Niche grain production as a diversification strategy for sustainability and risk resilience: evidence from Ukraine

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Citation:
Style APA
Vasylieva, N., & Nazarenko, D. (2026). Niche grain production as a diversification strategy for sustainability and risk resilience: evidence from Ukraine. *Agricultural and Resource Economics*, 12(2), 26–46. https://doi.org/10.51599/are.2026.12.02.02

Ukrainian style
Vasylieva N., Nazarenko D. Niche grain production as a diversification strategy for sustainability and risk resilience: evidence from Ukraine. *Agricultural and Resource Economics*. 2026. Vol. 12. No. 2. Pp. 26–46. https://doi.org/10.51599/are.2026.12.02.02

Purpose. *Grain crops play a pivotal role in providing global food security. The goal of this study is to assess the diversification level in production of niche grain crops and develop models to clarify its patterns focusing specifically on Ukrainian agriculture as it navigates through the unprecedented crisis caused by the Russian military invasion.*

Methodology. *The methodological framework of the research includes methods of comparative analysis, cluster modelling, and optimisation theory. The examined statistical data for 2019–2025 were retrieved from official websites and reliable online sources. This approach underpins substantiated recommendations on how niche grain production can remain resilient in times of turbulence and shocks.*

Results. *The article findings highlight that, owing to exceptional environmental and economic advantages, the production of buckwheat, millet, oats, and rye complies with the principles of green and circular economies, reducing waste, dependence on chemical inputs, and and requirements for of natural resource quality. Balanced diversification of niche grain crops results in higher adaptability to climatic patterns and pricing uncertainty, as observed in Ukraine during wartime. Optimisation models of regional clusters and scenario analysis suggest workable management approaches to develop sustainable and highly beneficial cultivation strategies.*

Originality. *The novelty of the work lies in the mathematical integration of production indicators (volumes and harvested areas) with market and environmental dynamics (prices and yields), which together uncover untapped potential for fostering diversified cultivation of niche grain crops in unstable natural and market environments.*

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Practical implications. *The major practical value of the research outcomes stems from the fact that the development of niche grain crop production can provide nutritious healthy food, enhance biodiversity, improve soil parameters, shorten supply chains, and empower smallholder farmers to remain competitive regardless of risks and external pressure.*

Key words: *sustainable development, niche crops, resilience in agriculture, biodiversity, circular and green economies, model of cluster diversification, model of scenario analysis.*

JEL-Classification: *O13, Q13, Q56*

1. INTRODUCTION

Grain production is a crucial factor in ensuring food security on a global scale. Cereal crops are used for food, animal feed and biofuel production. Consequently, there is a steady increase in global demand for grain. However, stable grain production is a multifaceted problem as there are numerous risks that prevent high yields and profits. The most significant issues stem from climate risks related to drought, floods, freezing, biological threats from the outbreaks of plant diseases and the infestations of crop pests. Other detrimental economic risks are manifested through rising costs of fertilisers, plant protection products, fuel and other resources, risks of post-harvest losses, price fluctuations in grain markets, which endanger farmers' incomes. Collectively, these factors complicate the maintenance of consistent yields and profitability. Hence, risk management strategies have become critical, particularly the diversification of crop cultivation to alleviate monoculture dependence.

The authors define "niche grain crops" as cereals that do not dominate the market in terms of production volumes and harvested areas, yet maintain high recognition and stable demand within specific market segments. For Ukraine, buckwheat, millet, oats, and rye were selected due to their high strategic potential. Furthermore, the term "niche" is intentionally preferred over "minor". While "minor" merely reflects a smaller statistical scale of cultivation, "niche" emphasises the value of crops for specific consumer groups and types of agricultural entities.

Despite having much smaller production volumes than major crops such as wheat, maize, rice, and barley, niche grain crops are of global significance. This is caused by a number of economic, environmental, and social aspects that explain the high interest in growing and trading minor grains. Firstly, they are distinguished by their unique nutritional value, contribute to the diversification of food supply, are better adapted to different climates and require fewer resources. Secondly, another strong economic benefit of niche crops is their high profitability and export demand. They also serve as a buffer against the volatile market conditions typical of main cash grains, providing greater resilience and stability in farming. Thirdly, the environmental advantages of niche grain crops are manifested through improved crop rotation, soil health, and biodiversity. Ultimately, niche crops are usually more profitable compared to traditional cereals, which makes them economically attractive for small and medium-sized farms and will have a positive impact on the well-being in rural areas.

Therefore, niche crops are a vital element in achieving the desired balance between the economic, social and environmental components for the introduction of sustainable agriculture. Sustainable development draws on circular and green

economies aimed at replacing the traditional linear model that follows the "take, make, and dispose" principle. In contrast, circular economy is mainly based on the 3R principle, which focuses on "reduce, reuse, and recycle". A green economy pursues an eco-friendly intensification of production. In other words, the imperative of circular and green economies is to mitigate waste and alleviate environmental impacts [1; 2]. This approach is widely promoted to advance agriculture. Green and circular economies are the focus of many modern scholars including those from the most populous countries such as India, China, and the USA. In this context, scientists face the critical task of reconciling the rapid growth in demand for food with the global concerns over environmental degradation, resource depletion, and the threat of climate change [3; 4]. The need to transition to these eco-friendly economic models shaped the topic of the scientific research presented in this article that considers the role of niche grains in the implementation of sustainable farming.

The purpose of the study is to assess the diversification level in production of niche grain crops and develop models to clarify its patterns focusing specifically on Ukrainian agriculture as it navigates through the unprecedented crisis caused by the Russian military invasion. The strategic concept underlying this study is based on production diversification through the expanded cultivation of various niche grain crops. In this framework, diversification is interpreted as the optimisation of the cropping structure by integrating a balanced mix of niche grains (buckwheat, millet, oats, and rye). This approach serves as a stabilising element for sustainable development and resilience, especially for small and medium-sized farms. In line with this purpose, the research is structured around three tasks, namely:

(1) to assess the level of global diversification of niche grain crop production;

(2) to clarify and model regional specialisation in the cultivation of buckwheat, millet, oats, and rye in Ukraine;

(3) to determine optimal proportions of growing niche grain crops to increase their resilience to inherent climatic and market risks.

2. LITERATURE REVIEW

There is growing concern and interest in the development of sustainable agriculture that has enormous potential to increase yields, meet people's demands for more food, improve product quality, conserve resources and reduce energy consumed in farming [5]. A. Mana et al. noted that modern agriculture prioritises productivity and profitability over environmental limitations and long-term sustainability. This challenge can be addressed by deploying robots, drones, the Internet of Things, and integrating smart AI-driven technologies in different agricultural operations ranging from real-time monitoring of crop growing to controlled harvesting [6].

A. Barman et al. ranked crop diversification as the most powerful approach to sustainable agriculture development complicated by rapid urbanisation. The identified diversification benefits major encompassed nutritional benefits for customers, sound export prospects, income growth, employment generation, poverty alleviation, risk mitigation, stronger resilience and stability of the production systems, and the

availability of innovative agricultural technologies [7]. T. Mihrete and F. Mihretu investigated crop biodiversity, which is being displaced by monoculture farming when one crop is cultivated over extensive areas. By adopting spatial, temporal, genetic, and intercropping diversification strategies, farmers can enhance soil health, improve pest management, boost resilience to climate variability, distribute risks, stabilise revenues, ensure flexible supply chains and markets adapted to global shocks such as pandemics, extreme weather events, or geopolitical crises. The study revealed that crop diversification is an imperative viable strategy in the context of reinforcing food security. However, knowledge gaps and existing open questions impede successful crop diversification, which requires a deep understanding of crop selection and advanced management practices [8].

A considerable number of scientific studies explored how to elevate the efficiency of niche crop production. Recently, I. Bezhenar and H. Skyba highlighted that the cultivation of niche grains, oilseeds, vegetable, berry and medicinal plants is a promising direction of diversified farming. These crops are advantageous since they can be grown on small plots, are eco-friendly and quite profitable. However, they are more labour-intensive and demand for them can be unpredictable. Hence, niche crop growers need additional support from the government bodies, investors, and stakeholders [9]. K. Prokopenko and L. Udova argue that in crisis economic conditions, Ukrainian farmers should amplify their economic sustainability by diversifying the cultivation of grains, legumes, and oilseeds. This approach could become a primary strategy for the post-war restoration of Ukrainian agriculture [10].

Other scientists focused their studies on the fact that grain crops, particularly cereals, are rich in protein nutrients, and calories. That is why they are widely used for direct human consumption in the developing countries and are extremely important for the developed countries which use cereals to feed their livestock [11; 12]. L. Gazza and F. Nocente emphasised that agricultural intensification through increased application of fertilisers and pesticides, farmland expansion, and cultivation of only a few selected grain crops, such as wheat, rice, and maize, has caused biodiversity loss and profound negative impacts on the global ecosystem [13]. At the same time, minor cereals have proven their inherent ability to withstand adverse climatic conditions and grow under low-input cultivation management on marginal lands. Thus, they have a less negative effect on the environment. Owing to the rising demand for healthy, sustainably produced food packed with proteins, vitamins, minerals, fibre, and antioxidant compounds, minor cereals are regaining prominence among scholars, farmers, stakeholders, and consumers.

Scientific research on production and trade for niche grain crops is widely published worldwide. The most investigated and demanded niche grain crops in global markets are buckwheat, millet, oats, and rye. A comprehensive review by Y. Gao et al. sheds light on contemporary findings of scholars from China, Japan, Poland, the USA, and South Korea related to the economic potential and environmental benefits of growing buckwheat [14]. Other researchers identified the effects of the dynamic interaction between climate change, soil quality, and biological stressors that affect rye

yield and, respectively, its harvest, profitability and contribution to food security [15]. Oats production is increasing due to unique nutritional properties and new processing methods, which ensure a high-quality product and make it an appealing source of plant-based protein [16]. J. Joshi et al. identified millet as a competitive versatile niche crop because it is exceptionally resistant to natural stresses, has a short growing season, and can be cultivated in adverse drought conditions on saline soils with minimal irrigation [17].

In general, the publications reviewed do not suggest abandoning traditional staple grain crops. Rather, they substantiate that diversified grain production is a promising strategy to enhance revenues and advance the implementation of sustainable agriculture. The aforementioned factors established the rationale for the current research. Its distinctive feature is the use of mathematical methods to evaluate and optimise the diversification of niche grain crops, taking into account the modern realities of the dynamic business environment and the emerging challenges associated with climate change.

The research hypothesis posits that the mathematical integration of production metrics (volumes and areas) with market and environmental dynamics (prices and yields) via cluster optimisation and economic scenario analysis can uncover untapped regional potential for diversifying grain crops production, allowing farms to maximise profitability while minimising exposure to natural and market risks. This integration reveals untapped potential by shifting the focus from isolated farm metrics to an interconnected ecosystem approach. Mathematically, tracking these indicators simultaneously allows the models to identify regions where high yield stability aligns with favourable price dynamics, mapping out optimal production clusters that are currently underutilised.

3. METHODOLOGY

The methodological basis of the performed study included methods of comparative analyses and optimisation theory. The corresponding calculations were performed in free software such as Google Sheets and PSPP.

The analysed statistical data for 2019–2025 was retrieved from official websites and reliable online sources [18; 19]. The selected timeframe covered the crisis period of Ukrainian farming exacerbated by the Covid-19 pandemic in 2020–2021 and the Russian military invasion of Ukraine, which began in 2022.

In accordance with the study plan, the *first research task* started by assessing the current diversification in global niche grain crop market. Initial data for this were the number of countries producing (*NCP*), exporting (*NCE*), and importing (*NCI*) buckwheat, millet, oats, and rye. Calculated indicators were obtained using the formulas:

$$EP = NCE/NCP,\ IP = NCI/NCP, IE = NCI/NCE, \quad (1)$$

where *EP* described how trade-oriented the relevant market is, *IP* clarified how open or closed it is, and *EI* measured trade concentration and diversification.

Then the study continued by estimating how diversified the cultivation of niche

grain crops was in pressing times of the Covid-19 pandemic (as of 2021) and during the Russian-Ukrainian war (as of 2024). This was implemented by comparing the relative shares of the global and Ukrainian production of buckwheat, millet, oats, and rye. The level of imbalance (ΔD, p.p.) between the actual (Dj) and desired 25% shares of production of the j-th crop, $j=1,\ldots,4$, was assessed by the formula:

$$\Delta D = \sum_{j=1,\ldots,4} |Dj - 25|. \quad (2)$$

The *second research task* examined regional specialisation in Ukraine to define clusters with similar diversification patterns of niche grain crops. By switching to ranks we were able to identify relative cultivation preferences across the regions considering harvested areas of buckwheat, millet, oats, and rye in 2025. The general concept of the offered cluster optimisation model was as follows. The model operated with rank indicators Xnk assigned to each of N regions by each of $K=4$ crops, $n=1,\ldots,N$, $k=1,\ldots,K$. Each of M clusters was represented by its centre, described by sought variables Cmk, $m=1,\ldots,M$, $k=1,\ldots,K$. The objective function of the model was defined by the formula:

$$\sum_{n=1,\ldots,N} min_{m=1,\ldots,M}\left(\sum_{k=1,\ldots,K}(Xnk - Cmk)^2\right) \rightarrow min. \quad (3)$$

Arguments of the calculated minima allocated regions to their optimal clusters such as:

$$m(n) = argmin_{m=1,\ldots,M}\left(\sum_{k=1,\ldots,K}(Xnk - Cmk)^2\right),\ n=1,\ldots,N. \quad (4)$$

This approach made it possible to reveal regional segmentation through diversification of niche grain crops that will foster sustainable development via tackling similar issues and sharing applicable positive practices.

The *third research task* was represented by an optimisation model based on the productivity and profitability of niche grain crops. These two factors cause essential uncertainty in production outcomes [20]. This aspect was analysed by means of coefficients of variation, which were used to compare the price and yield volatility of the crops in question, as well as their combined impact on the farmers' revenue. In particular, the coefficients of variation (CV) were calculated by the formula

$$CV = 100 \cdot StDev/Mean, \quad (5)$$

where $StDev$ and $Mean$ denoted the standard deviation and mean value of the considered data sample.

Sustainable diversification implied that the model takes into account environmental and economic factors in the production of niche grain crops. The model analysis covered $S=5$ annual scenarios for 2019–2023 including the crisis period of the Covid-19 pandemic in 2020–2021 as well as wartime in 2022–2023, for which the official statistics were available. The model parameters included crop yields and farmers' prices that have an imminent impact on agricultural revenues in difficult times [21]. The sought $I=4$ non-negative variables $Y1$, $Y2$, $Y3$, and $Y4$ referred to the shares of buckwheat, millet, oats, and rye cultivation, where:

$$\sum_{i=1,\ldots,I} Yi = 1. \quad (6)$$

The minimal feasible shares of the harvested areas of buckwheat (*F1*), millet (*F2*), oats (*F3*), and rye (*F4*) imposed the following restrictions:

$$Yi \geq Fi, i = 1, \ldots, I. \quad (7)$$

Ris was the total revenue per ha from the *i*-th crop concerted with the *s*-th scenario, *i=1,…,I, s=1,…,S.* The constraints, linked to the gross revenue per ha under the *s*-th scenario ($GRHs$), were calculated by the formula:

$$GRHs = \sum_{i=1,\ldots,I} Ris \cdot Fi \geq GRH, \; s=1,\ldots,S, \quad (8)$$

where *GRH* denoted the guaranteed gross revenue per ha.

The objective function (9) intended to provide the maximal possible gross revenue per ha under the worst-case scenario for 2019–2023:

$$GRH \rightarrow max. \quad (9)$$

General scenario analysis drew on the relative deviations of the gross revenue by annual scenario ($\Delta GRHs$), which were estimated by the formula:

$$\Delta GRHs = 100 \cdot (GRHs - GRH)/GRH, \; s=1,\ldots,S. \quad (10)$$

All of the above theoretical approaches have been implemented in calculations, practical interpretations, and recommendations presented in the following sections.

4. RESULTS

4.1. Assessment and analysis of global diversification of niche grain crops production

Crisis conditions can be addressed through the concept of resilience. It combines the most effective strategies to manage risks, integrating three core dimensions: robustness, adaptability, and transformability. Within the context of agriculture, resilience serves as a tool that enables farms to recover and evolve amid internal and external shocks. Robustness ensures stability against minor disruptions without altering core operations. Adaptability is applicable to the case of moderate challenges and suggests enhancing technologies and supply chains. Transformability empowers the farm to reinvent its entire system and set new objectives. Being resilient suggests being diversified enough to survive and thrive regardless of challenges [22; 23].

Globally, the combined harvested areas of the selected niche grain crops in 2024 were 4.9 and 4.7 times smaller than those of wheat and maize, respectively. Similar indicators in Ukraine were 11.5 and 9.5, signalling substantial untapped potential for promoting diversified production in Ukrainian farming. The main features of the diversification observed in niche grain markets are revealed in Table 1. According to *NCP*, millet and oats markets were the most numerous and globally distributed. That is why they are the most protected from any disturbances and collapses. The buckwheat market was highly localised in 19 countries. Consequently, it was exposed to substantial risks associated with dependency on limited producers. According to the *NCE*, the largest export diversification by country was found for millet, whereas oats and buckwheat were ranked in the middle. Rye exporters were the least diversified. Coefficients *EP>1*, calculated by formula (1), show that buckwheat, millet, and oats

markets are trade-oriented and characterised by a tendency to re-export processed products. On the other hand, owing to *EP <1*, it can be concluded that a significant part of farmers in those countries cultivate rye exclusively for domestic consumption.

Table 1

Diversification of niche grain markets by country, 2024

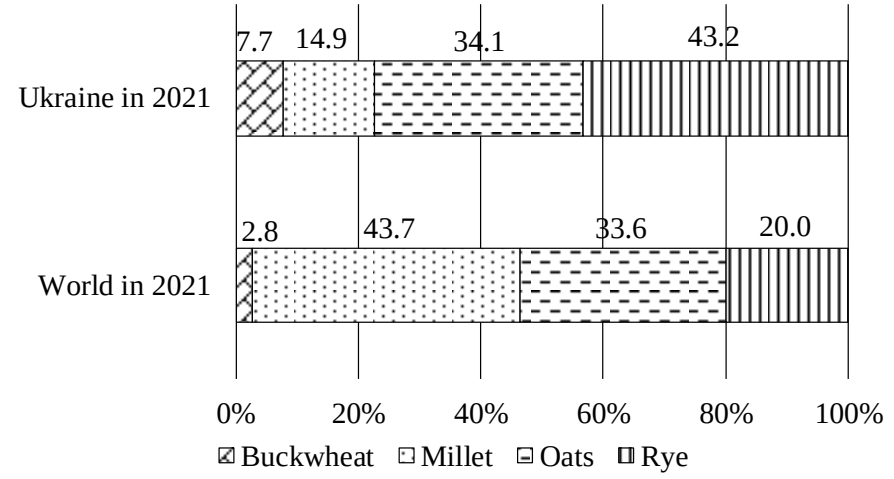
Indicator	Buckwheat	Millet	Oats	Rye
NCP	19	74	74	62
NCE	69	92	80	53
NCI	118	148	148	77
EP	3.6	1.2	1.1	0.9
IP	6.2	2.0	2.0	1.2
IE	1.7	1.6	1.9	1.5

Source: authors' calculations based on data from [19].

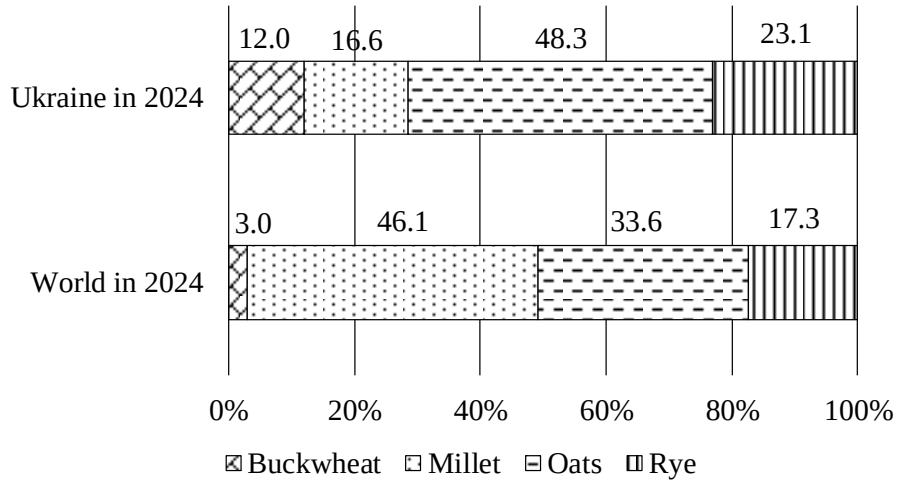
Driven by the growing number of health-conscious consumers, particularly in Europe and North America, the *NCI* indicated the highest level of diversification among millet and oat importers. However, due to the diversified producers, their corresponding *IP* is average, indicating reasonable load for the countries that grow these crops. In the case of buckwheat, the situation is the opposite, for which an extremely high level of *IP* puts supply chains and product availability at risk. Meanwhile, in terms of relative parameters, the buckwheat market is the most open to international trade. The lowest *NCI* and *IP* for rye emphasise that it is less popular than the other niche grains. Therefore, in terms of relative parameters, the rye market is the most closed regarding international trade. Moderate values of *IE* suggest that all the markets considered are equally balanced by the proportion between importing and exporting countries. A more detailed analysis reveals that relationships between exporters and importers are the most diversified for oats**,** moderate for both buckwheat and millet, and the least diversified for rye.

Diversified cultivation of niche grains is advantageous as it allows farmers to balance drawbacks and use benefits typical of separate crops. In addition to the clarified market features, various crops can have different environmental and economic resilience depending on certain farming conditions [24]. Encouraging crop diversification is a consistent step towards preventing the loss of biodiversity which is a corner stone of a green economy [25]. In this regard, the first task findings of our study compared the level of diversification of niche grain crops globally and within Ukraine (Figure 1).

Figure 1, *a* illustrates that biodiversity of the considered niche grain crops was relatively similar in the world and in Ukraine with the imbalance level ΔD (2) of 54.5 p.p. and 54.7 p.p. in 2021, correspondingly. In 2024, as displayed in Figure 1, *b*, the global level of diversification imbalance rose to 59.4 p.p. owing to the prevalence of millet and the neglect of buckwheat. Such proportions are explained by significant benefits of millet and oats which are widely consumed as healthy staple food and also used for feeding animals. Besides, millet is renowned for its tolerance of extreme drought and heat, while oats are resistant to cool weather conditions and excessive moisture.



a)



b)

Figure 1. Diversification of niche grain production volumes in 2021 (a) and 2024 (b)

Source: authors' calculations based on data from [18; 19].

In contrast, given the challenges of wartime in 2024, Ukrainian farmers demonstrated a strong resilient transformation with an improvement in the level of imbalance ΔD (2) that dropped to 46.6 p.p. (see Figure 1, *b*). It defines farming productivity as an interplay between inputs, uncontrolled climatic challenges, and the farmer's conscious choice to provide the local population with a variety of food products derived from nutritious buckwheat, millet, oats, and rye. Buckwheat and rye serve as the backbone of domestic food security and cultural identity, exhibiting a much higher domestic prominence than observed on the global market. This Ukrainian phenomenon stems from the fact that buckwheat is not just healthy gluten-free product, but a conventional staple food. Similarly, mixed-grain rye bread is in demand in Ukraine due to traditional eating habits.

4.2. Modelling regional specialisation in the cultivation of niche grain crops in Ukraine

The study results related to the second research task had the following

assumptions. Given the current wartime risks of Russian invasion of Ukraine and lack of complete statistics, we set the number of regions *N*, which were able to cultivate niche grain crops in 2025, to 20, excluding Donetsk, Kherson, Luhansk, Zaporizhzhya regions. Regional priorities of growing niche grain crops in question are given in Table 2. These proportions are attributed to the variety of agro-climatic zones in Ukraine. In particular, the northern regions of the Polissia are characterised by cooler temperatures, higher humidity and special soil that are favourable for growing rye and oats. The central regions of the Forest-Steppe are beneficial for producing buckwheat that is dependent on fertile black soil, moderate heat, and humidity. The southern regions in the Steppe are suitable for the cultivation of millet which thrives in high heat and is drought-resistant.

Table 2

Shares of harvested areas (in %) under niche grain crops in Ukraine, 2025

Region	Buckwheat	Millet	Oats	Rye
Cherkasy	14.7	20.6	20.6	44.1
Chernihiv	8.1	8.7	56.5	26.7
Chernivtsi	8.3	8.3	66.7	16.7
Dnipropetrovsk	8.1	50.0	25.7	16.2
Ivano–Frankivsk	11.3	1.6	62.9	24.2
Kharkiv	15.0	40.7	31.0	13.3
Khmelnytskiy	54.5	1.1	26.1	18.2
Kirovohrad	18.8	56.3	9.4	15.6
Kyiv	19.7	11.2	33.1	36.0
Lviv	7.9	0.6	75.8	15.7
Mikolayiv	28.0	44.0	8.0	20.0
Odesa	6.0	62.0	28.0	4.0
Poltava	10.5	33.7	22.1	33.7
Rivne	26.5	0.7	43.8	29.0
Sumy	23.8	10.0	49.4	16.9
Ternopil	42.4	1.2	52.9	3.5
Vinnytsya	58.9	13.7	11.0	16.4
Volyn	3.6	1.0	65.0	30.3
Zakarpattya	28.1	5.3	52.9	13.7
Zhytomyr	14.7	20.6	20.6	44.1

Source: authors' calculations based on data from [18].

According to the empirical rule of thumb, the number of clusters *M* was 3, which is approximately equal to the square root of half of the regions under consideration. The results of model calculations using formulas (3)–(4) are presented in Table 3.

It comprises regions collected in the found optimal clusters, which are identified by their optimal centres. Namely, cluster 1 is the least numerous, uniting farmers from 3 regions that prioritise growing buckwheat and millet, while oats have the smallest harvested areas there. Cluster 2 unites the largest number of 12 regions where oats are dominant and millet is the least grown crop among the analysed niche grains. Cluster 3 covers 5 regions which are focused on producing millet and oats, while rye is evenly spread within these areas.

Table 3

Modelled regional clusters of diversified production of niche grain crops by harvested area in Ukraine, 2025

Cluster	Regions	Cm1	Cm2	Cm3	Cm4
1	3: Kirovohrad, Mikolayiv, Vinnytsya	1.67	1.67	4.00	2.67
2	12: Chernihiv, Chernivtsi, Ivano–Frankivsk, Khmelnytskiy, Kyiv, Lviv, Rivne, Sumy, Ternopil, Volyn, Zakarpattya, Zhytomyr	2.58	3.83	1.17	2.42
3	5: Cherkasy, Dnipropetrovsk, Kharkiv, Odesa, Poltava	3.60	1.20	2.40	2.60

Source: authors' calculations based on data from [18].

The identified cluster profiles are illustrated in Figure 2, which demonstrates regional specialisation in producing niche grain crops. It shows striking differences between clusters 1 and 2 regarding opposite priorities in growing buckwheat, millet, and oats. Clusters 1 and 3 have similar specialisations related to millet and rye.

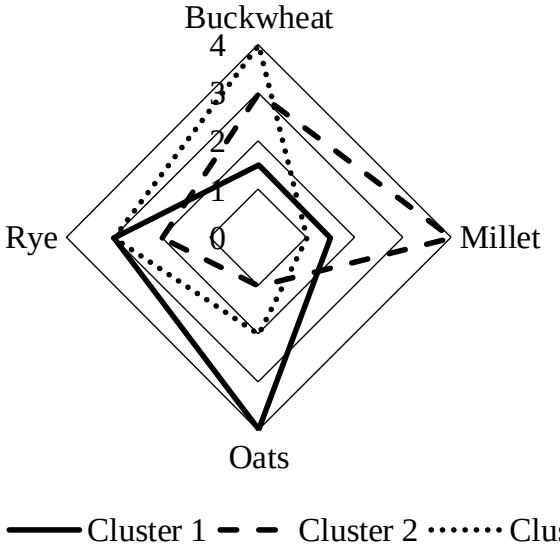


Figure 2. Cluster priorities in growing niche grain crops in Ukraine, 2025

Source: authors' calculations based on data from [18].

Clusters 2 and 3 exhibit totally different patterns in millet production, but are alike in the cultivation of other niche grains. These results reveal that in addition to agro-climatic conditions, there are many more factors that shape priorities in growing niche grain crops. Firstly, the availability of processing facilities and proximity to the densely populated areas incentivise farmers to produce buckwheat for the domestic market. Secondly, foreign demand for organic harvests encourages eco-friendly farming of oats and rye in the western regions of Ukraine. Thirdly, concerns about soil health in the areas overloaded with growing sunflower makes farmers substitute it with millet. All of the above drive regional clustering on the way to optimal diversification in producing niche grains.

4.3. Optimal proportions of growing niche grain crops to increase their resilience to climatic and market risks

The obtained coefficient of variation of prices, yields, and revenues for

buckwheat, millet, oats, and rye, illustrated in Figure 3, unveiled differences between the uncertainties of growing the explored crops and the combined risks that arise from natural and market factors during the crisis period of 2020–2023. Indeed, the CV indicators, calculated by formula (5) in %, reported that compared to other crops, oats had the smallest fluctuations explained by its strong resilience to natural and market challenges. Buckwheat was prone to the greatest deviations as this crop is largely produced for domestic consumption and is the most receptive to economic shocks in crisis conditions. Millet and rye showed moderate instability. However, the major driver of volatile millet revenues was yield. It is due to the strong global demand, which buffers the price for millet produced in Ukraine for export. At the same time, the volatility of rye prices brought about the major changes in its revenue. This phenomenon is associated with the lower liquidity of rye grown in Ukraine for local consumption.

Figure 3 also displayed that the variations of yields were less influential than price changes. In other words, costs of inputs and disrupted supply chains contributed more to the revenue deviations for all crops except millet. For millet, oats, and rye, price and yield provided a combined synergetic effect on revenue from these crops. In case of buckwheat, price and yield deviations acted in the opposite directions and slightly reduced revenue fluctuations. By and large, the specified intricate relationships between natural and market factors should be taken into account when making management decisions regarding optimal diversification of niche grains.

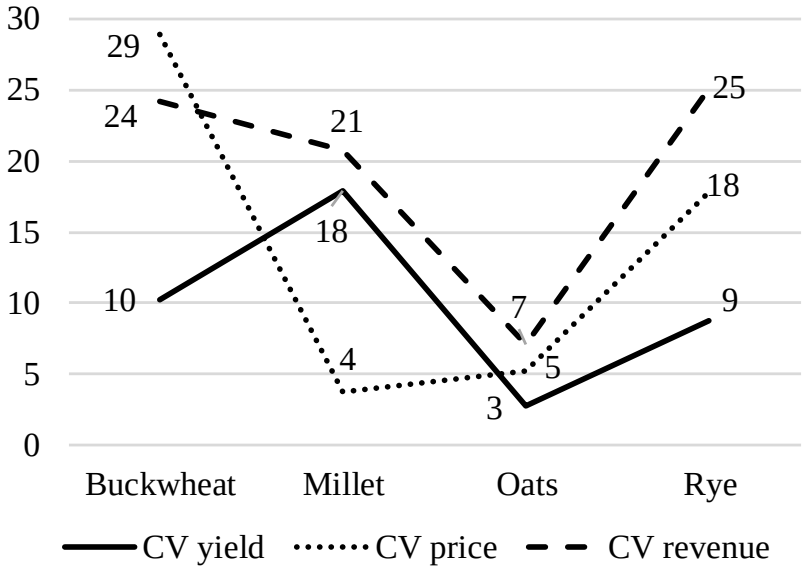


Figure 3. Fluctuations in parameters of niche grain production in Ukraine, 2020–2023

Source: authors' calculations based on data from [18; 19].

According to the third research task, Table 4 contains the results of the model calculation for sustainable diversification of niche grain crops by formulas (6)–(10). The minimal feasible shares of the harvested areas of buckwheat, millet, oats, and rye were set as:

F1=0.145; F2=0.116; F3=0.337; F4=0.164.

The calculated gross revenue per ha was equal to *GRH*=431 USD/ha. Given the investigated scenarios, the obtained result can provide an additional income of up to 30.71%.

Table 4

Modelled diversified production of niche grain crops according to scenarios for 2019–2023

Indicator	2019	2020	2021	2022	2023
R1s, USD/ha	340.3	626.7	755.4	898.4	505.5
R2s, USD/ha	487.7	356.6	565.8	412.9	521.7
R3s, USD/ha	386.5	442.1	476.6	407.4	417.9
R4s, USD/ha	480.0	564.8	566.5	453.9	314.8
GRHs, USD/ha	431.0	458.7	563.4	488.1	450.5
ΔGRHs, %	0.00	6.41	30.71	13.25	4.53

Source: authors' calculations based on data from [18; 19].

The optimal values of the model variables were:

Y1=0.145; Y2=0.354; Y3=0.337; Y4=0.164,

recommending that 14.5%, 35.4, 33.7, and 16.4% of available farmland should be allocated to buckwheat, millet, oats, and rye respectively (Figure 4).

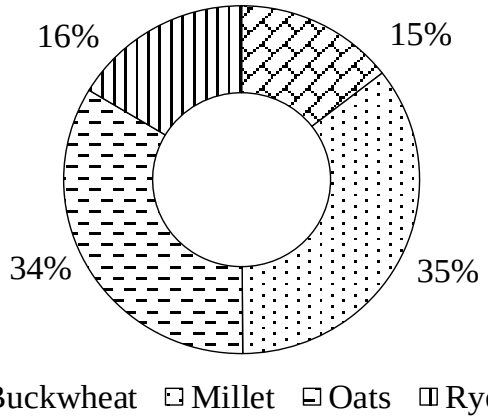


Figure 4. Optimal shares of growing niche grains according to scenarios for 2019–2023

Source: authors' calculations based on data from [18; 19].

The modelled sustainable diversification of niche grains (see Table 4) enables farmers to benefit from positive features of the selected crops and be successful regardless of risky business scenarios. Indeed, according to formula (2) applied to the calculated harvested areas (see Figure 4), the respective imbalance of growing niche grains is 38.2 p.p. It means that the modelled land distribution is more rational in the framework of crop rotation. Growing buckwheat, millet, oats, and rye can bring significant synergetic benefits. In particular, these crops belong to different families and will prevent extensive infestations by the same pests. Buckwheat and rye are powerful natural fertilisers that unlock phosphorus and capture nitrogen. Millet root system improves soil aeration and delivers water during hot, dry summer months. A crop rotation including winter rye and oats, harvested in late autumn, as well as spring buckwheat and millet, harvested in summer, can maintain the year-round coverage of

farmland, with the soil never being bare and unproductive.

Struggling with the price volatility in niche grains, farmers need to keep in mind that it arises from relatively poor market liquidity and a lower ability to absorb economic shocks because of fewer participants and undeveloped future contracts. The niche grain market is prone to unpredictable supply and price surges for inputs. This can be particularly true in the case of late-season farmers' decisions to sow niche grains to recover some income if cash crops fail to produce due to adverse weather conditions. Another volatility factor is attributed to retail price inflation owing to panic-driven expectations of end-consumers. Given all the above, data-driven recommendations for optimal diversification of niche grains will be relevant since growing a variety of crops can offset fluctuations inherent in separate crops and improve biodiversity.

5. DISCUSSION

5.1. Summary of the results

Overall, crop diversification is a powerful risk management strategy in farming that acts as a natural insurance policy. By spreading risk across multiple crops, farmers are less vulnerable to weather conditions, pest infestations, and disease outbreaks that can deteriorate harvests and negate expected profits. Moreover, by growing a few crops, farmers are able to protect themselves from market risks caused by price fluctuations, creating multiple income flows to stabilise their revenue.

The research findings related to task 2 offer insights into optimal diversification, demonstrating how regional clusters can unite fragmented niche grain producers into an integrated ecosystem. Owing to geographic concentration, they can offset supply chain fragility typical of the niche grain market. Combined analysis of yields and prices is especially valuable as it can prepare farmers for challenges and provide useful insights on the factors and risks behind them.

While the studies examined in the survey provide foundational insights into sustainable agriculture [5; 6], general crop diversification [7; 8; 26], and the broader economic potential of niche crops [9; 10], our results keep the narrow focus on diversified production of specific niche grain crops and are better tailored to their features derived from the corresponding empirical statistical data. Consequently, the primary advantage of our research lies in its transition from general recommendations to highly localised, crop-specific insights that stakeholders can leverage for precise decision-making.

Unlike the scientific outcomes from [11–17], which primarily highlight nutrition, environmental impacts, or localised production under stable conditions, the findings of the current research directly address the modern challenges of wartime that Ukraine is currently facing. Our results strive to cover the emerging scientific gap in addressing this unprecedented empirical experience, which is invaluable for understanding crisis management and supply chain disruptions. Furthermore, our findings are beneficial as they are highly adaptable to other economic areas and can be calibrated regardless of geographical borders. This applicability is explained by the versatile nature of the offered mathematical models and input metrics utilised in our research, making the

framework relevant to global crisis events well beyond the original field of research.

5.2. Theoretical implications

Theoretical implications related to task 1 are consistent with those of T. Mirzoeva et al. [27]. Indeed, niche grain crops can significantly boost food security, as their cultivation will contribute to the diversification of agribusiness. The study findings have proven that modern risks and the exacerbated global food insecurity will encourage farmers to produce niche crops, among which cereals have to fulfill a special strategic mission of sustainable agricultural development. To succeed in its implementation and to achieve the desired increase in efficiency, it is critical to practice regular monitoring of the niche grain market and simultaneously manage risks that emerge in the economic, environmental and social dimensions.

Furthermore, from a theoretical perspective, regional clusters of growing niche grains can substantially underpin the implementation of the fundamental 5R-concept of a circular economy, which involves reducing inputs, reusing agricultural residues, recycling water, refusing excessive application of chemical fertilisers and pesticides, and replacing conventional practices with eco-friendlier farming methods [28]. This is because buckwheat, millet, oats, and rye are less tough on resources, less dependent on weather conditions, have lower energy costs per product unit, and have shorter supply chains so that they bring about lower greenhouse gas emissions.

Finally, the calculated optimal clusters of regional crop diversification (see Table 3) align with multi-dimensional managerial decisions that combine economical resource application and ecological constraints [29]. To some extent similar to the models created by W. Shaowen [30], the offered model measures output benefits, provides environmental optimisation, and points out significant regional differences in the cultivation of the analysed niche grain crops.

5.3. Practical and policy implications

Policy implications are as follows. Optimal cluster diversification is in line with the European approach to farming resilience [31]. In this context, short-term shocks and long-term pressures can be addressed through system robustness and adaptability. Joint development within clusters guarantees faster economic recovery, disseminates efficient buffering experiences, facilitates the introduction of flexible management practices and advanced technologies, which cushion the consequences for farms before and after crisis events.

With shared storage facilities and cheaper logistics, niche grain producers are capable of improving grain quality, creating cluster product hubs, and upgrading processing. Besides, regional clusters are capable of being a powerful engine for socio-economic regeneration in rural communities. It can happen by transforming local isolated farmers into competitive producers who move from price-taking to value-creating, bypassing middlemen in shorter supply chains. Regional clusters can offer jobs for rural youth who might otherwise relocate to cities. The whole year demand for local experts in management, agronomy, agricultural machinery, digital logistics, quality control, and processing will break the unfavourable cycle of seasonal employment. Consequently, it will ensure a sustainable future for farmers engaged in

high-value agribusinesses of buckwheat, millet, oats, and rye production.

Practical implications related to task 3 correlate with those of other scientists and underscore the importance of scenario analyses to maintain farmers' profitability. The practical application of the crop-specific findings involves several key considerations for farm managers.

Buckwheat is ranked as one of the most profitable niche grain crops in Ukraine with the prospect of increasing exports and production even under the current wartime economic crisis [32]. However, buckwheat is sensitive to summer heat blast and frost that can have a negative effect on the yield, implying a practical need for heat-mitigation strategies.

Rye is a good option for Ukrainian farmers who are interested in diversifying their income, given its agro-technological advantages, high profitability, and consistent demand in both domestic and global market [33]. At the same time, rye is vulnerable to rainy humid weather and excessive moisture. As a result, these climatic risks can threaten the rye harvest.

Oats, according to A. Dibrova and L. Stepasiuk, are especially valuable as a multifunctional grain crop with high potential in premium food markets. Oats have a positive effect on soil quality in crop rotations, especially with soil-depleting oilseed crops. Careful treatment of limited agricultural land is a priority for small-scale farmers. Growing oats can help them enter a specific market segment and even gives them access to foreign markets [34]. Nevertheless, there is a natural risk of reduced oats yields if the weather is atypically dry or wet.

Positively assessing the prospects for growing millet, O. Drebot and M. Vysochanska pointed out that it is a grain-forage crop suitable for implementation in various regions. Thus, it is highly expedient to expand its cultivation and use it as a robust insurance crop to diversify farming and guarantee higher production efficiency [35]. However, severe winds and prolonged torrential rains during the harvesting period can trigger a substantial decline in millet production.

Future research will focus on comprehensive digitalisation, broader crop selections, and a comparative regional analysis of post-war recovery to establish more resilient production for niche grain crops.

6. CONCLUSIONS

Growing niche grains can help implement foundations of green and circular economies into agriculture. Niche grain crops fully comply with the fundamentals of sustainable development. They amplify biodiversity, improve soil condition, mitigate chemical load, reduce the carbon footprint, bolster the production of organic and gluten-free food products, are used with zero waste for feed and biofuels, stimulate local value chains, and boost the competitiveness of smallholder farmers.

The combined harvested area of the selected niche grain crops was 4.9 and 4.7 times smaller than that of wheat and maize globally in 2024. Similar indicators in Ukraine were 11.5 and 9.5, respectively, meaning that there is significant untapped potential in promoting diversified production in Ukrainian agriculture. The

diversification in the niche grain market is unbalanced around the world, including not only production but also export-import relations in international trade. In particular, as of 2024 the volumes production of buckwheat, millet, oats, and rye were 3%, 46, 34, and 17%, respectively. At the same time, Ukrainian farmers demonstrated a better alignment with well-balanced diversification, with buckwheat, millet, oats, and rye production shares of 12%, 17, 48 and 23%, correspondingly. It means that this approach empowers farm resilience via more flexible management, diversified produce and markets, adaptive ecosystems, and the provision of acceptable livelihoods in rural communities.

The calculated Ukrainian clusters of 3, 12, and 5 niche grain producers reflect regional profiles and priorities in farming based on the availability of resources, the development of infrastructure, local demands, and export orientation. Due to the scaling effect, regional farmers within clusters can reinforce their resilience and sustainability. The research findings exposed a strong impact of prices and yields on financial results in growing niche grain crops. In the case of Ukraine, scenario analysis based on these indicators demonstrates the potential to increase farmers' revenues up to 30.7% as a part of a stabilisation mechanism against natural and market risks.

The proposed diversification models by means of cluster optimisation and scenario analysis can be extended to different countries to identify patterns of regional segmentation with regard to the explored niche grains or other crops mostly cultivated at the local level. This is achieved by substituting the empirical statistical data with country-specific universal indicators of yield, harvested areas, and pricing, allowing the mathematical models to map unique regional vulnerabilities, optimal crop proportions, and customised scenarios of the diversified production regardless of the geographic locations.

The substantiated model recommendations, such as diversification proportions, optimal regional clustering for shared crop profiles, and scenario optimisation models for productivity and profitability, can enable farmers to withstand the long-term pressure of climate change and turbulent shocks in agricultural markets. These mathematical frameworks let farmers alleviate market shocks by adjusting crop proportions based on optimised financial scenarios and buffer climate pressures by aligning with resilient regional clusters whose shared practical development can contribute to the implementation of sustainable agriculture.

Ultimately, the results of this study fully verify the research hypothesis, demonstrating that the offered mathematical integration of volume, area, yield, and price indicators successfully identifies viable, risk-resilient pathways for expanding niche grain cultivation.

7. LIMITATIONS AND FUTURE RESEARCH

The research limitations are linked to restricted data and unavailable statistics on recent agricultural performance in Ukraine during wartime. Firstly, farmers' financial statements are officially simplified to make up for military risks. Secondly, reliable calculations of inputs and harvests are complicated or even impossible because of

safety concerns, especially in the regions which are close to active hostilities. This introduces specific geographical limitations, leaving frontline and de-occupied territories underrepresented.

Another research limitation arises from the fact that the study inferences depend on actual data on the global cultivation of niche grain crops. Therefore, the calculations conducted should be updated regularly to track the ongoing trends and address negative deviations that could impede sustainable development and jeopardize food security. Furthermore, rapid changes in pricing for farming inputs and harvests as well as volatile climatic patterns demand regular updates of the study recommendations to capture the contemporary economic context.

To overcome the current challenges and address these limitations, our future research will expand in several directions including broader timespans, other niche crops and a precise focus on the identified clusters of grain producers. Additionally, as safer access becomes possible, further studies will extend the geographical scope to include a comparative analysis of post-war recovery across different regions of Ukraine, ultimately establishing more resilient production frameworks for niche grain crops.

AUTHOR CONTRIBUTIONS

Both authors contributed equally to this work.

Both authors have read and approved the final version of the manuscript.

Funding: this study was conducted without external funding.

Acknowledgments: the authors are grateful to the Editor-in-Chief and anonymous reviewers for their valuable feedback and recommendations that helped improve this article.

Conflicts of interest: the authors declare no conflict of interest.

Use of artificial intelligence: the authors confirm that they did not use artificial intelligence technologies during the creation of this work.

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Article history:
Received: 30 January 2026
Revised: 1 June 2026
Accepted: 6 June 2026
Published: 20 June 2026