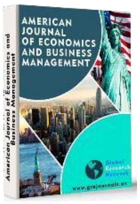

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Article

The Nexus Between Agricultural Water Productivity and CO_2 Emissions in River Basin Countries of Central Asia: The Role of Governance

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Abstract: This study analyzes the relationship between water productivity and CO2 emissions of Agriculture Amudarya and Sirdarya river basin depending countries of Central Asia over the period 1996–2024. An important contribution of this study is to assess the role of governance in water productivity. The Fixed-effects regression with Driscoll–Kraay heteroskedasticity and autocorrelation consistent standard errors are used for panel data. The empirical results show that water productivity has a significant negative impact on agricultural CO2 emissions. The estimates show that a one-unit increase in water productivity leads to approximately 0.08–0.21 unit decrease in agricultural CO2 emissions. We also find that water productivity decreases agricultural CO2 emissions faster in countries with higher rule of law, regulatory quality, government effectiveness, and voice and accountability.

Keywords: Water Productivity, Agricultural CO_2 Emissions, Governance Quality, Central Asia, River Basin Economies, Agricultural Sustainability, Panel Data, Fixed Effects, Driscoll–Kraay Estimator, Water Governance.

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1. Introduction

Availability of freshwater and environmental degradation have emerged as some of the key challenges for performance sustainability during the twenty-first century, especially in areas characterized by irrigation-dependent agriculture systems and transboundary river basins. Agriculture is already one of the top three human causes of water depletion and ecological pressure, as reports from the Food and Agriculture Organization indicate that the majority of global freshwater withdrawals are dedicated to agriculture. Meanwhile, agricultural production, through irrigation, groundwater pumping, fertilizer input, and fossil-fuel-based mechanization, also plays a key role in the greenhouse gas emissions of all sectors. Thus, the linkages between water resources for agriculture and environmental degradation have become a vital topic in both environmental economics and sustainability literature [1].

The modeling of the water–environment nexus has its theoretical precursors in pioneering work on virtual water, which argues that to understand scarcity, one must analyze it within the broader context of economic production and trade structures. Subsequently, researchers developed the water footprint framework and showed that through the excessive use of agricultural water, ecological deterioration and environmental fragility can be exacerbated. Similarly, literature argues the need to improve agricultural water productivity for sustainable agricultural development and to mitigate environmental stress at the same time. These results indicate that efficient irrigation techniques and water-saving mechanisms can significantly reduce energy consumption and carbon-intensive production processes. Improving water productivity in agriculture through efficient irrigation and water-saving technologies eases environmental pressure and promotes sustainable agriculture [2].

By contrast, some scholars found that agricultural modernization and irrigation expansion tend to increase carbon emissions due to intensive energy consumption and groundwater extraction. Likewise, it has been reported that fossil-fuel energy use, agricultural production, and weak institutional quality together intensify environmental degradation in emerging economies. On the other hand, better institutional quality and improved governance reduce emissions by ensuring better management of resources and stricter environmental regulation [3].

The environmental impacts of agricultural water use are particularly acute in Central Asia, where the economies of Uzbekistan, Kazakhstan, Kyrgyzstan, Tajikistan, and Turkmenistan largely depend on the transboundary waters of the Amudarya and Syrdarya river basins. The Aral Sea crisis remains one of the most visible cases of environmentally unsustainable irrigation policies and inefficient water governance. Scholars have shown that outdated irrigation infrastructure and inefficient water allocation systems in Central Asia significantly increase water losses, electricity consumption, and environmental degradation. Similarly, institutional fragmentation and weak regional cooperation continue to hinder sustainable water management and agricultural transformation throughout the region [4].

The ecological disaster of the Aral Sea is frequently considered one of the most evident consequences of decades of unsustainable irrigation practices and poorly coordinated water management policies. Over time, excessive diversion of river water for agriculture, along with outdated irrigation infrastructure, caused serious ecological and economic problems throughout Central Asia. Aging irrigation networks and inefficient water distribution systems continue to cause major water losses, increase electricity consumption, and put additional pressure on the environment. Weak institutional coordination and limited regional cooperation remain some of the main obstacles to effective water governance and sustainable agricultural development in Central Asia [5].

Literature Review

The literature highlighting the importance of governance quality for environmental sustainability and natural resource management is growing. Good governance institutions are the foundation for sustainable water allocation and environmental protection. Where there are no sound institutional systems, inefficient resource use and environmental degradation are common. Weak governance worsens the economic and environmental effects of water scarcity and climate change, particularly in water-scarce developing economies. Moreover, a high quality of institutions, efficiency of public administration, and political stability significantly improve environmental performance and speed up the process of carbon mitigation. Weak institutions are inherently associated with inefficient resource use and environmental degradation. Good governance institutions are a precondition for sustainable water allocation and environmental protection, whereas poor governance in water-stressed developing economies aggravates the negative economic and environmental effects of water scarcity and climate change. Likewise, institutional quality, political stability, and regulatory effectiveness are crucial in environmental performance and expedite the process of carbon mitigation [6].

Several empirical studies have applied sophisticated econometric techniques to investigate the water-energy-food nexus. Inefficient use of water and energy is identified as one of the important reasons for higher environmental pressures and carbon emissions in developing economies. An increase in the efficiency of agricultural water use contributes to achieving environmental sustainability by reducing emissions from irrigation. Similarly, modernizing irrigation and improving water productivity play a critical role in helping agricultural economies reach their carbon neutrality objectives. The inefficient utilization of water and energy results in higher environmental pressure and carbon emissions in developing countries. Increased agricultural water-use efficiency contributes to environmental sustainability by reducing emissions linked to irrigation, and the modernization of irrigation systems is crucial for the realization of carbon neutrality goals in agricultural economies [7].

Earlier studies show that in Central Asia, inefficient irrigation increases water losses, energy use, and environmental degradation, while modern irrigation and water-saving technologies decrease carbon-intensive agricultural activities. It has been emphasized that increasing agricultural water productivity helps achieve sustainable development in water-scarce economies. Empirical studies in the Environmental Kuznets Curve framework confirm a long-run relationship between agricultural production, water use, and carbon emissions [8].

The economies of Central Asia are heavily dependent on the Amudarya and Syrdarya river basins, but poor irrigation systems and transboundary water management have led to ecological problems, such as the Aral Sea crisis. Recent studies also emphasize the importance of governance quality in improving water management and reducing environmental degradation. However, governance indicators are seldom integrated with water productivity and carbon emissions using advanced panel econometric methods in prior research.

The present study investigates the effect of agricultural water productivity on agricultural carbon emissions in the countries of the Amudarya and Syrdarya river basins using fixed-effects regression with Driscoll–Kraay robust standard errors. Weak governance and inefficient irrigation aggravate environmental degradation in Central Asia. Conversely, higher agricultural water productivity, improved irrigation technologies, and robust institutions mitigate carbon emissions and enhance sustainability. However, very few studies have combined governance, water productivity, and agricultural emissions using advanced panel econometric methods. Thus, the present study examines these relationships in the Amudarya and Syrdarya river basin countries using fixed-effects regression with Driscoll–Kraay robust standard errors [9].

Data Description

The majority of studies consider agricultural water use, governance quality and carbon emissions individually, with their integrated relationship in transboundary river basin economies. Governance indicators are rarely incorporated in environmental-economic models. Also, conventional econometric techniques often do not account for heteroskedasticity, serial correlation and cross-sectional dependence in panel data. This paper fills these gaps by exploring the nexus between agricultural water productivity and agricultural CO2 emissions in the Amudarya and Syrdarya river basin countries panel dataset of five Central Asian countries of river basins Uzbekistan, Kazakhstan, Kyrgyzstan, Tajikistan and Turkmenistan during the period 1996–2024. The Worldwide Governance Indicators (WGI) provide six commonly used governance measures: Voice and Accountability, Political Stability and Absence of Violence/Terrorism, Government Effectiveness, Regulatory Quality, Rule of Law, and Control of Corruption Kaufmann et al. (2010). Agricultural CO2 emissions are measured in metric tons per capita. Agricultural water productivity is measured as economic output generated per cubic meter of freshwater withdrawal. We include GDP per capita and GDP per capita squared term to consider the existence of the Environmental Kuznets Curve (EKC). We also include water stress, measured as freshwater withdrawals as a percentage of available freshwater resources, to quantify the pressure on regional water systems. Agricultural water use, industrial water use and domestic water use as a fraction of total freshwater withdrawal in order to evaluate the environmental impacts of different types of water use. Population refers to total population and urbanization refers to the percentage of urban population. Demographic and water resource indicators are introduced to account for the influences of resource use and population dynamics on environmental degradation, in line with Liu et al. and Yang et al. [10].

2. Materials and Methods

The relationship between agricultural water productivity and agricultural CO2 emissions was tested assuming OLS and FE estimators. However, environmental and macroeconomic variables in panel data sets are often plagued by heteroskedasticity, serial correlation and cross-sectional dependence due to common regional shocks, climate variability and interlinked economic structures . Therefore, conventional fixed-effects estimators may produce biased standard errors and unreliable statistical inference. To address these econometric problems, the study employs Fixed Effects regression with Driscoll-Kraay heteroskedasticity and autocorrelation consistent standard errors using the xtscc estimator by Hoechle (2007). The Driscoll–Kraay estimator is particularly appropriate when the panel data are related to cross-sectional dependence, serial correlation, and heteroskedasticity. Because the Central Asian economies are strongly interconnected by transboundary river systems and common environmental conditions, it is very likely that the dataset exhibits cross-sectional dependence [11]. Thus, Driscoll–Kraay standard errors yield more robust and efficient estimates than conventional panel estimators. Following the environmental sustainability and governance literature, agricultural CO_2 emissions are modeled as a function of agricultural water productivity, governance quality, and several control variables:

$$\begin{aligned} AGR\_CO2_{it} = {} & \alpha_0 + \alpha_1 AGR\_GDP_{it} + \alpha_2 WP_{it} + \alpha_3 RUR\_POP_{it} + \alpha_4 TRADE\_GDP_{it} + \alpha_5 GI_{it} \\ & + \alpha_6 (WP_{it} \times GI_{it}) + \varepsilon_{it} \end{aligned}$$

Where: AGR_CO2-agricultural carbon dioxide emissions; AGR_GDP-agricultural value added or agricultural economic growth; WP-agricultural water productivity; RUR_POP-rural population; TRADE_GDP-trade openness as a percentage of GDP; RL-Rule of Law; CC-Control of Corruption; RQ-Regulatory Quality; GE-Government Effectiveness; PS-Political Stability; VA-Voice and Accountability. The empirical model further incorporates interaction terms of agricultural water productivity with governance indicators to test for the moderating role of governance quality. The interaction term WP×GI tests whether a better institutional quality increases or decreases the environmental impacts of agricultural water productivity.

Thus, the empirical models are estimated separately for each governance indicator as follows:

$$\begin{aligned} GR\_CO2_{it} = {} & \alpha_0 + \alpha_1 AGR\_GDP_{it} + \alpha_2 WP_{it} + \alpha_3 RUR\_POP_{it} + \alpha_4 TRADE\_GDP_{it} + \alpha_5 RL_{it} \\ & + \alpha_6 (RL_{it} \times WP_{it}) + \varepsilon_{it} \end{aligned}$$

Similar specifications are projected for Control of Corruption, Regulatory Quality, Government Effectiveness, Political Stability and Voice and Accountability. Moreover, the interaction terms between governance indicators and water productivity are mostly negative and statistically significant, suggesting that the better the quality of governance, the greater the environmental benefits of efficient agricultural water use. In particular, Rule of Law, Regulatory Quality, Government Effectiveness and Voice and Accountability reinforce the negative relationship between water productivity and agricultural CO_2 emissions across the economies of Central Asian river basin [12].

3. Results and Discussion

Table 1. presents the descriptive statistics of the variables used in the study for Central Asian countries. The results indicate considerable heterogeneity among economic, environmental and governance indicators. The average agricultural CO_2 emissions (AGR_CO2) is 0.46, but there is a lot of variation between countries and years. The agriculture value added (AGR_GDP) averages 18.26% of the GDP confirming the important role of agriculture in the region. The squared term (AGR_GDP2) shows a high dispersion supporting the existence of possible nonlinear relationships. The WP shows striking differences across countries with an average of 1.89 and maximum of 8.98 indicating an unequal water resource use efficiency [13].

Table 1. Descriptive statistics.

Variables		Mean	Std. Dev.	Min	Max	Skewness	Kurtosis
AGR_CO2	Agricultural CO_2 Emissions	0,46	0,57	0,01	1,97	1,38	3,66
AGR_GDP	Agriculture Value Added (% of GDP)	18,26	9,29	3,83	46,32	0,24	2,41
AGR_GDP2	AGR_GDP2	419,08	373,31	14,63	2145,32	1,35	5,76
WP	Water Productivity	1,89	2,35	0,19	8,98	1,92	5,39
RUR_POP	Rural Population (% of Total)	57,01	10,92	37,93	73,87	0,26	1,76
TRADE	Trade (% of GDP)	82,95	32,66	28,73	181,59	0,69	2,92
CC_EST	Control of Corruption	-1,14	0,28	-1,50	-0,07	1,59	6,02
GE_EST	Government Effectiveness	-0,88	0,42	-1,74	0,16	0,35	3,00
PS_EST	Political Stability	-0,45	0,54	-2,40	0,70	-0,71	4,02
RQ_EST	Regulatory Quality	-1,01	0,63	-2,16	0,11	-0,12	1,78
RL_EST	Rule of Law	-1,06	0,31	-1,82	-0,37	0,29	2,46
VA_EST	Voice and Accountability	-1,24	0,46	-2,07	-0,25	0,14	1,97

The results of the Fisher-type panel unit root test Table 2 show that the variables used in the empirical analysis have different orders of integration. The null hypothesis of the existence of the unit root could not be rejected for levels of AGR_CO2, WP and TRADE_GDP due to statistically insignificant p-values. However, the three variables are stationary at 1% significance level when taking first difference, i.e. they are integrated of order one, I(1).

Table 2. The Fisher-type panel unit root test results.

Variables	Level Statistic (P)	Level p-value	First Difference Statistic (P)	First Difference p-value
AGR_CO2	11,617	0,312	63,352	0,000
AGR_GDP	39,450	0,000	100,842	0,000
AGR_GDP2	69,219	0,000	159,170	0,000
WP	7,439	0,684	59,797	0,000
RUR_POP	65,582	0,000	70,178	0,000

TRADE_GDP	12,506	0,253	91,069	0,000

Therefore, the empirical analysis is suitable for estimation methods capable of handling mixed orders of integration, such as panel ARDL and fixed-effects regression with Driscoll–Kraay robust standard errors. Moreover, the Table 3. stationarity results confirm the reliability of the long-run environmental relationships that have been estimated in the study.

Table 3. Westerlund ECM Panel Cointegration Test Results.

Statistic	Value	Z-value	P-value
Gt	-2,26	-0,61	0,27
Ga	-4,31	1,75	0,96
Pt	-4,97	-1,07	0,14
Pa	-3,13	0,91	0,82

The results of the Westerlund ECM panel cointegration test do not reject the null hypothesis of no cointegration among the variables included in the empirical model. Specifically, the p-values of the group-mean statistics (Gt and Ga) and panel statistics (Pt and Pa) are statistically insignificant at conventional significance levels, suggesting no stable long-run equilibrium relationship between agricultural CO 2 emissions, agricultural economic growth, water productivity, rural population, and trade openness in the Central Asian river basin countries [14].

The results indicate that variables do not co-move in the long-run in the panel data set. Thus, our empirical analysis is mainly concerned with contemporaneous and medium-run relationships and is based on a fixed-effects regression with Driscoll-Kraay heteroskedasticity and autocorrelation consistent standard errors, which allow for robust statistical inference in the presence of heteroskedasticity, serial correlation and cross-sectional dependence. Moreover, the lack of cointegration could also be attributed to the relatively small number of cross-sectional units, structural heterogeneity among Central Asian economies, institutional differences, and changing environmental policies during the sample period 1996–2024. Similar results are frequent in environmental panel studies of small-N macroeconomics and transboundary river basin economies. The Hausman specification test was used to identify the most appropriate estimator between fixed-effects and random-effects models. The Table 4. alternative hypothesis says that the fixed-effects estimator is more appropriate due to correlation between the unobserved individual-specific effects and the explanatory variables. To address this, the study employs fixed-effects regression with Driscoll–Kraay heteroskedasticity and autocorrelation consistent standard errors to obtain robust and reliable empirical estimates in the presence of serial correlation, heteroskedasticity, and cross-sectional dependence.

Table 4. Wooldridge Test for Autocorrelation in Panel Data.

Test	F-statistic	Probability	Decision
Wooldridge Test for First-Order Autocorrelation	124.848	0.0004	Reject H_0

The table 5. Wooldridge test for autocorrelation in panel data reveals that there is first order serial correlation in the model. The probability value is less than 0.05 (p=0.0004) and the null hypothesis of no first order autocorrelation is rejected at 1% significance level. These results suggest that the error terms are serially correlated over time within panel units, which implies that standard fixed-effects estimators may yield biased standard errors and unreliable statistical inference. In such a case, the existence of autocorrelation justifies the use of robust panel estimators that can adjust for serial correlation and heteroscedasticity. The Driscoll–Kraay estimator is particularly appropriate, because it accounts for serial correlation, heteroskedasticity, and cross-sectional dependence simultaneously in panel data sets with relatively small cross-sectional dimensions and moderate time dimensions, such as the Central Asian river basin panel used in this study.

Table 5. The role of institutional quality.

Variables	I (RL)	II (CC)	III (RQ)	IV (GE)	V (PS)	VI (VA)
AGR_GDP	-0,014	-0,019	-0,014	-0,005	-0,022	-0,018
	(-2,45)	(-2,5)	(-2,54)	(-0,84)	-2,420	-4,160
AGR_GDP2	0,000	0,000	0,000	0,000	0,000	0,000
	-2,030	-1,660	-2,490	-0,020	-1,850	-3,180
WP	-0,084	-0,060	0,019	-0,007	0,035	-0,216
	-3,100	-2,440	-1,170	-0,400	-2,570	-4,660
RUR_POP	-0,076	-0,103	-0,056	-0,076	-0,068	-0,031
	-4,350	-3,790	-3,240	-3,850	-3,270	-1,770
TRADE_GDP	0,000	-0,001	0,001	0,001	-0,001	0,000
	-0,090	-2,520	-1,290	-1,370	-1,900	-0,050
RL_EST	0,353	—	—	—	—	—
	-2,440	—	—	—	—	—
RL_WP	-0,262	—	—	—	—	—
	-5,070	—	—	—	—	—
CC_EST	—	0,168	—	—	—	—
	—	-1,230	—	—	—	—
CC_WP	—	-0,150	—	—	—	—
	—	-3,790	—	—	—	—
RQ_EST	—	—	0,345	—	—	—
	—	—	-4,370	—	—	—
RQ_WP	—	—	-0,167	—	—	—
	—	—	-6,740	—	—	—
GE_EST	—	—	—	0,447	—	—
	—	—	—	-5,900	—	—
GE_WP	—	—	—	-0,135	—	—
	—	—	—	-5,770	—	—
PS_EST	—	—	—	—	0,161	—
	—	—	—	—	-1,980	—
PS_WP	—	—	—	—	0,037	—
	—	—	—	—	-1,130	—
VA_EST	—	—	—	—	—	0,438
	—	—	—	—	—	-3,810
VA_WP	—	—	—	—	—	-0,290
	—	—	—	—	—	-5,120
Constant	5,045	6,693	3,891	5,108	4,664	2,780
	-5,270	-4,370	-4,450	-4,450	-3,680	-3,120
Within R²	0,510	0,483	0,587	0,588	0,405	0,461
F-statistic	8,940	14,050	46,820	69,860	53,060	40,380
Observations	145,000	145,000	145,000	145,000	145,000	145,000
Countries	5,000	5,000	5,000	5,000	5,000	5,000

To evaluate the role of governance in the relationship between water productivity and agricultural CO 2 emissions, in Table 5 we add interaction terms between six dimensions of governance quality and water productivity. The empirical findings suggest that the interaction terms for Rule of Law (Model I), Control of Corruption (Model II), Regulatory Quality (Model III), Government Effectiveness (Model IV), Political Stability (Model V), and Voice and Accountability (Model VI) are negative and statistically significant in most of the specifications. These results indicate that the effects of water productivity improvements in reducing agricultural CO2 emissions are more significant in countries with higher levels of institutional quality and governance performance. Specifically, the interaction terms of the Rule of Law and Voice and Accountability have the strongest negative effects, indicating that transparent legal systems, higher institutional accountability and participatory governance structures, greatly enhance the environmental benefits of efficient agricultural water use. Likewise, Regulatory Quality and Government Effectiveness significantly contribute to the enhancement of water productivity improvements to decrease agricultural carbon emissions. Results indicate that good institutions support the adoption of sustainable irrigation technologies, environmental regulations, and water-saving agricultural practices in the countries of the Central Asian river basin. However, the interaction term of Political Stability and water productivity is statistically insignificant, which implies that political stability itself does not significantly influence the effectiveness of water productivity to reduce agricultural CO2 emissions. One interpretation of this might be that political stability does not necessarily translate into institutional efficiency, environmental enforcement or technological innovation in the agricultural water management systems. Also, in several specifications, the direct impacts of governance indicators are generally positive, suggesting that countries with better governance structures may simultaneously face higher levels of agricultural modernization, economic activity, and efficiency in reporting, which may initially coincide with higher measured emission levels. However, the negative interaction terms confirm that the quality of governance ultimately enhances the environmental efficiency of agricultural production systems through improved water resource management. The empirical evidence reveals the critical moderating role of the governance quality in the water productivity-environment nexus. The results reveal that it is crucial to enhance institutional quality, improve regulatory framework, enhance government effectiveness and promote transparent governance mechanisms in order to realize the environmental benefits of agricultural water productivity in the economies of the Amudarya and Syrdarya river basin [15].

4. Conclusions

In this study, we examined the link between agricultural water productivity, governance quality, and agricultural CO2 emissions in the Amudarya and Syrdarya river basin countries in Central Asia over the period 1996–2024 based on fixed-effects regression with Driscoll-Kraay heteroskedasticity and autocorrelation consistent standard errors. The empirical results support the existence of a nonlinear Environmental Kuznets Curve (EKC) type relationship between agricultural economic growth and agricultural CO_2 emissions in Central Asian river basin economies. The estimated coefficients suggest a U-shaped relationship, implying that agricultural growth first leads to environmental improvement, but excessive agricultural expansion and irrigation intensification eventually cause an increase in agricultural carbon emissions. Agricultural water productivity has a significant negative impact on agricultural CO 2 emissions in most of the model specifications. The results indicate that the improvements in the water use efficiency lead to lesser environmental degradation by decreasing excess freshwater withdrawals, energy consumption from irrigation and inefficient agricultural production practices. The environmental effect of water productivity is much stronger in countries with higher institutional quality. The interaction terms of water productivity with Rule of Law, Regulatory Quality, Government Effectiveness and Voice and Accountability are negative and statistically significant. Results show that improved governance systems enhance the emission-reducing potential of agricultural water productivity. Best moderating dimensions of governance in the water productivity-emission nexus are voice and accountability, rule of law and regulatory quality. This suggests that transparent institutions, strong legal systems and efficient regulatory regimes matter in improving environmental sustainability in the agricultural sectors. The findings of this study indicate that agricultural water productivity is an important channel for the Central Asian countries to improve agricultural efficiency and reduce environmental degradation simultaneously. Therefore, the study has a number of important policy implications. Governments in the region should focus on investments in modern water-saving irrigation technologies, digital monitoring systems and sustainable agricultural practices to increase water productivity. In addition, institutional reforms to improve governance quality, regulatory enforcement, transparency, and accountability are needed to maximize the environmental benefits of efficient water resource management. There must also be an expansion of public investment in agricultural innovation and environmentally sustainable irrigation infrastructure to drive long-term green agricultural transition. In particular, greater support for research and development of precision irrigation, climate-smart agriculture and efficient water allocation mechanisms could greatly reduce agricultural carbon emissions and enhance resource sustainability throughout the region.

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