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The impact of agriculture in Visegrad countries on CO_2 emissions using the FMOLS and DOLS methods in an empirical panel data study[2]

Introduction

The impact of agriculture on carbon dioxide emissions (CO_2) is a significant subject of scientific research and public debate amidst current environmental and climate change challenges. Climate change poses an urgent problem with far-reaching consequences for society, ranging from the economy and agriculture to health and cultural diversity. The relationship between natural sciences and socio-economic knowledge is fundamental in investigating climate change and its socio-economic outcomes (Danilov-Danil'yan et al., 2020).

The impact of climate change on productivity varies across economic sectors, with global warming and weather instability having a significant impact on agricultural productivity (Nath, 2020). Changes in atmospheric greenhouse gas concentrations, and changes in land structure that lead to climate change affect agricultural crops (Jones et al., 2022). Climate warming also directly and indirectly affects human health, leading to diseases, accidents, and negative psychological effects (Bunz, Mücke, 2017). Overall, tackling climate change is crucial for the sustainable long-term development and well-being of societies.

Excessive CO_2 emissions can cause an increase in temperature, which can lead to reduced plant and animal production, and increased social inequalities (Prandecki, Sadowski, 2010). Additionally, global warming may negatively impact the natural environment by reducing milk production, conception rates

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in animals, appetite, and even increasing mortality (Cho et al., 2011). Changing rainfall patterns and growing seasons can lead to unequal production rates among farmers from different countries. According to Prandecki *et al.* (2020), global temperature increase negatively affects farmers' lives by causing water scarcity, reducing pasture availability, increasing feed costs, and raising expenses for maintaining appropriate building temperatures.

Agriculture is a significant contributor to greenhouse gas (GHG) emissions. The main sources of GHG emissions in agriculture are agricultural soil management, fertiliser application, livestock management, fossil fuel combustion and land use change (Zaman et al., 2021). In the European Union, the structure of agricultural GHG emissions in 2021 was dominated by enteric fermentation, agricultural soils, and manure management (Mielcarek-Bocheńska, Rzeźnik, 2021). Livestock farming is the largest sector of greenhouse gas emissions in EU agriculture, responsible for 70% of total emissions (Panchasara et al., 2021). The remaining 30% is generated by the fuel consumption of machinery, and the use of electricity in agricultural production, fertiliser use and soil exploitation (Caldwell, Smukler, 2020). Crop cultivation, land use change, and post-harvest residue burning are additional sources of agricultural GHG emissions (Jaiswal, Agrawal, 2020). To mitigate these emissions, climate-smart agricultural practices such as conservation tillage, use of cover crops and strategic use of fertilisers can be implemented (Fall et al., 2021). Efforts to reduce GHG emissions from agriculture are crucial to address climate change and ensure sustainable food production.

Agriculture plays an important role in the economies of the Visegrad Group (V4) countries[3], which consists of Poland, the Czech Republic, Slovakia and Hungary. These are diverse regions with a rich agricultural tradition, but agriculture has a significant impact on CO_2 emissions in these countries. At the same time, the V4 countries are striving to reduce greenhouse gas emissions by implementing international climate agreements, such as the Paris Agreement, or the EU's Green Transition Plan (Fit for 55)[4].

There are, however, challenges to achieving the targets set for reducing CO_2 emissions. Due to the constant economic transformation, low-carbon development is still an important issue in the V4 countries and efforts are being made to improve the quality of life while protecting the environment. These efforts include, among others, assessing the eco-efficiency of energy resources and technologies, promoting renewable energy sources and developing distributed energy systems (Dzikuć et al., 2021). The V4 countries also have different approaches and levels of energy transition, with Poland facing the greatest challenges due to its dependence

[3] The Visegrad Group, also known as the Visegrad Four or the V4, is a cultural, economic, and political alliance of four Central European countries: the Czech Republic, Hungary, Poland, and Slovakia.

[4] Fit for 55 is a legislative package of legislation that is intended to be applied to greenhouse gas emissions by 55% by 2030 to the full extent set in 1990.

on coal production (Kochanek, 2021). Among the V4 countries, Poland has not even met its existing commitments to reduce greenhouse gas emissions (Tucki et al., 2021). In general, V4 countries are working on energy transition and GHG emission reductions, but there are different levels of progress and challenges within the group (Gostkowski et al., 2021).

Given the challenges of the energy transition facing the V4 countries, the study aims to answer the question: how do agricultural production, energy consumption, fertiliser usage, and cultivated land area collectively contribute to carbon emissions from agriculture in the Visegrad group countries?

With this research question in mind, this study aims to investigate the factors that contribute to carbon emissions in agriculture, with a focus on the Visegrad countries. Achieving the stated objective required investigating how agricultural production, energy and fertiliser use, and cropland area affect CO_2 emissions from agriculture. The study used empirical econometric modelling methods for panel data such as fully modified ordinary least squares (FMOLS), dynamic ordinary least squares estimator (DOLS) and Granger causality analysis based on the Juodis, Karavias and Sarafidis estimator.

An additional aim of the study is to provide information for policy makers in the formulation of zero-emission policies in agriculture and the adaptation of the economy to the Fit for 55 package.

Literature review

Most studies looking for a relationship between environmental pollution and economic development are based on the concept of the Environmental Kuznets Curve (EKC). It illustrates a hypothetical relationship between environmental quality, and the level of economic development (Selden, Song, 1994). According to the hypothesis underlying the EKC, various indicators of environmental degradation worsen with economic growth until per capita income reaches a certain point during development. Many studies consider in EKC model factors such as the economy's structure, energy consumption, environmental policy, or technological change in various countries and regions (Shahbaz, Sinha, 2019).

European and global CO_2 emissions are largely the responsibility of agriculture, which is also highly sensitive to climate change (Naseem et al., 2020). Econometric studies, to date, have shown that food crop production and livestock farming contribute to CO_2 (Caldwell, Smukler, 2020). The use of machinery, electricity and fossil fuels in agricultural practices such as ploughing, cultivation, and irrigation results in significant carbon dioxide emissions (Shakoor et al., 2022). In addition, the cultivation of certain crops contributes to increased greenhouse gas emissions.

Agricultural value added has been found to have a significant impact on CO_2 emissions in several studies. Some studies suggest a negative association between agriculture value added and CO_2 emissions, indicating that increased agricultural activities can reduce emissions due to the environmentally improving effect of the sector (Doğan, 2018). Research in China using the ARDL method also shows a negative relationship between industrial, agriculture, and services sector value-added and CO_2 emissions in both the short and long run (Huan et al., 2022).

In Pakistan, it was observed that in the long run, agriculture value added is negatively related to CO_2 emissions, indicating that the agricultural sector has the potential to mitigate it (Khurshid et al., 2022). Similarly, in a sample of middle-income countries, it was found that agriculture value added is negatively associated with per capita CO_2 emissions (Majewski et al., 2022). Additionally, in a panel of five North African countries, it was observed that an increase in agricultural value-added leads to a reduction in CO_2 emissions (Adedoyin et al., 2020). Similar observations were also obtained in Bangladesh (Rahman et al., 2020). These findings suggest that promoting sustainable agricultural practices and increasing agricultural value added can contribute to the reduction of CO_2 emissions in underdeveloped countries.

However, some studies conducted in developed countries have found different relationships. The increase in value added from agriculture to GDP has been identified as a driver of CO_2 emissions in developing and transition economies (Adedoyin et al., 2021). Long and Tang (2021) analysed the relationship between economic growth and agricultural carbon emissions in China using the EKC model. They found that economic growth and production growth are the main drivers of agricultural carbon emissions. Khan (2020) examined the determinants of environmental degradation and CO_2 emissions in developing and developed countries. He found that agricultural production has a positive impact on CO_2 emissions from liquid sources and a negative impact on the total CO_2 emissions.

Land use change, including deforestation and conversion of natural ecosystems to agricultural land, also generates increases in carbon emissions (Khan, 2020). Conversion of land for agricultural use, such as deforestation and peatland drainage, is a major contributor to CO_2 emissions (Tubiello et al., 2021).

Agricultural land use plays a significant role in CO_2 emissions and mitigation strategies. Studies have shown that the global technical mitigation potential from agriculture by 2030 is estimated to be around 5500–6000 Mt CO_2-eq, excluding fossil fuel offsets from biomass (Panchasara et al., 2021). The effects of forests and agricultural land on CO_2 emissions have been quantified using the Environmental Kuznets Curve framework, indicating a relationship between land use and emissions (Parajuli et al., 2019). Additionally, the FAOSTAT database highlights that agriculture, forestry, and land use changes contribute up to 30% of anthropogenic greenhouse gas emissions (Tubiello et al., 2013).

The use of fertilisers in agriculture is another factor that contributes to CO_2 emissions. Some studies have shown that increasing atmospheric CO_2 concentrations can lead to a fertilisation effect, enhancing biomass productivity in non-agricultural areas (Amann, Hartmann, 2018). In addition, inappropriate fertilisation and intensive tillage practices can lead to loss of soil carbon and increased CO_2 emissions to the atmosphere (Li et al., 2014). Also, econometric studies indicate that the use of fertilisers to increase agricultural production can contribute to greenhouse gas (GHG) emissions, which have a significant impact on the environment (Wu et al., 2021).

The results of short-run study described that fertilisers usage in agriculture revealed a negative linkage to CO_2 emission in Bhutan (Rehman et al., 2022). The long-term evidence shows that fertiliser usage is positively and significantly associated with carbon dioxide emissions in Pakistan (Rehman et al., 2019). However, according to research by Khan *et al.* (2022), the consumption of chemical fertilisers in China does not show a significant association in the short or long term.

The relationship between energy, agriculture, and CO_2 emissions is intricate and influenced by various factors such as income levels, governance quality, and technological advancements. Studies have shown that there is a significant interplay between these factors in different regions (Ben Jebli, Ben Youssef, 2017). Saidmamatov *et al.* (2023) suggest that economic growth, water production, energy consumption, and electricity production are factors that tend to increase CO_2 emissions from agriculture. Qiao *et al.* (2019) examined the impact between agriculture and economic growth, and renewable energy and CO_2 emissions in G20 countries. They found that agriculture increases CO_2 emissions, while renewable energy use decreases them. Gokmenoglu and Taspinar (2018) tested the EKC hypothesis for agriculture in Pakistan and found that energy has a positive impact on CO_2 emissions. Ali *et al.* (2021) modelled the impact of income, agricultural innovation, energy use, and environmental degradation on CO_2 emissions in Nigeria. The study confirmed the significant impact of energy use on emissions from agriculture.

To date, a wide range of models have been used to investigate the relationship between CO_2 emissions and agriculture. To date, the Auto Regressive Distributed Lag model has been used (Zahoor, 2018), the VAR model (Gurbuz et al., 2021), quantile panel regression techniques (Nwaka et al., 2020), non-linear least squares estimation (Murad, Ratnatunga, 2013), vector error correction model, and Granger causality tests. Some studies have also used FMOLS and DOLS methods (Koshta et al., 2020; Chandio et al., 2020; Dogan, 2019).

In the global literature, the relationship between agriculture, broadly defined, and CO_2 emissions has been investigated using panel data analyses for different groups of countries and regions. The results show that income, economic integration, agricultural value added, and energy consumption are the main drivers of agricultural emissions in both the short and long term (Nguyen et al., 2021; Nwaka et al., 2020; Khan, 2020; Naseem, Guang Ji, 2021).

Several studies have also analysed models that assess the relationship between agricultural CO_2 emissions in the Visegrad countries. The analysis of GHG emissions in these countries showed that the agricultural sector plays an important role in contributing to CO_2 emissions (Wawrzyniak, 2020). Factors such as agricultural exports, cultivated area, agricultural production, agricultural imports, value added in agricultural production and fertiliser use have also been shown to influence CO_2 emissions in the agricultural sector (Simionescu, 2021). At the same time, no study examining the indicated factors, and using modern estimation methods such as panel data analysis or causality tests for the V4 countries, has appeared to date. The analysis aims to fill a gap in the research on this topic, as studies of this nature are infrequent even in European countries.

Methodology

The empirical study was based on the statistics from the World Bank (WDI) and the United Nations Framework Convention on Climate Change (UNFCCC). Time series for the Visegrad countries were examined for the period 1995–2020, covering the maximum available data range for the variables. The variables included in the study were: agricultural carbon emissions (ACO2), fertiliser consumption (F), agricultural energy consumption (AEC), agricultural value added per capita (AGDP), and agricultural land as a share of total land (ALS). Detailed characteristics of the studied variables are presented in Table 1.

Table 1. Variables and description of measurement

Variables	Full name	Unit	Source
lnACO2	Agricultural carbon emissions	tonnes per capita	UNFCCC GHG Data
lnAEC	Agricultural energy consumption	tonnes of oil equivalent per capita	UNFCCC GHG Data
lnAGDP	Agriculture value added	constant 2015 USD per capita	WDI World Bank
lnALS	Agricultural land	% of land area	WDI World Bank
lnF	Fertiliser consumption	kilogrammes per hectare of arable land	WDI World Bank

Source: author's calculation.

The empirical study used panel methods. Due to the relatively small number of cross-sectional units (number of cross-sectional units) of 4, the FMOLS and DOLS model estimation methods were used (Granger, 1988). The model used in the study is a modification of the models previously used by Dogan and Seker (2016), Saboori and Sulaiman (2013) and Zwane *et. al* (2023). However, the variables used in the current study differ from those used in the studies cited. The general form of the model is as follows:

$$ACO2 = c_{0t} + \beta_1 AEC_{it} + \beta_2 AGDP_{it} + \beta_3 ALS_{it} + \beta_4 F_{it+}\varepsilon_{it} \quad (1)$$

The coefficients *β* represent the values of the model variables, *t* the variation of the variables over time and the error termε_{it}.

This paper conducts an empirical analysis of the impact of agricultural activity variables on CO_2 emissions. The study utilised the dynamic least squares (DOLS) method and the fully modified method of ordinary least squares (FMOLS) to determine their long-term relationship. Following the panel data testing methodology, stationarity tests were performed first, succeeded by a cointegration test between variables.

The unit root tests in the study were based on the Im, Pesaran and Shin (IPS) tests (Im et al., 2003). The optimal number of lags was determined using the Akaike information criterion (AIC). Since there was no statistically significant trend in the observations, the tests were conducted for the variant with an intercept point.

Two tests were conducted to identify long-term (cointegration) relationships. Pedroni's residual cointegration test (2004) and Kao's cointegration tests (1999).

Due to the study's relatively small number of cross-sectional units, the FPW estimation method using pooled weight FMOLS was employed. The following is the general form of the estimator used in this study (Pedroni, 2001):

$$\hat{B}_{FPW} = \left(\sum_{i=1}^{N} \sum_{t=1}^{T} \tilde{X}_{it}{}^{*} \tilde{X}_{it}{}^{*,} \right)^{-1} \sum_{i=1}^{N} \sum_{t=1}^{T} (\tilde{X}_{it}{}^{*} \tilde{y}_{it^*} - \lambda_{12i^{*\prime}}) \quad (2)$$

Where weighted variables are created as follows:

$$\tilde{X}_{it}{}^{*} = \hat{\Omega}_{22i}^{-\frac{1}{2}} * \tilde{X}_{it} \quad (3)$$

$$\tilde{y}_{it}{}^{*} = \hat{\omega}_{22i}^{-\frac{1}{2}} * \tilde{y}_{it}^{++} \quad (4)$$

$$\lambda_{12i^*} = \widehat{\omega}_{12i}^{-\frac{1}{2}} * \lambda_{12i}^{+} * \widehat{\omega}_{22i}^{-\frac{1}{2}} \quad (5)$$

In the last phase of the investigation, the testing of causality was conducted utilising the panel data test designed by Juodis, Karavias, and Sarafidis (2021). This test considers cross-sectional dependence and cross-sectional heteroskedasticity in the errors, resulting in more resilient results compared to typical Granger causality tests. Eviews and Stata software, along with the xtgranger package, were used for the computations.

RESULTS

Table 2 presents the fundamental characteristics of the study variables, including the mean, median, standard deviation, maximum, minimum, kurtosis, and skewness measures. The majority of examined variables demonstrate a skewness value close to zero, indicating normality. The kurtosis values, an except lnAGDP are below 3, suggesting the normality of variables. In the case of the variable in question, data distribution that is more pointed (sharper) than a normal distribution.

Table 2. Descriptive statistics

Parameter	lnACO2	lnAEC	lnAGDP	lnALS	lnF
Mean	-3.979	-1.350	5.782	3.931	4.742
Median	-3.873	-1.269	5.863	3.927	4.716
Maximum	-2.908	-0.37	6.355	4.234	5.280
Minimum	-5.356	-2.441	4.509	3.666	4.058
Std. Dev.	0.613	0.512	0.386	0.165	0.289
Skewness	-0.168	-0.306	-1.489	0.116	0.126
Kurtosis	2.082	2.351	5.037	2.020	2.111
Observations	104	104	104	104	104

Source: author's calculation.

Table 3 displays the findings of the panel unit root tests. The results demonstrate that all variables are stationary at the first difference. With the exception of the lnAGDP variables, the study variables are non-stationary in I(0). The results from the stationarity test suggest that the FMOLS and DOLS estimator can be applied.

Table 3. Panel unit root test (IPS)

Variables	Level	1st difference
lnACO2	0.753	-4.619***
lnAEC	-0.680	-4.946***
lnAGDP	-1.315*	-6.675***
lnALS	0.836	-3.828***
lnF	1.664	-5.601***

Note: ***, **, * indicate significance at the 1%, 5%, and 10% levels, respectively.

Source: author's calculation.

After confirming that the variables were not stationary, a cointegration test was performed to determine the link between CO_2 emissions in agriculture and the consumption of fertiliser, energy, value added through agriculture, and the area of agricultural land. The Pedroni cointegration test results are presented in Table 4. Since most of the tests were statistically significant, the null hypothesis of no cointegration was rejected.

Table 4. Pedroni residual cointegration test

Test Statistic	Statistic	Prob.	Weighted Statistic	Prob.
v-Statistic panel	-0.046	0.519	0.190	0.425
rho-Statistic panel	0.392	0.652	-0.388	0.349
PP-Statistic panel	-1.335	0.091	-2.957	0.002
ADF-Statistic Panel	-1.456	0.073	-3.336	0.000
Test Statistic			Statistic	Prob.
Group rho-Statistic			0.141	0.556
Group PP-Statistic			-3.825	0.000
Group ADF-Statistic			-3.949	0.000

Note: Alternative hypothesis: common AR coefs. (within-dimension) and alternative hypothesis: individual AR coefs. (between-dimension).

Source: author's calculation.

To reinforce the reliability of the outcomes, a Kao cointegration examination was executed and shown in Table 5. The null hypothesis of no cointegration was rejected since the test statistic is significant at the 1% level. Thus, the results ratified a long-term correlation's presence among the variables investigated.

Table 5: The Result of Kao's cointegration test

Kao Residual Cointegration Test	t-Statistic	Prob.
ADF	-4.324	0,000
Residual variance		0.006
HAC variance		0.005

Source: author's calculation.

After confirming that the variables are co-integrated, a FMOLS model was estimated to investigate the relationship between the variables. The results are presented in Table 6. The choice of the optimal model parameters was based on the values of the R and R^2 parameters. All coefficients are statistically significant at the 1% level, indicating their significant impact on CO_2 emissions in Visegrad country agriculture. It is important to note that these results should be interpreted in a long-term perspective:

– a 1% increase in energy consumption in agriculture leads to an increase in CO_2 emissions of 0.73% in the long term,
– a 1% increase in added value from agricultural production leads to an increase in CO_2 emissions of 0.43% in the long term,
– a 1% increase in fertiliser use leads to a 0.29% increase in CO_2 emissions over the long term,
– an increase in the share of agricultural land of 1% leads to an increase in CO_2 of 0.95%.

Table 6. Results from the panel fully modified ordinary least square approach (FMOLS)

Variable	Coefficient	Std. Error	t-Statistic	Prob.
lnAEC	0.733	0.072	10.207	0.000
lnAGDP	0.426	0.066	6.435	0.000
lnALS	0.945	0.042	22.549	0.000
lnF	0.288	0.077	3.720	0.000
R-squared				0.947
Adjusted R-squared				0.943
S.E. of regression				0.147
Long run variance				0.015

Source: author's calculation.

The DOLS model was estimated to confirm the findings from the FMOLS model (Table 7). Both models yielded consistent results in terms of coefficient signs and significance, bolstering the robustness of the study's conclusions. The DOLS model provided a higher level of fitness, as evidenced by the R and R^2 values. The estimation further validates the robustness of the results.

Table 7. Results from the panel dynamic least square approach (DOLS)

Variable	Coefficient	Std. Error	t-Statistic	Prob.
lnAEC	0.548	0.064	8.589	0.000
lnAGDP	0.503	0.114	4.416	0.000
lnALS	1.325	0.377	3.516	0.001
lnF	0.644	0.138	4.674	0.000
R-squared				0.985
Adjusted R-squared				0.963
S.E. of regression				0.119
Long run variance				0.007

Source: author's calculation.

Causality tests

The study's final stage entailed examining the causal relations amongst CO_2 emissions, fertiliser consumption, agricultural energy consumption, agricultural value added per capita, and agricultural land area as a proportion of total land. The aim of this approach is to validate the long-term relationship between the time series under consideration, and to determine its direction. At this stage of the research, we employed the estimator for Granger non-causality tests for panel data, which was developed by Juodis, Karavias, and Sarafidis (JKS). Table 8 presents the z-statistic and statistical values indicating the cause-effect relationship between the variables.

Table 8. Panel Approach to Granger's causality test

Causality → effect	*Z*-statistics	*p*-value
lnAGDP → lnACO2	2.79	0.005
lnACO2 → lnAGDP	-1.47	0.141
lnAEC → lnACO2	2.57	0.010
lnACO2 → lnAEC	-0.97	0.332
lnALS → lnACO2	2.00	0.046
lnACO2 → lnALS	0.02	0.988
lnF → lnACO2	2.69	0.007
lnACO2 → lnF	5.9	0.000
Half-Panel Jackknife Wald test statistic	17.44	0.002

Note: The null hypothesis in the procedure in question is defined as "variable X does not cause causality of variable Y".

Source: author's calculation.

The BIC information criterion determined the lag length. A test statistic of 17.438 and a *p*-value of 0.002 demonstrate solid evidence of rejecting the null hypothesis of Granger non-causality. This implies that the observed results are highly probable. The z-statistic values for the individual variables indicate both unidirectional and bidirectional causality. Bidirectional causality exists between fertiliser consumption and CO_2 emissions (lnF←→lnACO2).

Increased carbon dioxide emissions from agriculture can reduce the worth added by agriculture. This occurs due to the impact on climate change, making crop growth and livestock rearing more challenging. Moreover, ascertaining reduced CO_2 emissions also impacts agricultural profitability. Increased added value in agriculture can result in higher CO_2 emissions due to the greenhouse gases released by more efficient and extensive cultivation and breeding methods. Similarly, increased fertiliser usage can lead to higher CO_2 emissions as soil amendments release more greenhouse gases into the atmosphere. Additionally, increased CO_2 emissions can result in more fertiliser usage due to the detrimental effects of climate change, such as reduced soil fertility caused by droughts.

Unidirectional causality was instead confirmed between farm area and CO_2 emissions (lnALS→ lnACO2) and agricultural energy consumption and CO_2 emissions (lnEC→ CO2).

Farm area emerges as the key driver of agricultural CO_2 emissions, with larger farms contributing more. That causality highlights the need for strategies that address area-related emissions in agricultural practices. In the second case, on the other hand, the result indicates that energy consumption in agriculture is also the main factor influencing CO_2 emissions from agriculture. The greater the energy consumption in agriculture, the greater the CO_2 emissions from agriculture. All relationships are illustrated in Figure 1.

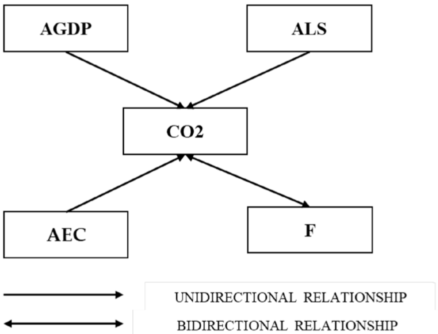

Figure 1. Relationships between study variables established by the causality test

Note: AGDP – added production by agriculture, ALS – agricultural area, F –fertiliser consumption, AEC – energy consumption by agriculture.

Source: author's calculation.

Conclusions and discussion

The results obtained from the model estimations for the Visegrad countries confirm that CO_2 emissions are influenced by an increase in the volume of production in agriculture expressed in terms of value added. These results are in line with previous studies, which indicated that there is a relationship between economic growth and agricultural output growth and CO_2 emissions from agricultural production (Adedoyin et al., 2021). However, it is worth noting that in developing countries, an increase in agricultural production has been observed to lead to a reduction in CO_2 emissions, which is in contrast to what is typically observed in developed countries (Doğan, 2018; Huan et al., 2022).

Another observation obtained, indicating that increasing the area of agricultural land increases CO_2 emissions, corresponds with these results. Such results were previously confirmed by Zhang *et al.* (2018) and Yerli *et al.* (2019). Therefore, it should be noted that a rise in agricultural production volume has an adverse effect on the environment, as it leads to higher consumption and utilisation of natural resources.

The results also indicate that increasing energy consumption by agriculture increases CO_2. Previously, similar relationships were indicated by Appiah *et al.* (2018) and Flammini *et al.* (2021). However, it is important to note that an increase in energy consumption in agriculture does not always have a negative impact on the environment. Numerous studies show that increasing the use of renewable energy has a positive impact on the environment by reducing CO_2 emissions from agriculture (Ben Jebli, Youssef, 2017). Studies have shown that it has a one-way causal impact on both agriculture and emissions, highlighting its potential for positive environmental impact (Appiah et al., 2018). Furthermore, the use of renewable energy has been shown to significantly reduce CO_2 emissions, especially in countries with lower incomes (Naseem, Guang Ji, 2021).

Also, the results of the study indicate negative environmental impacts of fertilisers used by the agricultural sector in the V4 countries, which corresponds to the findings of Zwane *et al.* (2023). The results confirm that CO_2 emissions in the Visegrad countries are increased by agricultural production, energy and fertiliser consumption, and the area of cultivated land.

Summary and implications

The study analysed the correlation between agricultural growth, fertiliser consumption, energy consumption, agricultural land expansion and agricultural carbon dioxide emissions in the Visegrad countries from 1995 to 2020. Cointegration was used to establish long-term associations between variables and both FMOLS and DOLS models were estimated. Finally, to establish the links between variables and to highlight potential future research avenues, a cointegration analysis was conducted using the seminal JKS estimator.

The results suggest that the agricultural sector is positively related to CO_2 emissions from agricultural activities in the V4 countries. As a result, policies aimed at reducing these emissions should centre on lowering energy consumption in agriculture and enhancing the agricultural production efficiency with limited resources. Additionally, the results indicate that reducing CO_2 emissions should involve decreasing the amount of land devoted to agriculture and lowering fertiliser usage. However, such activities of the Fit for 55 package and the "From Farm to Fork" strategy for the accessible have access to users who use external resources and may impact productivity. Farmers must require support from the Member State to ensure emissions levels with reduced greenhouse licensing. Without applying the procedure that followed, the agriculture of the V4 countries will suffer due to the issuance of the Green Deal.

It is therefore worthwhile for the right measures to be implemented at the time of the energy transition. Firstly, it should focus on promoting new, greener agricultural practices. Over the past decade, the share of EU agricultural land under organic farming has increased by more than 50%, with an annual growth rate of 5.7%. Small-scale ecological farming can lead to equity and efficiency gains, while land redistribution toward smaller farms can promote economic growth. In V4 countries, ecological farming has share of on average 15% of farmland (Wrzaszcz, 2023). However, it should be borne in mind that due to the lower efficiency of organic crops, small farms will not be able to replace the reduction in production resulting from the implementation of climate goals (Chiarella et al., 2023). Secondly, it is required to improve energy efficiency in agriculture by investing in new technologies and machinery, low and zero carbon. The implementation of individual RES on farms may also be a solution.

Thirdly, increasing the added value from agricultural production should be done by promoting smaller farms and organic production methods, while at the same time using more efficient farming methods. Fourthly, with alternative methods such as composting and biopesticides, V4 countries should aim to reduce the use of fertilisers. Furthermore, it will be necessary to decrease the amount of agricultural land by reclaiming it and repurposing it for other uses, such as forests and parks.

In contemplating the future, the integration of renewable energy sources emerges as a pivotal consideration for agriculture. Embracing energy derived from renewables such as solar, wind, and biomass offers farmers the prospect of diminishing reliance on conventional, frequently pollutant-laden, energy outlets. This not only fosters the advancement of sustainable practices but also yields positive ramifications for the environment by mitigating the greenhouse gas emissions linked to traditional energy sources. Future-oriented initiatives might encompass the implementation of photovoltaic panels, the adoption of wind turbines, or the extraction of biogas from agricultural waste. Envisioned in this manner, agriculture charts a course toward heightened environmental sustainability, concurrently playing a substantive role in advancing global objectives for reducing CO_2 emissions.

Implementation of the proposed solutions will also require a significant investment in research and development (R&D), as well as in agricultural subsidies. Increased investment in R&D directed towards sustainable agricultural practices, precision farming technologies, and climate-resilient crop varieties can lead to innovative solutions that enhance productivity while minimising environmental impact. By fostering advancements in agroecology, water management, and energy-efficient farming techniques, R&D contributes to a more sustainable and low-carbon agricultural sector.

Simultaneously, agricultural subsidies can be strategically employed to incentivise practices that reduce CO_2 emissions. Redirecting subsidies towards eco-friendly practices, such as organic farming, agroforestry, or the adoption of renewable energy in agriculture, can stimulate a transition to more sustainable and environmentally conscious approaches. This financial support serves as a lever for steering agricultural activities towards practices that align with climate mitigation goals. It will also require the organisation of educational and awareness-raising initiatives on the matter.

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Summary

The primary aspiration of this paper is to learn about the effects of agricultural energy consumption, agriculture value added, agricultural land and fertiliser consumption on environmental pollution in Visegrad countries. The research employs panel data from long-run models FMOLS and DOLS, covering the period from 1995 to 2020. The study suggests that there is a positive and statistically significant correlation between CO_2 emissions from agriculture in Central and Eastern European countries, and factors such as higher energy consumption, increased value from agricultural production, greater fertiliser consumption, and larger arable land areas. The FMOLS and DOLS models' long-term coefficients suggest that energy consumption in agriculture and crop area are the main factors contributing to the increase in CO_2 emissions from agriculture in the studied countries. The study recommends a sustainable energy transformation of agriculture by limiting the use of fossil fuels in agricultural production and reducing share of arable land.

Keywords: agriculture, CO_2 emissions, Visegrad Group, panel methods, energy.

Wpływ rolnictwa krajów Grupy Wyszehradzkiej na emisję CO_2. Dowody z badania empirycznego danych panelowych przy wykorzystaniu metody FMOLS i DOLS

Streszczenie

Głównym celem niniejszego artykułu jest poznanie wpływu zużycia energii w rolnictwie, wartości dodanej w rolnictwie, zużycia gruntów rolnych i nawozów na zanieczyszczenie środowiska w krajach Grupy Wyszehradzkiej. W badaniu wykorzystano długookresowe modele danych panelowych FMOLS i DOLS, obejmujące okres od 1995 do 2020 roku. Wyniki badania wskazują, że istnieje pozytywna i statystycznie istotna korelacja między emisjami CO_2 z rolnictwa w krajach Europy Środkowej i Wschodniej a czynnikami takimi jak wyższe zużycie energii, zwiększona wartość produkcji rolnej, większe zużycie nawozów i większe obszary gruntów ornych. Długoterminowe współczynniki modelu FMOLS potwierdzają, że zużycie energii w rolnictwie i powierzchnia upraw są głównymi czynnikami przyczyniającymi się do wzrostu emisji CO_2 z rolnictwa w badanych krajach. W oparciu o wyniki badania, zaleca się zrównoważoną transformację energetyczną rolnictwa poprzez ograniczenie wykorzystania paliw kopalnych w produkcji rolnej i rekultywację części gruntów.

Słowa kluczowe: rolnictwo, emisja CO_2, Grupa Wyszehradzka, metody panelowe, energia.

JEL: Q15, Q32, Q43, Q50, B23.