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Applying ploughs for determining the optimal depth of soil cultivation: the development of the scientific views

Aplicación de arados para determinar la profundidad óptima de cultivo del suelo: el desarrollo de los puntos de vista científicos

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Abstract

The presented article examines the historical process of using deep and shallow ploughing of the fertile soil. Therefore, the most optimal option for achieving the highest possible productivity is considered, for example, multi-depth tillage of the soil, when deep, medium, shallow and surface inversion and non-inversion tillages alternate in crop rotations. In particular, when ploughing to the depth of 30 cm, the level of available moisture remains the highest during chiselling, and in conditions of deep ploughing (from 30 to 75 cm), the level of available moisture falls for any type of tillage. As a result of the study, the authors came to the conclusion that when choosing the depth of tillage, it is necessary to take into account the information on the crops to be grown and, first of all, the condition of the root layer of the specific field. Thus, in the course of the full-scale Russian aggression against Ukraine and the possible food crisis in some countries of the world caused by this armed conflict, the conducted research cannot be seen as comprehensive and thorough and has further prospects.

Keywords: ploughing, furrow, applying plough, flat tillage, inversion tillage, non-inversion tillage, mineralisation.

Resumen

El artículo presentado examina el proceso histórico de usar el arado profundo y superficial del suelo fértil. Por lo tanto, la opción más óptima para lograr la mayor productividad posible se considera, por ejemplo, la labranza del suelo en profundidad múltiple, cuando se alternan labranzas profundas, medias, superficiales y superficiales con inversión y sin inversión en la rotación de cultivos. En particular, cuando se ara a una profundidad de 30 cm, el nivel de humedad disponible sigue siendo el más alto durante el cincelado, y en condiciones de arado profundo (de 30 a 75 cm), el nivel de humedad disponible cae para cualquier tipo de labranza. Como resultado del estudio, los autores llegaron a la conclusión de que al elegir la profundidad de labranza, es necesario tener en cuenta la información sobre los cultivos a sembrar y, en primer lugar, el estado de la capa de raíces del campo especifico. Por lo tanto, en el curso de la agresión rusa a gran escala contra Ucrania y la posible crisis alimentaria en algunos países del mundo causada por este conflicto armado, el estudio no está agotado y tiene más perspectivas.

Palabras clave: labranza, surco, aplicación de arado, labranza plana, labranza de inversión, labranza de no inversión, mineralización.

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Introduction

Research Problem. The problem of improving soil fertility can now be considered one of the main among scientific research to improve the research methodology in the field of certain practical models (Ravshanov et al., 2020; Vanderhasselt et al., 2022). One aspect of saving money in agriculture is considered as shallow tillage as possible (Prymak et al., 2005). However, the effectiveness of a particular depth of tillage, depending on certain crops and specific soil and climatic conditions, has not been determined (Tuba et al., 2021; Bhattacharyya et al., 2022). This issue is particularly relevant under conditions of full-scale Russian aggression against Ukraine, which provoked food shortages in many countries of the world.

Research Focus. The object of research selected the existing history of tillage in different countries, taking into account the influence of nutrients on plants, that is, the components of biological, chemical and physical fertility.

Research Aim. The aim of this study was to find the optimal model of tillage of root zone depending on certain soil conditions for growing agricultural crops.

Theoretical Framework or Literature Review

The generally accepted opinion that productivity yield depends on the depth of tillage gradually emerged from the Middle Ages. In the second half of the 18th century the opinion about the usefulness of deep ploughing became dominant in the scientific circles. These issues were investigated by Acharya et al., (2019), Artursson et al., (2006), Buragienė et al., (2019), Ravshanov et al., (2020). At the turn of the 19th–20th centuries, the experimental material began to accumulate rapidly, which proved that soil properties, climate, and biological features of plants should be taken into account when finding out the depth of ploughing. In the 19th century scientists and practitioners recommended deep ploughing, but did not specify the maximum depth in relation to the specific soil and crop while in the 1920s a large amount of experimental material had already been accumulated regarding the depth of tillage. Most researchers came to the conclusion that even for the crops which are the most demanding of deep tillage, the optimal ploughing depth of black soils is 18-22 cm and only in some cases 27 cm. With the further deepening, yields, as a rule, did not increase or their increase was very insufficient. For grain crops, shallow tillage is sufficient (Prymak et al., 2005). Scientists Tomchuk (2021) and Nouri et al., (2019), who received the support of the power structures of the former USSR, spoke against shallow ploughing.

Researches conducted in 2022 by Azimi-Nejadian et al. (2022) proved the advantage of cultivation to the depth of the humus layer with the most complete overturning the soil layer. From that time, the theory and practice of the soil cultivation began a sharp turn towards deep ploughing, and till almost the 1950s, this opinion was dominant. However, there is still no unanimous opinion regarding the optimal depth of tillage, as well as scientific grounding the need for a certain depth of tillage.

Byrne et al., (2022) also spoke against deep tillage in the USA, who called ploughing a mistake and named the inverse plough a thief in the world agricultural drama and suggested shallow soil cultivation with disk tools with leaving the organic matter on the soil surface. His ideas became the beginning of the critical review of the basics of the scientific agriculture in the USA, which received the greatest development after 1950. In the USSR also, after the publication of the works of Umurzakov et al., (2020), the issues of deep soil cultivation began to be completely reviewed again.

Onasanya et al., (2021), summarizing the work of the Academy of Sciences of Nigeria team on the no-tillage system, expressed doubts about the conservation and accumulation of soil humus with this approach. They noted that with systematic no-tillage, 70-75% of the roots are concentrated in the surface layer up to 10 cm deep, and since this layer is repeatedly loosened, this part of the roots along with post-harvest residues is heavily mineralized and is unlikely to be a source for humus layer formation.

According to the results of the research of the agricultural experimental stations of Ukraine, the following optimal tillage depth was determined: Kharkiv experimental station – 9-13 cm for grains and 18-22 cm for root crops; Sumy – 18-22 cm for sugar beets; Nosivska – 13 cm for winter and spring grain; Mariupol – 11 cm for winter and spring wheat; Adzhams'ka – 11 cm for May and black fallows (Prymak et al., 2005).

The issue of turning over the soil layer is important in the theory of tillage. The theoretical grounds of inverse ploughing were developed by the Ukrainian scientists and summarized in the works of Tomchuk (2021). According to them, in the upper part of the arable layer, as a result of the aerobic conditions and other circumstances, the structure of the soil, which was considered the basis of the fertility, is destroyed, while in the lower layers, where the conditions are anaerobic, it is restored. Hence, the task of ploughing included the mutual movement of the upper sprayed and lower structured parts of the plough layer. The researches of Battisti et al., (2022), Gulyarenko and Bembenek (2022) found out that the upper part of the arable layer of the soil of various genesis, as a result of the large accumulation of roots in it, alternating moistering and drying, increases its fertility at the end of the summer season. After cultivation, in the soil there is a kind of differentiation of the arable layer in terms of fertility, and after 5-6 months, sometimes even earlier, its upper part turns out to be more fertile than the lower one. In practice, it was proven that not after all crops at the end of the growing season the lower part of the arable layer is better structured than the upper one (Prymak et al., 2005).

Ovsinskiy (1899) was the first researcher to widely promote non-inverse tillage, and he recommended loosening the soil no deeper than 2 to 3 inches with multi-body peelers or specially designed knife cultivators, believing that the top layer of the soil, as more fertile, should be left on top. He attached great importance to dew and fog, which supposedly enrich the soil with moisture and nitrogen. According to the scientist, manure wrapped in a two-inch plough layer, gives better results. However, the experimental verification of his recommendations by the Poltava and Odesa research stations did not confirm the results that the author promised. Researchers Nouri et al., (2019) criticized Ovsinskiy's theory for its advertising nature and weak theoretical base. In general, the ideas and recommendations of Ovsinskiy and his followers did not have much success.

However, at this time, in particular, Vanderhasselt et al., (2022) suggested a kind of compromise option: alternating years and fields of deep (40-50 cm) tillage (once every 4-6 years) with special, narrowly streamlined risers, ploughs and surface tillage with disc peelers to the depth of 10-12 cm in the fallow-grain and fallow-grain-crop rotations. The scientist believed that both annual plants and perennial grasses are capable of enriching the soil with humus and improving its structure under certain conditions.

Thus, a large number of experiments were conducted on the issues of depth, measures and methods of soil cultivation and their results were covered in numerous publications. Experimental data on these issues were analyzed in detail in the articles of de Lima et al. (2021), Tuba et al., (2021), Cavalcanti et al. (2019), Cheboi et al., (2021), Kurok (2009), Celik et al., (2020), Kurylo and Pryshlyak (2020), textbooks and manuals on agriculture, "Scientific bases of agricultural management" by country zones and in the other works. The scientists came to the conclusion that on the soils, even with the deepest humus horizon, the depth of the plough layer should be 28-32 cm. The further increase of the ploughing depth, as a rule, does not increase the yield and is not economically justified.

Methodology

Our research used the complex of the historical methods for the study and interpretation of primary source texts and bibliographic material, as well as presenting the scientific historical events. In addition, due to the general scientific and source science methods, the evolution of the views of scientists and practitioners regarding increasing soil fertility depending on the depth of their plowing was analysed.

Results and Discussion

The further numerous studies proved that in the process of the obligatory differentiation of the root layer, the upper soil layer (0-10 cm) acquires higher fertility, but not the lower one, as it was predicted by Tomchuk (2021). However, the requirement to turn over the cultivated soil layer remained strict. New arguments were found that confirmed its necessity. In particular, Al-Dosary et al., (2022) stated that after moving the upper part of the arable layer to the place of the lower one, the cultivated plants most intensively use the elements of fertility accumulated in the layer that became in the process of cultivating the bottom layer of the furrow. The lower part of the arable layer, which was moved upwards by tillage, must restore fertility during the growing season. At the same time, it was noted that in the absence of overturning of the cultivated soil layer due to the differentiation of the root-containing layer and the increase in fertility in its upper part, cultivated plants form the bulk of the root system in the upper layers. Under the conditions of moisture deficit, this leads to a decrease in the yield level and stability, as well as a decrease in the sustainability of agriculture in general. Therefore, it is necessary to turn over the treated soil layer. This conclusion was made by

Abbaspour-Gilandeh et al., (2020), Kim et al., (2020), as well as Acharya et al., (2019). On the basis of the presented research results, the idea was formed that the main and the most important condition for obtaining high and stable yield is creating the deep, relatively homogeneous, cultured root-containing soil layer.

In Europe and Asia, Mamatov et al., (2021), Morgun et al., (1988), Nadeem et al., (2019) and others advocated the complete rejection of ploughing the soil. They believed that tillage in combination with fertilizers contributes more than ploughing to the increase of humus reserves and would be able to ensure its deficit-free balance with applying a smaller amount of manure. According to Nadeem et al., (2019), the localization of plants remnants, roots and fertilizers in the surface layer of the soil is necessary to ensure the soil protective effect, improve forming soil, increase amount of humus in the soil; while cultivation without turning over the soil layer and mulching the soil with post-harvest residues simulates the sod (black soil) process of forming soil in the conditions of production.

The majority of scientists support the idea that the differentiation of the arable layer in surface and flat cut cultivation with the localization of nutrients in its upper (up to 10 cm) part of the layer has its negative effect on the development and yield of crops (Prymak et al., 2005). The researchers stress that the systematic use of flat cut and surface (10-12 cm) tillage is accompanied by the increased acidification of the upper part of the tilled soil layer, which is obviously caused by the shallow application of mineral fertilizers (Prymak et al., 2005).

At present, among the agricultural practitioners and scientists (Artursson et al., 2006; Buragienė et al., 2019; Kurylo and Pryshlyak, 2020; Palamarchuk et al., 2020), the prevailing opinion is that tillage of the soil in crop rotations should be of various depths, in which deep, medium, shallow and surface inverse and non-inverse tillage alternate.

Correct modern soil cultivation in accordance with the biological requirements of agricultural plants significantly affects the yield. When analysing the factors that ensured the growth of corn grain yield in the state of Minnesota (USA) from 0.20 to 0.65 t/ha in the period from 1930 to 1980, it was found that a 5% increase in the yield was due to the improvement of soil cultivation (Cardwell, 1982).

However, recently, for some crops in a number of countries around the world, soil cultivation systems were developed, including “no-till” one. It is believed that this is due to the increase in the use of herbicides and pesticides, which significantly narrows the functions of the mechanical soil cultivation, with the increase in the price of fuel, the appearance of high-performance advanced equipment for the minimum soil cultivation and special seed drills (Chekrizov, 2004).

That is, the minimisation of soil cultivation is not effective in all the soil and climatic conditions and not for all crops, and sometimes it is even inferior to the traditional methods of cultivation in terms of impact on the harvest. It was found that for the transition to minimum tillage, the necessary conditions include the presence of a powerful highly fertile root soil layer, applying phosphoric and often potash fertilizers to the soil, the cultivation of varieties of agricultural crops adapted to the conditions of minimum tillage and stubble crops, the availability of the necessary amount of appropriate herbicides (Chekrizov, 2004).

When tillage is minimized, after-harvesting remnants are located on the surface of the soil or partially wrapped in the soil. At the same time, in addition to the positive effect on soil properties (increasing moisture supply, lowering soil temperature, reducing erosion, etc.), their phytotoxicity can be seen, immobilization of soil nitrogen can be observed. The negative effect of post-harvest residues can be largely overcome by applying mineral fertilizers, primarily nitrogen-phosphorus ones.

Fallowing makes a great influence on the conditions of the mineral nutrition of plants. It was found that long term use of fallow and grain crop rotations leads to rapid depletion of humus, nitrogen and phosphorus reserves. Therefore, nitrogen fertilizers are often applied even for crops that are sown in pairs taking into account the amount of mineral nitrogen in the soil in the root layer. The use of fallowing is justified mainly in the areas of insufficient moisture, where the soils are provided with phosphorus or a sufficient amount of phosphorus fertilizers is applied (Stanford, 1981).

The use of mechanical equipment with the high specific pressure causes compaction of the arable and even subsoil layer, especially in the case of overmoistering soils with a heavy mechanical composition, acidic ones, with unsatisfactory physical properties, which leads, especially in ruts, to a decrease in the yield due to the deterioration of the water-air condition, mechanical conditions for the growth and activity of the root system. Increasing phosphorus and potassium nutrition while applying fertilizers does not completely compensate for the decrease in yield caused by the excessive soil compaction. Liming the acidic soils reduces the negative impact of soil compaction, providing improvement of the physical properties, creating the soil reaction favourable for the root system, increasing access to phosphorus and the other elements to plants, increasing soil biological activity.

According to the views of Hallsworth (1981), the ability of the soil to form a yield of agricultural crops consists of three main components: chemical fertility – the ability to provide the plant with the elements of mineral nutrition; physical fertility – the ability to provide the plant with water, creating the environment favourable for root growth; biological fertility – the result of the interaction of various constituent parts of the soil biota, which affects the condition of mineral nutrition and the sanitary condition of the soil. These components of soil fertility are closely interrelated, so a managing them human is able to influence plant nutrition in the targeted manner, overcoming some of the negative effects of climate and other factors on plant fertility in production conditions.

The direct and indirect effect of tillage helps to regulate the availability of nutrients and makes it possible to influence the individual components of soil fertility (Chekrizov, 2004). Undesirable formation of the soil compaction was observed during the long-term cultivation of the soil to the same depth with the inverse tools. According to the researches (Soil Fertility Manual, 1979) conducted in the USA, with the long term use of the inverse plough the soil compaction is formed at the depth of ploughing with the volumetric mass of up to 1.75-2.00 t/cm2, with a small number of macrogaps, which sharply limits the depth of root penetration and the total size of the root system (Sommers and Biederbeck, 1978). During a relatively short drought in such areas, plants experience a lack of moisture, because the moisture available deeper than 25 cm (under the soil compaction) cannot be used by them due to the lack of a significant number of roots there. Therefore, the nutrients of the soil and fertilizers cannot be effectively used from the parched arable layer.

An interesting investigation was conducted by Kamprath et al., (1979). On the loamy soil (Arenic Paleudult) with the presence of the soil compaction after inverse ploughing to a depth of 25 cm, they grew soybeans after the conventional cultivation (inverse ploughing to the depth of 25 cm +3 cm disking before sowing), chiselling to the depth of 27 cm, loosening between rows to the depth of 45 cm (Table 1).

Table 1.
The influence of the tillage method on the distribution of the soybean root system in loamy soil

Depth, cm	Soil tillage method		
	Inverse tillage	Chiselling	Loosening undersoil
Weight of dry root matter (mg/1000 cm^3)			
0-10	334	323	326
10-20	219	276	198
20-30	64	236	101
30-45	14	45	65
45-60	10	48	74
60-75	6	59	87

Source: Kamprath et al., (1979)

The expediency of removing the the soil compaction in depth as a result of ploughing process is obvious: 4% of the roots penetrated deeper than 30 cm with the conventional (inverse) tillage, 14% – with chiselling, and 27% with deep loosening between rows. While in the first case the soybean yield was 2755 kg/ha, the destruction of the soil compaction contributed to its increase by 29%. At the same time, the removal of nutrients from the soil increased almost proportionally. This can be explained by the direct connection with the size of the root system, which increased (in terms of dry mass) by 30-50% when the plough compaction was destroyed.

According to the agronomic research station of the Department of Ain (France), deep loosening prevents forming the soil compaction in depth as a result of ploughing process. At the same time, ripening the soil for cultivation in spring is somewhat delayed, but the infiltration of moisture into the deep layers of the soil is enhanced and its profile is more evenly moistened. The root system of agricultural plants becomes more powerful. As a result, absorbing nutrients from the soil by plants increases significantly, the yield of sugar beets and other crops increases. But during soil cultivating the total surface of soil particles and aggregates increases, which contributes to the growth of potential opportunities for evaporation and losing moisture.

In general, soil cultivation leads to increasing moisture loss, which is undesirable, especially when there is a lack of it. This is confirmed by numerous studies of moisture accumulation with various methods of soil cultivation and in its absence.

In the state of Texas (USA), the amount of available moisture before sowing in the 0-180 layer in the variants without tillage, with the flat cut (subsoiling) cultivation and disking is 217, 170 and 152 mm, respectively (Table 2), during the fallow period of the previous summer, it was preserved, respectively, 32.5%, 22.7% and 15.2% of the amount of moisture that arrived with precipitation (Sommers & Biederbeck, 1978).

When the soil is characterized by overmoistening, accompanied, as a rule, by weakening aeration, the availability of phosphorus and potassium to plants decreases. This is primarily due to weakening root growth and their weak activity in absorbing nutrients. In addition, one of the reasons for the weak supply of phosphorus to plants is slowing down the mineralization of soil organic matter and organic fertilizers as the most important sources of phosphorus, especially if overmoistening occurs at the low temperature (Soil Fertility Manual, 1979).

Table 2.
The influence of soil cultivation methods on accumulating moisture

Parameter	The method of soil cultivation		
	without cultivating	flat cut tillage (subsoiling)	loosening soil by disks
Moisture saved during the fallow period (% of precipitation)	32,5	22,7	15,2
Amount of available moisture in180-cm soil layer before sowing, mm	217	170	152

Source: Soil Fertility Manual (1979)

In Germany, the most important conditions for creating the high level of soils fertility and their effective use include involving subsoil layers into the intensively used root zone, periodic deep ploughing, increasing the size and improving the configuration of the fields (Kundler et al., 1977), which contribute to the higher quality, uniform tillage of the soil.

In a number of countries, the practice of very deep tillage of the soil for field crops has traditionally developed. Thus, in Italy, ploughing for winter wheat is done to a depth of about 50 cm, and for potatoes and sugar beets or can be even up to 75 cm, without the sufficient experimental grounding, taking into account the level of chemicalization of agriculture, appearing new varieties and hybrids. Researches in this direction have already been started, in particular by the University of Bologna (Chekrizov, 2004).

On the soils with the heavy mechanical composition, deep ploughing (for example, in the sub-humid area of the Ethiopian highlands) when creating highly productive crop rotations, cultural meadows and pastures in combination with liming (if necessary) to the depth of ploughing and applying high doses of fertilizers, ensures the improvement of the water and air conditions and obtaining high yields of agricultural crops, especially having deep root system, like sugar beets and alfalfa, according Hussein et al., (2019).

Loosening the subsoil is effective, as a rule, only when fertilizers are simultaneously applied to a great depth. If high doses of fertilizers are not applied to the loosening horizon, then a positive result will not be obtained or it will be negative, as it was evidenced by studies in many countries of the world.

In addition, while deepening the arable layer, as a rule, it is undesirable to bring infertile subsoil with the poor physical and chemical properties to the surface. Research conducted in Sweden using isotopes showed that grain crops in areas with systematically high doses of fertilizers and calcareous materials are able to absorb a significant amount of nutrients from the soil: after the tillering phase – 0-25% of phosphorus, 0-25% of potassium and 10- 40% of calcium, in the earing phase – 10-50% of phosphorus and potassium and 40-80% of calcium (Chekrizov, 2004). Therefore, applying the system approach allows defining the influence of interaction between the components of the agricultural system, creating the logic and mathematical models of the researched processes that are close to reality. However, with a small root-rich layer, applying high amounts of fertilizers is ineffective, since the part of the nutrients may be outside of the layer and become positionally inaccessible to the roots; in addition, there may be large losses of nutrients because of leaching.

Conclusions

Thus, one of the main problems of the scientific research into the aspects of increasing soil fertility is the need to improve the research methodology in the direction of creating models of processes that more closely correspond to the reality. Researches of the agrarian scientists and practitioners in different countries of the world found that the minimization of tillage is not effective in all soil types and climatic conditions and not for all crops. Under certain conditions, it is inferior to the traditional methods of cultivation in terms of impact on the yield. Obligatory conditions for the transition to shallow soil cultivation are the presence of a powerful, highly fertile root layer, applying sufficient amount of phosphorous and often potassium fertilizers, the cultivation of varieties of agricultural crops adapted to the conditions of minimal cultivation and stubble crops, the presence of the necessary amount of the appropriate herbicides.

The existing history of tillage is based on the need to regulate the impact of nutrients on plants. Thus, the ability of the soil to form a crop requires the presence of three main components: biological fertility – the result of the interaction of various constituent parts of the soil biota which affects the regime of mineral nutrition and the sanitary condition of the soil; chemical fertility – the ability to provide plants with the elements of mineral nutrition; physical fertility – the ability to provide the plant with water, to create an environment favourable for root growth.

At the same time, the basis for the choice of the technological operation and a means for implementing the depth of soil cultivation is operational information about the state of its root layer in the specific field with the determination of the correspondence of the data indicators of the quantitative model of the optimal state of the soil layer for growing crops. Therefore, in the course of creating the effective means for the mechanization of cultivation and the depth of soil ploughing, the problem that always bothered and is bothering the whole humanity right now, concerns the conditions of the full-scale Russian aggression in Ukraine: if there is a sufficient amount of food and its affordable cost for the population. Therefore, the research conducted by us is not comprehensive and has further prospects for the study, especially in the conditions of the food crisis and the need to further increase the yield of agricultural plants.

Conflicts of interest

The authors declare no conflict of interest.

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