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Carbon farming and economic growth: Empirical evidence on the role of Emission Trading System (ETS) from a GMM Model

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Abstract:

Purpose: This study examines the impact of carbon farming on economic growth and investigates whether the Emission Trading System (ETS) moderates this relationship across countries. While carbon farming has emerged as a critical strategy for integrating agricultural productivity with climate mitigation, existing literature remains inconclusive on whether its economic benefits materialize in the absence of market-based carbon regulation.
Design/methodology/approach: This study employs the System GMM estimator to examine the impact of carbon farming on economic growth using a panel dataset covering 103 countries over 2000-2024, with the main System GMM estimation based on 1,584 observations from 99 countries, focusing on the moderating role of the Emissions Trading System (ETS). In this study, carbon farming is operationalized based on the EU regulatory definition and previous literature.
Findings: System GMM results indicate that the impact of carbon farming on economic growth differs markedly between agriculture and forestry. In the absence of an ETS, CFA exerts a negative impact on growth ($\beta = -0.035$; $p < 0.05$), whereas CFF has a positive impact ($\beta = 0.058$; $p < 0.10$). Notably, the ETS moderates these two relationships in opposite directions: the CFAE (CFA × ETS) coefficient is positive ($\beta = 0.161$; $p < 0.01$), while the CFFE (CFF × ETS) coefficient is negative ($\beta = -0.136$; $p < 0.05$). These findings suggest that the ETS does not generate a uniform economic impact, implying that the economic value of carbon farming can vary depending on the land-use sector and resource allocation mechanisms.
Originality: This study contributes to the literature by linking carbon farming to economic growth at the transnational level and testing ETS as a moderating variable. Based on this, it addresses a problem that has been less considered in previous studies. A more important novelty is the distinction between CFA and CFF, showing that the internalization of carbon externalities can produce contrasting economic outcomes between agriculture and forestry. Thus, the study expands on the theoretical approaches of Pigou (1920) and Coase (1960) by demonstrating that ETS not only prices carbon but also alters the relative price and allocation of land, capital, and production activities.

Keywords: carbon farming; GDP; carbon market; emission trading system; GMM.

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1. INTRODUCTION

Rapid economic expansion and intensive resource use have intensified environmental pressures and contributed to growing concerns over climate change and climate-related risks, which are urgent issues that need to be addressed. Lindsey (2025) argues that the long-term upward trend of CO_2 is strongly influenced by human-induced factors; excessive CO_2 increase causes the greenhouse effect, thereby leading to an increase in global temperature. According to the UNEP Emissions Gap Report 2024, CO_2 is one of the main factors accounting for a large proportion of greenhouse gases (GHG), and the increase in CO_2 is also the main factor in the increase of GHG (UNEP, 2024).

The solutions mentioned include the vigorous deployment of renewable energy, the reduction of deforestation, infrastructure development, and support for developing and least developed countries (UNEP, 2024). In general, the measures mentioned aim at a common goal: reducing CO_2 emissions - a major factor influencing global temperatures. With these measures, carbon farming is emerging as a sustainable method, significantly impacting environmental protection and ensuring continuous and sustainable economic growth for nations. Regulation (EU) No. 2024/3012 of the European Parliament and Council (2024), dated November 27, 2024, established the European Union certification framework for permanent carbon removals, carbon farming, and carbon storage in products, affirming its objectives. Carbon farming not only opens up a new way to build a circular economy but also presents a strong opportunity for agriculture, forestry, and other carbon credit-related activities, thereby opening the door to trade for many countries. Although many countries have not yet clearly signaled the adoption of carbon farming, afforestation and agricultural activities in the process of promoting sustainable development have inadvertently achieved the core goals of carbon farming. The direct economic impacts of carbon farming remain a relatively uncommon topic. Generally, studies on the economic impact of carbon farming only appear at the micro level, such as farms and agricultural practices, and do not consider the impact of carbon farming at the macro level or specific national development indicators. Furthermore, existing studies primarily rely on qualitative approaches (e.g., Bryan *et al.*, 2010; Conant, 2011; Raina *et al.*, 2024) or quantitative simulations combined with ecological models (e.g., Antle *et al.*, 2001), leaving limited cross-country econometric evidence on the direct relationship between carbon farming and economic growth. However, the environmental benefits generated by carbon farming may not be fully reflected in private economic returns, a mechanism that can be explained through the externality theories of Pigou (1920) and Coase (1960). Therefore, this study examines the combined regulatory role of the emissions market (ETS) in internalizing the positive externalities of carbon farming.

This study addresses three critical gaps in the existing literature. First, although micro-level studies have documented positive economic returns from carbon farming at the farm level (Antle *et al.*, 2001; Capalbo *et al.*, 2004), macro-level evidence linking carbon farming to national GDP growth remains lacking. Second, while externality theory (Pigou, 1920; Coase, 1960) posits that market-based mechanisms play a central role in internalizing environmental benefits, no quantitative study has empirically tested this mechanism within the context of carbon farming. Third, the literature has yet to establish a standardized cross-country measure of carbon farming, thereby constraining comparative analysis.

To address these gaps, we construct a novel binary indicator of carbon farming based on EU regulatory criteria and FAO land-use data, and employ the GMM estimator to account for

endogeneity and dynamic effects in a panel dataset covering 103 countries over the period 2000-2024. The final sample comprises 103 countries, after excluding Cuba and North Korea from the 105 countries with sufficient data to construct the CFA and CFF, as these two countries severely lacked the macroeconomic variables necessary for the model. This study provides cross-country macroeconomic evidence on the growth effects of carbon farming, while examining whether the empirical evidence is consistent with externality internalization theory through the moderating role of emissions trading systems (ETS). Specifically, we address three research questions:

RQ1*: Does carbon farming directly contribute to national economic growth in the absence of market mechanisms?*

RQ2*: What is the moderating role of emissions trading systems (ETS) in translating carbon farming into economic growth?*

RQ3*: Do the growth effects differ between agricultural and forestry carbon farming?*

2. LITERATURE REVIEW

2.1 Carbon Farming

Regarding the concept of carbon farming, previous studies support the view that carbon farming is a modern agricultural practice that profoundly supports sustainable development. Ghosh *et al.* (2024) argue that carbon farming is "the intersection of agriculture and climate change mitigation efforts" with the aim of increasing carbon sequestration in agricultural ecosystems, reducing greenhouse gas emissions. Similarly, Saikanth *et al.* (2023) suggest that carbon farming is an innovative agricultural method aimed at minimizing climate change risks by sequestering carbon dioxide from the atmosphere into soil and biomass. Vistarte *et al.* (2024) assert that carbon farming is a sustainable agricultural method that absorbs CO_2, mitigates climate change, improves soil health, and enhances biodiversity.

In this study, the concept of carbon farming is built on the concept of the European Parliament and Council of the European Union (2024) that carbon farming is "any practice or process carried out over an activity period of at least five years, related to the management of a terrestrial or coastal environment and resulting in the capture and temporary storage of atmospheric or biogenic carbon in biogenic carbon pools, or in the reduction of soil emissions".

2.1 Pigou and Coase's theoretical framework on externality internalization

Externalities are a classic concept in economics. Livernois (2019) study defines externalities as components created when activities that are not valued generate benefits from exchange but are not exploited, associated with potential benefits that have not yet been realized. Another study on the theory of externalities by Batabyal (2023) expands the concept by stating that externalities in the economy arise when an economic entity is involuntarily affected, either positively or negatively, by the actions of a third party, where the third party is neither punished nor rewarded for any damage or benefit caused.

Pigou (1920) concluded that the essence of the problem is that entity A, in the course of business, provides products or services to entity B through normal economic exchanges, inadvertently creating benefits or losses for other entities such as C, D, or E. There is no collection of fees from those who benefit, nor can compensation be claimed for those who suffer losses. Considering greenhouse gas emissions, negative externalities are created, and the emitter does not bear any cost from harming the environment. Conversely, an entity that reduces emissions or absorbs carbon, thus reducing pollution, does not directly receive any value. Therefore, without a mechanism reflecting the value of carbon, the social benefits of carbon reduction or absorption may outweigh the private benefits, while the costs are still directly borne by the producers. This gap between social and private benefits creates the economic basis for internalizing externalities. From this, carbon farming can be considered a type of activity with positive externalities when implementing sustainable agricultural methods that absorb CO2, reduce emissions, improve soil health, and enhance biodiversity (Vistarte *et al.*, 2024). From that premise, Pigou (1920) argued that eliminating the difference between net social product and net market product (externalities) could still be achieved through state intervention with strong incentive mechanisms or special restrictive policies, most commonly taxes and subsidies.

Contrary to Pigou, Coase (1960) presented opposing views on internalizing externalities. Coase (1960) argued that limiting the unintentional harm caused by externalities from subject A is a misguided approach. He believed the main issue was considering the overall and marginal level of harm rather than limiting subject A. Instead, Coase (1960) indirectly addressed the role of property rights, market bargaining, and transaction costs, stating that "the ultimate result (which maximizes the value of production) is independent of the legal position if the pricing system is assumed to work without." Coase (1960) suggested that clearly defining rights and improving bargaining power can internalize the effects of externalities. In this context, defining rights and bargaining power closely mirrors the carbon credit market, which enables farmers or carbon-sequestering entities to sell sequestered carbon to businesses seeking to offset their emissions, thereby transforming environmental benefits into direct economic value.

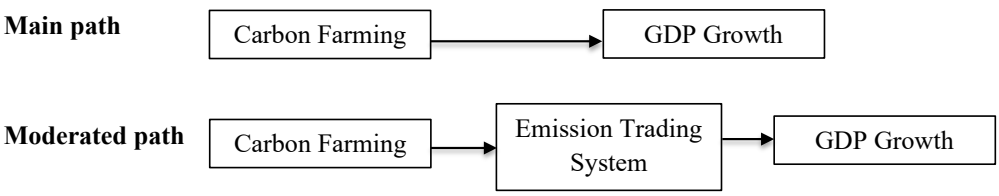


Figure 1

2.2 The impact of carbon farming on economic growth and research hypotheses

Carbon farming is not merely a climate-focused method; it is also recognized as a solution for achieving the dual goals of long-term economic growth and the preservation of the environment and natural capital. Early studies primarily approached carbon farming from an agricultural or farm-level perspective. Antle *et al.* (2001) and Capalbo *et al.* (2004) argued that carbon farming is an environmentally sound agricultural practice that entails significantly lower costs than other emission-reduction methods, while simultaneously boosting productivity and protecting soil quality—such as by mitigating erosion.

Pinto *et al.* (2010) and Tang *et al.* (2016) further supported the view that carbon farming fosters growth by outlining channels for economic value creation, including increased productivity, higher farm household incomes, and the potential to generate revenue from carbon credits. Similarly, Sharma *et al.* (2021) demonstrated that agroforestry systems can enhance carbon sequestration compared to monoculture systems while also supporting agricultural output and food security. Furthermore, Raina *et al.* (2024) summarized that carbon farming can improve soil and water quality, curb erosion, and boost biodiversity, thereby yielding benefits that extend beyond direct carbon sequestration.

More recent research by Frank *et al.* (2024), utilizing the GLOBIOM model, has reinforced these earlier findings using a larger dataset. Frank *et al.* (2024) concluded that incorporating agricultural carbon sequestration strategies can reduce economy-wide emission abatement costs. Under a 1.5°C temperature-limiting scenario, the adoption of agricultural carbon sequestration practices results in a global GDP in 2050 that is approximately 0.6% higher than in a climate scenario where these measures are not employed. At a carbon price of \$160 per tCO_2e, payments to producers could reach \$375 billion annually (in 2022 prices). The underlying mechanism involves not only agricultural productivity but also the fact that carbon farming offers a relatively low-cost emissions reduction option, thereby lowering the economy-wide cost of transition.

Ajatasatru *et al.* (2024) utilized India's Social Accounting Matrix to simulate the impacts of climate-smart agricultural practices on output, GDP, income, and emissions footprints. Their findings indicate that intensive rice and wheat cultivation systems generate GDP multipliers of approximately 2.77 and 2.75, respectively, while boosting productivity by about 22% and 30%. These results demonstrate that emissions reductions cannot be viewed in isolation when assessing economic benefits; economic outcomes also depend on productivity, labor and capital requirements, and input-output linkages. Notably, the study acknowledges that technology adoption costs were not incorporated into the model; consequently, the simulation results may not fully reflect the actual costs of transition.

Meng *et al.* (2024) provide further evidence regarding the potential decoupling of agricultural development from emissions. In Sichuan between 2010 and 2020, total agricultural carbon emissions fell from approximately 40.03 million tonnes to 34.66 million tonnes—a 13.4% reduction—while the value of agricultural output rose from roughly 205.9 billion to 470.2 billion CNY. However, this decoupling process was not steady. LMDI decomposition reveals that capital, emission intensity, and agricultural structure can facilitate emission reductions, whereas economic expansion and certain types of technological investment drive emissions up. Consequently, technology can simultaneously boost output and trigger a rebound effect if it encourages input expansion or the use of energy-intensive equipment.

Branca *et al.* (2021)—using data from 505 households with 1,433 plots in Malawi and 695 households with 1,264 plots in Zambia—also identified a synergy between economic benefits and emission reductions across various climate-smart agricultural practices. The negative marginal abatement costs associated with many of these methods demonstrate the potential to simultaneously improve livelihoods and lower emissions. However, the magnitude of benefits varies significantly among practices. Methods with high emission-reduction potential may require substantial upfront investment and yield economic benefits only after a time lag, making financial barriers a critical factor in their adoption.

Overall, while the gathered quantitative and qualitative evidence offers differing interpretations of the underlying mechanisms, the majority of findings indicate that agricultural carbon farming plays a significant role in boosting crop yields, improving soil quality, and reducing carbon emissions. Therefore, the study anticipates that agricultural carbon farming will have a positive impact on economic growth.

H1*: The state of carbon farming in agriculture (CFA) has a positive impact on economic growth (GDP).*

Compared to the approach of farm or agriculture and crop yield, the approach of carbon farming from forests, some studies have directly examined economic outcomes at the local level, thereby providing clearer evidence of the link between forest carbon sequestration and economic growth potential.

Zhang *et al.* (2023) used panel data combined with satellite data of 2735 Chinese counties and cities to assess the impact of carbon sequestration by vegetation on economic development. The results showed that the amount of carbon absorbed by vegetation had a positive and significant impact in Northeast, Central, South and Southwest China, while it was not significant in some other areas. The mechanisms identified by the authors include upgrading the sectoral structure, improving resource allocation and increasing vegetation cover. This suggests that forest carbon farming can generate benefits not only through ecosystem services but also through forestry development, forest resource-related activities, and economic structural transformation.

Liu *et al.* (2023) provided closer causal evidence through data from 140 counties in Sichuan from 2002-2018 and a paired trend-point method combined with double difference. The results showed that farmed forest carbon sequestration projects increased agricultural total factor productivity by approximately 1.7-2.4%. Mechanism analysis showed that these projects were associated with improved health, increased savings, and structural changes in the sector, with the primary sector share decreasing by approximately 3.7%, while the service sector share increased by approximately 4.9%. This implies that the economic impact of carbon forests can spill over into human capital, income, and labor allocation.

Wu *et al.* (2021) moved closer to the GDP outcome variable by using data from 56 counties in Guangdong from 2006-2018 and the PSM-DID model to assess carbon-absorbing reforestation projects. Evidence generally leaned towards positive impacts on the local economy, while dynamic analysis showed that economic benefits lagged significantly and only began to manifest after about six years of implementation. Channels considered included primary and secondary regional development, revenue collection, savings, and local finance. However, results should be interpreted cautiously as the statistical significance of the principal coefficients varied among several model specifications.

Overall, studies on forests provide relatively consistent evidence that enhanced carbon absorption and the development of carbon-absorbing forest projects can support local productivity, income, economic structure, and economic activity. However, the extent of impact varies by region and often appears with a time lag due to the biological characteristics and long investment cycles of forests. Based on the available evidence, the study proposes the following hypothesis:

***H2**: The state of carbon farming in forestry (CFF) has a positive impact on economic growth (GDP).*

For emission trading systems (ETS), this can be a component that alters the economic impact of carbon farming by shaping carbon prices and changing the allocation of emission reduction costs. According to Pigou (1920) and Coase (1960), market mechanisms can incorporate a portion of the social value of emission reduction into the economic decisions of stakeholders. However, studies show that the ultimate impact depends on how ETS influences investment, production, and resource allocation.

Wang *et al.* (2015) showed that when Guangdong implemented emission reduction targets without trading, GDP decreased by approximately 1.4%. When ETS was implemented, the equilibrium carbon price was approximately US$38/tCO$_2$, and GDP recovered by approximately US$2.6 billion compared to the non-trading scenario. The results suggest that ETS can reduce economic costs by allocating emission reduction activities to areas with lower costs. Furthermore, Marcu *et al.* (2022) showed that EU ETS also incentivizes investment in low-carbon technologies, although it simultaneously generates compliance costs and affects competitiveness. However, Fowlie *et al.* (2016) pointed out that carbon pricing, if designed inappropriately to the market structure, can reduce investment and output, increase imports and carbon leakage, while mechanisms such as output-based rebates or carbon adjustments at the border can mitigate adverse effects. Therefore, ETS does not necessarily create a uniform economic impact but can alter the relationship between each form of carbon farming and growth.

For agriculture, transitioning to low-emission production often requires investment and adjustment costs before economic benefits are realized. Frank *et al.* (2024) shows that when agricultural carbon sequestration is priced, it can become a cost-competitive emission reduction option and ease the transition burden on the economy. At a carbon price of US$160/tCO$_2$e, payments to producers could reach US$375 billion per year. Branca *et al.* (2021) also showed that initial investment costs are a significant barrier to the adoption of low-emission agricultural practices and argued that payments for emission reductions could help bridge this financial gap. However, carbon only creates economic value when it can be measured, verified, and recognized. Zhang *et al.* (2024) emphasized permanence, additionality, leakage, uncertainty, and transaction costs as key challenges affecting the credibility and economic feasibility of agricultural soil carbon sequestration, while Phelan *et al.* (2024) showed that market demands can also limit farmers' participation.

Thus, ETS does not necessarily directly pay for all CFA activities, but the existence of a carbon pricing environment can increase the relative value of investments and low-emission technologies. According to Pigou (1920), this helps to narrow the gap between the social and private benefits of emission reductions. For Coase (1960), the formation of tradable carbon

rights helps to better reflect environmental value in production decisions. Therefore, the study proposes the hypothesis:

***H3**: ETS actively regulates the relationship between agricultural carbon farming status (CFA) and economic growth.*

In forestry, the role of carbon pricing is more complex because forests simultaneously provide at least two types of economic value, including value from biomass maintenance and carbon sequestration along with value from timber harvesting or land conversion to other productive purposes. Therefore, when carbon is priced, ETS can not only increase the benefits of forestry carbon farming but also change land use and resource exploitation decisions.

Paul *et al.* (2013) simulated 22 forestry farm and environmental tree planting options over a 100-year period, combining biological models with cash flow analysis and 10,000 Monte Carlo simulations. Many options have low economic value when carbon is not priced, but carbon pricing increases net present value and can push projects beyond the break-even point. This study shows that carbon pricing has the potential to directly change the economic returns of forest preservation and development.

However, increasing the value of forest carbon simultaneously alters the opportunity cost of harvesting. Pukkala (2020) optimized the management of 48,842 private forest plots in Finland over a 100-year period and showed that the optimal harvesting level decreased sharply as carbon prices increased. When credits were based on the amount of carbon held in the forest, a price of approximately 27.3 EUR/tCO_2 was sufficient to make non-harvesting the optimal choice in Northern Finland. At a price of approximately 40.9 EUR/tCO_2, cessation of harvesting could become the optimal choice on a broader scale. Thus, carbon pricing can increase carbon sequestration but simultaneously reduce timber production.

Practical evidence from New Zealand reinforces this mechanism. Carver *et al.* (2022) analyzed the response of the forestry sector under the NZ ETS and showed that land-use decisions clearly respond to emission prices. Using the New Zealand carbon quota unit (NZU) directly, when the average NZU price was relatively low during 2008-2018, new forest planting averaged around 9,000 ha/year. When the price increased to around 28 NZD in 2019-2020, new forest planting increased to around 34,000 ha/year. At a NZU price of 20 NZD, the net present value from low-risk carbon units is estimated at around 2000 NZD/ha. However, the sharp increase in carbon prices is also associated with concerns about the conversion of agricultural land to forests, permanent forests, reduced land-use flexibility, and a decline in employment or economic activity in some areas.

Peña-Lévano *et al.* (2019) showed that these trade-offs can spread across the entire economy. The author's CGE GTAP-BIO-FCS model shows that encouraging forest carbon sequestration can reduce the cost of achieving emission reduction targets under stable agricultural productivity. However, when climate change simultaneously degrades crop yields, increasing the return on forest land pulls land away from agriculture, increasing land rent and food prices, which can then reduce GDP and welfare. Thus, the same carbon pricing mechanism can generate emission reduction benefits but also create opportunity costs through land competition.

Therefore, current theoretical frameworks and evidence do not allow us to assume that ETS always regulates the positive impact of forest carbon farming. According to Pigou and Coase's logic, carbon pricing makes the carbon-absorbing capacity of forests more

economically valuable, but when relative prices change, land, capital, and labor can also shift to forestry or away from logging. The net impact on growth therefore depends on the balance between carbon revenue and environmental benefits against the opportunity costs of land, timber production, employment, and displaced production activities. Because two opposing mechanisms exist and evidence has not provided a unified direction of impact, the study proposes a non-directional moderating hypothesis based on empirical research:

H4*: The ETS significantly moderates the relationship between the status of forestry carbon farming (CFF) and economic growth.*

2.3 Research gaps

The available literature reveals three main gaps. First, much of the research on carbon farming focuses on productivity, income, costs, and environmental benefits at the farm or local level, while cross-country evidence on impacts on GDP growth remains limited (Antle *et al.*, 2001; Capalbo *et al.*, 2004; Pinto *et al.*, 2010; Tang *et al.*, 2016; Sharma *et al.*, 2021; Raina *et al.*, 2024; Zannol, 2025).

Second, agriculture and forestry are often grouped together despite having different economic mechanisms. Agriculture is more closely tied to productivity, inputs, and switching costs, while forestry is heavily influenced by land use, investment cycles, and resource exploitation. Therefore, it is necessary to distinguish between CFA and CFF within the same research framework.

Third, research on carbon farming and ETS has largely developed separately. Studies on ETS primarily examine emission reduction costs, investment, and market design (Wang *et al.*, 2015; Marcu *et al.*, 2022; Fowlie *et al.*, 2016), while studies on forest carbon show that carbon prices can influence land use and forest management decisions (Paul *et al.*, 2013; Pukkala, 2020; Carver *et al.*, 2022). However, the moderating role of ETS in the relationship between carbon farming and economic growth across the country has not been fully tested.

Therefore, this study distinguishes between CFA and CFF, and tests ETS as a moderating variable for the relationship between these two states and economic growth.

3. DATA AND RESEARCH METHODS

3.1 Research Data

The data used are secondary data collected from reputable organizations such as the World Bank, IMF.The master panel covers 103 countries over 2000-2024, corresponding to a maximum of 2,575 potential country-year observations. Due to missing values in several variables, the complete estimation sample is reduced to 1,584 observations from 99 countries over 2001-2021. This common sample is used for the correlation matrix, FEM, and System GMM estimations. Difference GMM uses 1,440 observations from 95 countries because first-differencing and lag requirements further reduce the effective sample. In addition to macroeconomic variables, the study constructs a Carbon Farming variable based on a concept publicly supported by numerous previous studies and the theoretical framework of the European Parliament and Council of the European Union (2024).

Author	Author's concept
Ghosh *et al.* (2024)	Carbon farming is the intersection of agriculture and climate change mitigation, using sustainable practices such as cover cropping, reduced plowing, agroforestry, and grazing management to increase carbon sequestration in soils and agricultural ecosystems.
Vistarte *et al.* (2024)	Carbon farming is a sustainable agricultural practice that aims to sequester CO_2 from the atmosphere, reduce greenhouse gas emissions, and improve soil health and biodiversity through regenerative practices.
European Commission (2022)	"Carbon farming is a green business model that pays land managers for implementing land management improvements that lead to increased carbon sequestration in living biomass, organic matter, and soil, adhering to ecological principles and benefiting biodiversity."

Regarding how to measure Carbon Farming

The variable Carbon Farming is constructed as a binary variable, 0 and 1, where 0 represents the absence of carbon farming and 1 represents the presence of carbon farming in the country under study. This is further divided into two types of carbon farming: forestry and agriculture, each representing a different approach to carbon farming.

- ***CFF (Forest Carbon Farming)*** assign 1 when the condition is met.

- **ΔAOF (Area of Forest) ≥ 0:** Explain that the forest area of that country has increased.
- **ΔEMF (Emissions from Land-Use Change and Forestry - CO_2) < 0:** Explain that emissions from land-use change and reforestation are reduced.

- ***CFA (Agriculture Carbon Farming)*** assign 1 when the condition is met.

- **ΔAOA (Area of Agriculture) ≥ 0:** Explain why the agricultural land area of that country increased.
- **ΔEMA (Emissions from Agriculture - CO_2) < 0:** Explain that emissions from farming are reduced.

With the core objectives of carbon farming, carbon farming measurement variables are built based on ensuring crop yields and the appearance of CO_2 emission reductions after planting, with the prerequisite being a reduction in atmospheric CO_2. This necessitates an increase or maintenance of the cultivated land area due to:

While a decrease in forest land area may be due to better forest management through technology or other objective factors, this does not guarantee that planting more trees will lead to a reduction in CO_2. Therefore, it can be concluded that net emission reduction, disregarding an increase in planted land area, does not guarantee the presence of carbon farming.

As the area of cultivated land increases, it can be said that more crops appear, accompanied by the condition that CO_2 from afforestation and agriculture decreases. It can be said that afforestation has a reduced impact on atmospheric CO_2, giving rise to "carbon farming". Tubiello *et al.* (2021a) studied the period 2011-2020 and showed that emissions from forest conversion (approximately +3.1 $GtCO_2$/year) were almost offset by the accumulation of remaining forest carbon (approximately -3.3 $GtCO_2$/year). This demonstrates that only with an increase in forest area and increased carbon sequestration capacity can forests create a net carbon trap.

Tubiello *et al.* (2021b) indicated that there has been a significant reduction in greenhouse gas (GHG) emissions due to land-use change, particularly related to forests and agriculture. Specifically, CO_2eq-equivalent greenhouse gas emissions from agricultural land decreased by 3% between 1990 and 2018, mainly due to a 19% reduction in emissions from land-use change. This decline is explained by the fact that per capita emissions from land-use change decreased by more than half during the same period. According to Tubiello *et al.* (2021b), for developing countries (NAIs), the share of food system emissions in total national emissions has sharply decreased from 56% to 36%, largely due to a significant reduction in emissions from land-use change, especially from the reduction in deforestation.

Thus, forest management and expansion are considered measurable man-made factors in carbon sequestration, providing a practical basis for the creation and trading of carbon credits - an important economic tool in emission reduction and sustainable development strategies. Ideally, the carbon farming measure would be a continuous variable in terms of carbon absorption; however, global data on changes in actual carbon stocks were not available in the context of this study. Using a binary variable offers three advantages: (1) capturing the presence of carbon farming activities, a crucial factor for policymakers when considering whether to implement them, (2) binary variables mitigate the biases from complex measurement methods found in biological models, and (3) binary variables are suitable for the discrete nature of environmental policy implementation. The research team acknowledges this as a research gap due to potential limitations in measurement; future studies on stored carbon stocks could use continuous methods to capture the intensity of effects, thereby clarifying the extent of impacts in more detail and specificity. Robustness consideration: To validate the binary coding, we conducted sensitivity analyses by varying the thresholds for ΔForest Area and ΔEmissions. Results remained consistent when requiring $\Delta\text{Area} \geq 1\%$ (instead of >0) and $\Delta\text{Emissions} \leq -2\%$ (instead of <0), confirming that our baseline coding captures substantive carbon farming activities rather than marginal fluctuations (results available upon request).

3.2 Research Methodology

Ramsey's test was used to validate the model and identify any missing variables or functional inaccuracies. Additionally, the study employed multiple regression methods to address data issues, including FEM, the Driscoll-Kraay fixed effects model with standard errors, and GMM. The optimal model was determined through tests such as Hausman, Modified Wald, Wooldridge, and Pesaran CD, addressing issues of heteroskedasticity, autocorrelation, and cross-dependency. Furthermore, the research team identified endogeneity issues using a two-stage regression model (2SLS) and GMM estimation to draw conclusions.

Research model

$$GDP_{it} = \beta_0 + \beta_1 ETS_{it} + \beta_2 CFF_{it} + \beta_3 CFA_{it} + \beta_4 CFFE_{it} + \beta_5 CFAE_{it} + \beta_6 FDI_{it} + \beta_7 REC_{it} + \beta_8 INF_{it} + \beta_9 EDU_{it} + \beta_{10} NET_{it} + \beta_{11} TRA_{it} + \xi$$

Variable Definitions:

- **GDP**: Annual GDP growth rate (%)
- **ETS**: Binary indicator (1 = country has operational emissions trading system, 0 = otherwise)
- **CFF**: Binary indicator for forestry carbon farming (1 = ΔForest Area > 0 AND ΔEmissions from forestry < 0)
- **CFA**: Binary indicator for agriculture carbon farming (1 = ΔAgriculture Area > 0 AND ΔEmissions from agriculture < 0)
- **CFFE** = CFF × ETS (interaction term capturing forestry carbon farming under ETS)
- **CFAE** = CFA × ETS (interaction term capturing agriculture carbon farming under ETS)

Control Variables:

- **FDI**: Foreign direct investment, net inflows (% of GDP)
- **REC**: Renewable energy consumption (% of total final energy)
- **INF**: Inflation rate (annual %)
- **EDU**: Gross tertiary enrollment ratio (%)
- **NET**: Internet penetration rate (% of population)
- **TRA**: Trade openness ((Exports + Imports) / GDP).

All continuous variables are winsorized at 1st and 99th percentiles to mitigate outlier influence.

4. RESEARCH RESULTS

4.1 Descriptive Statistics

Table 1: Descriptive Statistics

	Obs	Mean	Std. Dev.	Min	Max
GDP	2572	3.417	4.544	-29.825	34.466
ETS	2575	0.251	0.434	0.000	1.000
CFF	2354	0.232	0.422	0.000	1.000
CFA	2357	0.210	0.407	0.000	1.000
CFFE	2354	0.102	0.303	0.000	1.000
CFAE	2357	0.044	0.204	0.000	1.000
FDI	2558	4.227	17.545	-296.013	431.789
REC	2268	27.899	25.514	0.000	95.500
INF	2450	6.891	19.816	-8.238	557.202
EDU	1977	49.438	27.510	0.643	166.390
NET	2523	46.572	32.388	0.000	100.000
TRA	2445	78.590	38.863	0.000	258.780

(Source: Authors' calculations)

The table above presents descriptive statistics of the variables used in the study. GDP growth has a mean of 3.417, a standard deviation of 4.544, ranging from -29.825 to 34.466, indicating significant differences in economic growth among the countries in the sample.

The principal variables, ETS, CFA, and CFF, are all binary variables, with mean values of 0.251, 0.210, and 0.232, respectively. This suggests that the conditions defining carbon farming and the presence of emission trading systems are not widespread throughout the study sample. The two interaction variables, CFFE and CFAE, have mean values of 0.102 and 0.044, respectively, reflecting the relatively limited number of observations simultaneously meeting the carbon farming condition and having ETS. The control variables FDI, REC, INF, EDU, NET, and TRA also exhibit significant dispersion, reflecting differences in economic conditions, energy, education, digitalization, and trade integration among countries.

Table 2: Correlation matrix

Variables	GDP	ETS	CFF	CFA	CFFE	CFAE	FDI	REC	INF	EDU	NET	TRA
GDP	1.000											
ETS	-0.206	1.000										
CFF	-0.048	0.184	1.000									

CFA	0.080	-0.055	-0.032	1.000								
CFFE	-0.140	0.562	0.611	-0.017	1.000							
CFAE	-0.023	0.347	0.083	0.474	0.221	1.000						
FDI	0.027	0.117	0.015	0.010	0.042	0.071	1.000					
REC	0.094	-0.097	-0.143	0.040	-0.060	-0.032	-0.079	1.000				
INF	-0.019	-0.234	-0.020	0.057	-0.113	-0.069	-0.036	-0.020	1.000			
EDU	-0.261	0.566	0.169	-0.120	0.281	0.200	0.042	-0.344	-0.076	1.000		
NET	-0.332	0.598	0.106	-0.049	0.301	0.210	0.052	-0.263	-0.194	0.727	1.000	
TRA	0.039	0.362	0.123	0.033	0.192	0.171	0.160	-0.262	-0.103	0.266	0.283	1.000
Obs	1584	1584	1584	1584	1584	1584	1584	1584	1584	1584	1584	1584

(Source: Authors' calculations)

Table 2 presents the Pearson correlation coefficients calculated using a common sample of 1,584 observations with complete data for all variables. Using the same estimation sample for every pair ensures that the reported coefficients are directly comparable and avoids differences caused by varying numbers of available observations.

Table 3: Ramsey Test

Test	p-value
Ramsey RESET Test	0.3554

(Source: Authors' calculations)

The Ramsey RESET test yields a p-value of 0.3554, indicating that the null hypothesis of no functional-form misspecification cannot be rejected. However, this test does not rule out potential endogeneity or omitted-variable bias, these issues are examined separately through the endogeneity tests and dynamic GMM estimations.

Table 4: Econometrics test

Test	Test statistic	p-value
Hausman test	$\chi^2(11) = 92.67$	0.001
F-test for individual effects	$F(98, 1474) = 3.83$	0.001
Modified Wald test	$\chi^2(99) = 6{,}194.32$	0.001
Wooldridge test	$F(1, 92) = 12.376$	0.0007
Pesaran CD test	$CD = 148.99$	0.001

(Source: Authors' calculations)

The Hausman test and F-test results are both statistically significant, indicating that the fixed effects model (FEM) is more suitable than the random effects model and pooled

regression. Simultaneously, the Wald, Wooldridge, and Pesaran CD tests confirm the existence of heteroskedasticity, autocorrelation, and cross-dependence in the panel data. Therefore, the study uses FEM and FEM with Driscoll-Kraay standard errors as baseline models to increase the reliability of the results. However, these models do not fully address the endogeneity and dynamism of economic growth.

Table 5: Endogeneity test

Variable	Durbin (p-value)	Wu-Hausman (p-value)	Conclusion
CFA	0.7660	0.7670	Exogenous
CFF	0.2963	0.2983	Exogenous
ETS	0.0124	0.0127	Endogenous
CFAE	0.2322	0.2342	Exogenous
CFFE	0.1093	0.1108	Exogenous
FDI	0.0055	0.0056	Endogenous
REC	0.001	0.001	Endogenous
INF	0.2445	0.2465	Exogenous
EDU	0.001	0.001	Endogenous
NET	0.8406	0.8412	Exogenous
TRA	0.001	0.001	Endogenous

(Source: Authors' calculations)

Durbin and Wu-Hausman tests were used to determine the endogeneity of the explanatory variables in the model. The results showed that ETS, FDI, REC, EDU, and TRA all had p-values less than 0.05 in both tests, indicating statistical evidence of endogeneity. Conversely, CFA, CFF, CFAE, CFFE, INF, and NET had p-values greater than 0.05,

suggesting no evidence to reject the exogenous assumption. These results provide a basis for further research to identify variables that need to be addressed for endogeneity during the GMM estimation process.

4.2 Main regression results

The Hausman test results showed that the fixed effects model (FEM) was a better fit. Therefore, the study continued to estimate FEM and FEM with Driscoll-Kraay standard errors to test the robustness of the results.

Table 6: FEM and Driscoll-Kraay

	FEM	**Driscoll-Kraay**
CFA	0.006**	0.004*
	(0.003)	(0.002)
CFF	-0.003	-0.001
	(0.003)	(0.003)
ETS	-0.009*	-0.008
	(0.005)	(0.006)
CFAE	0.003	-0.001
	(0.005)	(0.004)
CFFE	-0.002	-0.000
	(0.005)	(0.002)
FDI	0.009*	0.005
	(0.005)	(0.003)
REC	-0.075***	-0.038
	(0.022)	(0.030)
INF	-0.083***	-0.100***
	(0.016)	(0.015)
EDU	0.013	0.003
	(0.012)	(0.017)
NET	-0.062***	-0.085***
	(0.007)	(0.017)
TRA	0.084***	0.052***
	(0.008)	(0.012)
Country fixed effects	Yes	Yes
Year fixed effects	No	Yes
Observations	1584	1584

(Source: Authors' calculations)

Results from the FEM and the Driscoll-Kraay fixed-effect model with standard error showed that CFA has a positive impact on economic growth, with a coefficient of 0.006 in the FEM ($\beta = 0.006$; $p < 0.05$) and 0.004 in the Driscoll-Kraay model ($\beta = 0.004$; $p < 0.10$). This result is consistent with Ajatasatru *et al.* (2024), which noted that low-emission agricultural practices can support output and GDP. Meng *et al.* (2024) also noted the potential for increased agricultural output simultaneously with reduced emissions.

Conversely, CFF did not show a clear impact in either model ($\beta = -0.003$ and -0.001; $p > 0.10$). ETS was only weakly significant in FEM ($\beta = -0.009$; $p < 0.10$) and no longer significant in Driscoll-Kraay, while CFAE and CFFE were both statistically insignificant. Therefore, these estimates do not yet show clear evidence of the moderating role of ETS.

For the control variables, inflation had a negative and highly statistically significant impact in both FEM ($\beta = -0.083$; $p < 0.01$) and Driscoll-Kraay ($\beta = -0.100$; $p < 0.01$), consistent with the adverse impact of price instability on purchasing power and economic activity. Trade openness has a positive and stable impact, with a coefficient of 0.084 in FEM and 0.052 in Driscoll-Kraay ($p < 0.01$), suggesting that trade can support growth through market expansion and access to external resources.

Internet usage rates have a negative and statistically significant coefficient in both models ($\beta = -0.062$ and -0.085; $p < 0.01$). This result does not necessarily imply that the level of Internet penetration reduces economic growth, but may reflect the convergence characteristic of the study sample: economies with high levels of digitalization are generally already highly developed and have lower growth rates. Therefore, this coefficient should be considered a conditional association after controlling for country characteristics, time, and other macroeconomic factors.

Overall, the FEM and Driscoll-Kraay models provide preliminary evidence for the relationship between the study variables and economic growth. However, since the previous 2SLS and Wu-Hausman tests revealed the presence of endogeneity, these estimates are insufficient to draw definitive conclusions. Therefore, the study continues to use dynamic GMM models to address endogeneity and test the robustness of the results.

Table 7: Main Results

	Difference GMM	**System GMM**
L.GDP	0.337	0.016
	(0.346)	(0.185)
CFA	-0.047	-0.035**
	(0.030)	(0.017)
CFF	0.103	0.058*
	(0.078)	(0.029)
ETS	-0.036	-0.049
	(0.056)	(0.035)
CFAE	0.193*	0.161***
	(0.098)	(0.055)
CFFE	-0.237	-0.136**
	(0.161)	(0.063)

FDI	-0.019	-0.012
	(0.140)	(0.104)
REC	0.615	0.384**
	(0.489)	(0.156)
INF	0.165	-0.016
	(0.179)	(0.057)
EDU	0.307	0.182***
	(0.348)	(0.068)
NET	0.021	-0.035
	(0.103)	(0.033)
TRA	-0.125	0.048
	(0.315)	(0.048)
AR(1)	0.030	0.000
AR(2)	0.684	0.478
Sargan	0.902	0.635
Hansen	0.988	0.956
Difference-in-Hansen (null H = exogenous)	0.990	0.790
Number of instruments	20	29
Number of groups	95	99
Observations	1440	1584

Standard errors in parentheses
* p < 0.10, ** p < 0.05, *** p < 0.01
(Source: Authors' calculations)

The study selected the two-step SGMM as the main estimation model. According to Arellano and Bond (1991), DGMM may have a weak tool problem when the variables are stable over time. On the other hand, Arellano and Bover (1995) and Blundell and Bond (1998) showed that SGMM can improve this limitation by adding level equations and corresponding moment conditions. Both DGMM and SGMM passed the AR(2) and Hansen tests proving that both models are specification valid. However, SGMM exploits more information from the level equations, while the Difference-in-Hansen test does not reject the validity of this additional tool group (p = 0.790) and the estimates generally have lower standard errors than DGMM. Simultaneously, the study limits the overfitting of instruments by limiting lags and reducing the instrument matrix, in line with Roodman's (2009) recommendation to reduce the risk of overfitting endogenous variables and weakening the Hansen test. The results used only 29 instruments for 99 countries. Therefore, SGMM was chosen as the main model, while DGMM was used to test the robustness of the results.

The SGMM results show that the lagged GDP growth variable (L.GDP) has a β coefficient of 0.016, but this is not statistically significant, implying that the growth of the previous period has not had a clear impact on the growth of the current period. This indicates that there is no evidence of the persistence of growth after controlling for other factors in the

dynamic model. For the main research variables, the impact of carbon farming on economic growth depends significantly on the presence of the emissions trading system. When ETS is zero, carbon farming in agriculture (CFA) has a negative impact with a β coefficient of -0.035 and is statistically significant at the 5% level, while carbon farming in forestry (CFF) has a positive impact with a β coefficient of 0.058 and is significant at the 10% level. ETS itself has a β coefficient of -0.049 but is not statistically significant, indicating that the presence of the emissions market has not yet created a clear direct impact on growth.

The moderating role of ETS is evident through the two interacting variables, but in opposite directions. CFAE has a β coefficient of 0.161 and is statistically significant at the 1% level, indicating that ETS significantly improves the impact of carbon farming in agriculture on growth. Considering the total impact, CFA shifts from β = -0.035 in the absence of ETS to approximately β = 0.126 when ETS is present. Conversely, CFFE has a β coefficient of -0.136 and is significant at the 5% level, indicating that ETS diminishes the initial positive impact of carbon-based forestry farming; the total impact of CFF shifts from β = 0.058 to approximately β = -0.078 when ETS equals 1. Thus, ETS does not create a uniform moderating mechanism but promotes the growth impact of carbon-based agricultural farming, while reversing the impact of carbon-based forestry farming.

For the control variables, renewable energy consumption (REC) and education (EDU) have positive and statistically significant impacts, with coefficients of β = 0.384 and β = 0.182, respectively. Meanwhile, FDI, inflation, internet usage, and trade openness do not show statistically significant impacts.

The DGMM results generally reinforce the direction of impact of the interacting variables: CFAE continues to have a positive coefficient, while CFFE has a negative coefficient, although the statistical significance is weaker. L.GDP in the DGMM is also not statistically significant, thus showing that the conclusions about the impact of previous period growth are relatively consistent between the two methods. Post-estimation tests of both models did not reject the validity of the tools and did not detect second-order autocorrelation.

5. DISCUSSION

This study provides cross-country empirical evidence linking carbon farming to national economic growth through the lens of externality internalization theory. Our findings offer three key contributions to theory, methodology, and policy.

5.1 Carbon Farming without markets as an externality

The first research question examines whether carbon farming affects economic growth and whether the impact differs between agriculture and forestry. Using the System GMM results, it was found that when ETS = 0, CFA has a negative impact on growth ($\beta = -0.035$; $p < 0.05$), while CFF has a positive impact ($\beta = 0.058$; $p < 0.10$). Therefore, H1 is not supported, while H2 is supported. More importantly, these findings indicate that agricultural and forestry carbon farming do not generate homogeneous economic outcomes.

For CFA, the negative results suggest that maintaining agricultural land while reducing emissions may incur adjustment costs before economic benefits are realized. Ajatasatru *et al.* (2024) showed that the most aggressive emission reduction method does not necessarily produce the greatest GDP impact, as the outcome also depends on productivity, capital, and production linkages. Branca *et al.* (2021) also indicated that initial investment costs are a

significant barrier to transitioning to low-emission agriculture. According to Pigou (1920), when emission reduction benefits are not priced, producers bear the switching costs while a portion of the climate benefits remain a positive externality. The negative CFA estimate does not imply that agricultural emission reductions cause social losses, but rather shows that environmental benefits from low-emission agriculture are not necessarily directly translated into growth.

Conversely, CFF has a positive impact even without ETS. Liu *et al.* (2023) showed that forest carbon sequestration projects increase agricultural total factor productivity by approximately 1.7-2.4% through health, income, and structural shift channels. Wu *et al.* (2021) also found evidence of economic benefits from carbon sequestration reforestation projects, although the impact appears lagged. The empirical results suggest that forests can generate economic value through forestry production, ecosystem services, and related activities even when carbon is not priced through other transformation channels.

A key finding of this section is that carbon farming does not have a unified economic impact. If CFA and CFF are combined, the negative impacts of carbon farming states from agriculture and the positive impacts of forestry may cancel each other out. The study thus narrows the gap of previous literature, which primarily considered carbon farming at the farm or local level, by showing on cross-country data that the impact on growth depends on the sector producing the emission reductions.

5.2 Emissions trading systems as the internalization mechanism

The second research question examined whether ETS alters the relationship between carbon farming and economic growth. This is a central gap in the study, as the literature on carbon farming and the literature on ETS largely developed into two separate streams.

The results showed that the individual coefficient of ETS was not statistically significant ($\beta = -0.049$; $p > 0.10$), but the two interaction coefficients were significant and opposite in sign. CFAE (CFA×ETS) recorded a positive effect ($\beta = 0.161$; $p < 0.01$), while CFFE (CFF × ETS) recorded a negative effect ($\beta = -0.136$; $p < 0.05$). Therefore, hypothesis H3 regarding the moderating role of ETS is supported, but the moderating direction differs significantly between agriculture and forestry.

For CFA, ETS makes the relationship with growth more favorable. This result is consistent with the externality internalization mechanism developed by Pigou (1920) and Coase (1960). Pigou (1920) argued that carbon pricing helps bridge the gap between the social and private benefits of emission reductions. Coase (1960) argued that tradable emission rights facilitate the inclusion of carbon value in economic decision-making. Wang *et al.* (2015) showed that in Guangdong, ETS helped reduce GDP losses compared to the case of achieving the same emission reduction target but without allowing trading. Frank *et al.* (2024) also showed that when agricultural carbon sequestration is included in the pricing mechanism, the cost of climate transition can be significantly reduced. The CFAE (CFA×ETS) results add cross-country evidence that ETS not only influences emissions but can also alter the economic impact of agricultural emission reductions.

However, the negative CFFE (CFF×ETS) indicates that internalizing externalities does not always increase GDP. This finding supports H4, confirming that ETS significantly moderates the relationship between forestry carbon farming and economic growth, although the moderating effect is negative. Pukkala (2020) showed that high carbon prices significantly

reduce optimal logging levels because retaining carbon in forests becomes more valuable. Carver *et al.* (2022) noted in New Zealand that high carbon prices strongly encourage reforestation but simultaneously raise concerns about agricultural land conversion, permanent forests, and regional economic activity. Peña-Lévano *et al.* (2019) also showed that encouraging forest carbon sequestration can shift land away from agriculture and create costs through land and food prices.

Therefore, a negative CFFE (CFF×ETS) does not necessarily mean that ETS is an environmental failure. On the contrary, it may reflect that the carbon price signal is strong enough to change land use and resource exploitation decisions. The deeper finding here is that ETS does not create an independent growth impact, but rather alters the returns of each type of carbon farming. This is precisely the point that expands on previous literature on ETS, which primarily assessed emissions, compliance costs, or direct GDP, and rarely considered ETS as an institutional condition regulating the relationship between carbon farming and growth.

5.3 Forestry versus agricultural carbon farming

The research results clearly answer the question of whether CFA and CFF should be considered as a homogeneous economic phenomenon. The System GMM estimates shows a distinctly opposite structure: CFA is negative but CFAE (CFA×ETS) is positive, while CFF is positive but CFF (CFF × ETS) is negative. The difference therefore lies not only in magnitude but also in the direction of impact and how the two sectors respond to ETS.

CFA primarily reflects a state of reduced emissions while agricultural land is maintained or increased. Therefore, the transition is more likely to occur within the production system through technology, input management, and efficiency improvement. Meng *et al.* (2024) showed that capital and technology play a crucial role in the process of decoupled agricultural growth from emissions. In the absence of a carbon price, the cost of transition may predominate, but the emergence of an emissions market could increase the returns on low-emission improvement methods.

Carbon farming in forestry (CFF) is more closely related to a biological asset that accumulates over time. Retaining carbon in forests may require delaying harvesting or changing land use. Paul *et al.* (2013) showed that carbon pricing significantly alters the returns of forestry alternatives. When carbon prices rise high enough, biomass retention may become more attractive than harvesting, creating a trade-off between carbon benefits and current output.

Therefore, a key contribution of the study is showing that CFA is primarily tied to the efficiency of current production flows, while CFF is also tied to land allocation decisions and carbon stock over time. This is why the same ETS can produce opposite moderating effects. This result goes further than Frank *et al.* (2024), which showed that carbon farming can reduce overall switching costs by demonstrating that those benefits are not necessarily distributed equally between agriculture and forestry.

5.4 Theoretical and Methodological contributions

Theoretically, the study extends the application of Pigou and Coase to carbon farming. The results show the traditional internalization logic in the state of carbon farming (CFA).

When carbon benefits are not priced, switching costs can have a negative economic impact. When ETS is introduced, the impact of CFA on GDP becomes positive. However, the CFF results show that externality internalization also creates a subsequent, often overlooked step: the carbon price changes relative prices and leads to resource reallocation. ETS internalizes carbon externalities by assigning an economic value to emissions and emission reductions, thereby changing relative prices. These price signals influence the allocation of land, capital, and production activities, which ultimately shapes the effect of carbon farming on economic growth.

This is the deepest theoretical contribution of the study. External internalization does not necessarily produce the same economic outcome for all carbon activities; the outcome depends on the type of resources that need to be reallocated. This explains why ETS can improve the impact of CFA but weaken the impact of CFF.

The study also contributes by viewing ETS as an institutional moderating variable rather than just an independent policy variable. The fact that ETS has no direct significant impact is significant, but CFAE (CFA × ETS) and CFFE (CFF × ETS) are both significant, suggesting that the economic role of ETS lies largely in its ability to alter the returns of different emission reduction activities.

Methodically, the study distinguishes CFA and CFF as land states and observed emissions at the national level, rather than assuming a unified measure of carbon farming adoption. This approach allows for cross-country research in the context of limited direct data on carbon farming, while clarifying that CFA and CFF are variables representing carbon farming states rather than direct measures of the number of projects or carbon credits.

The endogenous treatment also had significant implications for the conclusion. FEM and Driscoll-Kraay gave positive CFA and did not determine the role of interactions, while System GMM gave CFA = −0.035, CFF = 0.058, CFA × ETS = 0.161 and CFF × ETS = −0.136 with most of the high statistical significance levels. Difference GMM maintained the same direction of impact although with lower precision. System GMM tests did not show second-order autocorrelation (AR(2), $p = 0.478$), and Sargan ($p = 0.635$) and Hansen ($p = 0.956$) did not reject the validity of the tool set; the number of tools 29 was also lower than the number of groups 99.

In summary, the study did not simply answer whether carbon farming increases or decreases GDP. A more important finding is that the economic impact of conditional carbon farming depends on the land-use sector and on how ETS alters the value of carbon and resource allocation. The contrast between CFA and CFF, along with the opposing regulatory role of ETS, is the key finding and core contribution of the study.

5.5 Limitations and directions for future research

Several limitations should be acknowledged. First, the binary nature of the carbon farming variable does not capture differences in sequestration intensity across countries. Future research could employ continuous measures derived from national greenhouse gas inventories to examine nonlinear or dose response relationships. Second, the ETS indicator reflects only the presence of a system, not its maturity or effectiveness. Incorporating carbon prices, market liquidity, or transaction volumes would allow a more nuanced assessment of market performance.

Third, no carbon farming observations are available for 2024, so the analysis cannot capture the effects of the EU Carbon Removal Certification Framework introduced that year. Extending the analysis to include this regulatory development would be a natural next step. Fourth, further heterogeneity analysis by income level, institutional quality, or climate conditions could shed light on context specific effects, particularly in countries with limited measurement and verification capacity.

6. POLICY IMPLICATIONS

The research findings suggest three main implications. First, carbon farming policies need to be tailored to agriculture and forestry. For agriculture, ETS can support the transition to low-emission production by improving investment incentives and reducing transition costs. Second, for forestry, policies should prioritize reducing barriers to reforestation credits on marginal lands where the opportunity cost of land is lower, rather than encouraging indiscriminate forest expansion. Third, the effectiveness of ETS is strongly dependent on measurement, reporting, and verification (MRV) capacity. Developing countries need to invest simultaneously in MRV infrastructure and carbon markets so that carbon farming practices can be reliably verified, certified, and traded.

7. CONCLUSION

The study provides cross-national empirical evidence on the relationship between carbon farming and economic growth, while clarifying the moderating role of the Emissions Trading System (ETS). The System GMM results show that the impact of carbon farming is not uniform between agriculture and forestry. Without ETS, CFA has a negative effect on economic growth, whereas CFF has a positive effect. ETS positively moderates the relationship between CFA and economic growth but negatively moderates the relationship between CFF and economic growth. Accordingly, H1 is not supported because CFA has a negative effect on economic growth when ETS is absent, whereas H2 is supported by the positive effect of CFF. H3 and H4 are also supported, as ETS significantly moderates the effects of both CFA and CFF, although in opposite directions. This finding suggests that carbon farming should not be viewed as a single emission reduction tool with a uniform economic impact, but rather as a transition process dependent on the characteristics of each land-use sector and the institutional environment in which it takes place.

The most profound contribution of the study lies in extending the theoretical explanations of the internalization of carbon externalities as described by Pigou (1920) and Coase (1960). ETS not only incorporates the value of emission reductions into the price system but also alters the relative prices and allocation of land, capital, technology, and production activities. Therefore, internalizing externalities does not necessarily produce the same growth outcomes for all forms of carbon farming. For agriculture, carbon pricing can improve the returns on efficiency enhancement and emission reduction within existing production systems. Conversely, for forestry, higher carbon values can increase incentives for biomass retention, delaying harvesting or converting land to forest, thereby incurring opportunity costs for current output. The study thus adds a channel for resource reallocation to the internalization of externalities mechanism, and shows that ETS is more appropriate

when viewed as an institutional condition that alters the impact of carbon farming, rather than simply as a policy variable directly affecting GDP.

In terms of empirical and methodological aspects, the study narrows the literature gap by shifting carbon farming analysis from the farm, project, and local levels to a transnational scope, and by distinguishing between CFA and CFF instead of lumping agriculture and forestry together as a single homogeneous group. The way land and emission states are constructed also facilitates carbon farming research in the absence of a unified international dataset on application levels. From a policy perspective, the results show that emission reduction and economic growth are not inherently opposed, but neither do they automatically support each other. The ultimate effect depends on how carbon value is internalized and resources are reallocated. Therefore, carbon farming policies need to be tailored specifically to agriculture and forestry, and coordinated with ETS to both encourage emission reduction and mitigate opportunity costs for production and land use.

8. DATA AVAILABILITY STATEMENT

The data supporting this study's findings are publicly available from the World Bank World Development Indicators (https://databank.worldbank.org) and International Monetary Fund (https://www.imf.org/en/Data). The constructed carbon farming variables (CFF, CFA) and replication code (Stata syntax) are available from the corresponding author upon reasonable request.

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Conflict of interests statement
All authors confirm there is no conflict of interests.

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References

Ajatasatru, A., Prabhu, V., Pal, B. D., & Mukhopadhyay, K. (2024). Economy-wide impact of climate smart agriculture in India: a SAM framework. Journal of Economic Structures, 13(1), 4.

Antle, J. M., Capalbo, S. M., Mooney, S., Elliott, E. T., & Paustian, K. H. (2001). Economic analysis of agricultural soil carbon sequestration: an integrated assessment approach. Journal of Agricultural and Resource Economics, 344-367.

Arellano, M., & Bond, S. (1991). Some tests of specification for panel data: Monte Carlo evidence and an application to employment equations. The review of economic studies, 58(2), 277-297.

Arellano, M., & Bover, O. (1995). Another look at the instrumental variable estimation of error-components models. Journal of econometrics, 68(1), 29-51.

Batabyal, A. (2023). The Theory of Externalities. SSRN Electronic Journal. https://doi.org/10.2139/ssrn.4643096

Blundell, R., & Bond, S. (1998). Initial conditions and moment restrictions in dynamic panel data models. Journal of econometrics, 87(1), 115-143.

Branca, G., Arslan, A., Paolantonio, A., Grewer, U., Cattaneo, A., Cavatassi, R., ... & Vetter, S. (2021). Assessing the economic and mitigation benefits of climate-smart agriculture and its implications for political economy: A case study in Southern Africa. Journal of Cleaner Production, 285, 125161.

Bryan, E., Akpalu, W., Yesuf, M., & Ringler, C. (2010). Global carbon markets: Opportunities for subSaharan Africa in agriculture and forestry. Climate and Development, 2(4), 309-331.

Capalbo, S. M., Antle, J. M., Mooney, S., & Paustian, K. (2004). Sensitivity of Carbon Sequestration Costs to Economic and Biological Uncertainties. Environmental Management, 33(S1). https://doi.org/10.1007/s00267-003-9134-1

Carver, T., Dawson, P., O'Brien, S., Kotula, H., Kerr, S., & Leining, C. (2022). Including forestry in an emissions trading scheme: Lessons from New Zealand. Frontiers in Forests and Global Change, 5, 956196.

Coase, R. H. (1960). The Problem of Social Cost. The Journal of Law and Economics, 3(3), 1-44. https://doi.org/10.1086/466560

Conant, R. T. (2011). Sequestration through forestry and agriculture. Wiley Interdisciplinary Reviews: Climate Change, 2(2), 238-254.

European Commission. (2021). Sustainable Carbon Cycles. COM(2021) 800 final.

European Parliament and Council of the European Union. (2024). Regulation (EU) 2024/3012 of the European Parliament and of the Council of 27 November 2024 establishing a Union certification framework for permanent carbon removals, carbon farming and carbon storage in products. Europa.eu. http://data.europa.eu/eli/reg/2024/3012/oj

Fowlie, M., Reguant, M., & Ryan, S. P. (2016). Market-based emissions regulation and industry dynamics. Journal of Political Economy, 124(1), 249-302.

Frank, S., Lessa Derci Augustynczik, A., Havlík, P., Boere, E., Ermolieva, T., Fricko, O., ... & Wögerer, M. (2024). Enhanced agricultural carbon sinks provide benefits for farmers and the climate. Nature Food, 5(9), 742-753.

Ghosh, B., Barman, B., Ranjan, A., Quader, S. W., & Kumar, S. S. (2024). Carbon Farming: Best Management Practices and Factors Affecting Farmers' Acceptance. Journal of Experimental Agriculture International, 46(8), 900-913.

Lindsey, R. (2025, May 21). Climate Change: Atmospheric Carbon Dioxide (J. Miller, Ed.). Climate.gov; National Oceanic and Atmospheric Administration. https://www.climate.gov/news-features/understanding-climate/climate-change-atmospheric-carbon-dioxide

Liu, J., Ren, Y., Hong, Y., & Glauben, T. (2023). Does forest farm carbon sink projects affect agricultural development? Evidence from a Quasi-experiment in China. Journal of Environmental Management, 335, 117500.

Livernois, R. (2019). A philosophical analysis of the concept of an externality in economic theory and policy.

Marcu, A., Hernández, J. F. L., Alberola, E., Faure, A., Qin, B., O'Neill, M., ... & Vollmer, A. (2022). 2022 State of the EU ETS Report. European Roundtable on Climate Change and Sustainable Transition

Meng, Y., Shen, Y., Wang, W., Liu, Y., Wang, F., & Wang, H. (2024). Who affects carbon emissions? Drivers and decoupling effects of agricultural carbon emissions—evidence from Sichuan, China. Frontiers in Sustainable Food Systems, 8, 1441118.

Paul, K. I., Reeson, A., Polglase, P., Crossman, N., Freudenberger, D., & Hawkins, C. (2013). Economic and employment implications of a carbon market for integrated farm forestry and biodiverse environmental plantings. Land use policy, 30(1), 496-506.

Peña-Lévano, L. M., Taheripour, F., & Tyner, W. E. (2019). Climate Change Interactions with Agriculture, Forestry Sequestration, and Food Security: LM Peña-Lévano et al. Environmental and Resource Economics, 74(2), 653-675.

Phelan, L., Chapman, P. J., & Ziv, G. (2024). The emerging global agricultural soil carbon market: the case for reconciling farmers' expectations with the demands of the market. Environmental Development, 49, 100941.

Pigou, A. C. (1920). The Economics of Welfare. Libertyfund.org. https://oll.libertyfund.org/titles/pigou-the-economics-of-welfare

Pinto, D., Magalhaes, M., & Ringler, C. (2010). Potential of carbon markets for small farmers: A literature review.

Pukkala, T. (2020). At what carbon price forest cutting should stop. Journal of forestry research, 31(3), 713-727.

Raina, N., Zavalloni, M., & Viaggi, D. (2024). Incentive mechanisms of carbon farming contracts: A systematic mapping study. Journal of Environmental Management, 352, 120126.

Roodman, D. (2009). How to do xtabond2: An introduction to difference and system GMM in Stata. The stata journal, 9(1), 86-136.

Saikanth, D., Kishore, A. J., Sadineni, T., Singh, V., Upadhyay, L., Kumar, S., & Kumar, P. C. (2023). A review on exploring carbon farming as a strategy to mitigate greenhouse gas emissions. Int. J. Plant Soil Sci, 35(23), 380-388.

Sharma, M., Kaushal, R., Kaushik, P., & Ramakrishna, S. (2021). Carbon farming: Prospects and challenges. Sustainability, 13(19), 11122.

Tang, K., Kragt, M. E., Hailu, A., & Ma, C. (2016). Carbon farming economics: what have we learned? Journal of Environmental Management, 172, 49-57.

Tubiello, F. N., Conchedda, G., Wanner, N., Federici, S., Rossi, S., & Grassi, G. (2021a). Carbon emissions and removals from forests: new estimates, 1990-2020. Earth System Science Data, 13(4), 1681-1691.

Tubiello, F. N., Rosenzweig, C., Conchedda, G., Karl, K., Gütschow, J., Xueyao, P., ObliLaryea, G., Wanner, N., Qiu, S. Y., & Barros, D. (2021b). Greenhouse gas emissions from food systems: building the evidence base. Environmental Research Letters, 16(6), 065007.

UNEP. (2024). Emissions Gap Report 2024. In UNEP - UN Environment Programme. https://www.unep.org/resources/emissions-gap-report-2024

Vistarte, L., Kubule, A., Rozentale, L., & Pubule, J. (2024). Carbon farming: a systematic literature review on sustainable practices. Environm Clim Technol 28: 895-909.

Wang, P., Dai, H. C., Ren, S. Y., Zhao, D. Q., & Masui, T. (2015). Achieving Copenhagen target through carbon emission trading: Economic impacts assessment in Guangdong Province of China. Energy, 79, 212-227.

Wu, J., Hou, F., & Yu, W. (2021). The effect of carbon sink plantation projects on local economic growth: An empirical analysis of county-level panel data from Guangdong province. Sustainability, 13(24), 13864.

Zannol, P. (2025). The economic impact of carbon farming practices at farm level mapping - Epsilon Archive for Student Projects. Epsilon.slu.se. https://stud.epsilon.slu.se/21812/1/zannol-z-20251020.pdf

Zhang, K., Liu, Z., McCarl, B. A., & Fei, C. J. (2024). Enhancing Agricultural Soil Carbon Sequestration: A Review with Some Research Needs, Climate, 12, 151.

Zhang, Z., Wan, X., Sheng, K., Sun, H., Jia, L., & Peng, J. (2023). Impact of carbon sequestration by terrestrial vegetation on economic growth: evidence from Chinese county satellite data. Sustainability, 15(2), 1369.