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Assessment of the potential use of winter intermediate fodder crops for fodder production and carbon sequestration

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ABSTRACT

The article highlights the results of a comprehensive assessment of the productivity and sequestration potential of winter catch crops and post-harvest soybeans in the conditions of the Western Forest-Steppe of Ukraine. The study is aimed at substantiating the possibilities of increasing the efficiency of arable land use by obtaining two crops during the year and simultaneously reducing the concentration of carbon dioxide in the atmosphere. In the context of global climate change and increasing pressure on the agricultural sector, the search for agricultural technologies that can combine feed production with ecosystem services, in particular carbon absorption and accumulation, is of particular relevance. The sequestration potential of crops was assessed based on yield indicators and the yield of absolutely dry biomass, taking into account both above-ground and underground parts of plants. Field studies were conducted in 2022–2023 in the Ternopil region. It was established that the cultivation of hybrid winter rye Prokhas F1 in a system with post-harvest soybeans does not lead to a decrease in soybean productivity and provides a significant increase in the total yield of organic matter per unit area. The average yield of the above-ground mass of winter rye in terms of absolutely dry matter was 8.86 t/ha. Taking into account surface and root residues, the share of which for annual grasses was estimated at about 20% of the above-ground mass, the total yield of dry biomass reached 10.6 t/ha. This level of biological productivity indicates an intensive accumulation of organic matter and a high potential for binding atmospheric carbon. The results obtained confirm the feasibility of using winter catch crops as an important element of the adaptation of agricultural systems to climate change. Their implementation contributes to increasing the feed base, optimizing the use of the growing season, enriching the soil with organic matter, and enhancing carbon sequestration processes, which generally increases the ecological and economic sustainability of agroecosystems.

Keywords: intercrops, carbon sequestration, fodder production, rye, post-harvest soybeans.

INTRODUCTION

Among the many global problems of modern civilization identified by the United Nations (Kaletnik et al., 2020; FAO, 2023), climate change and provision of food for population have greatest impact on agricultural production. According to latest data from the Food and Agriculture Organization of the United Nations (FAO), in 2022, about 735 million people worldwide faced food insecurity, and it is projected that in 2030, almost 600 million people will be chronically undernourished (NASA, 2023; Pantsyreva et al., 2023; Palamarchuk, et. al., 2024; Tkachuk, et. al., 2025). In 2022, only 68.9% of world's population consumed daily food allowance, an insufficient amount of dietary energy to ensure maintenance of a normal, active and healthy life (Bakhmat et al., 2023). Another extremely important problem on a global scale is climate change, which has been observed for several decades. It is caused mainly by anthropogenic human activity, which leads to an increase in content of carbon dioxide in atmosphere.

Modern climate change is manifested primarily in the steady increase in average annual and seasonal air temperatures, as well as in significant spatial and temporal unevenness of precipitation both within individual regions and on a global scale

(Gurdeep et al., 2021). Such transformations of the climate system have a particularly significant impact on the agricultural sector, since agricultural production directly depends on meteorological conditions and is one of the most vulnerable to changes in weather factors. In this regard, agricultural producers around the world are faced with the need to adapt crop cultivation technologies to new climatic conditions, which includes revising sowing dates, selecting varieties and hybrids, and improving farming systems (Hetman et al., 2024; Hnatiuk et al., 2019). At the same time, increasing the temperature regime during the growing season carries not only potential risks, but also creates certain agronomic advantages. In particular, extending the period of active plant vegetation opens up opportunities for intensification of agriculture, including by obtaining two crops from the same area during the year (Honcharuk et al., 2024; Dubik et al., 2024). This approach allows for a more complete use of thermal resources and increasing the overall productivity of agricultural lands. One of the effective ways to realize this potential is the introduction of intermediate winter crops into crop rotations, which are grown in the autumn and early spring periods, with subsequent sowing of late spring crops after their harvest. Such crops include, in particular, soybeans, sunflowers and corn, which, under favorable conditions, are capable of forming a full-fledged harvest in the second half of the growing season (Jantke et al., 2020).

In addition to increasing the efficiency of using soil and climatic resources, the cultivation of intermediate agrocenoses is of important ecological importance. Such crops contribute to the reduction of carbon dioxide concentration in the atmosphere due to the processes of fixation and sequestration of carbon in plant biomass and soil (Kaletnik et al., 2025). In the conditions of Ukraine, the most common winter catch crops are winter rye and winter triticale, which are grown both in pure crops and in mixtures with Pannonian peas. Such agrocenoses are characterized by high adaptability, stable productivity and a positive impact on soil fertility (Razanova et al., 2025).

MATERIALS AND METHODS

The research was carried out in a production field experiment, established in the limited liability company «Agrarna marka» in the Ternopil district of the Ternopil region, during 2022–2023.

The field experiment included two variants of arable land use – with and without winter intercrops. Their fodder productivity and carbon dioxide sequestration were studied. Agrocenosis of hybrid winter rye KWS Prohas F1 was used as winter intermediate crops, after harvesting of which post-harvest soybeans of the Mentor variety were sown in phase of BBCH 37-39. Research was conducted on the Mentor variety, which was sown in traditional way and after harvesting intermediate agrocenosis. The experiment was replicated three times, with a plot size of 5 hectares.

Field research was conducted in accordance with generally accepted methods. The amount of sequestered carbon was calculated based on crop yields; ratio of aboveground and belowground parts of winter rye and soybean plants; and average carbon content in plant mass (47%).

RESULTS AND DISCUSSION

The conducted studies show that the combination of growing hybrid winter rye as an intermediate crop with post-harvest soybean is an effective agro-technological solution that provides a simultaneous increase in the productivity of arable land, the feed value of the obtained biomass and the ecological sustainability of agrocenoses. It was established that the use of hybrid winter rye does not lead to a significant decrease in the yield of post-harvest soybean, since the difference between the yield indicators of post-harvest and traditional soybean is within the limits of statistical error. This confirms the possibility of introducing intermediate crops without a negative impact on the main crop (Tkachuk et al., 2024).

At the same time, the use of hybrid winter rye allows you to significantly increase the total yield of feed products per unit area. Obtaining a significant amount of silage with a high content of crude protein provides an additional conditional yield of protein and increases the overall efficiency of land resource use. The total conditional yield of crude protein due to the cultivation of intermediate crops is significantly higher compared to the traditional technology of growing soybeans (Tkachuk et al., 2025; Didur et al., 2024).

An important result of the research is also the establishment of a significant ecological effect, which is manifested in the significant absorption of carbon dioxide by agrocenoses of hybrid winter rye and post-harvest soybeans. The total amount of

CO_2 sequestration in catch crops is several times higher than the corresponding indicator of traditional soybean cultivation technology, which is of particular importance in conditions of increasing greenhouse gas concentrations in the atmosphere. Thus, the introduction of catch winter agrocenoses in combination with post-harvest crops is a promising direction for adapting agriculture to climate change, which combines economic feasibility with a positive impact on the environment and requires further comprehensive research**.**

A characteristic feature of second half of twentieth and early twenty-first centuries is increase in temperature on a global scale (Figure 1).

This process began in late 70s and continues to this day, with a tendency for the temperature to rise further. In particular, 2023 was marked by largest upward deviation in temperature over the entire observation period, with the figure amounting to +1.17 °C. In addition, average global surface temperature in 2023 was highest on record since records began in 1880. Overall, in 2023, the Earth was about 1.36 °C warmer than in any period since end of the 19th century (1850–1900). The last 10 years have been the warmest on record (Nunes et al., 2023).

Global warming, along with negative impact on agricultural production manifested in growing aridity during growing season, creates preconditions for obtaining two crops per unit area by growing intermediate and post-cut crops. This is especially important for fodder industry, as it is possible to use fodder crop rotations more efficiently, as well as field crop rotations. This increases yield of raw materials for feed preparation and creates prerequisites for reducing shortage of feed protein for animals (Table 1).

Our research has shown that growing hybrid winter rye as an intercrop does not reduce yield of post-harvest soybeans by 5%, which is statistically proven, compared to its traditional cultivation in main crop. Thus, on average, in 2023–2024, yield of post-harvest soybeans was 2.83 t/ha, and yield of soybeans grown using traditional technology was 3.11 t/ha. The difference in yields of 0.17 t/ha is within statistical error.

The crude protein content in soybean seeds was also at the same level of 38.6–38.9%, and its conditional yield was 1.21–1.13 t/ha.

However, by growing a hybrid winter rye as an intermediate crop, 1 hectare of arable land can yield 13.3 t/ha of silage with a crude protein content of 16.7% in dry matter, which ensures a conditional yield of 1.42 t/ha.

In general, due to cultivation of hybrid and post-harvest soybeans as an intercrop of winter rye, it is possible to provide a conditional yield of crude protein at level of 2.55 t/ha. The rise in temperature on a global scale is inextricably linked to increase in carbon dioxide in atmosphere, as carbon dioxide is one of greenhouse gases that cause global warming (Maslinov et al., 2018).

According to researchers, since the mid-18th century, human activity has increased atmospheric CO_2 by 50%, meaning that amount of CO_2 is now 150% of its value in 1750 (Mazur et al., 2020; Mazur et al., 2021; Petrychenko, et. al., 2024; Novgorodska, et. al., 2025).

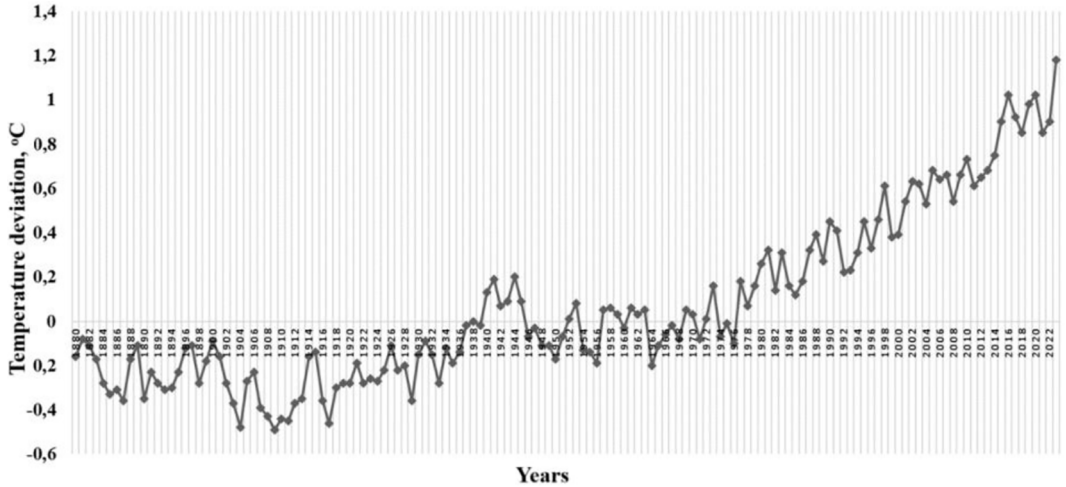

Figure 1. The Earth temperature changes (according to NASA) compared to the time period 1951–1980 (Global Temperature, 2023)

Table 1. Main indicators of arable land productivity in cultivation of intermediate and post-cut crops

Indicators	Culture								
	Soybeans (main crop)			Soybeans (post-cutting crop)			Winter rye Prohas F1 for silage (winter intermediate crop), dry matter content in silage mass 30%		
	years								
	2023	2024	Average for 2023–2024	2023	2024	Average for 2023–2024	2023	2024	Average for 2023–2024.
Main product yield, t/ha	3.25	2.96	3.11	3.05	2.83	2.94	14.0	12.7	13.3
Crude protein content, %	39.2	38.5	38.9	39.0	38.1	38.6	16.5	16.9	16.7
Conditional crude protein yield, t/ha	1.27	1.14	1.21	1.19	1.08	1.13	1.46	1.37	1.42
HIP_{05}, t/ha soybean seeds	2023: 0.27 t/ha; 2024: 0.18 t/ha								

Our analysis of the information base indicates that from 1958 to 2023, CO_2 content in atmosphere increased by 105.9 ppm or 33.6% (Figure 2).

Such disappointing dynamics significantly exacerbates already extremely urgent problem of climate change and threat it poses to agricultural production and food security. At same time, agricultural ecosystems are capable of accumulating a significant amount of carbon, which can be up to 1 Gt/year on a global scale (Mirzabaev et al., 2022; Mazur et al., 2022; Tkach et al., 2024).

According to the Carbon Cycle Institute, among various spheres of human activity, agricultural production has greatest potential for carbon dioxide sequestration. Annual intermediate crops play a special role in this regard. They assimilate atmospheric carbon into aboveground and underground organs, help mitigate effects of global warming, and improve soil fertility and fodder base for livestock (Pantsyreva et al., 2024; Solona et al., 2025). As part of the research, the volume of carbon dioxide absorption from the atmospheric air by winter catch crops and post-harvest soybeans was calculated under the conditions of their cultivation in the Western Forest-Steppe zone (Table 2). The sequestration potential was assessed based on yield and dry biomass yield indicators, taking into account both aboveground and underground parts of plants.

It was established that the average yield of the winter rye hybrid Prokhas F1 for 2022–2023 in terms of absolute dry matter of the aboveground mass was 8.86 t/ha. At the same time, for a more complete assessment of the biological productivity of the agrocenosis, the proportion of surface and root residues was taken into account, which for annual grasses is usually about 0.2 of the yield of the aboveground mass. Taking into account this indicator, the total yield of absolutely dry plant biomass of hybrid winter rye reached 10.6 t/ha.

The obtained values indicate a high intensity of organic matter accumulation in agrocenoses of hybrid winter rye, which determines its significant potential for binding atmospheric carbon.

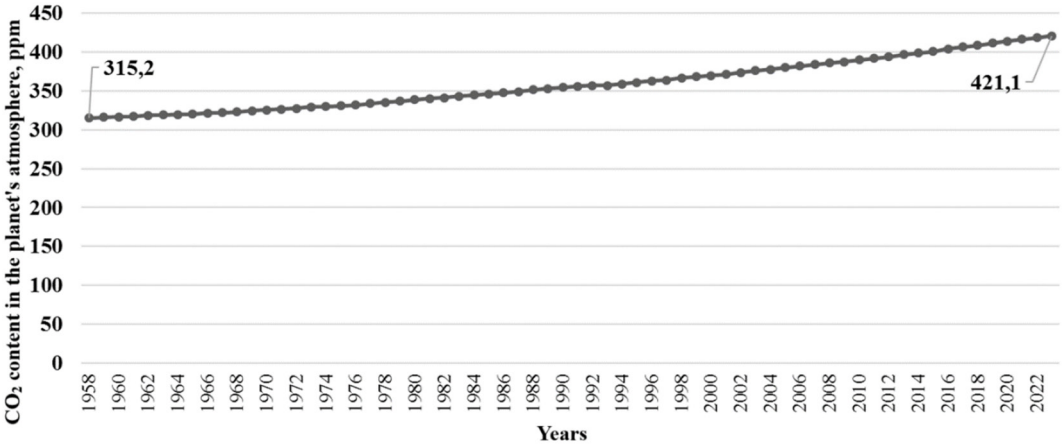

Figure 2. Dynamics of CO_2 content in atmosphere

Table 2. Main indicators of carbon dioxide sequestration by crops

Indicators	Hybrid rye Prohas F1	Post-cutting soybeans	Total	Soybeans of traditional sowing
Yields of main products, t/ha	8.86	2.94		3.11
Surface and root residue yields	0.20	1.40		1.40
Total biomass yield, t/ha	10.6	4.12		4.35
Carbon content in biomass, %	47.0	47.0		47.0
Amount of carbon sequestered, t/ha	5.00	1.93		2.05
Conversion factor from C to CO_2	3.70	3.70		3.70
Amount of sequestered carbon dioxide, t/ha	18.5	7.20	25.7	7.57

The formation of such an amount of biomass creates the prerequisites not only for increasing the productivity of agroecosystems, but also for more effective sequestration of carbon dioxide, which is especially relevant in the conditions of modern climate change. In addition, the inclusion of root and crop residues in the calculations allows a more objective assessment of the role of intermediate winter crops in the processes of carbon accumulation in the soil and stabilization of its organic part.

Assuming that the average carbon content in plant biomass is 47.0%, the potential for carbon sequestration by the studied agrocenoses was assessed. Calculations showed that agrocenoses of hybrid winter rye are capable of accumulating about 5.0 t/ha of organic carbon in aboveground biomass. Taking into account the molecular ratio between carbon and carbon dioxide, this indicator corresponds to the absorption of approximately 18.5 t/ha of CO_2, which indicates the high potential of this crop to reduce the concentration of greenhouse gases in the atmosphere.

Similar calculations were carried out for post-harvest soybean crops. With an average seed yield of 2.94 t/ha, the total dry biomass yield of soybean agrocenoses was 4.12 t/ha. This amount of biomass accumulated about 1.93 t/ha of carbon, which in terms of carbon dioxide equivalent is 7.2 t/ha of CO_2. Thus, even during a shortened growing season, post-harvest soybean crops demonstrate a significant ability to fix atmospheric carbon.

A comprehensive analysis of the data obtained showed that winter intermediate agrocenoses of hybrid rye in combination with post-harvest soybeans provide a total amount of carbon dioxide absorption at the level of 25.7 t/ha. This indicator significantly exceeds the level of CO_2 sequestration under traditional soybean growing technology in the main crop.

Under the conditions of classical soybean growing technology, the average seed yield was 3.11 t/ha, which corresponded to the formation of 4.35 t/ha of absolutely dry biomass. Such crops provided the accumulation of about 2.0 t/ha of organic carbon, which is equivalent to 7.57 t/ha of carbon dioxide. Comparative analysis confirms that the use of intermediate winter agrocenoses significantly increases the overall level of carbon sequestration per unit area and is a promising tool for reducing anthropogenic impact on the climate.

CONCLUSIONS

Based on results of research, cultivation of soybeans and hybrid winter rye as an intercrop is effective in terms of obtaining more high-quality feed, total biomass and carbon dioxide sequestration. This suggests that such crops are effective from both an environmental and economic point of view, which requires further research in this area. Based on the experimental data obtained, it was established that the introduction of hybrid winter rye as an intermediate crop in combination with post-harvest soybean is an effective agrotechnological technique that ensures more rational use of arable land without significantly reducing the productivity of the main crop. According to the results of research in 2023-2024, the average yield of post-harvest soybean was 2.83 t/ha, while under traditional cultivation technology – 3.11 t/ha. The difference in yield of 0.17 t/ha was within the statistical error, which confirms the absence of a negative impact of intermediate crops of hybrid winter rye on the formation of soybean yield. At the same time, the cultivation of hybrid winter rye provided an additional 13.3 t/ha of silage mass with a crude protein content of 16.7% in dry matter, which corresponded to a conditional protein yield of 1.42 t/ha. Together

with the yield of post-harvest soybeans, the total conditional yield of crude protein reached 2.55 t/ha, which significantly exceeds the indicators of the traditional technology of soybean cultivation and indicates an increase in the feed value of agrocenoses. The results also confirm the high ecological potential of the studied technology. Agrocenoses of hybrid winter rye accumulated about 5.0 t/ha of carbon, which is equivalent to 18.5 t/ha of CO_2, while post-harvest soybean crops provided additional absorption of 7.2 t/ha of CO_2. The total amount of carbon dioxide sequestration by intermediate winter agrocenoses was 25.7 t/ha, which is several times higher than the indicator of traditional soybean crops (7.57 t/ha of CO_2).

Thus, the results of our research prove the feasibility of using hybrid winter rye as an intermediate crop in modern agricultural systems, since such technology combines stable productivity, increased feed potential, and a significant contribution to reducing anthropogenic pressure on the climate.

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