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TILLAGE EFFECTS ON SOIL FUNCTIONAL PROPERTIES: A REVIEW

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Abstract. *Soil is the foundation of all-natural production systems. There is a necessity to study the management systems impact on soil functional properties and crop productivity in response to climate change effects. Our review was conducted using published databases of Ukrainian and worldwide peer-reviewed publications, including high-quality databases in Scopus, Web of Science, ResearchGate, Ukrainian specialized publications, and other web sources to evaluate the effects of tillage, with- and without cropping diversity, cover crops, and chemigation, on soil functional properties associated with soil health and crop productivity. Globally used different types of tillage practices (plowing vs. no-till) affect soil biology, nutrient cycling and organic matter accumulation, water, nutrient, and air ecosystems, changes in the soil structural and hydrological properties, and factors responsible for soil erosion and degradation were evaluated. The relevance of the research is appropriate due to global climate change and the transition of farmers converting from plowing to minimum tillage technologies, including no-till in order to achieve economic crop production with enhanced agroecosystem services. While both plowing and minimum tillage technologies have contrasting benefits and limitations, there is a lacking of consistent advantages of one tillage technology over the other one to support economic crop production, regenerate soil health, and enhance agroecosystem services. Currently, no-till technologies are increasingly adopted by farmers in Ukraine; however, farmers are looking for evidence-based knowledge and the government to remove roadblocks. The issue is increasingly becoming more relevant in connection with climate change effects, which require further studies.*

Key words: *climate change, soil health, cover crop, chemigation, Scopus, Ukraine*

The relevance of the study**.** Soil is a complex dynamic ecosystem essential to support and provide ecosystem services. Currently, agricultural soils are under the immense pressure of intensification to achieve food security to meet the demands of increasing population growth in the world. In response to the effects of global climate change on ecosystem productivity, the study of the influence of management and environmental factors on the soil-plant-water systems is becoming urgent. There is a need for a comprehensive review of scientific research on changes in soil's performance under various tillage systems. It is expected to allow improving current and upcoming new management practices to modernize the compatibility of the agricultural production systems and create market opportunities for various produce and commodities. The improved soil cultivation technologies in conjunction with minimum or zero-tillage, precision fertilization and chemical protection against pests and diseases, land reclamation and adaptation of sustainable practices, and proactive genetics, breeding, and biotechnology are expected to regenerate or maintain soil's capacity to support crop production.

Analysis of recent research and publications. Currently, scientists around the world [10; 28; 58] emphasize the need to minimize soil cultivation (plowing) or adaptation of conservation tillage to improve soil health by enhancing biological diversity, increasing soil organic carbon sequestration, accumulating essential plant nutrients, improving soil structural stability, controlling soil erosion, and decreasing soil compaction and greenhouse gas emissions. It is believed that conventional tillage-induced subsoil compaction (plow pan) is a detrimental consequence to affect soil hydrological properties, crusting and poor infiltration, secondary salinization and drought, and restricted root growth of plants. It is reported that frequent cultivation that contributes to the loss of plant available moisture, depletion of soil organic carbon, and reduction of soil biodiversity and efficiency, leading to degraded soil functional properties [5; 41]. As a result, the agrogenic (regenerative) activities of the soil severely affected over time [8].

Changing from frequent and intensive plowing to conservation tillage is an environmentally compatible and economically viable approach to regenerate soil health with increased ecosystem services (Fig. 1). With conservation tillage especially zero or no-till, undisturbed surface accumulation of crop residue acts as a mulch to improve biodiversity, decrease soil temperature and evaporation, and store moisture for a longer period of time [50]. Potential benefits include enhanced fungal dominance in food webs, increased carbon sequestration, accumulation of nutrients, reduced greenhouse gas emissions, improved soil aggregate formation, decreased soil erosion, and ameliorate soil health [38; 50]. In contrast, it is reported that the no-till transition process is slow, especially in the first few years which can lead to debatable results depending on the type of soils and crops [7; 54]. Several studies have reported that it may take about 5 to 6 years to overcome the no-till transition process and achieve the expected results on soil's performance [20; 30]. Islam et al. [30] suggested that introducing cover crops into the crop rotation, as one of the measures to improve the no-till adaptation and performance while residues exerted positive effects to increase albedo – protect soil against overheating, prevent capillary loss of moisture from deeper soils, retain carbon, promote biodiversity, and improve functional properties associated with soil health.

Several studies [23; 40] have emphasized that the prospects of modeling the critical processes associated with the influence of tillage operations on changes in the functional properties of soil, and argued that the use of the concept of its homeostasis will be a holistic approach to evaluate soil's performance [8]. The proactive nature of the concept is explained by the fact that its change has an energetic nature – it is the intensity of subordinate processes of transformation of external energy flows of matter. Any changes in soil properties, for example, compaction, lead to a different level of soil enrichment with surface energy, and accordingly, the availability of moisture and nutrients to plants. The availability of water and nutrients to plants depends on the level of homeostasis: the higher soil homeostasis, that is, the use of the flow of external energy in it, the higher the availability of plant nutrition and water availability from the soil. Soil homeostasis, as a manifestation of the interaction of the thermodynamic system of the soil with the environment, depends on three components: the structure of the soil, as a design of the thermodynamic system, the presence of requirements as a working body in the system, and the intensity of external weather disturbances. The approach of homeostasis is promising to consider most of the factors affecting the soil's performance – tillage, irrigation, fertilization, climate changes, etc. [8].

Despite the relevance of research, there are no existing national programs to support the implementation of minimum or no-till practices. Based on practical experiences to achieve sustainable production, these technologies are greatly needed to implement for diverse soils and climate zones in Ukraine. The goal of our research was to evaluate the impact of various tillage systems and crop rotation with cover crops on the dynamics of soil functional properties.

Figure 1. Effects of conventional- and no-tillage practices on soil health

Research materials and methods. The methodology of our research was based on published databases of Ukrainian and worldwide publications, including high-quality databases of peer-reviewed literatures in Scopus, Web of Science, ResearchGate, Ukrainian specialized publications, and other web sources, by keywords. All the selected publications were sorted out by title and abstract, and then by a full text available for review against the specified keywords. Duplicate articles have been removed. About 22 % of the non-English-language articles published in other journals were included in the study.

Research results and their discussion. *The influence of soil cultivation on changes in its properties.* It is widely suggested that minimum tillage combined with crop residue mulching is be a promising agricultural management practice to ameliorate soil properties to support increased crop productivity [34]. As noted by researchers [6; 15], the zonal features of the minimum tillage are determined by the features of the soil cover. Tillage minimization is recommended on soils with an equilibrium antecedent density close to the optimum level for growing field crops; on these soils, the intensity of cultivation may be minimum, and certain methods may be discarded altogether [3; 16]. Minimum tillage or no plowing is a promising and easy-to-implement approach on well-drained structurally stable and potentially fertile soils, particularly chernozems. Also, minimum tillage is a highly effective agromelioration method for the retention and preservation of soil moisture and precipitation for a longer period of time [14]. A number of studies indicated that the annual soil moisture-accumulating effect is 30–50 mm, which contributes to the stabilization of processes, especially during severe drought events. Therefore, the most promising zone for the introduction of minimum tillage or no-till is the Steppe zones and a large part of the Right Bank Forest Steppe of Ukraine [2; 11; 13; 17].

Quirk [46] investigated that the soil moisture dynamics, in particular the processes of wetting and drying, freezing and thawing, and plant water consumption that underlie the soil physical properties. Potential impacts included changes in soil hydrological processes and water flows, including the timing and magnitude of surface runoff, discharge of runoff and percolation, and evaporation, which may affect other environmental variables, including the flow of nutrients and sediments [52].

Russell [6] indicated that when the soil oxygen concentration drops to 9–12 %, plant root growth significantly affected, and when oxygen content is less than 5 %, it stops functioning altogether. The absorption of water and nutrients by plants via roots significantly decreased with increasing soil anaerobiosis (oxygen content (9–12 %). Plants respond to oxygen deficiency during their maximum vegetative growth: winter plants – before and during earing; roots and tubers – during the formation of their productive organs and deposition of nutrients in them. Leguminous crops responded critically, because, in addition to root respiration, they require oxygen for bacteria that exist on it in symbiosis and absorb atmospheric nitrogen, which is later transformed into nitrogen compounds available to plants [4]. Hula et al. [35] reported that frequent tillage operations can contribute to soil erosion along the slopes. It is suggested that with minimum tillage, the off-site movement of soil particles from slopes can be fixed at a shorter distance than with the plowing.

A field experiment at the Institute of Sugarcane in India (ICAR-Indian Institute of Sugarcane Research, Lucknow), where different tillage technologies and their influence on soil hydrological properties were studied, results showed that plowing to different depths (45–50 cm and 25–30 cm depths) increased porosity and the soil bulk density decreased when compared to minimum tillage. Thus, at a depth of 0–15 cm, the bulk density decreased by more than 6 % during the budding phase of the sugarcane plants. Likewise, the highest nitrogen uptake of 158.5 kg/ha was recorded in plowed treatment; besides, increased soil biological and chemical properties along with sugarcane yield [32].

Based on the results of a three years study, both minimum tillage and plowing increased the moisture holding capacity by 3.1 to 7.9 % at 0–200 cm soil depths, when compared to the transitional no-till. The highest water holding was reportedly between 100–200 cm depth, while deep plowing showed the highest moisture holding at 0–100 cm depth. In contrast, the yield and protein content of grain were lower with minimum tillage and deep plowing when compared to the no-till [29].

Field research was conducted to study the different methods of main tillage by chiseling with different types of chisels looseners and plowing effect on the agro- and water-physical indicators of light chestnut soil, results showed that the methods of main tillage had better regulating impact on the agro- and water-physical condition of the soil with a significant impact on crop productivity [36; 37]. Other studies [12] conducted over a period of 11 years indicated that while the mesoporosity was more developed in the plowed soil, the macroporosity, in contrast, was higher in the no-till soil. Moreover, the highest values of moisture conductivity were observed in the no-till at deeper depths (700–850 cm) which was decreased at the soil surface. In contrast, the plowed soil had the highest values of moisture conductivity at 0–15 cm depth, which decreased with an increase in soil depth. The profile distribution of moisture conductivity in the no-till contributes to the higher infiltration of the groundwater and the capillary supply of the root layer of the soil from deep depths.

The soil hydrological properties under the transitional no-till lead to a decrease in the water infiltration and lower hydraulic conductivity rates due to the consequence of initial surface compaction when compared to conventional plowing. An initial soil compaction under short-term no-till (1 to 3 years) decreased porosity due to the lack of disturbance and inversion of soil, while frequent plowing breaks down compacted soil layers and increased porosity [50]. However, several studies have shown that long-term no-till significantly reduced surface soil compaction by adding greater amounts of residues from agronomic and cover crops with different root systems in crop rotation [18; 39; 50].

Blanco-Canqui and Ruis [22] discussed the implications of no-till management for assessing organic carbon dynamics, fertility, and yield, but a current synthesis of no-till impacts on soil physical properties. They argued that understanding changes in soil physical properties following the adaptation of no-till is important for soil management, agricultural production, and environmental quality.

The results of a simulated scenarios [33], included long-term (30 years) corn growth in a rainfed regime, the modeling have shown significant effects of tillage on crop yield and soil water balance. The chisel plowing increased corn yield by 14 %, but this positive effect of chiseling lasted only one cropping season. Under different tillage options (chiseling and no-till), root length density and stratification of soil hydrological properties within the profile generated different patterns of soils response to drought events during the harvest season.

According to Beltrao et al. [21], the highest crop yields were obtained at the most favorable ratios of the air and water in the soil during the critical periods of crop culture. They reported that all the components in the soil-plant-atmosphere system must be balanced to mitigate the consequences of climate change, while its can't be completely eliminated [27]. However, the added impact on soil properties under different tillage practices depends primarily on certain conditions at the soil-atmosphere interface, which requires a more detailed study.

The influence of cultivation on soil nutrients and microbiological activities. There is a close relationship between the availability of soil moisture and the assimilation of nutrients by plants as the intensity of absorption of nutrients and their movement along the plant decreases with a lack of moisture. It is known that under drought, the absorption of nutrients (such as phosphorus) by plants decreases by 7–28 % and precedes the decrease in the rate of absorption of potassium, especially nitrogen. However, the deficiency of phosphorus is a limiting factor for the development of the root system and grain formation [1]. Soil cultivation transiently improved the crop productivity of agricultural land by effective control of weeds, pests, and pathogens to optimized plant nutrition [25; 43].

Surface application of nutrients (either by chemical fertilization or amendments), under no-till, leads to the stratification of organic carbon and nutrients [42; 55]. However, cropping diversity with mixed cover crops under minimum tillage or no-till reduce stratification, control soil degradation, and consequently, mitigate the negative impacts of conventional agriculture on the environment. However, the combined effect of these measures on greenhouse gas emissions, particularly nitrous oxide and ammonia volatilization from soil ecosystems remains highly debated [44].

A field research study [32] to determine the tillage effects on corn nitrogen uptake and utilization, no-till results showed significant increase in phosphorus-use efficiency at the initial stages on the low-input plants. The effect of tillage was constant at all stages of crop growth and development, with higher plant phosphorus-use efficiency under the plow and chisel disc options than under the no-till. However, plants grown under the no-till had the highest phosphorus concentration in the shoots.

Other research results showed that the potential denitrification activity and the total number of denitrifying bacteria increased by 66 and 116 %, respectively, in response to the effects of no-till, while soil denitrification under the no-till led to an increase in nitrous oxide emissions [58]. When comparing tillage technologies, results indicated a significant decrease in soil pH with a variation of ± 0.28 % under the no-till, when compared to the conventional tillage. Thus, lower relative changes in soil pH observed on clayey loam (–2,44 %) were recorded for the long-term no-till [49].

Skaalsveen et al. [50] have reported that the no-till has great potential as a soil erosion mitigation with significant reductions in soil loss, providing beneficial effects on loading sediments and particulate phosphorus into fresh waterbodies. However, the no-till increased the edge-of-field loss of dissolved reactive phosphorus [48] but have a minor effect on nitrogen leaching. Sustainable soil management practices, in general, increased soil respiration (by 81.1%), microbial biomass (by 104%), and dehydrogenase enzymatic activity (by 59.2%) when compared to the combination of other soil cultivation technologies [51].

Under climate-smart agricultural practices, the transitional no-till decreased the soybean and winter wheat yields (by 14.9% and 20.7%), than under the conventional tillage in Ukraine [9]. However, soybean yield increased by 14% and winter wheat by 5.1% in response to salicylic acid chemigation under no-till compared to the control. The water-use efficiency of soybean increased by more than 2% under no-till when compared to conventional tillage. Likewise, microbial biomass increased by 19% and earthworm numbers increased by 8% under the no-till soil than that of the plowed soil. Soil moisture accumulation increased by 18% under the no-till, when compared to conventional plowing [9].

Froslev et al. [46] indicated a significant difference in the composition of the soil biology associated with the intensity of tillage, where plowing, minimum tillage, and no-till were compared. Despite the significant influence of tillage on biota composition, comparisons with natural ecosystems showed that experimental fields were much more similar in composition to other rotational fields than to more natural habitats, old fields, and forests, respectively. Long-term no-till farming practices (14 years) significantly increased the size of soil microbial communities and the activity of β-glucosidase, which is associated with the decomposition of soil organic matter and at the same time negatively affects the bacterial diversity due to lack of soil disturbance and accumulation of residues on the soil surface [57].

Reducing tillage and cover crops, which are widely recommended to improve soil health, significantly affect the functional diversity of microorganisms [45]. However, decreased the nutrient availability with soil depth under the no-till with uneven nutrient supply and homogenization than that of the conventional tillage.

Conclusions. Intensive tillage practices, while supporting greater food security, have adverse effects on soil biology and associated properties, disperse structural stability, and decrease organic matter associated with degraded soil health. Together with climate change, conventional tillage practices are expected to accelerate soil health degradation and affect global food security. In contrast, conservation tillage such as minimum tillage or no-till is a proactive approach to regenerate soil health properties. Despite no-till's importance in soil functionality, the major barriers to transitional no-till are nitrogen immobilization, transient soil compaction, weed pressure, and stratification of organic carbon and essential nutrients. Cropping diversity with cover crops, as a biological primer, is expected to complement no-till soil functionality. The water and nutrient contents, the activity and diversity of microbiota, and the influence of cover crops in crop rotation under different tillage technologies are all the issues that have not been thoroughly studied and further research is needed, taking into account climate changes and the characteristics of soils, in particular degraded ones.

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ВПЛИВ ОБРОБІТКУ ҐРУНТУ НА ЙОГО ВЛАСТИВОСТІ: ОГЛЯД ЛІТЕРАТУРИ

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Анотація. *Ґрунти є основною природною системою. Біологічна продуктивність сільськогосподарських культур серед усіх параметрів агроценозу є найбільш мінливим і інтегральним показником життєздатності сівозміни, яка акумулює генетичний потенціал культур, здоров'я ґрунту, погодні умови та агротехнічну ефективність. Обробіток ґрунту є основною технологічною операцією, яка є частиною більшості сільськогосподарських практик протягом багатьох років. Різні технології обробітку ґрунту впливають на його якісні характеристики, змінюючи водний, поживний, повітряний режими, а в окремих випадках призводять до низки негативних явищ, наприклад, зміни структурного складу ґрунтів, зниження стійкості до зовнішніх чинників, деградації та ерозії. Актуальність дослідження підсилюється змінами клімату та переходом виробників від використання оранки на мінімальні і нульові технології з метою економії та екологізації виробництва. Метою роботи було оцінити доступність і змістовність публікацій з даної теми у базах даних українських і закордонних видань, включаючи наукометричні бази рецензованої літератури Scopus і Web of Science, ResearchGate, українських спеціалізованих видань та перевірених веб-джерел, за ключовими словами. Усі відібрані публікації перевірялися за назвою та анотацією, а потім за доступним повним тестом для перегляду за вказаними ключовими словами. Публікації-дублікати було вилучено із аналізу. Крім того, до аналізу було включено 22 % неангломовних рукописів, опублікованих у нерецензованих журналах. Визначено, що питанням впливу різних технологій обробітку ґрунту на зміну його властивостей з охарактеризуванням позитивних і негативних сторін, встановлення закономірностей процесів приділено увагу багатьох вчених усього світу та висвітлено у численних роботах, проте спільного висновку щодо переваг однієї технології над іншою та змістовного обґрунтування агротехнологій не існує. Щодалі питання набуває все більшої актуальності у зв'язку зі змінами клімату та потребує детального вивчення.*

Ключові слова: *зміна клімату, здоров'я ґрунту, покривні культури, хімічний обробіток, Scopus, Україна*