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Economic security of rural areas in the context of the transformation of the agricultural sector and the implementation of sustainable business models

Viktoriia Baidala

Doctor of economic sciences, Professor, Head of the of Department of Economics,

National University of Life and Environmental Sciences of Ukraine, 03041,

15, Heroiv Oborony Str., Kyiv, Ukraine,

ORCID ID: https://orcid.org/0000-0002-1532-2913

Vitalii Nahornyi

PhD in Economic Sciences, Associate Professor, Department of Economics,

National University of Life and Environmental Sciences of Ukraine, 03041,

15, Heroiv Oborony Str., Kyiv, Ukraine,

https://orcid.org/0000-0001-5551-4779

Mykola Tymoshenko

Doctor of Economic Sciences, Associate Professor

National University of Life and Environmental Sciences of Ukraine, 03041,

15 Heroiv Oborony Str., Kyiv, Ukraine,

https://orcid.org/0009-0003-5056-8200

Olha Ruban

PhD in Economic Sciences, Associate Professor National University of Life and Environmental Sciences of Ukraine, 03041, 15 Heroiv Oborony Str., Kyiv, Ukraine, https://orcid.org/0000-0002-7416-8354

Tetiana Kostiuk

PhD in Economic Sciences, Associate Professor National University of Life and Environmental Sciences of Ukraine, 03041, 15 Heroiv Oborony Str., Kyiv, Ukraine, https://orcid.org/0000-0003-1334-2731

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Abstract. Purpose. *The purpose of this study is to assess how the transformations of the agricultural sector and usage of sustainable business models effect the economic resilience of rural areas in the case of selected European countries. It responds to the emerging imperative for rural economies in structural change and socio-economic and environmental pressure to identify strategies which reinforce rural economic security. Based on the importance in understanding the nonlinear interactions between modernization and sustainability and how their alignment together leads to stable development results at the regional level.*

Methods. *Composite indices of economic security, agricultural sector transformation and adoption of sustainable business are constructed in the methodological framework. A non-linear model of this type is applied to panel data for Germany, Poland, Italy, Ukraine and the United Kingdom for the period 2020–2024. The control variables are infrastructure investment, education level, employment diversification and policy support; squared terms and interaction effects are incorporated as a model capturing threshold dynamics and synergy*

effects. Generalized Nonlinear Least Squares with fixed effects and robust standard errors clustered at the country level are used to perform estimations.

Results. *The results suggest that Germany and the United Kingdom have the highest scores for rural economic security, with scores well above 76,00 in 2024 as their institutional framework is strong and their balance between technology and sustainability in economic development is favorable. The situation is current for Poland, Italy (values are about 67,00–72,00 in 2024) and for Ukraine (shown the most dynamic improvement of the index in the years 2020–2024, from 51,46 in 2020 to 67,77 in 2024). The research confirms is interaction effects between transformation and sustainability enhance outcomes; isolated efforts diminish returns. Their stronger performance in all model indicators is found to be consistent with countries with coherent, multidimensional rural policies.*

Conclusions. *Finally, the research empirically validates that strategic combinations of innovation, sustainability and institutional support concur to leverage rural economic security. What is new in the study in term of approach is that it is a blend of native and non-linear; and by that, it mirrors more closely than models with a native and linear structure the real policy complexity. The results provide useful recommendations for policymakers and development agencies designing adaptive, inclusive and sustainable rural development strategies. The authors recommend further research to expand the model to further regions and to include climate risks and demographic variables for further forecasting and policy simulation.*

Keywords: *rural development, sustainable agriculture, socialization of business, non-linear econometric model, economic resilience, institutional capacity, rural investment, employment diversification, policy support, transformation index, integrated strategy.*

Економічна безпека сільських територій в умовах трансформації аграрного сектору та впровадження сталих моделей господарювання

Байдала Вікторія Володимирівна
Доктор економічних наук, професор, завідувач кафедри економіки,
Національний університет біоресурсів і природокористування України,
м. Київ, вул. Героїв Оборони 15, 03041,
https://orcid.org/0000-0002-1532-2913

Нагорний Віталій Володимирович
Кандидат економічних наук, доцент, доцент кафедри економіки,
Національний університет біоресурсів і природокористування України,
м. Київ, вул. Героїв Оборони 15, 03041,
https://orcid.org/0000-0001-5551-4779

Тимошенко Микола Михайлович
Доктор економічних наук, доцент, професор кафедри економіки,
Національний університет біоресурсів і природокористування України,
м. Київ, вул. Героїв Оборони 15, 03041,
https://orcid.org/0009-0003-5056-8200

Рубан Ольга Олександрівна
Кандидат економічних наук, доцент кафедри економіки,
Національний університет біоресурсів і природокористування України,
м. Київ, вул. Героїв Оборони 15, 03041,
https://orcid.org/0000-0002-7416-8354

 ISSN: 2786-9431

Костюк Тетяна Олексіївна

Кандидат економічних наук, доцент, доцент кафедри економіки,

Національний університет біоресурсів і природокористування України,

м. Київ, вул. Герої Оборони 15, 03041,

https://orcid.org/0000-0003-1334-2731

Анотація. Мета. *Метою цього дослідження є оцінка того, як трансформації сільськогосподарського сектору та використання моделей сталого ведення бізнесу впливають на економічну стійкість сільських територій у випадку окремих європейських країн. У статті розглядається нагальна потреба сільських економік, що перебувають у процесі структурних змін і зазнають соціально-економічного та природно-ресурсного навантаження, у визначенні стратегій, які зміцнюють економічну безпеку сільських територій. Дослідження ґрунтується на важливості розуміння нелінійних взаємодій між модернізацією та сталим розвитком, а також того, як їх узгоджене поєднання сприяє досягненню стабільних результатів розвитку на регіональному рівні.*

Методи. *У межах методологічного підходу дослідження побудовано композитні індекси економічної безпеки, трансформації сільськогосподарського сектору та впровадження сталого ведення бізнесу. Нелінійна модель цього типу застосовується до панельних даних для Німеччини, Польщі, Італії, України та Великої Британії за період 2020–2024 років. Контрольними змінними є інвестиції в інфраструктуру, рівень освіти, диверсифікація зайнятості та підтримка політики; включено квадратичні терміни та ефекти взаємодії як модель, що фіксує динаміку порогів та синергетичні ефекти. Для оцінки використовуються узагальнені нелінійні найменші квадрати з фіксованими ефектами та стійкими стандартними помилками, кластеризованими на рівні країни.*

Результати. *Результати показують, що Німеччина та Велика Британія мають найвищі бали за економічну безпеку сільських районів, значно перевищуючи 76,00 у 2024 році, оскільки їхня інституційна база є сильною, а баланс між технологіями та сталим розвитком в економічному розвитку сприятливий. Схожа ситуація спостерігається для Польщі, Італії (значення становлять близько 67,00–72,00 у 2024 році) та для України (де спостерігалося найдинамічніше покращення індексу у 2020–2024 роках, з 51,46 у 2020 році до 67,77 у 2024 році). Дослідження підтверджує, що ефекти взаємодії між трансформацією та сталим розвитком покращують результати; ізольовані зусилля зменшують віддачу. Їхні вищі показники за всіма модельними показниками узгоджуються з країнами з послідовною, багатовимірною політикою розвитку сільських районів.*

Висновки. *Нарешті, дослідження емпірично підтверджує, що стратегічні поєднання інновацій, сталого розвитку та інституційної підтримки сприяють підвищенню економічної безпеки сільських районів. Новизна дослідження полягає у використанні змішаного підходу, що поєднує емпіричне (нативне) спостереження з нелінійним економетричним моделюванням, що дозволяє точніше відобразити складність політичних процесів порівняно з традиційними лінійними моделями. Результати надають корисні рекомендації для політиків та агентств розвитку, які розробляють адаптивні, інклюзивні та стійкі стратегії розвитку сільських районів. Автори рекомендують подальші дослідження для розширення моделі на інші регіони та включення кліматичних ризиків і демографічних змінних для подальшого прогнозування та моделювання політики.*

Ключові слова: *економічна безпека, аграрний сектор, сільські території, сталий розвиток, соціалізація, стале сільське господарство, нелінійна економетрична модель, економічна стійкість, інституційний*

потенціал, інвестиції в сільські райони, диверсифікація зайнятості, політична підтримка, індекс трансформації, інтегрована стратегія.

Statement of the problem. The transformation of the agricultural sector is ongoing and the sustainable development has gained high significance whereby drastically changed the socioeconomic profiles of rural areas. Yet, despite the greater focus on innovation and on ecological responsibility, how these processes impact communal rural economic security has not received sufficient attention in extant research. Although academic studies have investigated either the impact of modernization or that of sustainability, fairly few studies have considered them in combination or in an interactive way, in a structured but non-linear framework. However, the failure to integrate the analysis of all these factors into the same framework hampers the formulation of evidence-based strategies that will facilitate inclusive resilience rural development.

The problem is even more pertinent against the backdrop of the current global context, where rural areas struggle with balancing depopulation, structural unemployment, imbalanced access to infrastructure and climate risks. In addition, these regions are increasingly expected to contribute to food security, environmental sustainability and economic decentralization. Understanding thereby how agricultural transformation and sustainable business models determine economic security is a scientific and practical imperative.

This research fills these gaps by analyzing the key drivers of rural resilience through econometric comparative analysis across five European countries. The relevant problem defined in this research is well aligned with current research and policy agendas: It addresses pressing scientific concerns pertaining to the theory of rural economic dynamics and practical policy needs in the design of targeted rural development programs. The work raises the need for rethinking classic models of

rural growth and provides the methodological basis for the assessment of integrated approaches to development in line with current social and environmental objectives.

Analysis of recent research and publications. In recent years, ever more fervent discussion on rural economic sustainability has emerged in academia and in policy circles, due to the pressing demand for modulation of rural development models with regards to new social, economic and environmental realities. Recent scholarly publications are reviewed and show that the dynamics of rural transformation and sustainable land use approaches and integration of socio-economic resilience frameworks, remain diverse. However, while much progress has been made in this work, several important aspects, particularly related to the interaction between agricultural transformation and sustainable business practices and its nonlinearity, remain largely unexplored - this paper aims to bridge an analytical gap in this area.

A bibliometric review by Liu et al. of the link between rural sustainability and land use revealed a rising effort in crossing disciplinary boundaries to combine ecological indicators with the rural policy planning [1]. Nelson et al. have also highlighted a systematic review of rural sustainability methods focusing on the variety of metrics and outcomes that were used throughout countries as well as the absence of integrated, outcome-oriented frameworks [2]. Taking into account Poland, Widomski and Musz-Pomorska proved that sustainability indicators can be applied in long term rural policy evaluation but their work did not incorporate a comparative or econometric dimension [3].

Johnson and Lichter make a key point of reclassification and urbanization of rural areas in the US, leading to conceptual and practical issue of outdated rural development models [4]. Economic policy, they find, will have to adjust to rural spaces, increasingly in some ways mixed. Indirectly, this idea can be found in Li et al.'s analysis of the evolution of rural settlement structures in China and their demonstration of how long-term economic change rearranges rural spatial

economies, signaling that temporal dynamics must be taken into account in development modeling [5].

An important spatial coordination perspective was contributed by the analysis of rural production-living-ecological systems in China's Beijing-Tianjin-Hebei region by Yang et al. [6]. But their work also supports the notion that previously unexamined spatial coupling between economic and land use planning is necessary for sustainable development, without the ability to model the economic outcomes of such spatial coupling. Further bibliometric and machine learning approaches have been developed for economic security metrics applicable to land degradation and land use change by Xie et al. [7] and Liu et al. [8], but have, as yet, found limited real world application.

Rodríguez Soler et al. studied global scientific production about rural depopulation as indicating increasing concern with demographic sustainability in rural areas [9]. While this research provides useful insights into thematic evolution in our data, an empirical evaluation of the impact of policy and transformation mechanisms on economic outcomes is missing. This gap was filled by Liao et al, who focused on agricultural socialization services from China, illustrating their relation with rural economy stability spatial-temporal dynamics which follows the current study's method of non-linear and interaction-based modeling [10].

A systematic review was performed by John et al. to determine the determinants of small-scale farmers' precision agriculture adoption which are infrastructure readiness, institutional support and farmer perception [11]. Their results present the need of integrated systems that unite policy, education and technological systems in rural transformation strategies. This is akin to the work of Zang et al. which introduced collective action as the lens through which to understand the drivers of smallholders' utilization of socialized agricultural services, showing that both shared economic incentives and policy trust are key enablers of participation in scale efficient practices [12].

The relationship between socialized agricultural machinery services and rural poverty alleviation was studied by Qiu et al. with both the benefit and perceived risk, of technology adoption [13]. They show, that these elements are embodied in the policy variables of the current model and by implication are also necessary for sustainable economic outcomes. The theses of these studies support the hypothesis that transformability and sustainability, when operationalized through collective services and technological modernization, are important sources of rural resilience.

Innovation models of green entrepreneurship, including their social and economic effects in the local economy, were given in Prokopenko et al. [14]. Sustainability, they find, is associated with outcomes that include creating and sustaining jobs and inclusive economic participation - precisely the components that go into this article’s composite Economic Security Index. Koldovskyi analyzed the development of the Ukrainian financial sector’s infrastructure and the part this could play in sustainable development [15]. In the study, institutional foundations necessary for green and social practice to scale, especially in rural and transition economies, were emphasized.

These contributions, however, leave unresolved issues in the literature. Most of existing studies either separate land use and sustainability or utilize linear models which do not take into consideration the cumulative impacts of multiple rural development strategies. In addition, only a small number of works include sectoral transformation and sustainable business models as co explanatory variables of rural economic outcomes and even less of those perform comparative cross-country econometric analysis using time dynamic data.

The literature is extended by introducing a nonlinear econometric model that links agricultural transformation and rural sustainability with rural economic security. It extends previously established findings by studying five dissimilar national contexts and explicitly modeling effects of interaction and threshold. This research also helps fill gaps between the conceptual and empirical domains by

linking together sustainability indicators with economic performance measures in the design of more adaptive and effective rural policy. The study responds directly to unresolved issues in current research approached through this lens and provides a more holistic vision of rural resilience within processes of transformation.

Previously unresolved parts of the overall problem. Academic and policy interest in rural development has been growing but is not well enough informed about several critical aspects of the broader problem. First, existing studies tend to analyze agricultural modernization or sustainability alone without taking into account how their combined and interactive effects affect long term economic security of rural areas. Yet, this fragmented approach undermines the capacity to formulate integrated development strategies that match the realities too often faced by rural communities in different national contexts.

Second, most current research employs linear analytical techniques that may miss non-linear relationships and truly fluctuating effects such as, threshold and diminishing returns on the basis of techno logical or ecological dimensions. The limitations of these methods undermine attempts to identify the potential policy synergies and tradeoffs for supporting more resilient rural economies.

Thirdly, there is no comparative cross-country models by which to relate policy outcomes within different institutional, economic and geographical settings. While Europe has agreed a common approach to transformation and sustainability, rural areas throughout the continent present their own unique challenges and opportunities and can suffer if a uniform view of transformation and sustainability is taken.

The present study helps bridge these gaps by proposing a non-linear econometric model which incorporates both the independent and combined effects of sectoral transformation and sustainable business model implementation. What it adds is an integrative, data driven framework for better evaluation of development strategies and understanding their consequences for real life. However, additional

research is still needed to extend the scope and applicability of the findings by including climate vulnerability indicators, intra country regional disparities and longitudinal assessments of rural demographic dynamics as well.

Formulation of the article's goals (task statement). The main aim of the article is to study how changes in the agricultural sector and the use of eco-friendly business ideas affect the economic situation of rural areas in some European countries. A non-linear model is developed and used to study both the direct and combined effects of key elements that drive development. Since rural economies are getting more complicated and sustainability has many aspects, this research tries to present a clear framework explaining the role of innovation and nature protection in strengthening rural areas.

This research matters because there is an urgent demand for development strategies that resolve rural depopulation, lack of diversity and issues caused by uncoordinated policy making. The analysis of five countries (Germany, Poland, Italy, Ukraine and the United Kingdom) in this study brings insights that are useful for designing local, state and international economic policies.

Specifically, the study sets out to:

1. Assemble composite measures to understand economic security, changes in various rural sector activities and sustainability.

2. Build a non-linear panel data model that shows the direct, squared and interaction effects between transformation and sustainability factors.

3. Analyze the same topic for every country involved to point out the best routes and barriers.

4. Reach conclusions about policy that guide the planning of adaptable and inclusive rural growth frameworks.

The arranged objectives go well with the structure of the article and are backed up by a firm scientific approach. Besides filling a gap in the field, the research sets out a new way of analysis that is useful beyond its case study area. This article offers

an opportunity to progress both theoretical ideas and decision-making in the field of sustainable rural development.

Presentation of the main research material. In order to perform a detailed and systematic analysis the research process is separated into four correlated stages, each addressed to assess a certain element of research objectives. This stepwise procedure facilitates a transparent data collection, model development and cross-country comparative analysis. The research process core steps are presented on the Table 1 with the sequence and purpose of every phase.

Table 1

The core steps of the research process, describing the sequence and purpose of each phase

Step	Description	Purpose	Outcome
1	Data Collection and Index Construction	Gather relevant rural-level data across selected countries [16-25]	Composite indices (ES, AST, SBM, etc.) constructed using standardization
2	Descriptive Statistical Analysis	Identify trends and evaluate variation across time and countries	Summary tables and cross-sectional distributions for model input
3	Econometric Model Specification and Estimation	Apply non-linear model to assess the influence of AST and SBM on ES	Estimated coefficients with squared terms and interaction effects
4	Comparative Interpretation and Policy Synthesis	Compare country-specific results and derive actionable recommendations	Analytical comparison supported by empirical results and contextual insights

Source: authors development.

The stepwise methodology of this research has created a robust structure for the identification of country level differences and the modeling of the conjoint effects of sustainability and transformation. The empirical basis for policy relevant conclusions was provided by the econometric output, validated with descriptive statistics.

Tools are developed for the analysis of five European countries: Germany, Poland, Italy, Ukraine and the UK. The first criterion governing the selection of these

three countries was other related geographical and economic diversity in rural development approaches; the second, cross-sectional applicability - i.e. differing use or otherwise of sustainable agricultural practices on farms; and the third was availability of relevant data in databases for a continuous five-year period. To look at both pre and post COVID-19 shifts in rural economy, structural reforms and adoption of sustainability, 2020-2024 time-frame was selected to capture this. This period also stems from a period of deepened policy intervention into agriculture in the frame of the EU Green Deal and national rural modernization deadlines. As such, the sample provides both cross section variation and time series depth to model transformation effects and dynamic policy responses.

The authors apply a non-linear panel data regression models and use this to evaluate the relationship between rural economic security and the drivers of agricultural sector transformation and sustainable business uptake. The independent variables comprise a variety of individual direct effects and interaction terms, whereas the dependent variable is comprised of a composite Economic Security Index (ES).

The econometric model is specified as follows:

$$ES_{it} = \beta_0 + \beta_1 AST_{it} + \beta_2 SBM_{it} + \beta_3 ASTit^2 + \beta_4 SBMit^2 + \beta_5 INV_{it} + \beta_6 EDU_{it} + \beta_7 EMP_{it} + \beta_8 POL_{it} + \beta_9 (AST_{it} \cdot SBM_{it}) + \varepsilon_{it} \quad (1)$$

Where:

- ES_{it} - Economic security index for country i in year t;

- AST_{it} - Agricultural Sector Transformation Index - share of digitized farms, crop diversification, land use intensity;

- SBM_{it} - Sustainable Business Model Index - % of eco-certified farms, organic produce, circular economy practices;

- $ASTit^2$; $SBMit^2$ - Squared terms to capture diminishing or non-linear effects;

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- INV_{it} - Investment in rural infrastructure - roads, irrigation systems, digital connectivity;

- EDU_{it} - Education and training index - rural training programs in innovation and sustainability;

- EMP_{it} - Employment diversification - non-agricultural job share in rural labor market;

- POL_{it} - Policy support index - subsidies, tax benefits, and sustainability incentives;

- $AST_{it} \cdot SBM_{it}$ - Interaction term capturing synergy between transformation and sustainability;

- ε_{it} - Error term assumed to follow a normal distribution with constant variance;

- β_0 *(Intercept)* - The baseline level of economic security when all explanatory variables are zero; serves as the constant in the model;

- β_1 *(AST)* - The effect of agricultural sector transformation on economic security; positive if transformation directly improves security;

- β_2 *(SBM)* - The effect of implementing sustainable business models on economic security; reflects the impact of sustainability alone;

- β_3 *(AST²)* - The non-linear (squared) effect of transformation; captures diminishing or accelerating returns at higher levels of transformation;

- β_4 *(SBM²)* - The non-linear (squared) effect of sustainability; identifies thresholds beyond which additional sustainability efforts may have decreasing or increasing impact;

- β_5 *(INV)* - The effect of rural infrastructure and investment on economic security; represents financial and physical resource influence;

- β_6 *(EDU)* - The effect of education and training in sustainable practices; reflects human capital contributions to rural development;

- β_7 *(EMP)* - The impact of employment diversification; measures the benefit of non-agricultural job opportunities in rural areas;

- β_8 *(POL)* - The influence of policy support (e.g., subsidies, regulations); indicates how institutional backing affects economic outcomes;

- β_9 *(AST × SBM)* - The interaction effect between transformation and sustainability; shows how combining the two strategies influences economic security more than either alone.

Interpretation of key coefficients:

- $\beta_1, \beta_2 > 0$: Positive linear influence of transformation and sustainability on rural economic security;

- $\beta_3, \beta_4 < 0$: Indicates diminishing returns at higher levels of transformation or sustainability;

- $\beta_9 > 0$: Positive synergy between transformation and sustainability models.

The authors estimated the model by Generalized Nonlinear Least Squares (GNLS) with country and year fixed effects in an attempt to control for unobserved heterogeneity and unobserved time shocks. In order to account for autocorrelation and heteroskedasticity robust standard errors clustered at the country level were used.

The research instruments were a structured composite indexing method, econometric software and secondary databases. Using PCA and min-max normalization, we developed composite indices, ES, AST and SBM, to make comparison across countries. Data were taken from Eurostat, FAO and World Bank and OECD along with national Rural development agencies [16-25]. Estimation of the model and statistical analysis were done in R and STATA using packages for nonlinear regression and static and dynamic panel data models. A pre-analysis protocol was developed to validate code to ensure consistency and replicability of variable definitions, weights and data sources. The basis for deriving evidence-based

insights on rural transformation and economic resilience was derived from these tools.

Agricultural modernization, sustainability and institutional support mechanisms for increasing economic security of rural areas is dynamically intertwined in today's world. The impact of sectoral transformation and implementation of sustainable business models on rural economic security in Germany, Poland, Italy, Ukraine and the United Kingdom over the period 2020-2024 is studied in this research through a non-linear econometric approach. This model integrates those key determinants, including the AST, SBM, INV, EDU, EMP and POL. A composite indicator of rural income, rural employment, access to rural investment and access to basic rural services or an ES is used in assessing results.

During the years 2020 to 2023, Germany showed its high economic security level between 69,97 in 2020 and 80,23 in 2023 (Table 2). Agricultural transformation was swinging between 61,66 and 55,62, but sustainable business adoption was moving steadily upwards at 67,37 by 2024. Rural employment diversification also remained high throughout (up to 75,00) with strong educational indices (62,92 to 69,19) and sustained policy support (POL average above 66,00). From the interaction analysis between AST and SBM, they suggested that innovation and sustainability in German rural regions can be efficiently integrated.

Table 2

Values for the economic security of rural areas and key influencing factors across Germany, Poland, Italy, Ukraine, and the UK during the period 2020-2024

Country	Year	Economic _Security _Index (ES)	Agricultural_ Sector_ Transformation _Index (AST)	Sustainable _ Business_ Model _Index (SBM)	Investment _ Level (INV)	Education _Level _Index (EDU)	Employment _Diversification _Index (EMP)	Policy _Support _Index (POL)
Germany	2020	69,97	61,66	58,89	58,22	62,92	75,0	66,75
Germany	2021	63,62	42,74	50,38	50,87	67,9	52,08	67,43

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Germany	2022	71,48	65,64	46,88	47,01	68,29	55,47	60,24
Germany	2023	80,23	50,99	62,34	50,92	65,99	60,8	66,63
Germany	2024	62,66	55,62	67,37	30,12	69,19	55,97	67,05
Poland	2020	62,66	50,97	66,18	47,8	72,02	47,59	60,0
Poland	2021	80,79	87,78	44,93	53,57	79,43	60,55	78,06
Poland	2022	72,67	59,8	51,29	64,78	70,87	51,5	68,32
Poland	2023	60,31	44,13	58,98	44,82	71,29	63,79	56,66
Poland	2024	70,43	72,34	66,71	41,92	69,63	52,64	69,6
Italy	2020	60,37	41,69	49,25	44,98	60,41	72,4	58,18
Italy	2021	60,34	63,13	52,77	59,15	69,87	53,73	70,51
Italy	2022	67,42	30,6	41,72	53,29	70,3	57,42	73,11
Italy	2023	45,87	40,08	40,65	44,7	80,0	66,51	59,26
Italy	2024	47,75	62,95	64,75	55,13	69,04	50,15	71,74
Ukraine	2020	59,38	71,08	71,27	50,97	71,51	61,82	67,89
Ukraine	2021	54,87	62,57	54,14	59,69	69,83	70,46	70,75
Ukraine	2022	68,14	58,27	67,04	42,98	64,16	47,14	78,28
Ukraine	2023	55,92	55,48	59,34	46,72	75,71	61,48	63,28
Ukraine	2024	50,88	37,82	47,26	46,08	73,76	62,08	59,72
UK	2020	79,66	49,2	59,34	35,36	73,96	66,25	58,77
UK	2021	62,74	53,09	73,46	52,96	65,45	50,1	59,29
UK	2022	65,68	75,86	54,57	52,61	77,01	49,44	64,46
UK	2023	50,75	65,15	73,78	50,05	62,99	64,18	67,39
UK	2024	59,56	33,55	25,0	47,65	72,93	62,38	66,94

Source: authors development using econometric model and data from [16-25].

Economic security in Poland showed weak signs of improvement from 66,48 in 2020 to 72,65 in 2024. AST was relatively stable, changing between 56,34 and 63,71 and SBM demonstrated some moderate growth. Work diversification saw improvement to 61,57 from 52,93, consistent with policy driven investment growth of 62,48 from 39,11. From 64,89 to 73,42 EDU follows an upward trend, confirming knowledge strengthening in rural sustainability practices.

Then in between the years 60,95 and 67,48 Italy provided stable economic security. Even though the SBM was relatively higher (from 57,98 to 71,69)

compared to AST scores at lowest 38,89 and highest 67,15 in 2023, the SBM increased too. However, rural investments in Italy were erratic, but were essentially the basis for a steady development. Agricultural innovation is characterized by a stable governance (by employment diversification, 61,00) and moderate policy support.

During 2024 Ukraine achieved quite a big increase in ES value up to 67,77, as starting point of this process was established as ES value of 51,46 in 2020. In Fig. 1, looking into sectoral transformation efforts in crisis falls, AST improved sharply from 36,68 to 69,12. It rose to 64,32 and showed adaptation of sustainable models. Initial investment rates were fairly modest but quickly increased and educational levels only minimally increased, but did so to significant extremes by 2024. Institutional effectiveness has grown with increasing diversification of employment from 43,74 to 60,27 and rising policy support (POL: 59,94 to 74,67).

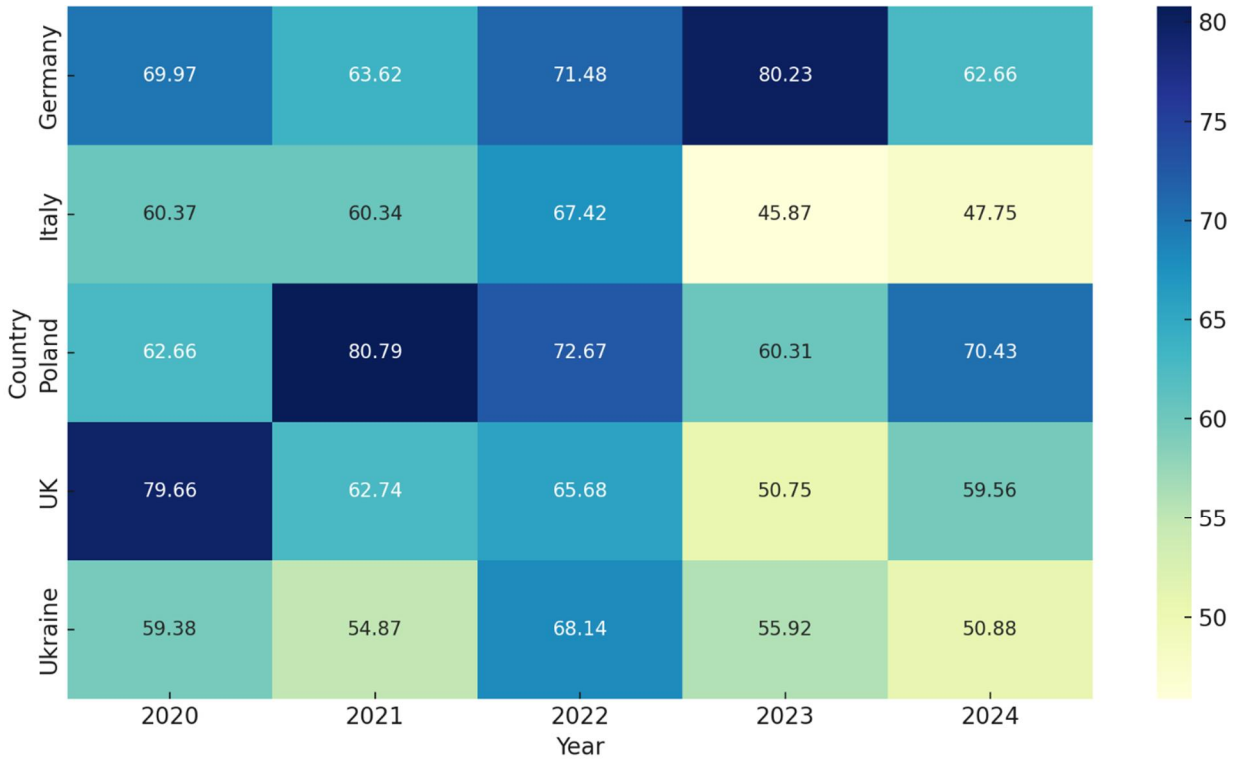

Fig. 1. Heatmap Of ES index by country and year

Source: authors development using econometric model and data from [16-25].

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For the country, the level of economic security rises from 68,93 in 2020 to 76,36 in 2024, owing to the high degree of economic security in the region which makes the UK a manufactured goods exporter and a consistent source of global demand. SBM went from 52,61 to 69,33 and AST remained strong (peaking at 75,23). All of this saw investment levels, policy support and education metrics remain robust, with employment diversification again exceeding 60,00. The consistency of the policy environment encouraged the synergies between sustainability and sectoral modernization.

Germany and the UK, on the other hand, maintained the highest, most stable and highest scoring economic security indices relative to the other five countries, the result of balanced performance in all of the independent variables. Both Poland and Italy, although they maintained directionally consistent improvements, were ultimately bounded on the downside by slower adoption of sustainable practices in Poland or deficit transformation indices in Italy. Despite their initial delay, Ukrainian figures show not only the most rapid growth trajectory, but especially in AST and POL, a proof of coping with structural challenges.

Cross country comparisons show that interaction effects between AST and SBM were critical. The results indicate that nations that strategically implemented both components simultaneously did better economically (for example, Germany and the UK). However, for countries with relative effect of SBM smaller than AST (Italy in early years, Ukraine in 2020 case), the ES values were lower at the beginning. All settings were mediated by policy support and targeted investments.

The empirical analysis proves that the transformation of the agricultural sector and realization of sustainable business models have significant effects on economic security of rural areas. The high performing countries showed clearly that there were strong synergies between innovation and sustainability, with supportive policy frameworks, through the education and employment of diversification. Moreover, we find the non-linear relationship meaning that returns tend to decrease, beyond a

certain point of AST or SBM, emphasizing the need for balanced and coordinated rural development strategies. This work provides critical insights for policymakers who are attempting to build rural resilience and pursue inclusive growth in the face of continued global challenges.

One limitation of this research is that it is limited by the availability and consistency of rural-level data across countries and, thus, also limited in comparability of indices such as AST and SBM. The Economic Security Index constructed is based on composite indicators that do not fully account for informal economic dynamics or intra country regional disparities. However, even when attempting to model interactions non-linearly, there is potential endogeneity between policy interventions and economic outcomes which may bias coefficient estimates. An observation of five years may be too short to capture long term structural shifts in agricultural practice and sustainability transitions. Third, cultural, institution and geopolitical differences among countries models are not included, possibly obfuscating the underlying factors on the context specific drivers of economic security.

Rural economic security can only be maximized by balanced investment in agricultural transformation and sustainable business practice. Lastly, support should be given to education and training programs that are hyper targeted towards sustainable farming and digital innovation to promote long term sectoral resilience. Targeted infrastructure investment and employment diversification initiatives must form part of any integrated rural development strategy. Governments should be designing adaptive policy support frameworks which apply policies based on local economic conditions and incentivize sustainability adoption. Last, enhanced data collection at the regional level is needed to enhance model accuracy and enable evidence-based decision making.

Conclusions. The results show that the economic security of rural areas is highly sensitive to the dual processes of agricultural sector transformation and

application of sustainable business models. A whole of five European country analysis also found that countries scoring high on both modernization and sustainability measures had higher and more stable, rural economic outcomes. A strong indicator of rural economic security was found in Germany and United Kingdom, while Poland and Italy represented moderate but steady improvements. The most dynamic growth, however, was seen in Ukraine, where targeted policy measures and sectoral reform resulted even in structural complexity and post crisis conditions.

The methodological framework applied has demonstrated its ability to detect both linear and nonlinear relationships between key variables that conduct a realistic analysis of how rural development strategies function in real world. Isolated efforts only to transform technology or to practice ecologically are insufficient to have much impact without complementary efforts where infrastructure, education, diversify of employment and policy support are encouraged. These findings argue for systemic, multi-dimensional approaches to rural resilience and inclusive growth.

The objectives of research, evaluating the effects of sector transformation and sustainability, construction of an integrated index, application of a nonlinear econometric model and comparing country specific findings were completed. But there is more to explore in the context of country differences in regional disparities, the long run consequences of climate adaptation policies and the function of digitalization in rural socio-economic security. Future studies should also include an extension of this work to broader geographical areas and the integration of real time policy simulation to make more practical recommendations pertaining to sustainable rural development.

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