{40}$	
Differentiated, using disk at 12-14 cm	5.46	5.88	6.5	5.88	5.93
Shallow plough-less, using disk at 12-14 cm	5.63	5.9	6.62	6.16	6.08
Multi-depth plough-less, using chisel at 23-25 cm	5.84	6.07	6.68	5.88	6.12
No-till	4.82	5.22	5.69	5.29	5.26
Average by the Factor B	5.44	5.77	6.37	5.80	
LSD_{05}, t/ha: A=0.26; B=0.19.					

Source: Own calculation based on data from the conducted research.

The lowest yield was formed by winter barley without till - 5.26 t/ha, which was less than the control variant by 0.67 t/ha at LSD_{05} 0.26 t/ha. This result is supported by another long-term study, where the best yields of the crop were obtained under conventional deep plough tillage rather than shallow tillage without ploughing [9].

The yield of winter barley was more influenced by fertilisation methods. Winter barley yield increased in all basic tillage systems with an increase in nitrogen fertiliser application from 120 to 180 kg/ha per year, when combined with the use of post-harvest sowing of spring mustard. This increase was 1.04 t/ha for a differentiated system with disk tillage done to a depth of 12–14 cm, 0.99 t/ha for a shallow single-depth system, and 1.04 t/ha for a multi-depth system with chisel loose Green manure fertilisers also had a favourable impact on the development of the yield of the crop. In the green manure variants, an increase in winter barley yield was up to 0.62 t/ha in the differentiated system, 0.46 t/ha in the shallow tillage system, 0.80 t/ha in the multi-depth system of tillage without ploughing, and 0.40 t/ha for no-till at the LSD_{05} value of 0.19 t/ha. The fact that fertilisers had a decisive effect on the crop productivity is not surprising, as it is well-established fact that most crops provide better feedback for nutrition rather than tillage options [25].

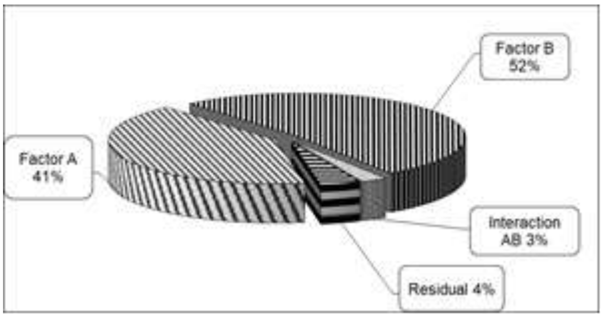

Fig. 5. Share of each of the studied factors and their interaction in determination of winter barley productivity
Source: Own calculation and graphical work based on data from the conducted research.

The statistical analysis of the study results proved that the variability of the effective signs of winter barley crop formation in the crop rotation under irrigation was 41% dependent on the choice of basic tillage system and 52% on the fertilisation system (Fig. 5).

The use of green manure crop in the short crop rotation allows to reduce the amount of mineral fertilizers applied for other cultivated crops. According to the results of the current study, the saving of mineral fertilisers in maize cultivation (as a fore crop for winter barley) is within 17% for differentiated, shallow single-depth and no-till systems, and about 37% for the multi-depth plough-less system.

CONCLUSIONS

The results of the study confirmed that:

– the highest bulk density of the soil (1.30 g/cm^3) was recorded for the no-till options, exceeding the control by 4.0%;

– the use of post-harvest green manure crop allows to reduce the bulk density of the dark-chestnut soil by 1.6% under disk and chisel tillage, and by 2.3% if continuous no-till is applied;

- the highest winter barley yields are obtained when the bulk density of the upper soil layer does not surpass 1.22–1.26 g/cm^3. Both increase and decrease in the indicator leads to a drop in the crop yield;

– the maximum water absorption was under chisel tillage, while the worst soil water permeability was fixed in the no-till variants;

- the use of shallow disk tillage (12–14 cm) or chisel tillage (23–25 cm) together with a fertilisation system using spring mustard as a green manure crop with further the application of mineral fertilisers $N_{180}P_{40}$ ensures the formation of the highest winter barley productivity of 6.08–6.12 t/ha on the irrigated dark-chestnut soils of the southern steppe zone of Ukraine.

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