JEL: F02, F42, O13, Q50

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INTERNATIONAL CONVERGENCE TOWARDS A CLIMATE-NEUTRAL ECONOMY: MODELING THE AGRICULTURAL SECTOR

Purpose. *This article aims to construct a comprehensive convergent model for assessing the global and EU's progress, degree of consolidation and symmetry of agricultural economies towards climate neutrality in the context of key international green initiatives.*

Methodology / approach. *This research employs both qualitative and quantitative analyses to assess convergence measures in the agricultural sector's carbon emissions. The quantitative component relies on the sigma and beta convergence models to evaluate international convergence in carbon emissions* CO_2 *dynamics. The dimensions of modeling are as follows: global sample within 194 countries with reliable emissions data; European Union, focusing on convergence within the EU27 member states, the United Kingdom, and Ukraine. The time period covers open data from 1972–2022. The dynamics of sigma and beta convergence is determined for the points, namely UN Stockholm Conference (1972), UN Rio Conference (1992), Kyoto Protocol (entry into force in 2005), Paris Agreement (2015). Additionally, statistical indicators of variation, skewness, Gini and Theil indices were calculated for delineating global smoothness and the concentration of agricultural emissions.*

Results. *The results of the study reveal an inertial and divergent trend of the agricultural economy towards decarbonisation, which slows down the overall movement towards "net zero" due to the presence of clubs of lagging agricultural countries that increase emissions in violation of international agreements. The reduction in emissions skewness in recent years shows that more countries are "pulling" decarbonisation due to their high capacity to move towards net zero, but this is not enough. The EU is the most prominent example of accelerated climate convergence, but markers of its weakening in recent years are identified due to the inability of economies to maintain the pace of decarbonisation caused by economic constraints, technological barriers, policy and regulatory issues, and misunderstandings of climate neutrality goals. It is shown that the long-term decarbonisation capacity of the agricultural sector is the key trigger for a country to make a positive contribution to the global convergence towards climate neutrality. At the current stage, the pace of decarbonisation plays a much greater role for consolidating efforts in the agricultural economy and achieving climate neutrality than the initial level of emissions in the sector. Factors in this process include proactive compliance with global climate agreements, technology sharing and cooperation, digitalisation and smart agriculture, and green financing and investment. Its implementation requires a three-way integration of stakeholder actions, strategy selection and results evaluation.*

Originality / scientific novelty. *The study's originality lies in its large-scale analysis of over 50 years of emissions dynamics and the context of five key green agreements that provided support for the green transition. It allows studying international convergence in agricultural sectors* *globally and within the EU. The novelty implies the integrated use of sigma and beta convergence models that identifies predictors of convergent and divergent processes and separates countries into leaders and laggards of agricultural decarbonisation. This approach provides a comprehensive view of modern climate policy, the impact of international green initiatives, and the position of individual towards climate neutrality in agriculture.*

Practical value / implications. *The practical value lies in the ability to adjust climate policies for the agricultural economy's decarbonisation, facilitating the determination of prospective outcomes for achieving climate neutrality. The aforementioned factors facilitate the process of governmental decision-making. The assessment of international programmatic agreements' effectiveness is enhanced through these models. The study offers a framework for global convergence towards climate neutrality in agriculture, highlighting the importance of digital technologies and smart agriculture as significant factors in global convergence.*

Key words: *agricultural economics, convergence, climate-neutral economy, digitalisation, agricultural decarbonisation.*

1. INTRODUCTION

The concept of a climate-neutral economy has emerged as a prominent topic on the global policy agenda, reflecting the growing urgency to address climate change. Over the past decade, countries around the world have demonstrated a significantly greater sense of unity in their efforts to combat climate challenge and a growing recognition of the irreversibility of this process. However, the level of international consolidation does not yet allow us to speak of multilateralism of the climate-neutral paradigm. While the EU offers a plethora of umbrella solutions for the development of a green economy, their implementation remains feasible for a select group of countries. Conversely, the majority of developing countries lack the capacity to implement effective climate policies without substantial external support. Moreover, the climate crisis is compounded by the continued dependence of national economies on fossil fuels, geopolitical instability, fragmented regulatory policies, technological capacity, and the relatively high capital intensity of green transition for industries that are the largest polluters of the global economy.

The issue of climate change is becoming increasingly pressing for the agricultural sector of the global economy. The multifaceted nature of its impact is a primary contributor to this urgency. On the one hand, the modern agricultural sector and related industries exert a significant influence on climate change. They are responsible for up to 24 % of global carbon emissions, as well as 10.5 % of EU emissions [1]. Conversely, the agricultural sector is particularly vulnerable to climate change, necessitating the implementation of effective adaptation and mitigation strategies. Given the unique characteristics of this sector, it may necessitate a greater degree of attention and scrutiny than is typically afforded to similar areas of the economy. This is due to the sector's high sensitivity to climate variability, which affects yield, quality of agricultural production, and resource availability [2]. The impact of climate change on the agricultural sector also has far-reaching social and economic implications, including food security and the incomes of rural communities, particularly in developing countries where agriculture is the primary source of livelihood [3].

In light of these considerations, the crucial and highly significant challenge in guaranteeing the climate neutrality of the agricultural economy is the necessity for a unified and unwavering commitment from global actors. The efficacy of this commitment is directly reflected in the international convergence towards global decarbonisation. Such a convergence is manifested in processes, which actively engages the agricultural economies in the global quest of achieving climate neutrality. Concurrently, this is the "sine qua non" importance to achieve a balance between the long-term climate resilience of the agricultural sector and its productivity.

The identification of convergent and divergent trends in agricultural decarbonisation allows for the clear distinction between leading countries that can serve as the locomotive of the global climate movement and lagging countries that now require special support. Such a partnership is crucial because the ultimate outcome of the movement towards net-zero of the entire global economy [4]. Conversely, an understanding of convergence is fundamental to the development of international targeted policies, the stimulation of innovation, the assessment of progress towards climate neutrality, and the revision of world objectives towards more realistic ones [5].

The European Union represents the most compelling example of convergent decarbonisation processes. Currently, the European Commission (EC) is proposing promising prospects for achieving climate neutrality in the agricultural sector by 2050. This is being accomplished through the EU-funded ClieNFarms project, which highlights the necessity for more real-life experiments and a clear framework to encourage sustainable carbon farming solutions is made evident [4]. This represents a component of an initiative with a broader scope, which aligns with the European Green Deal. However, the convergence and effectiveness of such programs can only be assessed in the long term, by analysing the entire retrospective dynamics of decarbonisation.

The objective of this article is to construct a convergent models for assessing the advancement of integration and consolidation of the international dynamics towards climate neutrality of the agricultural sector in the context of pivotal green initiatives. Additionally, recommendations will be formulated regarding the factors of convergent-divergent processes of global decarbonisation. An important concept to be explored is the convergence of decarbonisation processes within the agricultural economy over an extended period of time, in relation to the formative global environmental initiatives that imposed responsibility on countries under relevant international agreements in EU and globally.

2. LITERATURE REVIEW

The topic of global and regional convergence is periodically discussed in academic circles, sparking lively debate. An analysis of the academic literature reveals that modern researches examine global convergence in the context of policymaking, regional integration, and environmental considerations.

In his work, S. Tramel treats convergence as a strategic response to global crises. He poses an idea, that convergence is about disparate social justice movements (agrarian, environmental, indigenous) uniting human efforts in the face of common challenges such as climate change, resource exploitation, and social inequalities [5]. This highlights the strategic use of convergence to enhance the effectiveness of political and social activism.

The analysis of sources reveals that it is crucial to consider the following aspects when evaluating convergence:

1) a comprehensive historical review should be undertaken. It is essential to assess the convergence and divergence of processes based on wide samples of information and the historical context of international events [6; 7; 8];

2) economic convergence should be assessed beyond the income. The concept given by Chakraborty propose to include 'real' dimensions such as nutrition, health, education, emissions, and shelter [9]. Thus, it presents a methodology to assess convergence across regions, emphasising that true well-being extends beyond economic metrics to include broader quality-of-life aspects;

3) behind interdisciplinary nature of convergence, it is crucial to keep the key focus during several decades of investigation. For instance, Marelli et al. analyse economic convergence within the European Union and the Eurozone, focusing on real, conditional convergence in per capita income [10]. Profound samples allow discussing the impact of various crises and evidences on convergence processes, particularly highlighting slower convergence in the Eurozone compared to the broader EU. On the other hand, while Kinfemichael examines labor productivity from 1991 to 2016 across various sectors, he focuses exactly on the role of the service sector in leading the convergence of labor productivity globally, suggesting a shift in sectoral composition of economies that affects overall productivity [11].

Convergence research is an area with considerable potential, as evidenced by the impressive outcomes of these foundational studies. However, there is a need to devote more attention to convergence in the field of environmental and green economics.

Höhne et al. made the first and the most promising attempt to realize this problem. They introduced the concept of "common but differentiated convergence (CDC)" within international climate policy [12]. This approach aims to harmonise the per-capita emission allowances of countries over a set period, with allowances converging to a low level globally. However, since the targets for developing countries are described as "voluntarily" and "positively binding", there might be a lack of compelling mechanisms to ensure participation and compliance, which could undermine the overall effectiveness of the CDC approach.

Brown et al. discuss convergence in the context of physical predictors and consequences of human-induced climate change, such as emissions volume, meteorological phenomena, weather patterns etc. [13]. Thinking this way, Wilson uses convergence to describe an interdisciplinary approach to research that brings together diverse scientific disciplines to address complex societal challenges like climate change [14]. Sun et al set a concept of "environmental efficiency convergence" that is conditional on industrial structure, globalisation and consumer price index [6].

It is also worth noting the study by D. Liu, who uses carbon emissions as the basis for the study of the convergence of China's regions [15]. This is justified by the fact of reducing carbon emissions, adopting differentiated policies, adjusting the industry scale, and enhancing the industry technology intensity, global manufacturing can improve the energy efficiency of carbon emission and promote high-quality economic development. At the same, the possibility of "country club" should be taken into account within convergence evaluation [16].

Despite wide range of scientific ideas, we have noted the lack of studies on convergence processes in the agricultural economy, in particular the global decarbonisation. As for the studies on convergence between EU countries in other economic sectors, the selected sample periods are fragmentary and not linked to formative events, which also does not allow us to trace the cause-and-effect relationships and the effectiveness of the consolidated efforts of the international community. These aspects have been taken into account in the construction of the methodology of this study.

3. METHODOLOGY

The research methodology includes both qualitative and quantitative analysis. The quantitative assessment of convergence is based on the prominent mathematical models of sigma and beta convergence. Their mathematical apparatus was used to assess international convergence between the dynamics of carbon emissions in the agricultural sector of the economy in the following dimensions:

- global scale (194 countries, which provided reliable data on emissions from the agricultural sector of the economy);
- European Union;
- EU27 + Great Britain + Ukraine.

In order to construct the mathematical apparatus of the study, we used the methodical approaches for computing convergent models described in few papers [17; 18; 19].

Given the novelty of our study's approach, it is considered necessary to delineate the fundamental aspects of our methodology for constructing sigma (σ) and beta (β) convergence models.

Firstly, the concept of convergence is used to examine the disparities in socio-economic development among regions, premised on the idea that regional development indicators tend to converge to a specific level over time.

The sigma convergence used in the study is as follows autoregressive model:

$$\sigma^2_t = b \cdot \sigma^2_{t-1} + \sigma^2_e, \tag{1}$$

where σ^2_t is the variance of the indicator under study at time t. In the context of this equation, it reflects the current variability of emissions among countries;

b – the autoregression coefficient. It is a key parameter in the model. It quantifies the extent to which the variance observed in the previous period, denoted by σ^2_{t-1}, influences the current variance. This coefficient plays a pivotal role in determining the stability of emissions variance over time and serves as an indicator of sigma convergence. If b is less than 1, it indicates that dispersion decreases over time, suggesting that emissions in the sample of countries under study are converging;

σ^2_e is actually the variance of the random error of the model over time t (the stochastic element of the model), which takes into account random shocks or variations that cannot be explained by the past variance.

Interpretation: the conclusion about the presence of σ-convergence can be made if $0 < b < 1$, which indicates a tendency to reduce differences between regions in dynamics of agricultural sector emissions.

It is important to note that the determination of convergence based on the b coefficient may not provide a comprehensive understanding of the nuances of the global emissions trend, including its skewness, inequality, and concentration in specific periods. This knowledge can be particularly valuable in the context of assessing emissions dynamics in the context of international agreements and justifying governmental management decisions when convergence is implicit (e.g., the sigma convergence coefficient is close to 0). Thus, for a deeper understanding of sigma convergence, a set of classic statistical indicators was selected to assess the consolidation and smoothness between the emission dynamics of national economies:

1. The coefficient of standard deviation (K_{dev}) measures the homogeneity within a set of objects and is used to evaluate the distribution of agricultural emissions across different countries.

2. The asymmetry coefficient or coefficient of skewness (A) illustrates the skewness of the distribution, which indicates an uneven distribution of agricultural emissions across countries.

3. Gini index (G) is used to determine the average ratio of high emitting countries to low emitting countries. It allows for the assessment of the degree of inequality in the distribution of emissions among the world's agricultural economies. The index ranges from 0 to 1, with 0 corresponding to absolute equality (each country contributes a relatively equal share of emissions) and close to 1 corresponding to absolute inequality (one country or a limited club of countries is responsible for the aggregate emissions of the agricultural sector in global terms).

$$G = (\sum^n_{i=1}\sum^n_{j=1}|y_i - y_j|) : (2n^2 \cdot y_{mean}), \quad (2)$$

where y_i y_j – emissions of countries. In the context of the Gini index, both of these variables are used to calculate the total absolute difference between all possible pairs of countries, which makes it possible to assess the overall inequality of the distribution of emissions of the global agricultural economy;

y_{mean} is the average emissions based on the number of countries n in the sample.

4. Theil Index (T) is a measure of inequality that is typically used to assess the concentration of emissions.

$$T = 1 : n \sum^n_{i=1}(y_i : y_{mean})^2 - 1, \quad (3)$$

where y_i is the country's emissions;

y_{mean} is the average emissions for the country.

The indices facilitate the assessment of the uneven distribution of emissions across countries. This allows for the evaluation of the effectiveness of international agreements and policies to reduce emissions from the agricultural economy over time.

The beta convergence model builds upon the sigma model to identify regions (in our case country clubs), that produce the highest agricultural sector emissions but demonstrate promising emission reduction rates. This is in contrast to countries that have already achieved significant decarbonisation in their agricultural economies. Beta convergence enables us to highlight countries that are leading the transition towards climate neutrality, as well as those that are hindering overall progress and contributing to divergence.

Among the various interpretations of the beta convergence model, the Baumol regression model is the one of choice in our study:

$$ln(y_{i,T} : y_{i,0}) = \alpha + \beta \cdot ln \quad y_{i,0} + \varepsilon, \qquad (4)$$

where $y_{i,T}$ is the growth rate of the i-th country's indicator at the time point T;

$y_{i,0}$ is the growth rate of the i-th country's indicator at the initial time point;

α, β are the model parameters.

Interpretation: the presence of beta convergence is confirmed if the estimated coefficient $\beta < 1$ and is statistically significant. This indicates a tendency to reduce the differentiation of emissions between the agricultural economies of the countries studied.

The obtained convergent models are proposed to be evaluated in the following periods, for which the relevant samples of CO_2 emissions of the agricultural sector were formed:

Point 1. 1972 – UN Stockholm Conference. The sample is 1972–2022.

Point 2. 1992 – UN Rio Conference, Earth Summit. The sample is 1992–2022.

Point 3. 2005 – Kyoto Protocol (ratification). The sample is 2005–2022.

Point 4. 2015 – The Paris Agreement. The sample is 2005–2022.

Point 5. 2019 – Green Deal. This point is taken into account in the assessment of convergence, but a model for it has not been built in this study, given the small time interval of the sample, which does not yet allow for relevant results.

These points have been selected in alignment with key global initiatives that contribute to multilateral efforts to combat climate change and revise the economic paradigm.

The data samples for the convergence study were built using open big data from the authoritative GHG emissions report [20], which is produced annually under the patronage of the European Commission and provides a globally accepted methodology for collecting data on carbon emissions from various sectors of the economy.

In addition to quantitative analytical methods, qualitative retrospective and inductive analysis were used. This comprehensive approach allowed for the evaluation of the convergence model results, the assessment of the dynamics of joint development among countries, and the effectiveness of policies and collaborative efforts in decarbonisation. Furthermore, it enabled the identification of factors influencing convergent and divergent processes towards climate neutrality in the agricultural economy. In particular, joint international program initiatives, an understanding of decarbonisation goals, and the potential to maintain a stable rate of emissions reduction are of particular interest. Other factors include technological and innovation barriers, the application of smart technologies, fluctuations in the economy and energy consumption, changes in energy efficiency policies, and so forth.

4. RESULTS

The challenge of achieving climate neutrality in the agricultural sector promotes a new production paradigm wherein all agricultural activities do not contribute to an increase in atmospheric GHG concentrations. This balance is achieved by ensuring that the emissions produced by the sector are fully absorbed or offset. Thus, the volume of CO_2 emissions is viewed as a direct outcome of the agricultural sector's complex activities, reflecting the efficiency of agricultural practices, the adoption of clean technologies, and energy efficiency measures.

Achieving this goal typically relies on the following technology-oriented strategies, which should be integrated into agricultural business practices worldwide [3; 21]:

1) direct emission reduction entails the implementation of sustainable agricultural technologies, the optimisation of resource use, and the transition to renewable energy sources in place of fossil fuels. This approach is designed to minimise the emissions of CO_2 and other greenhouse gases;

2) enhanced resilience involves developing and applying adaptive agricultural practices that can withstand climate change and mitigate its impact on production;

3) carbon sequestration involves using natural or technological methods to capture carbon from the atmosphere. This includes practices such as afforestation, improved soil management, and various bioengineering approaches.

The complexity lies in the fact that the implementation of these strategies requires time and consolidated efforts by the global community. In addition, several years may pass between the ratification of green policy initiatives and the first results in terms of emissions reductions. Due to this significant time lag, the effectiveness of green policies can only be evaluated over a long period of time. Thus, climate neutrality presents a challenge for the economy, underscoring the need for broader systemic changes in agricultural practices to enhance sustainability and minimise their impact on the climate.

In this context, reviewing the convergence of agricultural economies in their collective movement towards climate neutrality allows us to analyse a range of critical issues. These include identifying leaders and laggards, developing targeted policies, stimulating innovation, assessing international cooperation, analysing progress, and setting targets. This comprehensive functionality is vital because, ultimately, the study of efficiency growth and convergence is crucial for enabling countries to evaluate their use of inputs and adopt technologies to increase productivity [6].

In the context of climate-neutral economy, the key outcome indicator for assessing the convergence of agricultural sectors is the volume of CO_2 emissions. This is due to a number of reasons:

Firstly, the obvious standardisation and comparability of CO_2 emissions, as a globally accepted and quantitatively measurable indicator, allows for the comparison of metrics across countries with varying agricultural conditions and levels of development [15]. This ensures objectivity and accuracy in assessments.

Secondly, CO_2 dynamic serves as a key indicator of an economy's impact on climate change, contributing to its global shifts [22]. Monitoring emissions in the agricultural sector enables the assessment of the direct impact of agricultural activities on the climate, which is crucial for understanding how effectively each country is progressing towards climate neutrality.

Thirdly, CO_2 emissions can be considered as an indicator of technological adaptation and innovation. Agricultural emissions reflect the application of technologies, sustainable practices, and the implementation of innovations [21]. A reduction in emissions may be indicative of effective resource utilisation, a transition to more sustainable production methods, and the adoption of alternative energy sources.

Fourthly, the volume of emissions is a critical target for international cooperation and policymaking in the context of "greener future". CO_2 emissions in agriculture are a significant component of international climate agreements, which aim to enhance coordination among countries in terms of technology exchange, joint initiatives, and adherence to international commitments.

By examining the evolution of carbon emissions in the agricultural sector in relation to pivotal international environmental initiatives, we can evaluate the extent to which these milestones have influenced the collective trajectory towards decarbonisation and climate neutrality.

The following international initiatives have been identified as directly influencing the climate convergence processes in different sectors of the global economy:

1) The UN Stockholm Conference (1972) established an "embryonic stage" for global environmental governance, with limited immediate implications for carbon emissions reduction specifically within the agricultural economy. The conference's outcomes were instrumental in raising awareness rather than enforcing actionable decrees on emissions.

2) The UN Rio Conference, Earth Summit (1992) laid the groundwork for future climate action, culminating in later protocols and agreements. Although the summit fostered the notion of sustainable development, it did not explicitly articulate actionable mandates targeting the agricultural sector's decarbonisation.

3) The Kyoto Protocol (2005) imposed emission reduction obligations on

developed countries and offered a system of flexible mechanisms designed to assist countries in their efforts to reduce emissions through economically oriented instruments. These included the mechanisms of clean development, joint implementation, and international emissions trading. However, it should be noted that the more substantial emission reduction obligations in terms of quantitative changes were imposed mainly on developed countries (List of Annex I countries of the Protocol).

4) The Paris Agreement (2015) has become a legally binding commitment of countries to reduce global emissions and support the concept of Nationally Determined Contributions. In particular, it motivates countries to update their own goals for progressive emission reductions every five years. The agreement is multilateral in nature and necessitates an integrated approach to the process of decarbonisation. Furthermore, it demands that governments implement measures to reduce emissions across all sectors of the economy, including agriculture. Finally, it requires the setting and achieving of measurable emission reduction targets.

5) The Green Deal (2019) represents the European Union's ambitious framework for achieving a decarbonised economy, encompassing agriculture. It represents a roadmap toward significant emissions reduction, employing innovative technologies and sustainable practices.

Accordingly, the agricultural economy produces emissions characterised by ambiguous dynamics (Figure 1).

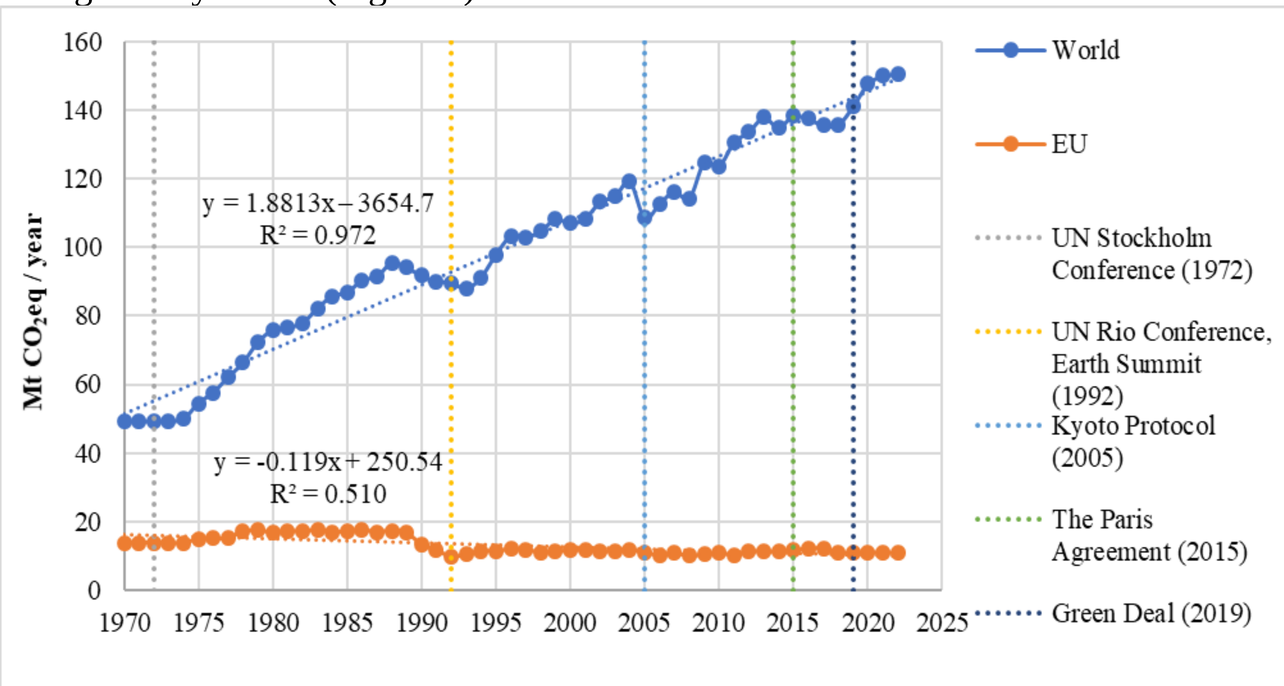


Figure 1. Dynamics of emissions from the agricultural sector of the economy in relation to the retrospective of international climate initiatives

Source: authors' delineation based on open data [20].

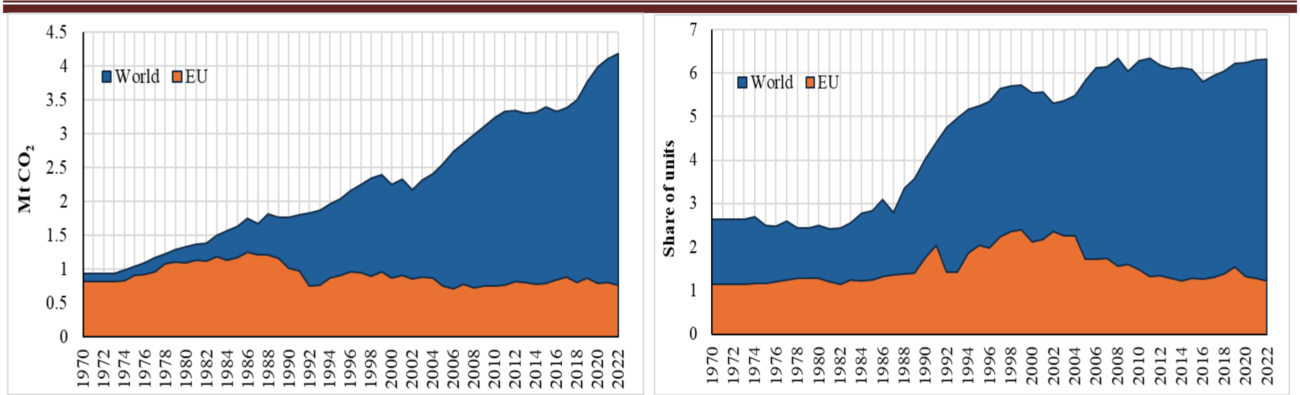
A consistent and notable increase in emissions from the agricultural sector is being observed globally. Emissions from the global agricultural economy have doubled in more than half a century. However, in 2022, the rate of growth slowed somewhat in comparison to the years following the key international agreements. Agricultural emissions in 2022 increased by 67.8 % since the Rio Conference in 1992. By 38.7 % to the level of emissions since the entry into force of the Kyoto Protocol in 2005; by 8.8 % since the 2015 Paris Agreement and, accordingly, 6.7 % since the signing of the Green Agreement in 2019. Concurrently, the implementation of several significant global environmental agreements has resulted in a temporary deceleration in the rate of emissions growth. Although the largest decline in agricultural emissions was observed after the Kyoto Protocol entered into force in 2005 (by 8.9 %), in other periods the decline was short-lived and remained in a small corridor of no more than 0.5–2.0 % (1990–1993; 1997; 2000; 2015–2017). Nevertheless, the overall trend indicates an increase in global emissions from the agricultural sector by at least 1.9 megatons of CO_2 per year. This suggests a hypothesis about the insufficient level of consolidation of global efforts and the lack of multilateral nature in global policies aimed at economy's decarbonisation.

In contrast to the global trend, the European Union is currently the only example of a steady decline in agricultural emissions. This significant reduction has been achieved through a combination of government efforts and policy initiatives. In the 1990s, the EU experienced a record drop in agricultural emissions from 17.6 to 9.7 megatons, marking the first such decrease in the history of green movement. However, emissions later increased due to a surge in agricultural production, although the EU managed to maintain this growth within a narrow range of 10 to 12.2 megatons. The next significant decline in emissions occurred in 2019, coinciding with the global COVID-19 pandemic, with emissions recorded at 10.8 megatons. Although this decline was not primarily due to the crisis, it was during this period that new framework programs for climate neutrality and innovation support were being implemented.

Thus, the depicted trend lines suggest that post-Kyoto, and especially following the Paris Agreement, the EU demonstrates a notable inclination towards stabilisation and a subsequent decrease in agricultural emissions, indicative of climate convergence within the region. Conversely, the global emissions trajectory continues to ascend, implying a divergence and suggesting that the aggregate global response to climate initiatives has not yet resulted in a uniform decline in agricultural emissions. This disparity highlights the uneven adoption and implementation of decarbonisation strategies across countries, underscoring the need for a more intensified and cohesive approach to achieving climate neutrality in agriculture on a global scale.

This example of consolidated decarbonisation in the EU agricultural sector deserves special attention as a kind of the first "decarbonisation phenomenon" against the backdrop of continuing dramatic growth in global emissions. It is of scientific interest to study the EU's "success formula" and to identify the components of convergence and possible factors of divergence in this process.

The sigma convergence model was developed separately for the EU and the global context. Its parameters enable the evaluation of convergence patterns and the consistency of countries' efforts in collectively advancing towards carbon neutrality in the agricultural sector (Figure 2).



a) Standard deviation *b)* Skewness

Figure 2. Deviations and skewness of the countries in the common movement towards the climate neutrality of the agricultural sector

Source: authors' delineation based on open data [20].

The graph above (Figure 2a) illustrates the standard deviation of carbon emissions from the agricultural sector globally and within the EU. This standard deviation measures the variability and homogeneity of agricultural carbon emissions across different countries. The data indicate that, despite diplomatic efforts, both the EU and the rest of the world followed a climate-aggressive trajectory from the Stockholm Environmental Protocol until the 1990s. The 1992 Rio Convention marked a turning point. Although it had a global impact, the positive trend was primarily observed in the EU, which was the first to implement concrete decarbonisation programs rather than making populist statements about a green economic future.

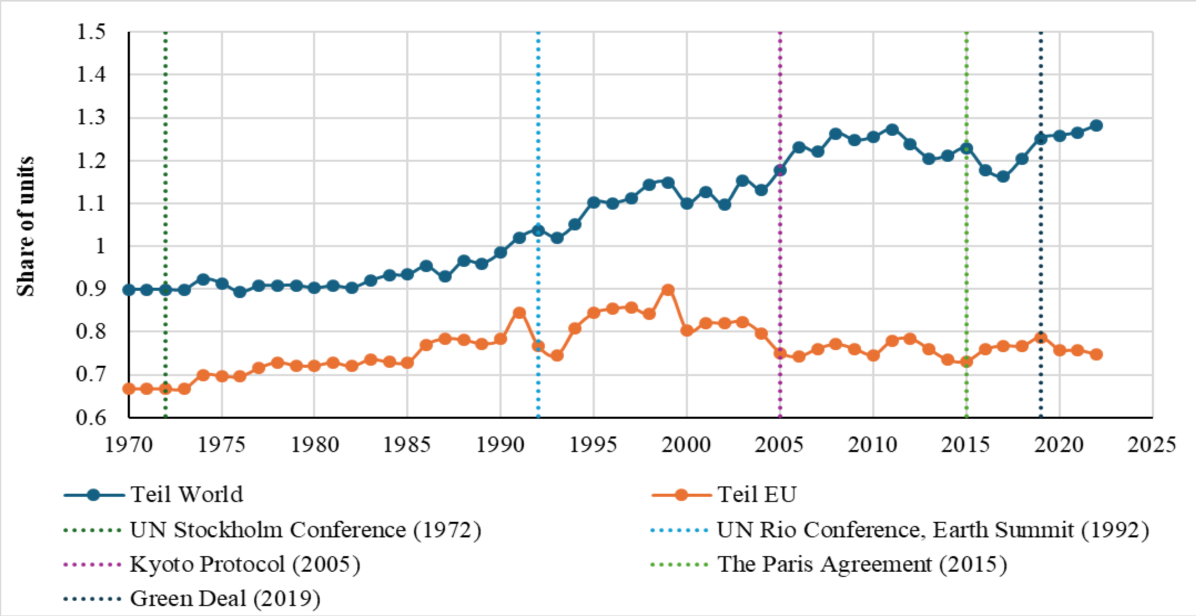
The increase in the standard deviation over several decades indicates growing dispersion of emissions between countries, reflecting pronounced differences in agricultural emissions worldwide. In contrast, the relatively stable standard deviation within the EU suggests less volatility and greater homogeneity in carbon emissions from the agricultural sector. This implies that EU countries are progressing more consistently towards achieving climate neutrality in agriculture. In the context of global convergence, the increasing standard deviation at the global level, in contrast to the relative stability in the EU, indicates significant differences in the pace and effectiveness of carbon reduction measures across different regions. This underscores the need for enhanced international cooperation and the exchange of best practices to achieve global climate neutrality, particularly in the agricultural sector, which is crucial for many countries.

The skewness of agricultural economies with regard to emissions is notable. Globally, increasing skewness indicates a rise in carbon emissions disparity within the agricultural sector. Furthermore, the "tails" of distribution indicate the presence of extremely large emissions among the world's agricultural economies, as well as their increasing frequency. The lack of coherence in decarbonisation efforts at the global level means that achieving net zero may not be achievable in the coming decades.

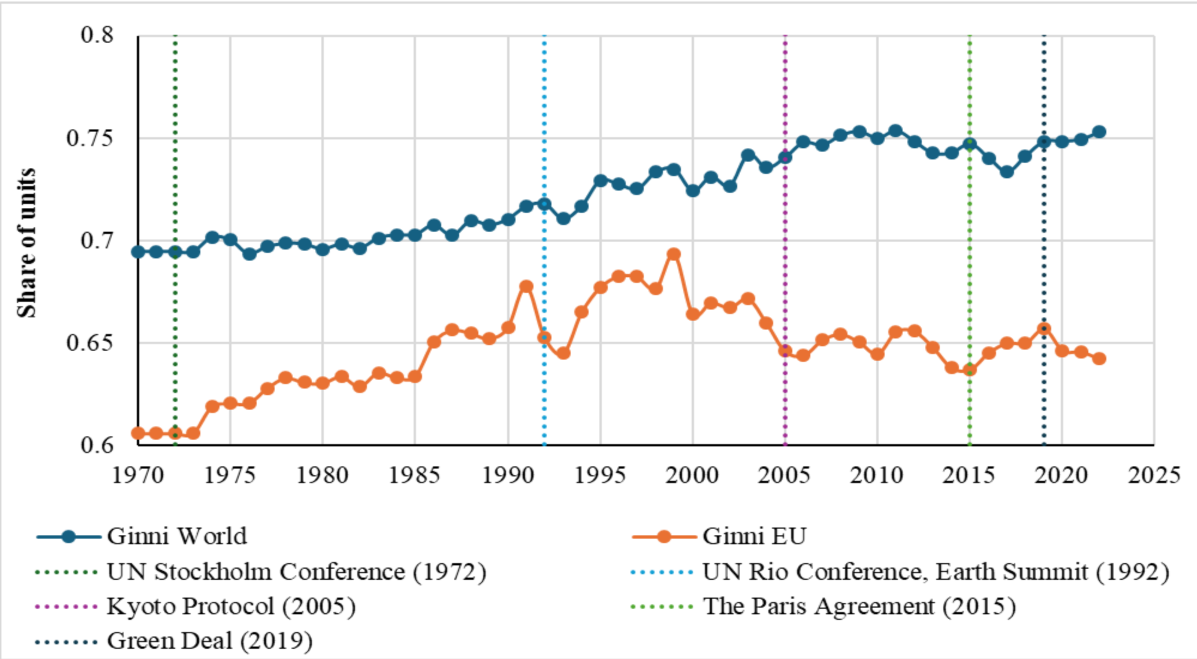
Conversely, EU skewness varies over time. The asymmetric wave from 1992 to 2005 illustrates the formation of distinct groups of leading and lagging countries within the EU, slowing the agricultural decarbonisation. However, the agreements of 2015 and 2019 have stabilised this trend, though it is too early to talk about full consolidation of efforts among EU member states.

These observations reflect the diverse approaches of the global community and the EU towards achieving climate neutrality. Despite the EU's significant efforts, global dynamics reveal other countries are not making similar progress, underscoring the need for further globalisation of climate initiatives to achieve overall climate convergence.

This unevenness is verified by the following indexes (Figure 3).



a) Theil index



b) Gini index

Figure 3. Assessment of the homogeneity and concentration of the agricultural sector of the economy in the global decarbonisation trajectory

Source: authors' delineation based on open data [20].

The provided graph illustrates the evolution of the Theil index for both the world (Theil World) and the European Union (Theil EU) over time. The Theil index measures inequality in carbon emissions within the agricultural sector. The global Theil index shows a general upward trend from 1970, indicating growing inequality in carbon emissions in the agricultural sector worldwide. This trend indicates that carbon emissions are becoming increasingly concentrated among countries that are able to ensure the decarbonisation of their economies. It should be noted that the further construction of the beta-convergence model allowed us to identify such countries directly (Figures 4, 5). The only significant decline in global Theil index occurred during the implementation of the Kyoto Protocol and the Green Deal, which temporarily achieved more uniform emissions reductions among agricultural economies. However, the gap in emissions continues to grow rapidly, highlighting the persistent and widening inequality.

When analysing these data in the context of climate policy or emission reduction strategies, the increasing Theil index on a global scale might point to the need to focus attention on countries or regions where emissions are particularly high, or to develop international mechanisms to reduce the gap between high and low emission countries.

In contrast, the Theil index for the EU appears relatively stable, with some fluctuations but no pronounced long-term upward trend. This suggests that the distribution of carbon emissions in the agricultural sector within the EU is more uniform compared to the global figures.

Based on the Gini index, we can observe trends in the inequality of carbon emissions within the agricultural sector for both the world (Gini World) and the European Union (Gini EU) from 1970 to 2022. The Gini index for the world has been gradually rising, indicating that inequality in carbon emissions has been increasing globally. This suggests that a smaller number of countries are responsible for a larger share of emissions. The Gini index for the EU shows variability with notable peaks and troughs, but overall it does not display a clear long-term trend of increase or decrease. These fluctuations may reflect the impact of various EU policies and changes in agricultural practices over time.

It should be noted that the trends of the indices in the pairs (Gini World – Theil World) and (Gini EU – Theil EU) seem almost identical, which is not typical for the nature of these indices, but turned out to be characteristic for the study of the dynamics of agricultural sector emissions. First of all, this indicates that the growing inequality of agricultural emissions between different countries (Gini World) is mainly due to a significant concentration of extremely high emissions in certain countries (Theil World). The increasing dynamics of both indices suggests that it is becoming increasingly difficult to consolidate this process at the global level.

Meanwhile, the situation in the EU differs slightly. The positive trend in emissions reduction, together with the downward trend in the Theil and Gini indices over the past decade, indicates a successful decarbonisation strategy and the overall effectiveness of green policies. The EU manages to localise extremely large emissions within the agricultural economies of individual countries and to gradually contribute to their reduction, as evidenced by the downward trend of both indices. These findings suggest that, on a global scale, not all countries are making equal progress in addressing climate challenges, whereas the European Union demonstrates more consistency in its efforts.

This underscores the need for more coordinated and equitable global strategies to ensure that all countries are moving towards climate neutrality. In the context of climate action and policy, these results could inform discussions on targeted interventions for countries with disproportionately high emission levels and highlight the need for more unified and equitable efforts to manage carbon emissions across different regions.

The specific positions of national economies in the convergence movement can be assessed on the basis of beta convergence. In fact, it is beta convergence that indicates the tendency of countries with higher initial emissions to catch up with countries with lower emissions. A negative trend in beta convergence means that countries with higher emissions tend to reduce their emissions at a faster rate and thus move closer to countries with lower emissions. Conversely, a positive trend indicates divergence (Figure 4).

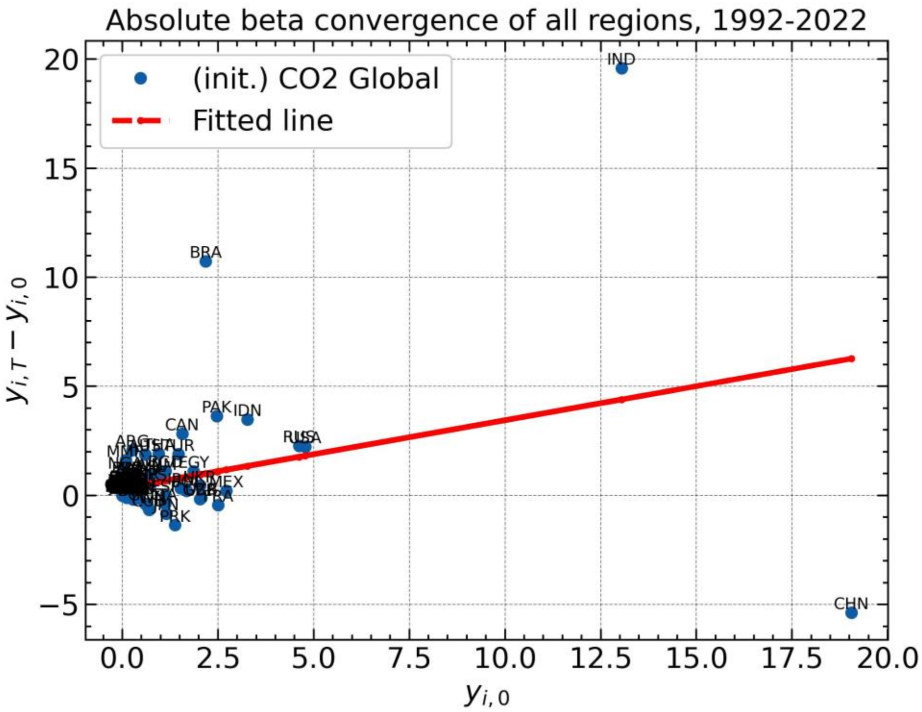
It is worth emphasising that the results of the convergence models clearly indicate a pronounced divergence between national economies in the decarbonisation of the agricultural sector at the global level. However, since 2015, the beta-convergence trend has shifted direction, indicating the onset of convergent processes in the global agricultural economy. Notably, the points situated significantly above the convergence line represent countries with the most pronounced increases in agricultural emissions, which exert a downward influence on the global trend (India, Indonesia, Brazil, Pakistan, and russia).

Conversely, the countries situated under the convergence lime demonstrate those that have achieved the most significant reductions in agricultural emissions over recent decades. In the agricultural sector, China stands out in this regard. The remaining countries are represented by clusters, indicating their greater consolidation in emissions and the relatively greater capacity of their economies to support the movement towards climate neutrality.

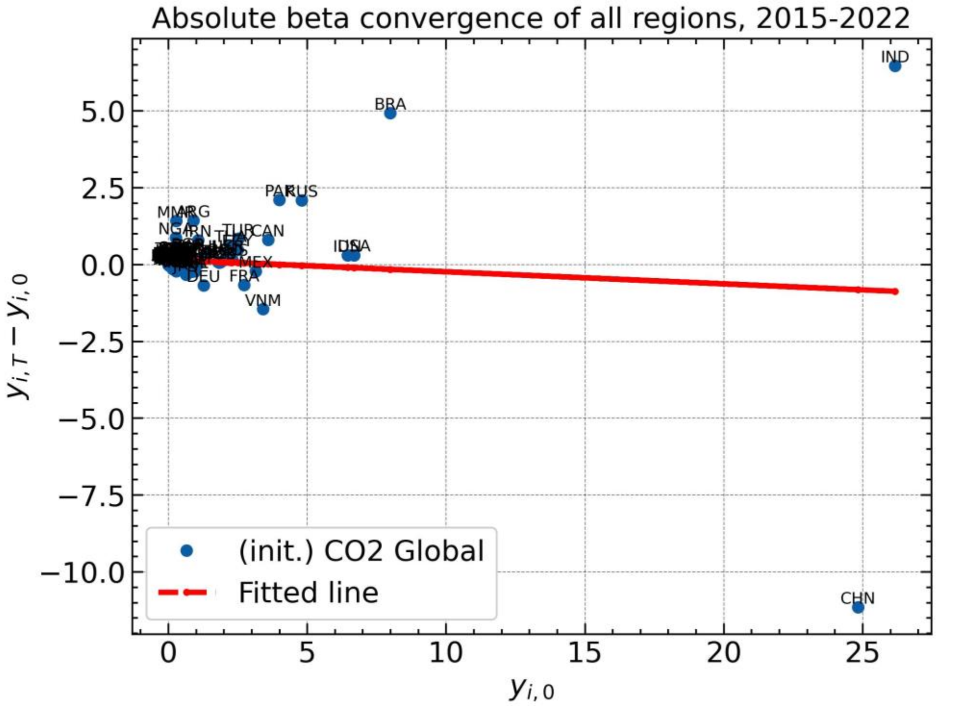
These global results are valuable for determining the effectiveness of individual countries' policies in the common commitment of "net zero". They demonstrate that not all global players are equally committed to meeting global climate goals, especially in the area of economic decarbonisation.

Concurrently, the EU has made considerably more progress in joint efforts. However, the graphs indicate the formation of a "club of leaders" in decarbonisation, the composition of which varies over time (Figure 5).

The data illustrates that international green initiatives have the most pronounced influence within the European Union (EU), notably evidenced by the convergence of emissions within the agricultural sector. Since the 1990s, several EU member states, including Germany, Italy, France, the Czech Republic, Spain, and Latvia, have demonstrated substantial and stable rates of decline in agricultural CO_2 emissions (3.5–5.0 % annually).



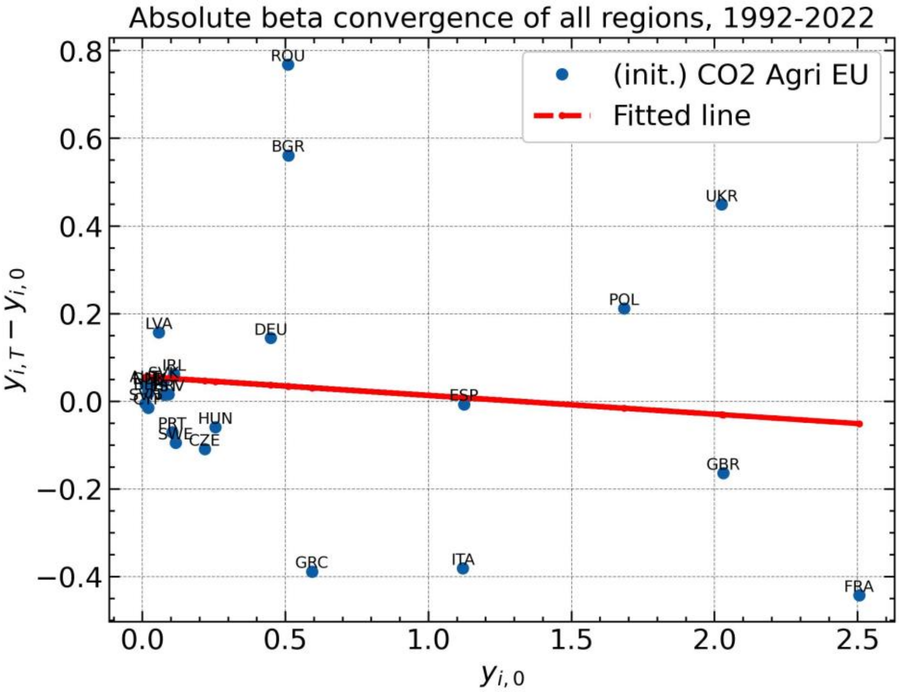
a) Divergence since 1992



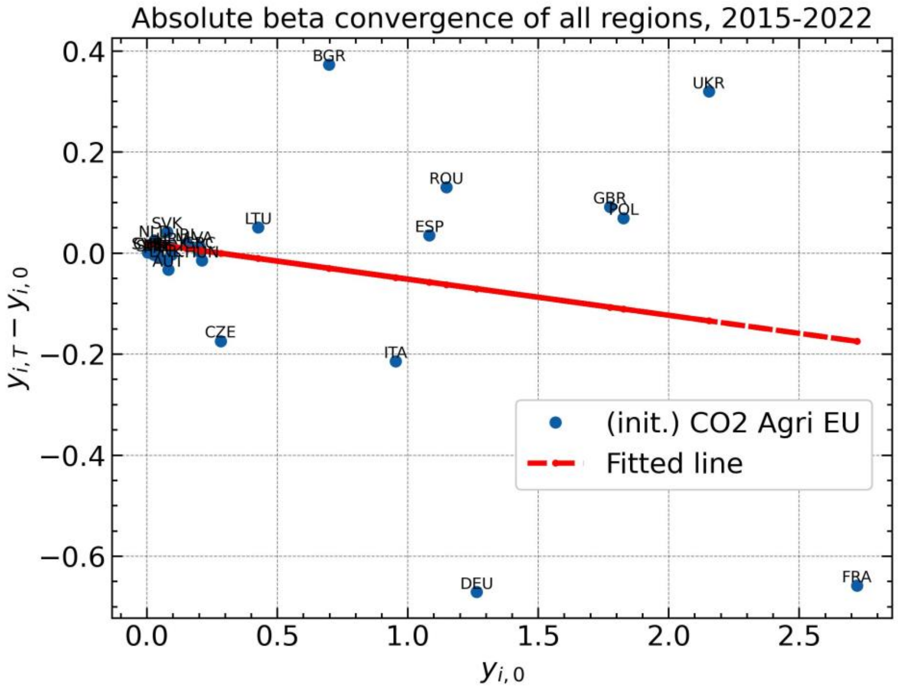
b) Convergence since 2015

Figure 4. Positions of world's countries in the convergent movement towards climate neutrality of the agricultural sector (global beta-convergence)

Source: authors' delineation based on modeling the open data [20].



a) Convergence since 1992



b) Convergence since 2015

Figure 5. Positions of countries in the convergent movement towards climate neutrality of the agricultural sector (EU27, Great Britain, Ukraine)

Source: authors' delineation based on modeling the open data [20].

Conversely, Romania, Bulgaria, Poland, and Greece made a negative contribution to overall decarbonisation by failing to reduce emissions from the agricultural sector, while demonstrating their cyclical growth. (2.7–3.5 % annually). It should be noted that Ukraine, which is not yet a member of the EU, also shows insufficient rates of reduction of emissions from the agricultural sector, deviating from the general convergent trend of decarbonisation of EU agriculture. The largest reduction of CO_2 emissions from Ukraine's agricultural sector was observed in the period from 1990 to 2000 (57 % over the period), after which the carbon footprint of the agricultural sector increases 2.7 times until 2021 (5.8 % annually). However, it seems possible to keep the emissions of Ukraine's agricultural sector within a narrow corridor of change, given the prospects for post-war reconstruction based on the criteria of sustainability, innovative digital development, and the gradual integration of climate policies in Ukraine and the EU.

It is worth highlighting that since 2015, the EU has persistently exhibited convergence processes, albeit with alterations in the composition of participating countries. For instance, countries such as Germany, Spain, and Lithuania, which previously led decarbonisation efforts, have now shifted to a group experiencing significant increases in agricultural emissions. These shifts in leading and lagging countries within agricultural decarbonisation suggest that a crucial metric for climate neutrality extends beyond emission dynamics within a specific timeframe to encompass the ability to sustain such progress into the future.

A summary on the convergence and divergence of agricultural sector emissions according to the sigma and beta convergence models is presented in Table 1.

Table 1

Convergent models of the agricultural sector of the economy

Dimensions	Beta – convergence *(β < 0)*		Sigma – convergence *(0 < b < 1)*		Convergence condition (beta via sigma)	
	World	EU27+GBR +UKR	World	EU27+GBR +UKR	World	EU27+GBR +UKR
1972–2022	1.149	-0.156	1.053	0.924	Divergence	Convergence beta via sigma
1992–2022	0.312	-0.043	0.815	0.701	Just sigma	Convergence beta via sigma
2005–2022	0.165	-0.164	0.667	0.481	Just sigma	Convergence beta via sigma
2015–2022	-0.039	-0.072	0.709	-0.137	Convergence beta via sigma	Just beta

Source: authors' calculations based on modeling of open data [20].

The Table 1 shows the main results of the analysis of global convergence. As we can see, a clear divergence was confirmed at the global level (according to both beta and sigma criteria) over the whole period under study, while convergence was observed at the EU level. However, the analysis of each dimension in time perspective shows an encouraging trend in the global movement towards climate neutrality of agriculture and, at the same time, some contradictions in the EU. The most controversial is the movement in the last decade since 2015. Although the obtained beta and sigma convergence indicators show convergence, their values have deteriorated somewhat. This may indicate the emergence of negative divergence factors, which may lead to increased skewness in countries' climate efforts in the future. One of these factors is the prolonged period of crisis that began with the outbreak of the global pandemic and continued with the war, which significantly shifted the focus of the international community from the green transition to more pressing security issues. These trends have been exacerbated by changes in energy policy in recent years, reflected in fluctuations in global oil and gas markets. In addition, the war has significantly exacerbated the geopolitical context of global decisions on pricing and general trade policies for fossil fuels, whose dependence underlies energy efficiency and the fight to reduce emissions. Another divergent factor is the widening gap between countries' levels of economic development and technological potential, which allows developed countries to implement more aggressive decarbonisation policies.

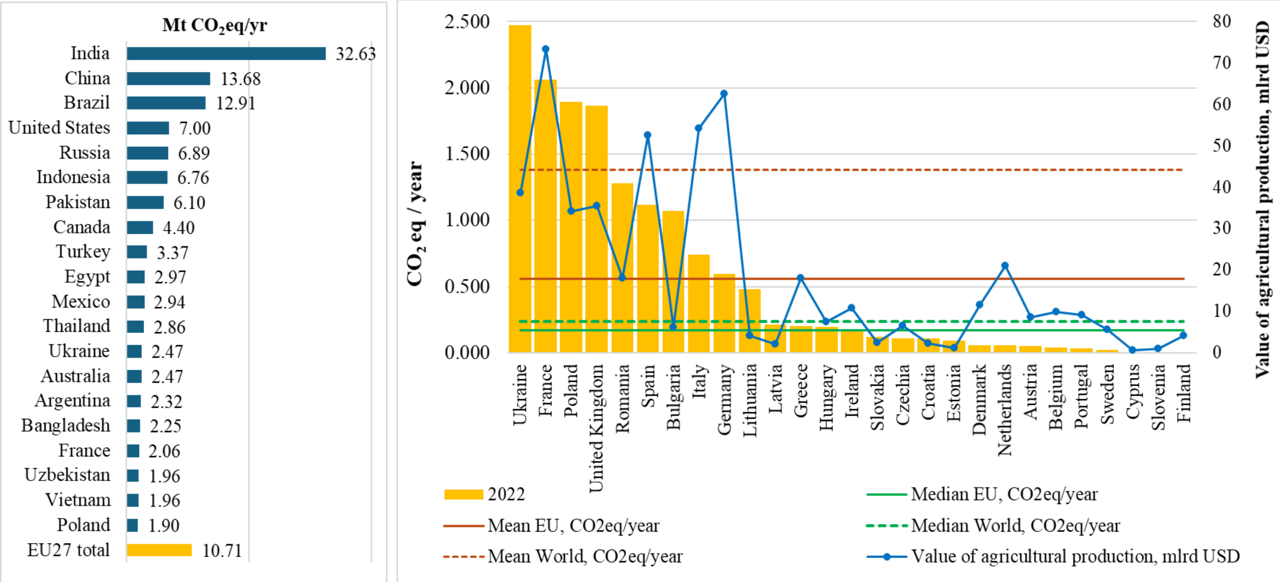
The identified patterns of beta and sigma convergence could potentially indicate the following causal relationships in the process of global decarbonisation (based on Table 1):

1. Sigma-convergence without beta-convergence (global convergent model after the Earth Summit in Rio, 1992; Kyoto Protocol, 2005). This combination implies an overall reduction in the variation of carbon emissions among countries (sigma convergence), which indicates a harmonisation of emissions and decarbonisation rates within the framework of club convergence, which involves the formation of clubs of countries among countries with extremely high emissions and leaders that ensure high rates of decarbonisation of the agricultural sector. At the same time, countries with high agricultural sector emissions are virtually not catching up with countries with relatively low emissions (no beta convergence), meaning that the gap and inequality in emissions between decarbonisation leaders and laggards is not being reduced. This scenario might arise if all countries are reducing emissions, but not at a rate that alters the relative standings, thus high emitters may continue to be high emitters even as the gap in absolute terms closes somewhat. At the global level, this shows that despite some positive convergence towards agricultural decarbonisation, countries with high emissions have not reduced the carbon footprint of their agricultural sector.

2. Beta-convergence without sigma-convergence (EU convergence model after the 2015 Paris Agreement). Conversely, this is a trend where national economies with initially high emissions are reducing their CO_2 at a faster rate (beta-convergence), yet the overall spread of emissions across all countries does not necessarily decrease (lacking sigma-convergence). This could occur if, while certain countries are making rapid reductions, others, perhaps due to economic expansion or less stringent environmental policies, are increasing their emissions, leading to a persistent or even widening range of emissions levels across the board. This is exactly the situation we have observed in the EU in recent years.

Thus, at the global level, the diffusion of emissions from the agricultural sector is becoming more fragmented. This reflects the uneven effectiveness of decarbonisation policies and strategies across regions. To achieve a climate-neutral economy, it is necessary to ensure that all countries move towards reducing emissions, which requires global convergence.

This unevenness is illustrated in the Figure 6.



a) TOP 20 countries of the world *b)* EU27+Great Britain+Ukraine

Figure 6. Ranking of countries by emissions from agricultural economy in 2022

Source: authors' delineation based on open data [20; 23].

The graphs above facilitate a more comprehensive understanding of the nature of the convergence processes previously identified. For instance, 20 countries collectively account for 80 % of global emissions from the agricultural economy, generating approximately 72 % of the global value of agricultural products (Figure 6a). It is noteworthy that the decarbonisation trajectories of the countries in the ranking exhibit considerable contrast. For instance, the agricultural sectors of India and Brazil, which produce the most carbon and have exhibited the greatest increase in emissions in recent years, have resulted in a divergent trend (Figure 4a, b). Conversely, China, which also generates the majority of agricultural emissions, has demonstrated a remarkable reduction in emissions over recent decades, contributing to global convergence.

Such contrasts serve to illustrate that the starting point from which a country begins to reduce emissions is of lesser importance in the context of climate neutrality than the ability of the national economy to decarbonise.

In the European Union, the situation is more balanced, with the majority of agricultural economies generating emissions below the global average (Figure 6b). However, there is a discrepancy between the volume of emissions and the gross value of agricultural products. A cluster of countries, including Italy, Germany, the Netherlands, France, Denmark, Belgium, and Sweden, generate a relatively high level of gross agricultural value, yet their emissions are relatively low. Concurrently, the agrarian economies of Poland, Romania, Bulgaria, Slovakia and the Baltic States generate considerable quantities of carbon dioxide relative to the value of their agricultural products. This negative trend is also identified in Ukraine and the United Kingdom. Neither country is currently a member of the European Union, but they support the EU's green initiatives. Compared to EU countries, Ukraine's agricultural sector generates the most carbon emissions. In terms of the gross value of agricultural production, Ukraine is among the top five, but the pace of decarbonisation does not allow it to be considered as a climate-neutral pathway in line with EU.

We found no clear correlation between agricultural production and the rate of decarbonisation, which determines the degree of international convergence. The analysis shows that both leading and lagging countries include agricultural heavyweights as well as small agricultural economies. However, the leading countries in global agricultural production, which also produce the most emissions, certainly have a double responsibility. After all, reducing emissions in these countries contributes the most to the convergent global movement towards "net zero".

In general, we identify the following components of international climate convergence in the agricultural sector (Figure 7).

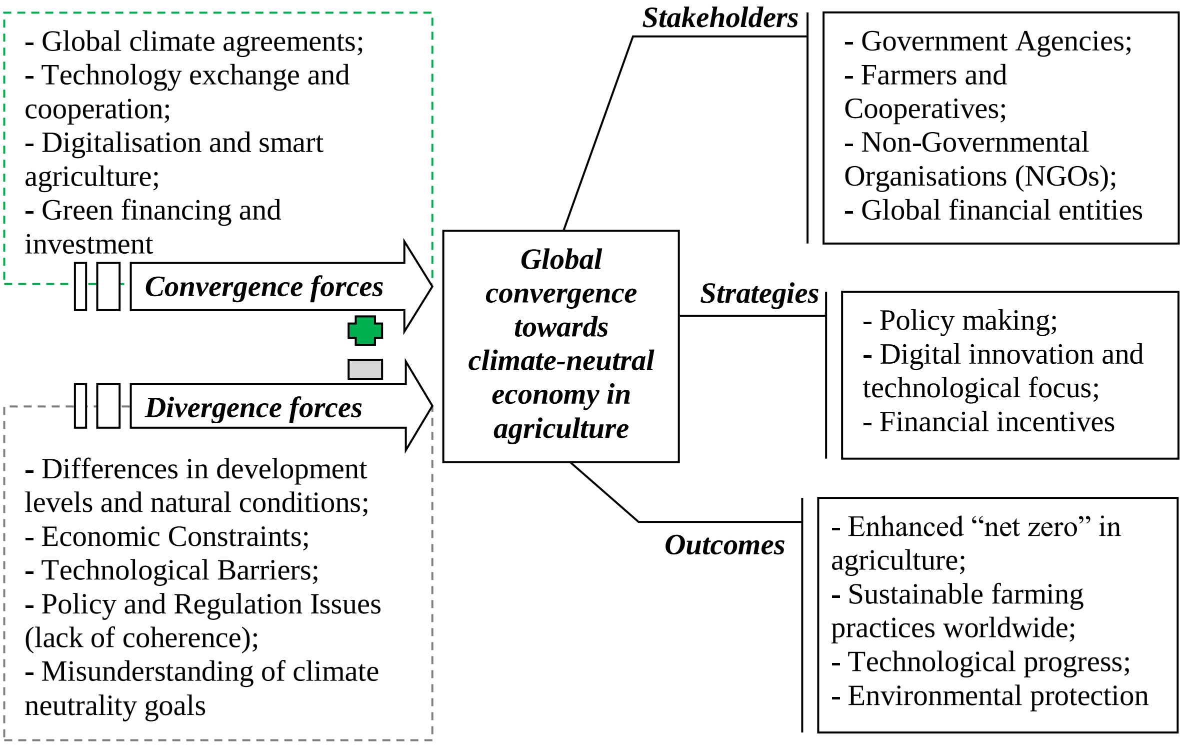


Figure 7. Overall framework of global convergence towards climate-neutral economy in agriculture

Source: authors' delineation.

The framework underscores the overarching vision of international convergence as a prerequisite for a coordinated, multi-level approach to climate neutrality in agriculture.

The incorporation of convergence factors, such as digitalisation and smart agriculture, is particularly pertinent at this time. These technologies possess transformative potential, enabling more precise resource management and reducing environmental footprints. Moreover, digitalisation becomes powerfull driver for clinate-neutral transition of the global economy [24]. Modern digital innovations demonstrate profound potential in emisioms reductions within climate projects in diferent areas of producion [25]. In 2023, the global smart agriculture market was valued at USD 22.65 billion. Projections indicate a compound annual growth rate (CAGR) of 13.7 % from 2024 to 2030 [26]. This anticipated growth is primarily driven by the increasing automation within commercial greenhouses and the expanding adoption of Controlled Environment Agriculture (CEA) techniques [27]. The implementation of CEA aims to optimise yield and maintain ideal conditions for crop growth, which are central drivers of the increasing market demand during the forecast period. The global market for agricultural robots was valued at approximately USD 11.3 billion in 2022 and is projected to reach around USD 48.5 billion by 2030. This represents a compound annual growth rate (CAGR) of approximately 20.2 % from 2023 to 2030 [28]. This contributes to the global distribition of low-carbon digital decisions for unmanned aerial vehicles, milking robots, driverless tractors, automated harvesting systems etc.

Thus, digitalisation and smart agriculture are crucial for achieving climate convergence in the agricultural economy for several reasons:

1) Digital technologies enable precise monitoring and control of resources such as water, fertilisers, and pesticides. This precision reduces the environmental impact, leading to more sustainable agricultural practices. Moreover, the implementation of digital tools like IoT devices, drones, data analytics and blockchain helps farmers optimise their operations [29]. Technologies such as automated irrigation systems and precision farming equipment contribute to lower energy consumption and reduced emissions [30]. These digital based decisions can lead to higher crop yields and better resource utilisation, thus improving overall agricultural productivity and reducing greenhouse gas emissions.

2) Smart agriculture contributes to climate resilience and better decision making on the basis of quality and transparanted data, since digitalisation provides real-time data on weather patterns, soil conditions, and crop health. This information helps farmers make informed decisions and adapt to changing climate conditions, enhancing the resilience of agricultural systems to climate variability and extreme weather events.

3) The fenomena of smart agriculture imply high scalability, since digital solutions can be scaled and adapted to different sizes and types of farms, making advanced agricultural practices accessible and adaptable to smallholder farmers as well as large agricultural enterprises all over the globe.

4) Digitalisation contributes to global policy making and climate compliance in agriculture within deep monitoring and reporting on environmental regulations and climate targets. This capability is essential for ensuring that agricultural practices align with national and international climate policies.

However, the framework of global clinate convergence also identifies significant barriers such as economic constraints and technological disparities. Addressing these challenges is crucial for policymakers, as they can disproportionately affect under-resourced regions and potentially widen global inequalities. The role of stakeholders is rightly emphasised as pivotal.

The success of transitioning to a climate-neutral agricultural system depends not only on technology and policy but also on the active participation of all sectors involved, from local farmers to international agricultiral corporations. This collaborative approach is essential to ensure that policies and technologies are both applicable and accessible at the grassroots level. Moreover, the strategies section focuses on actionable items such as policymaking and financial incentives, which are critical levers in encouraging the adoption of sustainable practices. Effective policy frameworks and financial support mechanisms can catalyse the adoption of sustainable technologies and practices by lowering the initial barriers to entry. The projected outcomes enhanced "net zero" achievements, green farming practicies and environmental protection. These outcomes not only address the immediate goal of climate neutrality but also support broader sustainable development goals, including economic and environmental sustainability.

5. DISCUSSION

This study develops sigma and beta convergence models for the agricultural sector of the world economy over a long period of time, 1970–2022, which significantly differs in terms of the subject matter and the period of data sample coverage. Nevertheless, we can draw some links in comparing methodological approaches to convergence research in other fields. As in the papers [17; 18], which examines the convergence of EU countries in terms of GDP, we also received signals of the existence of club convergence at the global level and in the EU in terms of CO_2 emissions. In our example of the agricultural sector of the economy, the methodological approach to recognising convergence in dynamics (linking to the dates of key international agreements focused on the green transition of the economy and society) shows efficiency and allows us to better understanding the nature of convergence in the field of study. In [16; 19], the authors test various beta convergence models to assess the convergence between regions within the country in terms of socioeconomic indicators. Our study has shown that Baumol's beta convergence model is quite representative for studying the convergence of decarbonisation dynamics at the international level. The paper [15], however, also contains the idea of studying convergence between emissions, but only between regions within a country (China). However, the author reduces the study of convergence to the analysis of individual statistical indicators. We contend that this approach is inadequate and open to question in understanding convergence at the global level. Only a comprehensive approach to assessing international convergence (including sigma, beta models and statistical indicators) allows for a comprehensive analysis of convergent trends and identification of leading and lagging countries.

It is appropriate to pay special attention to the further specification of the concept of "convergence" in accordance with the direction of its modeling. In our study, we built appropriate models to determine the international convergence of agricultural economies towards climate neutrality at the global level. This led us to the idea of using the term "climate convergence" for this purpose. However, this is controversial because we have focused on the decarbonisation and emissions reduction aspect of the agricultural economy, although the fight against climate change has a broader scope, covering aspects of adaptation, mitigation and cross-cutting impacts.

6. CONCLUSIONS

The concept of climate neutrality has emerged as a pivotal issue in global economic policy, driven by the pressing need to address climate change. The global agricultural economy is currently caught in a vicious cycle, as agricultural production contributes a significant emissions footprint and simultaneously suffers the most from its impact on yields, product quality, and resource availability. The aforementioned vicious circle could only be broken by maximising the consolidation of efforts across the entire global community, as measured by the level of international convergence.

The study has demonstrated that global convergence towards decarbonisation of the agricultural sector is a de facto requirement for the achievement of climate neutrality. It reflects the global level of consolidation of joint programmatic efforts and the uniformity of decarbonisation dynamics in both developed and developing countries.

Over the past 50 years, significant international initiatives in environmental economics have been implemented, such as the UN Stockholm Conference (1972), the Rio Earth Summit (1992), the Kyoto Protocol (2005), the Paris Agreement (2015), and the Green Deal (2019). However, the analysis indicates that these global agreements have had a fragmented impact on reducing agricultural emissions, which continue to grow globally. Modeling confirms a divergent trend in global decarbonisation, with the first signs of convergence emerging only since Paris Agreement in 2015. The statistical analysis of sigma convergence and emissions dynamics reveals that the positive effects of international initiatives appear with a notable lag, occurring after the ratification of green agreements.

The beta convergence analysis revealed that the global agricultural economy tends to be inertial and deregulated towards climate neutrality that casts doubts about the possibility of achieving net zero by 2050. In contrast, the EU agricultural economy demonstrates an accelerated scenario of more regulated decarbonisation and a much clearer convergent movement. Moreover, the EU is currently the only example of convergence in the agricultural sector, due to the implementation of policies and support programs. However, since 2015, the EU's convergent model has deteriorated, with only beta convergence observed, and no sigma. This indicates that while certain countries are making rapid reductions, others, perhaps due to economic expansion or less stringent environmental policies, are increasing their emissions, leading to a persistent or even widening range of emissions levels across the sample.

The constructed beta-convergence models highlight the existence of clubs of leading and lagging countries. Several EU member states, including Germany, Italy, France, the Czech Republic, Spain, and Latvia, have demonstrated most substantial reductions in agricultural emissions. Conversely, Romania, Bulgaria, Poland, and

Greece have contributed disparately to overall decarbonisation, as they not only failed to mitigate emissions but also experienced an increase in them. Despite considerable potential, Ukraine also shows insufficient progress in decarbonising its agricultural sector, which is a negative indicator for the prospects of European integration and the environmental negotiating framework.

Beta convergence models indicate a club of high-emissions countries, including India, Indonesia, Brazil, Pakistan, and russia, who demonstrate the greatest impact on divergence, yet they do not result in any reduction in emissions from the agricultural sector. This reflects the uneven effectiveness of decarbonisation policies and strategies across regions. However, high emissions from the agricultural sector are not a "sentence". The case of China has demonstrated how the country with the highest carbon emissions from the agricultural sector has been able to reduce them and contribute to global convergence. Such contrasts serve to illustrate that the starting point from which a country begins to reduce emissions is of lesser importance in the context of climate neutrality than the ability of the national economy to decarbonise.

An analysis of the general framework of international convergence towards climate neutrality of the agricultural economy has led to the conclusion that the current powerful forces of climate convergence are global climate agreements, technology exchange and cooperation, digitalisation and smart agriculture, green financing and investment. In summary, digitalisation plays a pivotal role in achieving climate convergence in the agricultural economy by enhancing efficiency, reducing environmental impact, and enabling sustainable practices through advanced technologies, qualitative and transparent data-driven decision-making. Concurrently, the international community must intensify its collective efforts to mitigate the forces of divergence, which is identified as disparities in developmental levels and natural conditions, economic constraints, technological barriers, policy and regulatory issues, and misunderstandings of climate neutrality goals. Therefore, in order to achieve climate convergence, stakeholders should be fully involved in the development of common strategies and the selection of consistent methodologies for the evaluation of results.

7. LIMITATIONS AND FUTURE RESEARCH

The study of international convergence covers a long period of time. Further discussion is necessary to assess the significance of the sigma and beta models of agricultural convergence in relation to the impacts of the 2019 Green Deal, which will become more evident in the coming years as data accumulate. Conversely, as data samples expand, it is crucial to construct a multivariate regression model of convergence and conduct a statistical assessment of the impact of digitalisation and smart agriculture on the convergence of countries in their collective movement towards a climate-neutral economy. A crucial aspect of the study of convergence and, consequently, the prospects for climate neutrality is to ascertain the nature of the interconnections within the groups of decarbonisation leaders and laggards, which were identified in this study at the EU and global levels. Another significant area of discourse in comprehending the climate neutrality of the global economy is the comparison of convergence rates in the agricultural sector with convergent models in other sectors of the world economy that are significant contributors to carbon emissions. These controversial topics represent the focus of the authors' future research endeavors.

Acknowledgments: the authors would like to express their gratitude to the journal's reviewers for their valuable comments and suggestions that improved the quality of the presentation of the results and prompted ideas for further research in this area.

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

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Citation:

Стиль – ДСТУ:

Krysovatyy A., Maksymova I., Kurilyak V., Radin M., Kurilyak M. International convergence towards a climate-neutral economy: modeling the agricultural sector. *Agricultural and Resource Economics*. 2024. Vol. 10. No. 2. Pp. 52–79. https://doi.org/10.51599/are.2024.10.02.03.

Style – APA:

Krysovatyy, A., Maksymova, I., Kurilyak, V., Radin, M., & Kurilyak, M. (2024). International convergence towards a climate-neutral economy: modeling the agricultural sector. *Agricultural and Resource Economics*, 10(2), 52–79. https://doi.org/10.51599/are.2024.10.02.03.