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The effect of winter rye green manure on soil fertility parameters and productive moisture dynamics in organic buckwheat cultivation

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ABSTRACT

Research has shown that extending the vegetation period of winter rye grown for green manure until the third ten-day period of May results in the highest yield of green biomass – 40 t ha^{-1} and, accordingly, the greatest accumulation of sequestered atmospheric carbon – 4.32 t ha^{-1}. However, with this incorporation date, the highest soil bulk density and hardness were recorded in the root zone during buckwheat cultivation. The lowest bulk density in the 0–30 cm soil layer was achieved when the green manure was incorporated in the second ten-day period of May – 1.14 g/cm^3 at the time of sowing and 1.16 g/cm^3 at flowering. Incorporation in the same period also resulted in the lowest soil hardness: 13.8 kg/cm^2 at sowing and 16.0 kg/cm^2 at flowering. Incorporating the green manure no later than 10 days before buckwheat sowing led to the highest reserves of productive moisture in the 0–10 cm topsoil layer – 12.2–12.4 mm. At flowering, the best moisture reserves in the 0–30 cm layer were observed after incorporation in the second ten-day period of May – 35.2 mm. The most favorable soil agrophysical parameters contributed to the highest buckwheat yield – 2.72 t ha^{-1} when winter rye was incorporated in the second ten-day period of May. The use of winter rye as green manure enriches the soil with organic matter and helps sequester carbon from the atmosphere by utilizing natural resources. This winter crop also protects soil from water and wind erosion, promotes biological loosening, and supports the activity of soil biota due to active root function. Incorporating green manure into the soil 10 days before buckwheat sowing allows achieving an optimal balance: obtaining the maximum amount of green biomass without significant loss of soil moisture. This is critical for successful germination of the organic buckwheat crop and for loosening the soil.

Keywords: green manure, productive moisture, water and wind erosion, soil density, soil moisture, yield.

INTRODUCTION

In the current era of climate change, organic farming is gaining significant relevance. Its key principles include the restoration of the soil's top layer, enhancement of biodiversity, improvement of the water cycle, support for biospheric carbon sequestration, increased climate resilience, and the strengthening of soil health, fertility, and viability [IPCC, 2015; Camarotto et al., 2020; Dietmar et al., 2021]. Organic agriculture aims to promote symbiosis between plants and soil biology to ensure natural and sustainable food production [Lange et al., 2015; Kovalenko et al., 2024].

By nature, organic farming closely resembles the natural symbiotic processes among biological organisms due to the presence of continuous plant cover and live roots in the soil. This environment stimulates the activity of soil organisms and prevents water and wind erosion. For example, the presence of plant cover or residues protects the soil surface from the destructive effects of overheating, overmoistening, or desiccation, while also providing the energy necessary for continuous soil biological functioning [Dietmar et al., 2021; Kvitko et al., 2021].

One of the most effective methods for protecting and enriching the soil with organic matter in organic farming is the use of intermediate cover crops. These crops are sown after the harvest of the main crop and are terminated before seed formation or the sowing of the next crop.

Thanks to intermediate green manure crops, farmers create soils rich in humus and biologically active, which minimizes the need for plant protection measures [IPCC, 2015; Dietmar et al., 2021]. Humus-rich soils can absorb and retain more water over a short period, which helps reduce water runoff during heavy rains and promotes moisture accumulation in soil horizons. This strategy enhances protection against erosion and flooding, shields crops from drought, and restores optimal soil moisture reserves.

The use of intermediate green manures in organic farming also enables the sequestration of carbon from the atmosphere into the soil, where carbon reserves are much higher than in the atmosphere or vegetation [Kassam et al., 2019; Camarotto et al., 2020]. A 1.0% increase in soil organic matter can sequester up to 12 tons of carbon per hectare from the atmosphere and enhance soil water retention, potentially adding 22.5 tons of moisture an essential limiting factor during hot vegetation periods [Camarotto et al., 2020; Voitovyk et al., 2023].

Fertile chernozem soils contain over 500 tons of organic matter per hectare, allowing them to retain precipitation for extended periods and support high yields under drought conditions. However, modern soils have lost more than half of their original organic matter, which has entered the atmosphere as carbon [Litvinov et al., 2020; Dietmar, 2021].

Therefore, growing intermediate green manure crops in organic farming offers an opportunity to capture excess atmospheric carbon in the soil. This helps restore optimal soil fertility parameters, enabling the stable production of sufficient and high-quality yields.

However, the cultivation of intermediate green manure crops under current climate-altered conditions requires adaptation of agricultural practices. Due to the prolonged and drier autumn growing period, winter cover crops are becoming more promising. This, in turn, necessitates identifying the optimal timing for terminating the spring growth of winter green manure crops to avoid excessive depletion of soil moisture, which must be conserved for the sowing of the next crop.

MATERIAL AND METHODS

The research was conducted in the northeastern Forest-Steppe zone of Ukraine, based at the organic field of Sumy National Agrarian University during 2023–2024. The climate in the study area is classified as moderately continental.

Throughout the research period, there were notable fluctuations in precipitation and air temperature. In particular, a lack of rainfall in August and September delayed the sowing of winter rye to later dates. However, the increase in average daily temperatures prolonged the autumn vegetation period and provided a sufficient accumulation of active temperatures to support full autumn tillering of the winter rye.

The timing of winter rye green manure incorporation prior to buckwheat sowing was structured as follows: (1) control (no green manure); (2) third ten-day period of April; (3) first ten-day period of May; (4) second ten-day period of May; (5) third ten-day period of May.

In the organic trial field, winter rye of the variety Syntetik was used as the green manure crop, while the buckwheat variety Antaria was used as the main crop. The green manure was incorporated into the soil using disk harrowing, and buckwheat was grown in accordance with organic farming standards.

During the study, at both the sowing and flowering stages of buckwheat, the following parameters were measured: soil moisture content thermostatic-gravimetric method according to DSTU ISO 11465:2001, soil bulk density Kaczynskiy's method according to DSTU ISO 11272:2001, soil hardness static penetrometer [Yeshchenko et al., 2014].

The aim of our study was to identify the most optimal date for incorporating winter rye green manure to ensure favorable conditions for plant growth and achieve the highest buckwheat yields.

RESULTS AND DISCUSSION

Observation of the winter rye cover crops used as green manure revealed that a longer growth period resulted in higher phytomass yields. Overall, the yield of winter rye green manure ranged from 15 to 40 tons per hectare (Table 1).

The highest green biomass yield – 40.1 t ha^{-1} was obtained when the rye was incorporated in the third ten-day period of May. The lowest yield, 15.2 t ha^{-1}, was recorded when rye was incorporated in the third ten-day period of April. Incorporation in the first and second ten-day periods of May yielded 22.1 t ha^{-1} and 29.4 t ha^{-1}, respectively. This clearly shows that the longer the spring growth period, the higher the green biomass yield.

Cover crops are currently a highly valuable tool for atmospheric carbon sequestration. In our study, the calculated amount of sequestered carbon in winter rye biomass during its growth ranged from 1.08 to 4.32 t ha^{-1}.

The maximum amount of sequestered carbon was found in rye biomass incorporated in the third ten-day period of May – 4.32 t ha^{-1}. The lowest amount – 1.08 t ha^{-1} was recorded in rye incorporated in the third ten-day period of April. Incorporation in the first and second ten-day periods of May resulted in 1.78 t ha^{-1} and 2.61 t ha^{-1} of sequestered carbon, respectively.

Thus, incorporating winter rye prior to buckwheat sowing in late May resulted in the highest biomass yield (40.1 t ha^{-1}) and highest carbon sequestration (4.32 t ha^{-1}) from the atmosphere.

The application of green manure improves the agrophysical properties of the soil by intensifying biological processes, loosening the soil, and improving its structure. As a result, typical chernozem soils become less compacted and regain optimal bulk density and hardness parameters.

Measurements of soil bulk density showed that the highest density in the 0–30 cm layer, both at the time of sowing (1.15 g/cm³) and at flowering (1.17 g/cm³), was observed when green manure was incorporated in the third ten-day period of May, i.e., just before sowing buckwheat (Figure 1).

The lowest and most optimal bulk density values at sowing and flowering were recorded when rye was incorporated in the second ten-day period of May, with values for the 0–10 cm layer at 1.09 and 1.11 g/cm³, and for the 0–30 cm layer at 1.14 and 1.16 g/cm³, respectively. Incorporation in the first ten-day period of May and the third ten-day period of April due to lower biomass volumes resulted in slightly higher soil densities: for the 30 cm layer at sowing, the values were 1.15 and 1.16 g/cm³, and at flowering – 1.17 and 1.18 g/cm³, respectively.

However, these values were still lower than those recorded in the control plot without green manure, where bulk density reached 1.17 g/cm³ at sowing and 1.20 g/cm³ at flowering.

Assessment of soil hardness under the buckwheat crop showed the lowest values in the treatment where green manure was incorporated in the second ten-day period of May. Specifically, soil hardness in the 0–10 cm and 0–30 cm layers at sowing was 9.6 and 13.8 kg/cm², and at flowering – 10.5 and 16.0 kg/cm², respectively (Figure 2).

When rye was incorporated in the first ten-day period of May and the third ten-day period of April, soil hardness was slightly higher, with values in the 0–10 cm layer of 10.2 and 11.2 kg/cm² at sowing and 11.1 and 12.2 kg/cm² at flowering. In the 0–30 cm layer, the values were 14.3 and 14.9 kg/cm² at sowing and 16.6 and 17.3 kg/cm² at flowering, respectively.

In the variant where rye was incorporated immediately before sowing buckwheat (third ten-day period of May), less soil moisture led to the highest soil hardness values: 11.6 and 15.1 kg/cm² in the 0–10 and 0–30 cm layers at sowing and 12.6 and 17.4 kg/cm² at flowering.

In the control variant without green manure, maximum soil hardness values were recorded: 12.3 and 15.7 kg/cm² at sowing and 13.4 and 18.2 kg/cm² at flowering in the 0–10 and 0–30 cm soil layers, respectively.

Under climate change conditions, soil moisture availability becomes the key limiting factor. If winter rye grown for green manure remains in

Table 1. Biomass yield and carbon sequestration

Parameter	The time for wrapping winter rye for green manure			
	April 3	May 1	May 2	May 3
Phytomass yield, t ha^{-1}	15.2	22.1	29.4	40.1
Amount of bound carbon, t ha^{-1}	1.08	1.78	2.61	4.32

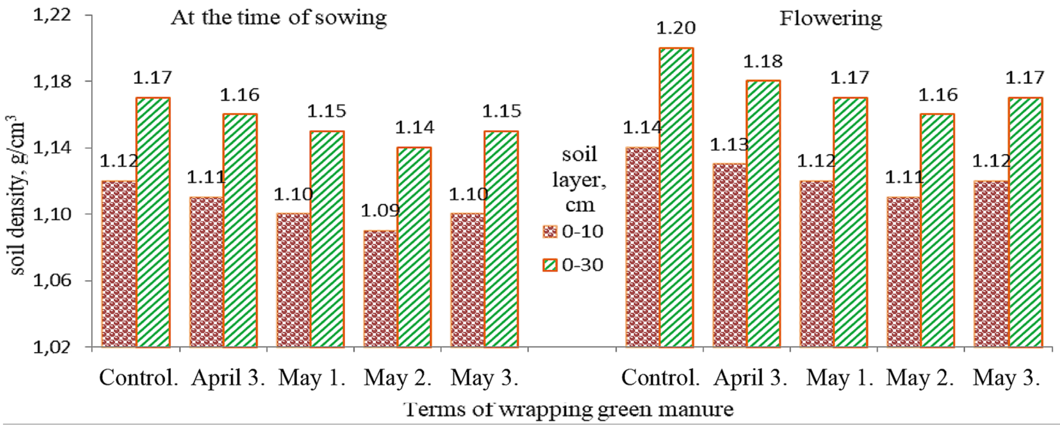

Figure 1. Dynamics of soil density during mulching of winter rye green manure, g/cm^3

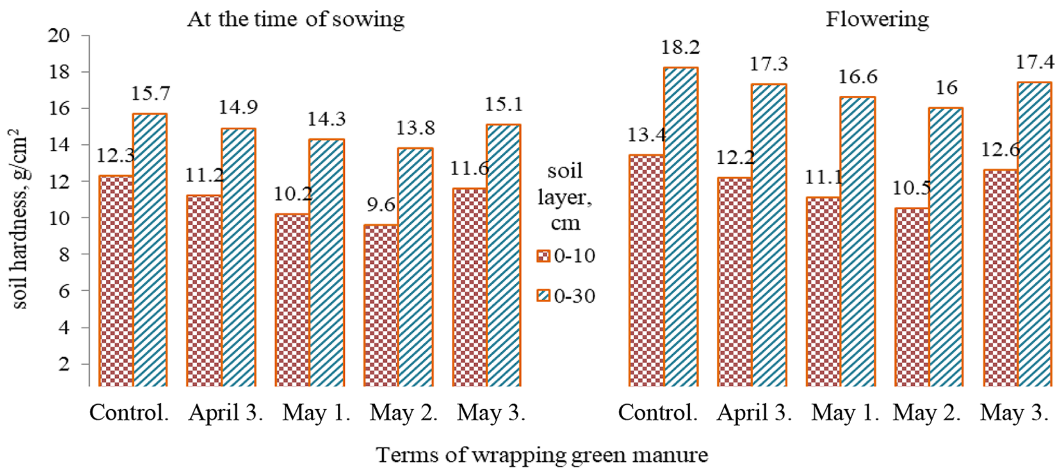

Figure 2. Dynamics of soil hardness during the mulching of winter rye green manure, kg/cm2

the field too long, it can excessively deplete moisture in the upper soil layers. This was observed when rye was incorporated in the third ten-day period of May: at the time of buckwheat sowing, productive moisture reserves in the 0–10 cm and 0–30 cm soil layers were the lowest, amounting to 6.7 mm and 35.1 mm, respectively (Figure 3).

A similar pattern of low moisture content was recorded at buckwheat flowering, resulting in delayed emergence and thinning of the crop.

In contrast, incorporation of rye 10 days before buckwheat sowing led to significantly higher reserves of productive moisture in both the 0–10 cm and 0–30 cm soil layers. At sowing, moisture levels were 12.4 mm and 39.6 mm, and at flowering – 9.3 mm and 35.2 mm, respectively. These values exceeded the control, where soil moisture at sowing was 11.2 mm (0–10 cm) and 43.4 mm (0–30 cm), and at flowering – 7.1 mm and 30.2 mm.

This result is explained by the mulching effect of the green biomass, which improves soil structure, protects the surface from overheating and evaporation, lowers compaction, and enhances water permeability contributing to more effective absorption of intense rainfall.

However, when winter rye was incorporated immediately before buckwheat sowing, the soil moisture was not sufficiently replenished. In this case, moisture content was only 6.7 mm and 6.4 mm in the 0–10 cm layer and 31.5 mm and 26.9 mm in the 0–30 cm layer at sowing and flowering, respectively.

Under unstable moisture conditions, soil water reserves directly determine the final seed yield of buckwheat (Figure 4).

In particular, better soil moisture conditions led to the formation of the highest buckwheat yield – 2.72 t ha^{-1}, observed after incorporation of winter rye in the second ten-day period of May.

Incorporation in the first ten-day period of May and third ten-day period of April resulted in slightly lower yields – 2.53 t ha^{-1} and 2.13 t ha^{-1},

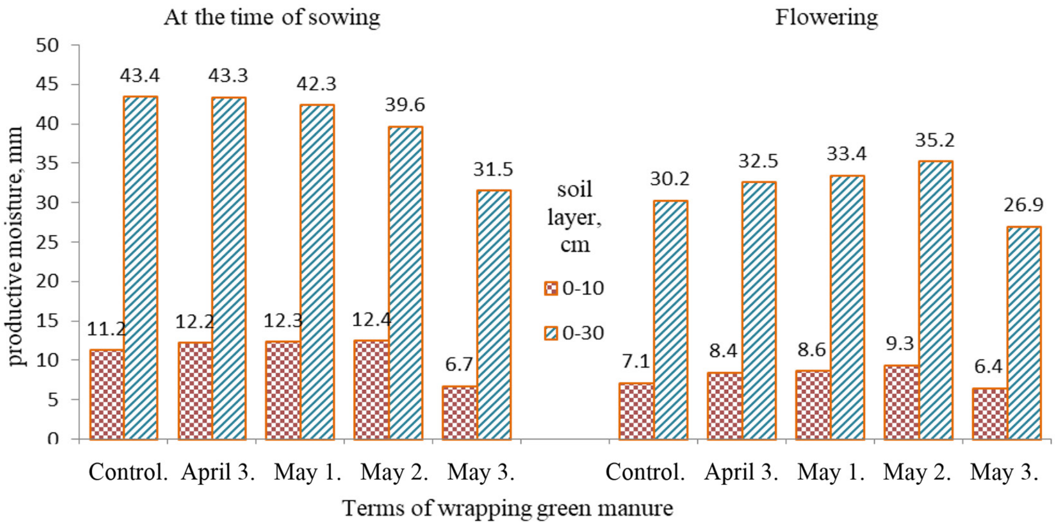

Figure 3. Dynamics of productive moisture when wrapping winter rye green manure, mm

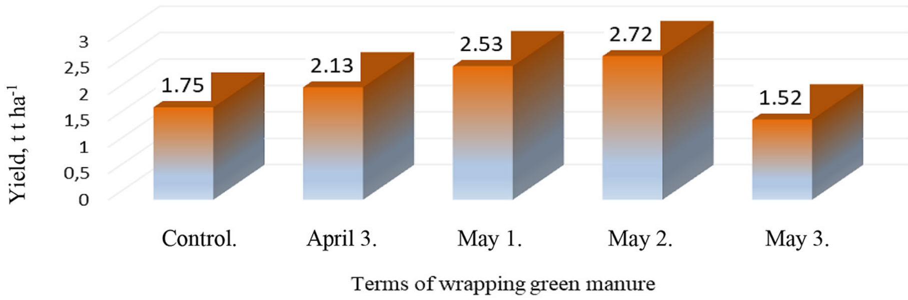

Figure 4. The effect of winter rye green manure on buckwheat yield, t ha^{-1}

respectively. Nevertheless, these yields were significantly higher than the control, which yielded only 1.75 t ha^{-1}.

The lowest buckwheat yield – 1.52 t ha^{-1} was obtained when winter rye was incorporated immediately before sowing (third ten-day period of May), which was even lower than in the control.

Inverse relationships were found between the level of buckwheat yield and soil density and hardness, and a direct relationship with the content of productive moisture (Figure 5).

Since soil hardness increases significantly with decreasing moisture content, this indicator had the closest influence with a high correlation strength on buckwheat yield – r = -0.82. A medium-strength relationship was established between buckwheat yield and productive moisture content – r = 0.6. Soil density had the least influence on buckwheat yield with a medium correlation strength r = -0.42.

The global need to increase agricultural production to ensure food security appears to contradict the urgency of reducing agriculture's negative impact on the environment [Lemaire et al., 2014; Oldfield et al., 2019]. The use of cover crops in agriculture allows for better regulation of biogeochemical cycles and reduces the leakage of substances into the atmosphere and hydrosphere. This approach contributes to a more diverse and structured landscape mosaic, which increases the flexibility of modern agricultural technologies in counteracting potential socio-economic and climate-related threats and crises.

The loss of organic matter in soils due to agricultural use significantly limits our ability to sustainably feed the growing global population and to mitigate climate change. According to statistics from 2018, an increase in the concentration of carbon dioxide and other greenhouse gases in the atmosphere has already led to a 1°C rise in global average temperature. Among anthropogenic sources, historical land use changes and conversion of natural ecosystems into agricultural land have been and remain major contributors

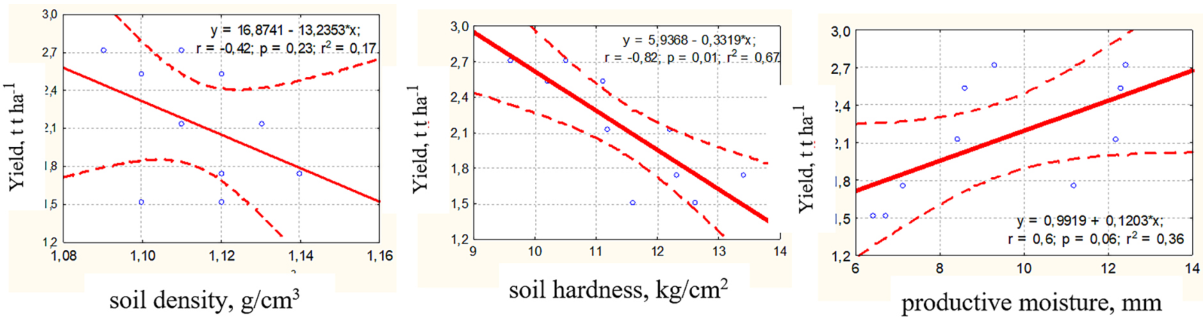

Figure 5. Dependence of buckwheat yield on the studied soil parameters

[Lal, 2020]. As such, new land use systems must offer win-win strategies that combine profitable food production with rapid improvement of soil quality, along with short-term climate change mitigation through carbon sequestration in soils [Machmuller et al., 2015; Tykhonova et al. 2021]. Winter cover crops possess significant potential for carbon biomass accumulation, which plays a vital role in enhancing soil fertility [Wang et al., 2012; Radchenko et al., 2022].

Cover crops used as green manure represent an effective management practice to increase organic carbon stocks in agricultural soils [Poeplau et al., 2014]. Their advantage over other carbon-enhancing strategies such as raw manure application is that they do not reduce crop yields or result in carbon losses elsewhere in the system.

The presence of cover crops greatly contributes to carbon retention in soil by increasing carbon inputs from the rhizosphere into the soil microbial community, leading to both enhanced microbial activity and long-term soil carbon storage [Lange et al., 2015; Mischenko et al., 2024].

Enriching the soil with organic carbon also stimulates mycorrhizal activity, which in turn improves the fertility parameters of soil – particularly soil structure. Improved structure leads to reduced soil compaction and hardness [Johnson et al., 2016; Datsko et al., 2025].

The activation of mycorrhizal mechanisms through cover cropping directly improves soil structure, and indirectly enhances the water-holding capacity of soil and increases crop resilience to environmental stressors [Johnson et al., 2016; Butenko et al., 2025].

In addition, the use of intermediate crops as green manure supports efficient absorption of short-term torrential rainfall, as their organic mass improves soil loosening and helps maintain this condition over time. Under such conditions, water is absorbed more effectively, higher reserves of productive moisture are formed, and summer droughts can be better tolerated by crops [Bunch et al., 2019; Kolisnyk et al., 2024].

Therefore, intensifying crop rotations with winter intermediate green manure crops provides an opportunity to optimize soil fertility parameters for buckwheat sowing.

CONCLUSIONS

The use of winter rye as green manure in organic farming provides multiple benefits: it enriches the soil with organic matter, improves its physical properties, and enhances the phytosanitary conditions for the succeeding crop, especially buckwheat.

The longer the rye grows before incorporation (up to the time of buckwheat sowing), the more green biomass it accumulates – up to 40 t ha^{-1}, and accordingly, the more atmospheric carbon it sequesters – up to 4.32 t ha^{-1}. However, under unstable moisture conditions, typical of the northeastern Forest-Steppe zone of Ukraine, it is crucial to avoid excessive soil drying caused by the green manure crop.

Termination of rye growth should consider not only the goal of maximizing biomass accumulation, but also the need to preserve sufficient soil moisture for the germination of the following crop. A lack of soil moisture can completely negate all the positive effects of green manuring.

Based on the research findings, for the northeastern Forest-Steppe of Ukraine, the most effective approach is to incorporate winter rye green manure 10 days before sowing buckwheat. This timing ensures the highest buckwheat seed yield – 2.72 t ha^{-1}, through optimized agrophysical soil properties and improved competitiveness of buckwheat against weeds.

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