



Effects of green manure intercropping and tillage on the fertility of irrigated dark-chestnut soil in a semi-arid climate

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Sustainable soil fertility management is crucial for maintaining agricultural productivity, particularly in semi-arid irrigated regions. This study aimed to evaluate the impact of tillage and fertilization systems, under continuous application of post-harvest residues and green manure intercropping, on the fertility of irrigated dark chestnut soil in a semi-arid steppe climate. The research was conducted through a two-factor field experiment within a four-field grain crop rotation system: winter barley with green manure intercropping – soybean – winter wheat with green manure intercropping – grain corn. The experiment followed a systematic design with three replications across a 12.5-hectare area at the Askaniiska Research Station (Kherson Region, Ukraine). Tillage treatments included a differentiated system (control), which alternated 12–14 cm disk tillage for cereals with deep plowing for row crops, and a long-term (13-year) no-till system with direct seeding. Fertilization treatments involved varying levels of nitrogen and phosphorus mineral fertilizers, combined with green manure crops: leaf mustard (*Brassica juncea*), buckwheat (*Fagopyrum esculentum*), annual white melilot (*Melilotus albus*), and lacy phacelia (*Phacelia tanacetifolia*). Soil samples from the 0–30 cm layer were collected annually and analyzed at the Institute of Climate-Smart Agriculture of NAAS with accordance to the standards of agrochemical soil analysis. Results indicated that green manure biomass yields were generally higher under differentiated tillage: leaf mustard – 12.38 vs. 8.46 t/ha; buckwheat – 11.97 vs. 10.74 t/ha; annual white melilot – 10.13 vs. 9.38 t/ha; and lacy phacelia – 14.47 vs. 13.25 t/ha (differentiated vs. no-till). The highest nitrogen and phosphorus content in biomass was observed in annual white melilot (on average, 2.62% and 0.76%, respectively), while buckwheat showed the highest potassium accumulation (2.81%). Green manure intercropping insignificantly changed soil NPK content in comparison to control. Significant difference was observed for potassium content only. The highest nitrogen content in the soil was recorded at the no-till and leaf mustard variant; the highest phosphorus content was at no-till and lacy phacelia; the highest potassium content was at no-till and lacy phacelia. As for the influence of tillage and fertilization on the crop rotation productivity, it was established that only tillage had significant impact on the indicator. Differentiated tillage was superior to no-till in this regard, providing the grain units yield higher by 11.67%. Statistical analysis underscores the benefits of the differentiated tillage system, especially when paired with higher fertilization levels and green manure, in enhancing the productivity of all studied crops. The Tukey HSD test confirmed significant differences between tillage-fertilization combinations, with differentiated tillage + N₁₂₀P₄₀ + green manure consistently achieving the highest yields. No-till tended to result in lower yields, particularly under reduced fertilization levels. This supports the agronomic recommendation to combine differentiated tillage with nutrient-rich fertilization strategies for optimized crop performance. Overall, the integration of green manure intercropping into crop rotations accompanied by rationally differentiated tillage proved to be an effective, environmentally sustainable, and agronomically sound strategy for maintaining soil fertility under irrigated conditions in semi-arid regions.

Keywords: short grain crop rotation; fertilization; plant biomass; soil nutrients content; tillage.

Introduction

Sustainable soil management in the course of agricultural activities is an important prerequisite for effectively working with dynamic and interrelated soil properties to ensure the sustainability of agroecosystems. Extensive agricultural methods and technologies that have been used for many years to meet the growing demand for food due to the increase in the world population – such as massive tillage, the enormous use of chemical fertilizers and pesticides, and monocropping – have caused soil degradation, contributed to the deterioration of physical, chemical, and biological properties, and led to environmental pollution. The irrational use of agrochemicals to increase soil fertility has resulted in a loss of soil quality, which also has a significant impact on human health and the environment.

Agricultural practice offers many ways to restore soil fertility, but the use of green manure has been recognized as a cost-effective and environmentally acceptable approach in contrast to agrochemicals. Green manure has a positive effect on soil fertility and the ecological state of agroecosystems, replenishing soil organic matter and increasing fertility by enriching it with vital macro- (such as nitrogen, phosphorus, potassium, calcium, etc.) and micronutrients (such as magne-

sium, copper, manganese, sulfur, etc.) used by cultivated plants as a basis for growth and development.

The relevance of green manure crops is increasing as a means to restore soil fertility in the post-war period. Therefore, one of the main goals of this research was to establish the effectiveness of green manure use as a factor in forming the main indicators and properties of soil under modern crop cultivation technologies.

Soil quality deterioration is considered a major environmental problem worldwide. According to domestic scientists, the degradation processes that take place in the soils of Ukraine are as follows: loss of humus at rates of 0.42–0.51 t/ha per year; topsoil erosion; overcompaction, structural destruction, clodding, and the formation of a soil crust; acidification – particularly pronounced in the Polissia and Carpathian regions – secondary salinization and sodification of irrigated lands, peatland depletion, and contamination of arable soils with radionuclides, pesticides' by-products and remnants, as well as heavy metals (affecting 11.1%, 9.3%, and 8.0% of arable lands, respectively). Over the last 14 decades, humus losses in the soils of the Forest-Steppe zone of Ukraine reached 22.0%, in the steppe zone – 19.5%, and about 19.0% – in the zone of Ukrainian Polissia. According to recent soil surveys, the NPK balance in Ukrainian agriculture is nega-

tive for all nutrients and totaled 36.0 kg/ha. Compared to European countries, where arable land accounts for 30–32% of the total area, Ukraine's ploughed land is almost 60% (Baliuk et al., 2021).

In the presence of such degradation processes, the use of traditional extensive agricultural methods and technologies is no longer acceptable. Soil organic matter, predominantly represented by organic carbon, is among the most important constituents and determines its general fertility. An important tool for increasing organic matter and other nutrients in the soil is green manure (Cherr et al., 2006; Adekiya et al., 2019). The cultivation of green manure crops, which are introduced into crop rotations to restore soil fertility, improve its structure, and control pests and diseases of agricultural plants, is one of the most promising tools for soil fertility preservation and restoration in the system of biologized regenerative agriculture (Salahin et al., 2013; Horodyska & Kravchuk, 2023).

Worldwide, there are many green manure plants that can help improve the biological, physical, and chemical properties of the soil and address numerous agricultural challenges (Chmel et al., 2019; Iderawumi & Kamal, 2022). Green manure is one of the alternative sources of soil nutrients, especially in the face of acute shortages and the unpredictable cost increases of mineral fertilizers. It has a complex effect on the soil by saturating crop rotations with legumes, minimizing tillage, using biological plant protection products, and more (Chimouriya et al., 2018; Borys et al., 2024).

In terms of impact on crop yields, green manure is comparable to common manure applied at rates of 20–30 t/ha, while the expenditures for are 2–4-fold lower. The incorporation of green plant biomass – characterized by high contents of sugars, starch, proteins, and nitrogen – along with its root systems, fundamentally differentiates green manure from other organic fertilizers, such as dry or partially decomposed materials applied to the soil. The application of green manure mobilizes nutrients from numerous sources, such as solar energy (insolation), the atmosphere (mainly nitrogen compounds), and the lower soil layers and transfers them to the topsoil. The organic matter derived from green manure crops serves as a reservoir of essential plant nutrients, including nitrogen, phosphorus, potassium, and a range of micronutrients. Unlike synthetic fertilizers that release nutrients rapidly, green manure undergoes gradual decomposition, steadily converting these nutrients into forms available for plant uptake. This slow-release mechanism ensures a sustained supply of nourishment throughout the growing season, thereby supporting the continuous growth, development, and resilience of the main crops under varying environmental conditions. The nitrogen used by green manure to create biomass is not removed from the soil and once returned, helps replenish the organic matter and nitrogen content of the soil (Fageria, 2007).

The value of green manure intercropping lies in the fact that such crops do not require a separate field, as conventional green manure crops do, but instead utilize agroclimatic resources that remain unused by the main crops in the crop rotation to form a green mass harvest. However, when selecting a particular green manure crop – especially for post-harvest cultivation – it is important to consider the climatic and soil conditions of the region, as well as the organizational and economic conditions of agricultural enterprises or farms. The growth and development phase in which green manure plants are incorporated into the soil is particularly important. Incorporation of green manure crops before legumes bloom or cereals spike activates microbiological processes in the soil and increases the yield of subsequent crops, but it does not significantly affect the quantity and quality of humus. This is because the delicate green mass of green manure is low in lignin, mineralizes quickly, and is not retained in humus compounds. An effective agricultural measure that helps intensify the humification of organic matter is the combined use of green manure crops and post-harvest residues, which, like organic fertilizers, contain all the necessary nutrients. The combination of green manure (C:N = 20–25:1) and straw (C:N = 80–100:1) creates favorable conditions for decomposition in the soil, inhibits nitrogen losses during the decomposition of green mass, and accelerates straw decomposition. In addition to organic matter, incorporating even half of the grain straw into the soil adds 15–20 kg/ha of nitrogen, 8–10 kg/ha of phosphorus, and

30–40 kg/ha of potassium. At the same time, essential trace elements such as boron, copper, manganese, molybdenum, zinc, and cobalt are returned to the soil (Balayev et al., 2003).

Soil enrichment with mineral forms of nutrients available to plants is also facilitated by tillage, which, by optimizing water, air, and thermal conditions, activates the vital activity of microorganisms that mineralize organic matter and enrich the soil with mineral compounds (Karlen et al., 2013). Due to the development of agricultural practices and the negative impact of the excessive intensification of crop cultivation – which reduces the resistance of the topsoil to wind and water erosion – there has been a recent shift away from multiple tillage towards a possible reduction or even complete abandonment of tillage. Scientific data and production experience confirm the feasibility of switching to zero tillage on well-structured, non-compacted soils (Islam & Reeder, 2014).

In contrast, most researchers in Ukraine confirm the effectiveness of a differentiated approach to using minimized and zero tillage systems, taking into account the ecological and technological classification of land and its reclamation status. Meanwhile, no-till alone appears to be less effective and less reasonable (Demydenko, 2023).

Considering that southern chernozems (sometimes referred to as black soils), dark chestnut, and chestnut soils, which are predominant types of soil in the ecological zone of the Southern Steppe of Ukraine, were formed under conditions of significant natural moisture deficit, have a medium to heavy loamy granulometric composition, and are characterized by salinity and low moisture retention capacity, the issue of minimizing and transitioning to zero tillage in this region requires further research. The aim of this study was to examine how tillage and fertilization affect soil fertility and the nutrient regime of irrigated dark chestnut soil under long-term green manure intercropping.

Materials and methods

The research work was carried out on the irrigated lands of the Askaniiska Research Station of the Institute of Climate-Smart Agriculture, National Academy of Agrarian Sciences of Ukraine (Kherson region), within the framework of a two-factor field experiment based on a four-field grain crop rotation. This crop rotation was deployed both spatially and temporally and included the following sequence: winter barley with green manure intercropping – soybean – winter wheat with green manure intercropping – grain corn.

Factor A represented the tillage system: I (control) – differentiated tillage, in which disk tillage (at the depth of 12–14 cm) was used for winter cereals, alternating with deep plowing for row crops (soybean and grain corn) within the crop rotation; II – no-till system with long-term (13 years) continuous direct sowing of crops.

Factor B involved organo-mineral fertilization systems incorporating mineral fertilizers applied to the main crops of the rotation, along with the utilization of all by-products (post-harvest residues and straw) and various cover crops (post-harvest green manure).

The experiment was conducted over the period 2016–2022, employing a systematic design with three replications. The total area of the stationary experimental field was 12.5 hectares. The soil of the experimental plots was characterized as dark chestnut, medium loamy, and slightly saline. The topsoil contained 2.5% humus, 3.0 mg/100 g of mineral nitrogen, 4.5 mg/100 g of mobile phosphorus, and 45 mg/100 g of exchangeable potassium. Soil pH ranged from 7.0 to 7.2. The water-holding capacity in the 0–100 cm layer was 21.8%, with a wilting point of 9.5%. Solid content was 34.1%, average bulk density was 1.39 g/cm³, porosity reached 49.2%, and water permeability (filtration rate) was 1.25 mm/min.

The climate of the study area corresponds to the southern steppe zone, classified as semi-arid. It is characterized by high thermal resources and insufficient moisture availability. The mean annual air temperature is 9.8 °C, with a sum of effective temperatures above 10 °C ranging between 3200–3400 °C. Average annual precipitation amounts to 440 mm, though it is distributed unevenly throughout the year, resulting in low precipitation-use efficiency. The aridity index varies between 0.3 and 0.7, showing a pronounced declining trend (Lykhovyd, 2021).

Green manure crops included leaf mustard (*Brassica juncea*) at a seeding rate of 20 kg/ha, buckwheat (*Fagopyrum esculentum*) – 100 kg/ha, annual white clover (*Melilotus albus*) – 12 kg/ha, and lacy phacelia (*Phacelia tanacetifolia*) – 12 kg/ha. This selection was based on their representation of different biological groups, each exerting distinct effects on the soil nutrient regime and, consequently, on crop productivity. The control treatment involved an organo-mineral fertilization system without the inclusion of green manure crops.

Sowing of green manure crops was conducted following the harvest of winter cereals. The green manure biomass was mowed at the onset of the flowering stage. In the no-till variants, the mowed biomass was left on the soil surface to serve as mulch. In contrast, in the conventional differentiated tillage treatments, the biomass was incorporated into the soil using disk harrows, followed by plowing to a depth of 28–30 cm.

Soil sampling was performed annually from the topsoil layer (0–30 cm) in three replications. The samples were analyzed in the laboratory of the Institute of Climate-Smart Agriculture of the National Academy of Agrarian Sciences of Ukraine. Nitrogen content was determined using the Kjeldahl method (Bremner, 1960), while the content of mobile phosphorus and exchangeable potassium was measured using the Machygin method (Bidnyina et al., 2025).

The cultivation practices applied to the main crops adhered to standard agrotechnological methods typical of the study region. Irrigation was managed to maintain soil moisture at 70% of field capacity within the 0–50 cm soil layer. The yields of the main crops in the crop rotation were converted into grain units. First, the crops were harvested using a self-propelled harvester. Subsequently, the yields were weighed and adjusted to standard moisture content (14% for winter wheat, winter barley, and grain corn; 12% for soybeans). The adjusted yields were then converted into grain units using the following coefficients: 1.0 for winter wheat, 0.9 for winter barley, 0.9 for grain corn, and 1.2 for soybeans. The average yield in grain units was used to assess the productivity of the crop rotation.

Statistical data processing was carried out using Python 3.13, employing relevant statistical libraries including NumPy, scikit-learn,

and statsmodels. A two-way analysis of variance (ANOVA) was conducted following standard methodology to evaluate the effects and interactions of the experimental factors. To identify statistically significant differences between treatment means, Tukey's Honestly Significant Difference (HSD) post-hoc test was applied at a significance level of $P < 0.05$ (Abdi & Williams, 2010). Standard deviations (SD) were calculated according to established procedures to quantify the variability of the data (Kragten, 1994). All statistical analyses ensured the assumptions of ANOVA were met, including normality and homogeneity of variances, which were preliminarily assessed using appropriate diagnostic tools. These analyses provided a robust foundation for interpreting experimental results and drawing scientifically valid conclusions.

Results

The impact of green manure crops on soil fertility depends primarily on the amount of biomass incorporated into the soil, which is influenced by both weather conditions and agronomic practices. According to the results of our research, green manure crops at the time of their mowing under a differentiated tillage in the crop rotation formed a greater crude biomass (leaf mustard – 12.38 t/ha, buckwheat – 11.97 t/ha, annual white melilot – 10.13 t/ha and lacy phacelia – 14.47 t/ha) than plants in the no-till system, where green manure yield was 8.46, 10.74, 9.38 and 13.25 t/ha, respectively (Fig. 1). Therefore, no-till provided no benefits in terms of improving crops productivity, and in this case zero tillage even led to undesirable result of decreased green manure crops biomass, which limited their potential positive effects on soil health and fertility. However, it should be noted that ANOVA results provided marginal evidence in favor of differentiated tillage, because the P-value of the statistical test (0.09) was higher than the conventional $P = 0.05$. As for the green manure crops, average yields were also different insignificantly between all the crops. Lacy phacelia was the only one to stand out with significantly higher average yields. This is related to high variability within the groups by the years of the study.

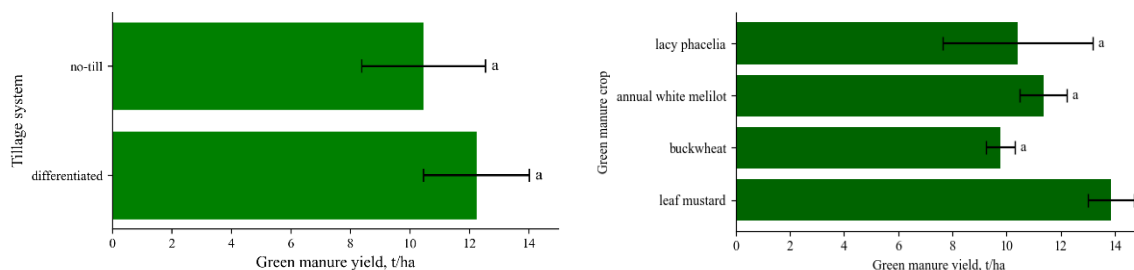


Fig. 1. Green manure yields (t/ha, mean \pm SD) on average for 2016–2022 depending on tillage options

Table 1

Content of NPK in the biomass of green manure crops depending on tillage (%), mean \pm SD, average for 2016–2022, $n = 3$)

Tillage	Green manure crop	Content of macronutrients in biomass		
		N	P	K
No-till	leaf mustard	1.61 \pm 0.032 ^e	0.52 \pm 0.022 ^b	1.80 \pm 0.033 ^c
	buckwheat	1.69 \pm 0.034 ^e	0.51 \pm 0.024 ^b	2.34 \pm 0.032 ^b
	annual white melilot	2.43 \pm 0.040 ^e	0.79 \pm 0.053 ^a	0.88 \pm 0.024 ^e
	lacy phacelia	1.14 \pm 0.023 ^f	0.48 \pm 0.022 ^b	2.22 \pm 0.030 ^b
Differentiated	leaf mustard	1.92 \pm 0.031 ^d	0.50 \pm 0.021 ^b	1.86 \pm 0.031 ^c
	buckwheat	2.59 \pm 0.053 ^b	0.78 \pm 0.040 ^a	3.28 \pm 0.050 ^a
	annual white melilot	2.81 \pm 0.053 ^a	0.72 \pm 0.043 ^a	1.03 \pm 0.023 ^d
	lacy phacelia	2.78 \pm 0.055 ^a	0.37 \pm 0.014 ^b	2.29 \pm 0.041 ^b

Note: different superscript letters indicate statistically significant differences between means, as determined by Tukey's HSD post hoc test at $P < 0.05$.

Regarding the content of NPK macronutrients in the biomass of green manure crops, a statistically significant difference was established, according to Tukey's Honestly Significant Difference (HSD) post-hoc test, among the studied crops and tillage treatments (Table 1). On average, all the investigated green manure crops accumulated significantly more nitrogen under differentiated tillage. Concerning phosphorus, a significant difference between tillage treatments was observed only in buckwheat, with greater accumulation under

differentiated tillage. Significantly higher potassium accumulation in plant biomass under differentiated tillage was evident only in buckwheat and annual white clover. Consequently, it can be concluded that, under the conditions of a semi-arid climate and dark chestnut soils, differentiated tillage should be preferred over no-till systems when seeking optimal efficiency in fertility restoration through the use of green manure crops. The highest nitrogen accumulation was recorded in annual white melilot and lacy phacelia; greater phospho-

rus accumulation was observed in annual white melilot and buckwheat; and the highest potassium accumulation was found in buckwheat biomass. These results facilitate the selection of specific green manure crops based on the need for increased soil macronutrients in a particular direction.

Table 2

Content of NPK in soil depending on tillage and green manure crops (mg/kg, mean \pm SD, average for 2016–2022, n = 3)

Tillage	Green manure crop	Content of N	Content of P	Content of K
No-till	control	24.48 \pm 3.95 ^a	55.08 \pm 1.12 ^a	484.45 \pm 9.83 ^b
	leaf mustard	53.76 \pm 16.45 ^a	69.00 \pm 11.03 ^a	489.98 \pm 112.88 ^a
	buckwheat	29.58 \pm 11.20 ^a	68.95 \pm 0.22 ^a	591.97 \pm 0.01 ^a
	annual white melilot	28.92 \pm 11.52 ^a	68.44 \pm 0.45 ^a	586.72 \pm 48.58 ^a
	lacy phacelia	29.28 \pm 11.63 ^a	69.32 \pm 0.28 ^a	593.74 \pm 10.41 ^a
Differentiated	control	26.62 \pm 1.45 ^a	62.10 \pm 10.58 ^a	337.90 \pm 48.37 ^a
	leaf mustard	47.50 \pm 22.46 ^a	61.06 \pm 10.31 ^a	535.57 \pm 148.94 ^a
	buckwheat	27.83 \pm 9.81 ^a	68.36 \pm 2.33 ^a	582.13 \pm 21.37 ^a
	annual white melilot	32.90 \pm 7.09 ^a	65.47 \pm 1.70 ^a	575.21 \pm 18.89 ^a
	lacy phacelia	31.16 \pm 6.04 ^a	67.89 \pm 3.64 ^a	577.72 \pm 22.12 ^a

Note: different superscript letters indicate statistically significant differences between means, as determined by Tukey's HSD post hoc test at $P < 0.05$.

Surprisingly, Tukey's post-hoc test did not reveal any statistically significant differences between the variants of different tillage treatments and green manure crops in the accumulation of NPK in the soil. A significant difference was found only for potassium content under the no-till control, indicating that all the green manure crop variants significantly improved the soil content of this macronutrient. This lack of significant difference across most treatments might be attributable to a high degree of variability in the soil content of the studied macronutrients, as evidenced by high standard deviation (SD) values in most variants of the experiment. The mentioned fact is strongly related on the impossibility of complete accounting for natural soil fertility variegation of the studied plots. Furthermore, this observation may suggest that the decomposition rates and subsequent macronutrient accumulation in dark chestnut soil are not substantially affected by tillage practices. Given that different green manure crops exhibit varying NPK content in their tissues and different yielding capacities, their combined effect may result in no significant difference regarding which specific crop is used for soil fertility improvement. Although no statistically significant difference was established, it is noteworthy that the highest nitrogen content in the soil was recorded under the differentiated tillage system when leaf mustard was used as the green manure crop. The highest phosphorus content was associated with leaf mustard green manure under no-till conditions, while the highest potassium content was observed with lacy phacelia under no-till.

Beyond the potential effects of green manure crops and tillage on soil fertility, an analysis of crop rotation productivity in grain units was conducted (Table 3). This analysis determined that there was no significant effect of fertilization options, with or without green manure crops, on the yields. Concurrently, tillage treatments exhibited distinct differences, with the differentiated tillage system showing a superiority of 11.67% on average.

The observed superiority of differentiated tillage over continuous no-till indicates that the complete abandonment of tillage in the irrigated conditions of a semi-arid climate zone is not advisable. Such a practice may not only lead to unfavorable alterations in soil fertility

Table 3

Average productivity of the crop rotation depending on tillage and fertilization (t/ha of grain units, mean \pm SD, average for 2016–2022, n = 3)

but also potentially reduce the yields of cultivated crops, resulting in economic losses. The results of the analysis of grain yields of each individual crop are summarized in Table 4, where mean yields are presented with standard deviations, and grouping letters indicate statistically significant differences at $P < 0.05$ with accordance to Tukey's HSD. Soybean yield was significantly influenced by both tillage and fertilization. The differentiated tillage system generally outperformed no-till across fertilization levels. The highest soybean yield was observed under differentiated tillage with N₁₀₅P₄₀ + green manure and N₁₂₀P₄₀ + green manure, forming a statistically homogeneous group with the best-performing treatments. Conversely, the lowest yields were recorded under zero tillage with N₁₂₀P₄₀ and N₉₀P₄₀ + green manure, significantly lower than the top group.

Table 4

Average productivity of the crop rotation depending on tillage and fertilization (t/ha of grain units, mean \pm SD, average for 2016–2022, n = 3)

Tillage	Fertilization	Grain units
No-till	N ₉₀ P ₄₀ + green manure	6.09 \pm 0.071 ^a
	N ₁₀₅ P ₄₀ + green manure	6.45 \pm 0.007 ^a
	N ₁₂₀ P ₄₀ + green manure	6.77 \pm 0.212 ^a
	N ₁₂₀ P ₄₀	6.06 \pm 0.007 ^a
Differentiated	N ₉₀ P ₄₀ + green manure	6.71 \pm 0.332 ^b
	N ₁₀₅ P ₄₀ + green manure	7.11 \pm 0.417 ^b
	N ₁₂₀ P ₄₀ + green manure	7.58 \pm 0.460 ^b
	N ₁₂₀ P ₄₀	6.93 \pm 0.693 ^b

Note: different superscript letters indicate statistically significant differences between means, as determined by Tukey's HSD post hoc test at $P < 0.05$.

Corn yield also showed sensitivity to both studied factors. The maximum yield was achieved under differentiated tillage and N₁₂₀P₄₀ + green manure, significantly higher than that under no-till with N₁₂₀P₄₀. Intermediate yields were observed with other no-till treatments and certain differentiated tillage-fertilization combinations. These findings emphasize the advantage of high fertilization rates combined with differentiated tillage in maximizing grain corn productivity.

Table 4

Yields of major crops in the crop rotation depending on tillage and fertilization system (t/ha, mean \pm SD, average for 2016–2022, n = 3)

Tillage	Fertilization	Soybean	Corn	Wheat	Barley
Differentiated	N ₉₀ P ₄₀ + green manure	3.44 \pm 0.45 ^b	9.73 \pm 0.86 ^{ab}	6.43 \pm 1.05 ^{abc}	5.56 \pm 0.97 ^{abc}
	N ₁₀₅ P ₄₀ + green manure	3.85 \pm 0.52 ^{ab}	9.88 \pm 0.91 ^{ab}	6.65 \pm 1.01 ^{ab}	5.97 \pm 0.58 ^{ab}
	N ₁₂₀ P ₄₀ + green manure	3.78 \pm 0.51 ^{ab}	10.30 \pm 0.77 ^a	6.95 \pm 0.90 ^a	6.18 \pm 0.39 ^a
	N ₁₂₀ P ₄₀	3.57 \pm 0.68 ^b	9.17 \pm 0.78 ^{bc}	6.55 \pm 0.78 ^{abc}	5.63 \pm 0.71 ^{abc}
No-till	N ₉₀ P ₄₀ + green manure	3.07 \pm 0.39 ^c	8.76 \pm 0.80 ^{cd}	5.95 \pm 1.36 ^c	5.00 \pm 0.83 ^c
	N ₁₀₅ P ₄₀ + green manure	3.32 \pm 0.45 ^{bc}	8.83 \pm 0.72 ^{cd}	6.28 \pm 1.30 ^{bc}	5.43 \pm 0.64 ^{bc}
	N ₁₂₀ P ₄₀ + green manure	3.51 \pm 0.38 ^b	9.61 \pm 0.66 ^{abc}	6.53 \pm 0.93 ^{abc}	5.72 \pm 0.83 ^{abc}
	N ₁₂₀ P ₄₀	3.09 \pm 0.68 ^c	8.17 \pm 0.86 ^d	6.27 \pm 1.09 ^{bc}	5.30 \pm 0.82 ^{bc}

Note: different superscript letters indicate statistically significant differences between means, as determined by Tukey's HSD post hoc test at $P < 0.05$.

For wheat, the effects of tillage and fertilization were evident but less pronounced. The highest yield was again obtained under differentiated tillage and N₁₂₀P₄₀ + green manure, significantly superior to zero tillage with N₉₀P₄₀ + green manure. Other treatments formed overlapping groups, suggesting moderate but statistically borderline differences due to treatment interactions. Barley yield followed a similar pattern. The best yield was recorded under differentiated tillage with N₁₂₀P₄₀ + green manure, significantly outperforming the no-till variant with N₉₀P₄₀ + green manure. The general trend indicated yield improvement with increasing fertilization, particularly under differentiated tillage conditions.

Therefore, in terms of pure yielding capacity, differentiated tillage slightly, but statistically significantly, outperformed zero tillage. Also, the highest fertilization option provided the highest yield for every studied crop. It must be noted that green manure has an important effect on yielding capacity of the crops, because yields were significantly higher on the variant with green manure compared to that without green manure intercropping.

Discussion

Effects of tillage on crops have been carefully studied in recent decades to ensure the use of the best soil treatment option for fertility conservation and simultaneous yield increase. Focusing on the topics addressed in the present study, it was determined that most academic reports claim that tillage significantly changes NPK accumulation in the biomass of cultivated plants, which is in agreement with our results. Szczepanek et al. (2024) revealed that minimization of tillage through the strip-till option had a positive effect on the uptake of macronutrients by cultivated plants from the soil, providing better yields and increased NPK accumulation in the biomass. Sidiras et al. (1999) showed that no-till combined with rational fertilization improved the growth and development of vetch plants, leading to better nodulation and nitrogen accumulation.

Tillage significantly changes the cycles of NPK in the “plant-soil” system, resulting in more or less efficient nutrient uptake and reutilization by cultivated plants, as was shown in the study by Tanchyk et al. (2020). Along with changes in this cycle, different amounts of NPK are accumulated in the plant biomass, as was confirmed by our results. Moreover, these amounts of NPK accumulation vary depending on the crop type. For example, it was established by multiple studies that legumes accumulate the highest nitrogen amounts in their root and aboveground biomass, leading to soil enrichment with this nutrient afterward (Palmero et al., 2022; Barbieri et al., 2023). This was also the case in our study, where the highest nitrogen accumulation was recorded in annual white melilot – a typical legume.

It should also be mentioned that nitrogen is usually the element with the highest accumulation rates in plants, followed by potassium and phosphorus. However, our study determined that this is not always the case: under the no-till option, all the green manure crops except annual white melilot accumulated more potassium than nitrogen, while under the differentiated tillage system, only buckwheat accumulated more potassium than nitrogen. This indicates that the rates and volumes of NPK accumulation in plant tissues strongly depend on the tillage system and crop characteristics.

The study by Sarrantonio & Scott (1988) revealed that conventional plowing at a depth of 20–22 cm resulted in better outcomes of green manuring with hairy vetch (*Vicia villosa* Roth) compared to no-till. The highest inorganic nitrogen accumulation in the soil was observed under conventional tillage, notwithstanding the fact that the yields of the next crop in the crop rotation (grain corn) were somewhat higher under no-till rather than conventional plowing.

Another interesting beneficial effect of the no-till plus green manure combination was described in the study by Lyu et al. (2024). It was determined that no-till mulch with green manure retention reduces N₂O emissions from grain corn fields, which is very important in the context of global warming and greenhouse gas emission reduction from agricultural activities. Wang et al. (2024) additionally claimed that green manure mulch under no-till systems can help reduce carbon dioxide emissions into the atmosphere. Taking into ac-

count the above, the combination of no-till and green manuring appears to be a promising strategy not only for soil fertility preservation but also as an additional lever for climate change mitigation. However, it must be considered that no-till can potentially reduce the yields of green manure crops, as was pointed out in our results.

As for the influence of green manure and tillage on soil fertility and NPK contents, it was determined that conservation tillage combined with a complex fertilization system (50% NPK in the form of mineral fertilizers and the other 50% in the form of green manuring) significantly improved soil properties by increasing the availability of NPK macronutrients under a crop rotation with rice and rapeseed in the conditions of the subtropical eastern Himalayas (Das et al., 2020). Kamran et al. (2021) reported positive effects of using green manure to improve soil organic carbon (the main source of nutrients for plants) in fluvo-aquic paddy soil. A positive influence was achieved even under minimal mineral fertilization. In calcareous soils, the application of green manure crops with 75% of the required mineral NPK fertilization resulted in significant enhancement of soil fertility owing to the increase in available NPK contents (Naz et al., 2023).

Soil nitrate nitrogen and mobile phosphorus contents increased substantially after green manure mineralization before maize sowing, but soil disturbance prior to maize sowing reduced maize growth, nutrition, and mycorrhizal formation, as reported by Ortiz-Salgado et al. (2021). In a stationary field experiment on sod-podzolic soil when growing corn, scientists have proven that the use of lupine green manure optimizes nitrogen nutrition of plants and contributes to pronounced increase in the content of the available forms of phosphorus compared to the control – by 0.8–1.9 mg/100 g of soil. The combination of green manure with mineral fertilizers has a positive effect on the yield of the crop following in the crop rotation, as green manure biomass acts as a kind of nutrient accumulator in the soil, including for mineral fertilizers, over a certain period of time (Miliutenko, 2014).

In a field experiment conducted between 2005 and 2010 at Sumy National Agrarian University, four mechanical methods of tillage were examined: ploughing up to 28–30 cm (conventional tillage), sweep ploughing up to 28–30 cm, disk tillage up to 14–16 cm, and disking to a depth of 4–6 cm. Oilseed radish (*Raphanus sativus* L.) was used as a green manure crop. As a result, the use of green manure significantly improved the NPK content in calcic black soils under potato and sugar beet cultivation. The combination of oilseed radish and ploughing to a depth of 28–30 cm ensured a soil balance of 101.7–136.0% for nitrogen and potassium (Mishchenko et al., 2020).

An experiment conducted on gleyic fluvisols investigated the effects of tillage methods (conventional, reduced, and no-till) on soil fertility across three soil depths (0–0.15, 0.15–0.30, and 0.30–0.45 m). Total nitrogen content significantly decreased under reduced tillage (by 5.2%) and no-till (by 5.1%) compared to conventional tillage (by 0.7%), indicating a potential reduction in nitrogen availability with less intensive tillage practices. Soil organic carbon also declined across all tillage methods, with reductions of 4.1% under reduced tillage, 4.8% under no-till, and 4.9% under conventional tillage, suggesting that tillage impacts carbon storage similarly across methods. Available phosphorus increased slightly under reduced tillage (by 4.1%) but decreased under no-till (by 9.5%) and conventional tillage (by 3.3%), highlighting variable effects of tillage on phosphorus availability. Available potassium showed no significant changes across tillage methods, indicating stable potassium levels regardless of tillage intensity (Soltysová & Danilovic, 2011).

The study by Kheyroldin & Antoun (2011) established that tillage intensity had no significant effect on meadow soil fertility indicators, such as soil organic carbon and total nitrogen content, over 15 years of research, demonstrating the limited influence of tillage practices on soil agrochemical properties. The study by Saygi (2021) revealed that soil organic matter content under strawberry crops increased by 12% in the first year and 5.1% in the second, while another study documented a 117% rise in soil organic carbon. At the same time, nitrogen levels rose by up to 75%, and available phosphorus and potassium generally increased by 38% and 33%, respectively.

Studies measuring biological indicators observed that applications of green manure – especially fresh and leguminous types – en-

hanced microbial activity, biomass, enzyme activity, and even altered microbial community composition. Regarding NPK content, the most significant effect of green manure was recorded in soil phosphorus and potassium concentrations. Hairy vetch (*Vicia villosa* Roth) was used as a green manure crop together with alfalfa meal in this study (Rudisill et al., 2015). Species differences – such as stronger nitrogen benefits from legume-based manures – and variations in incorporation methods and environmental conditions further influenced these effects.

Green manure crops in a rice–mustard crop rotation improved soil fertility, increasing soil organic matter by 0.02–0.07%, nitrogen by 0.05%, potassium by 0.2–0.5 meq/100 g, and phosphorus by 2–15 ppm across treatments with 100% and 50% fertilizer doses. Rice yields increased in treatments with green manure application, allowing for reduced nitrogen fertilizer use, thus highlighting the role of green manure in enhancing soil health and sustainability (Irin & Biswas, 2023).

A study in which such plants as pawpaw (*Carica papaya* L.), nimtree (*Azadirachta indica* A. Juss.), drumstick tree (*Moringa oleifera* Lam.), and Mexican lilac or glicirida (*Gliricidia sepium* (Jacq.) Kunth ex Walp.) were used as green manure showed that these crops improved soil health by reducing bulk density, increasing soil organic matter and NPK content, and had a more prominent positive effect – compared to mineral fertilization with a 15:15:15 NPK complex at a rate of 300 kg/ha – on tomato fruit yield. Among the treatments, gliricidia used as green manure resulted in the highest tomato yield and the most favorable payout of the technological expenditures (Agbede et al., 2019). This study provides additional evidence that, although all green manure crops have beneficial effects, the strength of these effects is highly dependent on species-specific characteristics.

One of the most comprehensive studies on green manure effects on soil properties was performed by Ma et al. (2021). The researchers carried out a meta-analysis of the reports and scientific articles on the effects of green manure application on soils and crop yields in Northern China. As a result, they established that green manure improved soil bulk density (average decrease by 5.6%) and prevented over-compaction. Also, it increased microbial biomass carbon by 28%, and improved the activities of soil enzymes by 14–39%. As most studies, including ours, testify, green manure of legumes provided the highest increase in soil nitrogen content, while non-legume crops provided a significant increase in soil potassium content. As for the yields of the main crops in crop rotations with green manuring, it should be noted that green manure ensured about an 11% increase in grain corn yields, while its effect on wheat and potato was insignificant (Ma et al., 2021). This result is in agreement with ours, as it was established that there was no significant difference between the variants with and without green manure intercropping in our study. Tillage had a more pronounced effect in a semi-arid climate on soil nutrient content.

Another comprehensive study on green manuring revealed that all the green manures (namely, *Trifolium pratense* L., *Brassica napus* L., and their mixture) had a positive effect on the soil biological properties, plant nutrition, and crop yield parameters. Besides, green manure resulted in higher grain corn yields by 20.0–22.1% depending on its composition (Tejada et al., 2008). A meta-analysis of the effects of green manure application in China established that legume green manuring increased the yield of three major grain crops (wheat, maize, and rice) on average by 12.6% compared to no green manuring. But it must be noted that yield increases were significant under crop rotation with grain crops but not under intercropping. This is in partial agreement with our study, where intercropping of green manure crops did not provide a statistically significant yield of grain units increase in the crop rotation, notwithstanding the fact that the difference was evident. At the same time, when assessing the individual pure grain yields, it was evident that green manure intercropping resulted in statistically significantly higher yields of major crops in crop rotation. The amount of legume green manure returned to the field at 2–4 t/ha increased yield significantly by more than 12%. The greatest yield increases were observed in specific meteorological conditions: annual precipitation exceeding 600 mm, annual average air temperature higher than 10 °C; soil organic matter content also mattered, and the best

results were obtained at its content of up to 10 g/kg (Liang et al., 2022). The last fact tells us about the importance of considering agro-ecological peculiarities of the zone when taking decisions on green manure application and green manure crop selection to achieve the best possible outcomes both for soil fertility and major crop production.

Conclusions

The results of the study revealed that both green manuring and tillage significantly influence the productivity of short-grain crop rotation under irrigated conditions in a semi-arid climate. Among the two factors, tillage had a more pronounced effect on the yields of major crops compared to green manure intercropping. Furthermore, tillage notably impacted the yields of green manure crops, with the differentiated tillage system demonstrating clear advantages over the no-till approach. Tillage also influenced the accumulation of NPK in the biomass of green manure crops. Despite these differences, the overall effect of green manuring on soil fertility was evident, although statistically significant only in the case of potassium content. The differentiated tillage system led to significantly higher grain yields and pure yields across all studied crops in the rotation, particularly in treatments that combined high mineral fertilization rates with green manuring. In contrast, the use of mineral fertilizers alone resulted in comparatively lower yields, further supporting the benefits of integrating green manuring. In conclusion, the combination of optimized differentiated tillage and balanced organo-mineral fertilization – including the use of green manure crops – proves to be an effective strategy for enhancing crop productivity and maintaining soil fertility in semi-arid climatic conditions. Further research should explore the long-term effects of combined tillage and green manuring practices on soil microbial communities, organic matter dynamics, and nutrient cycling. Additionally, studies across diverse agro-climatic zones and soil types would help validate the broader applicability of these findings. It would also be valuable to investigate the economic efficiency and environmental sustainability of these practices under varying irrigation regimes and levels of climatic stress.

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