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The Nexus between Agriculture, Water, Energy and Environmental Degradation in Central Asia—Empirical Evidence Using Panel Data Models

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Abstract: The primary aspiration of this paper is to learn about the effects of economic growth, energy consumption, agriculture and irrigation water consumption and agriculture productivity on environmental pollution in five countries of Central Asia. The data cover the period from 1992 to 2020 by applying panel data models, namely the Panel FMOLS, Panel DOLS and Panel ARDL-PMG approaches. The results indicate that there is a positive long-term impact of economic growth, water productivity, energy consumption and electricity production on CO_2 emissions while agriculture value added and trade openness have a negative and statistically significant influence on CO_2 emissions in Central Asia. Country specific short-run coefficients from Panel ARDL reveal that energy consumption is the main driver for rise in the level of CO_2 emissions in the countries under the study. Indeed, country level analysis generates unique nexus correlation among agriculture, energy and environmental degradation in each country of Central Asia.

Keywords: environment; climate change; Central Asia; water; energy; agriculture; Aral Sea region

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1. Introduction

The primary environmental issue facing humanity over the past few decades has been climate change. The main cause of the greenhouse effect, carbon dioxide emissions (CO_2), are thought to be the most significant environmental issue facing the planet. These greenhouse effects put human life at risk [1]. In the case of Central Asia (CA), pressure on energy and water resources are growing steadily [2]. However, environmental issues are caused by rising energy demand and greenhouse gas emissions in the region [3]. Given their heavy reliance on fossil fuels for energy, Central Asian nations produce significant amounts of CO_2 emissions because of the available resources [4]. Regarding the usage of renewable energy sources, there is a considerable lack of attention in the region [5].

Gross Domestic Product (GDP), agriculture, water, energy, fossil fuel energy consumption and trade elements are regarded as having high impacts on the countries of Central Asia [6]. Due to rising human demand and the effects of climate change, the value of water as a natural resource has increased in recent years [7]. The main water sources for the Aral Sea are the Amu Darya and the Syr Darya [8]. Prior to the 1960s, 63 km^3 of water per year on average poured from these rivers into the Aral Sea [9]. In 2006, it was observed that the water flow from these two rivers had considerably decreased up to 5 km^3/year [10]. The drop was accompanied by a sharp rise in the irrigated area which had grown from 30,000 km^2 (1913) to 79,000 km^2 (2000) [11]. The availability of water resources, particularly drinking water and crop yields, has been severely harmed by climate change [12]. Some adaptations, such as strengthening agricultural resilience to boost production, promoting smart water management and increasing public understanding are well documented in the literature to address this challenge [13–15].

Our interest in doing this study has emerged because extreme weather conditions have also been experienced in parts of Central Asia [16]. After 1990, the planned economies in Central Asian countries underwent reforms to become market-oriented ones [17]. Large state-owned farms were replaced with smaller, privately owned farms as the agricultural sector was reorganized [18]. Approximately 60% of the water in Central Asia is used for agriculture, especially in downstream countries—Uzbekistan and Turkmenistan [6]. As a result, environmental impact, notably water scarcity or pollution will hinder agriculture [1]. The deterioration of irrigation canals, high evaporation and drought all contribute to inefficient water use, and salinization frequently impacts flooded arable land, making the situation worse [19,20].

In Central Asia, the Belt and Road Initiative (BRI) was launched to encourage economic development [21]. This could, however, have an effect on the area's escalating environmental harm. Therefore, for the long-term economic growth and environmental conservation of Central Asia, a broader understanding of environmental sustainability is essential [22].

This paper tries to make four significant contributions to the current body of knowledge. This is the first study to examine the dynamic relationship between Central Asian nations' economic development, agriculture, water, energy, trade openness and CO_2 emissions from 1992 to 2020. Second, this paper seeks to provide insights on how agriculture and water productivity affect Central Asia's per capita CO_2 emissions. Third, we concentrate on CA nations over a long period of time, giving us a chance to draw broad conclusions about the whole of the developing economies. Lastly, this paper tries to add its contribution by applying cutting edge econometric methodologies, namely, dynamic panel data models, including Panel DOLS, Panel FMOLS and Panel ARDL, specifically the PMG approach, to analyze short- and long-term relationships between variables of interest.

The value of this paper also stems from its investigation of the dynamic association between CO_2 emissions and economic growth, agriculture, water, energy and trade openness in each of the Central Asian nations. Second, we examine CA countries over a considerable period of time, providing an opportunity to be the best sample for drawing conclusions about the other emerging countries. Lastly, this study is the first to investigate whether water production in Central Asia significantly affects CO_2 emissions.

The structure of this paper is as follows: an overview of the literature is provided in Section 2. The information and empirical approach are covered in Section 3. The empirical findings are reported in Section 4 together with their analysis. Policy recommendation completes Section 5.

2. Literature Review

Many empirical research published in the literature over the last two decades have thoroughly examined numerous factors influencing the evolution of CO_2 [23]. The literature review is divided into five sections studying the relationship of GDP, agriculture, water, energy and trade openness with CO_2 emissions.

2.1. CO_2—GDP Nexus

For the last years, vast amounts of research have been carried which are based on relationship CO_2 emissions and economic growth and the results differs from country to country because of the factors such as geographic situation, composition of GDP and use of natural resources [24–27]. ARDL Approach was applied [28] to find out positive correlation between economic growth and CO_2 emissions in Tunisia and Morocco. The Economic Growth and Pollution Nexus in Mexico, Colombia and Venezuela (G-3 Countries) are investigated [29], and the findings show that GDP and CO_2 emissions have a short-term negative co-integration but a long-term positive co-integration. In the case of Venezuela (1980–2025), the feasibility of stabilizing CO_2 emissions under a rapid increase in GDP was evaluated [30]. The results indicate that GDP has a favorable impact on the environment and exists in an inverted U-shape EKC [30].

Panel FMOLS and panel DOLS calculations are introduced using a panel data set of 17 OECD nations covering the years 1977–2010. Findings show that GDP per capita and GDP per capita squared have both positive and negative effects on CO_2 emissions, which are in line with the panel's EKC hypothesis [31]. Economic growth and non-renewable energy generation have positive effects on CO_2 emissions [32]. A 1% rise in GDP and non-renewable energy use results in an increase in CO_2 emissions of 0.53 to 0.82% and 0.30 to 0.37 percent, respectively [33]. These calculated coefficients are greater than the study of Wang et al. [34] and less than the findings of Hanif [35].

Similar to this, the authors of [36] study the impact of agriculture on CO_2 emissions in Saudi Arabia and find that once it accounts for more than 3.22% of GDP, agriculture starts to cut CO_2 emissions. A panel cointegration test was used [37] to investigate the correlation with CO_2 emissions in the case of CIS countries.

2.2. CO_2—Agriculture Nexus

By classifying China's 30 provinces into six quantile grades, the authors of [38] examined the variables affecting CO_2 emissions in the country's agricultural sectors. They then used the quantile regression method to look into the factors influencing CO_2 emissions at high, medium and low emission levels. The findings [38] demonstrate that economic growth has heterogeneous effects on CO_2 emissions, which should be taken into account when reducing CO_2 emissions in the agriculture sector. The authors of [39] used the FMOLS, DOLS and PMG techniques to analyze the effects of climate change on agriculture in India, from 1981 to 2017. The authors of [40] built a bottom-up inventory-based model and its findings confirm that agricultural non-CO_2 GHG emissions increased by 34% between 1980 and 2018, and by 2060, they are expected to have increased by another 33%. The authors of [41] concluded differently after utilizing the ARDL cointegration technique to examine the connection between income per capita and agriculture-related CO_2 emissions. Increased CO_2 emissions were highly cointegrated with agricultural contribution. This is consistent with [42] panel data analysis of BRICS utilizing a sample from 1992 to 2013.

In the study [43], data for ARDL from 1980 to 2018 were utilized to examine the long- and short-term effects of these factors on CO_2 emission in the case of Pakistan. According to the findings, food crop production has the potential to reduce CO_2 emissions in the short-term, but agriculture value added has a long-term, negative relationship with CO_2 emissions [44]. The authors of [45] investigate the interdisciplinary relationship between remittances and CO_2 emission in five countries. The authors of [46] show that for 14 African nations between 1990 and 2013, an expansion in the agriculture value added reduces CO_2 emissions.

2.3. CO_2—Water Nexus

The effects of population growth, freshwater resource stress and increased environmental protection regulations will all have an impact on agricultural production [47]. To improve decision-making in the future, drought management at farm level was examined [48]. To increase the water availability for irrigation when the crop is needed, new methods should be adopted [15]. Several studies [49–52] have shown that the agriculture industry is one of the most vulnerable to climatic shifts in emerging nations.

The world's food demand is expected to nearly double by 2050, raising serious concerns about the sustainability of agriculture [18]. Climate adaptations refer to a balance between ecological, society and the economy that can be accomplished by altering behavior, consumption patterns and infrastructure [53]. Although sustainable development is regarded as a lengthy, labor-intensive and effective process, it would be advantageous to adopt it as soon as possible [16,54]. Planning their adaptation is even more crucial [55] than creating integrated climate-land-water strategies [52,56].

Because water is scarce in many parts of the world, the irrigation industry is particularly in need of good water management, especially in Central Asia. This will increase crop output in the agricultural sector [57]. Genetic engineering can be used to create drought-resistant crop varieties, which can help to decrease the amount of water required without lowering output [48,58,59]. Due to rising water demand, there are water scarcity issues in many regions [58].

Semiarid and arid regions, mostly in Central Asia, are particularly susceptible to the effects of climate change and unpredictability on water availability and distribution [60]. The complicated interaction between climate variability and water availability has been quantified using resilience, reliability and vulnerability [61]. When water availability is insufficient compared to demand, there are societal, economic and environmental consequences. This is referred to as a socioeconomic drought [58,62]. In fact, Uzbekistan has the biggest proportion of irrigated land in the entire area vulnerable to drought risk [63]. In the SSP3 long-term scenario, 63.1 percent of the country's irrigated agriculture—which makes up 68% of the overall cropland in the region—is vulnerable to drought [10].

2.4. CO_2—Energy Consumption and Fossil-Fuel Based Energy Consumption

Central Asian (CA) economies as part of ex-Soviet Union countries are well known for their high technical and non-technical losses in the process of energy generation, transmission and consumption [64]. Power transmissions and electricity cables are carrying out high technical pressure leading to the technical loss of around 20% [5]. The entire energy chain was built in the 1960s connecting all Central Asia [65,66]. The energy blackout happened in January 2023 is evidence for the fact that that the whole energy system and its infrastructure are in an emergency situation [67]. One of the reasons behind this energy failure is high concentration on fossil-fuel based energy generation, especially in Kazakhstan, Turkmenistan and Uzbekistan, that leads to increased CO_2 emissions [65,68]. To diversify and decarbonize the energy portfolio of CA, renewable energy generation is the most feasible approach to decrease the pressure on fossil-fuel dependency for energy generation [37].

Using data from four ASEAN nations (Indonesia, Malaysia, the Philippines and Thailand), the authors of [33] investigate the effects of per capita renewable energy consumption and agricultural value addition on CO_2 emissions throughout the period of 1970 to 2013. They demonstrate using the environmental Kuznets Curve (EKC) hypothesis that growing agricultural and renewable energy reduces CO_2 emissions while non-renewable energy has a positive correlation with emissions. The dynamic correlations between renewable energy consumption, agricultural value added, CO_2 emissions and GDP for Brazil were examined [69]. The findings indicate that the variables under consideration have long-run cointegration. A unidirectional connection exists between agriculture, CO_2 emissions and GDP, according to recent empirical studies [70].

Empirical findings from Colombia [71], Indonesia, Malaysia and Thailand [72], China [73] and Australia [74] diversified the aforementioned findings. In general, the variety of results spanning different regions and indicators demonstrates a lack of agreement found in the literature.

2.5. CO_2—Trade Openness

The impact of trade openness on CO_2 emissions has been a subject of considerable research in recent years [75]. Studies have shown that trade openness can have both positive and negative impacts on CO_2 emissions [76]. On the one hand, trade openness can increase economic growth and lead to higher energy consumption and CO_2 emissions [77]. On the other hand, trade openness can promote the transfer of clean technology and improve the energy efficiency of economies, leading to lower CO_2 emissions [78]. The relationship between trade openness and CO_2 emissions was examined using a panel data approach [42]. According to the study, trade openness has a positive effect on CO_2 emissions in China, although this effect is constrained by elements like energy intensity and technical advancement.

Several empirical studies [79,80] have investigated the relationship between trade openness and CO_2 emissions using panel data and time series methods. One of the most notable studies [21] found that trade openness has a positive and statistically significant impact on CO_2 emissions in developing countries. This study [21] suggests that trade openness can increase the use of fossil fuels and lead to higher CO_2 emissions. Trade openness can promote the transfer of clean technology, which can reduce CO_2 emissions. However, in countries with low levels of technological development, trade openness may increase energy consumption and CO_2 emissions [81]. As a result of technological advancements enabling cleaner production, the economies experiencing technological transformation observe an improvement in the quality of the environment [82].

3. Material, Methodology and Data

3.1. Data and Materials

Table 1 displays the results of a large-scale sample taken from World Bank data for five developing economies in Central Asia, namely, Kazakhstan, Kyrgyz Republic, Tajikistan, Turkmenistan and Uzbekistan, between 1992 and 2020. Data on CO_2 emissions (tons per capita), GDP growth per capita (constant 2015 US$), agriculture (share of GDP), level of water stress (freshwater withdrawal as a proportion of available freshwater resources), energy use (kg of oil equivalent per capita), electricity production from oil, gas and coal sources (% of total) and trade openness (% of GDP) are sourced [83].

Table 1. Source of data and description of variables.

Variables	Description and Unit	Source	Period
CO_2	CO_2 emissions (kt)	WDI, (2022)	1992–2020
GDP	GDP (constant 2015 US$)	WDI, (2022)	1992–2020
AGR	Agriculture, forestry, and fishing, value added (% of GDP)	WDI, (2022)	1992–2020
WATER	Level of water stress: freshwater withdrawal as a proportion of available freshwater resources	WDI, (2022)	1992–2020
ENG	Energy use (kg of oil equivalent per capita)	WDI, (2022)	1992–2020
ELC	Electricity production from oil, gas, and coal sources (% of total)	WDI, (2022)	1992–2020
TO	Trade (% of GDP)	WDI, (2022)	1992–2020

Source: Author’s own contribution.

Table 2 provides a description of the statistically critical variables that have been included into our model. Due to data limitations, we can only examine a maximum of 144 observations over 7 variables, with only one of those variables dependent on any of the others.

Table 2. Descriptive Statistics.

Variable	Obs	Mean	Std. dev.	Min	Max
lnCO_2	140	10.3095	1.601232	7.663877	12.46848
lnGDP	144	23.62457	1.350189	21.53163	26.07563
lnAGR	131	4.452783	0.1500689	4.057057	4.584434
lnWATER	131	4.338419	0.5823849	3.346076	5.129452
lnENG	114	7.218931	0.9743152	5.635909	8.475568
lnELC	120	3.256355	1.764502	−1.54665	4.60517
lnTO	135	4.414645	0.3813467	3.373905	5.201752

Computed by Stata 17.0.

The correlation between the various study factors is outlined in Table 3, which can be seen here. The variables of income per capita (lnGDP), level of water stress (lnWATER), energy consumption (lnENG) and electricity from oil, gas and coal (lnELC) are positively correlated with carbon dioxide emissions (lnCO_2). Moreover, agriculture (lnAGR) and trade openness (lnTO) are negatively associated with carbon dioxide emissions (LogCO_2).

Table 3. Correlation Matrix.

	lnCO_2	lnGDP	lnAGR	lnWATER	lnENG	lnELC	lnTO
lnCO_2	1.0000						
lnGDP	0.7307	1.0000					
lnAGR	−0.4497	−0.6219	1.0000				
lnWATER	0.0451	−0.1241	0.7244	1.0000			
lnENG	0.6110	0.7880	−0.3838	0.0967	1.0000		
lnELC	0.7804	0.6945	−0.2462	0.1591	0.9046	1.0000	
lnTO	−0.4961	−0.5197	0.1433	−0.2689	−0.3252	−0.3914	1.0000

Computed by Stata 17.0.

3.2. Specification of the Econometric Model

To represent the relationship between economic development, agriculture, water, energy usage, electricity from oil and gas, trade openness and CO_2 emissions, a basic panel model is developed after a thorough review of the literature. This method assesses how different variables contribute to the total amount of CO_2 emissions in the targeted areas:

$$CO2_{2it} = f(GDP_{it}, AGR_{it}, WATER_{it}, ENG_{it}, ELC_{it}, TO_{it}) \quad (1)$$

where t is the period 1992 to 2020; $CO2$ represents carbon dioxide emission per capita; GDP is the per capita economic growth; AGR represents agriculture, forestry and fishing, value added (% of GDP); $WATER$ represents level of water stress; ENG represents energy use; ELC is the electricity production from oil, gas, and coal; TO denotes trade openness.

$$CO2_{2it} = \beta_0 + \beta_1 GDP_{it} + \beta_2 AGR_{it} + \beta_3 WATER_{it} + \beta_4 ENG_{it} + \beta_5 ELC_{it} + \beta_6 TO_{it} + \varepsilon_{it} \quad (2)$$

Using natural logarithms on both sides of Equation (2), we get a log-linear version of the production function, which helps to mitigate heteroskedasticity problems.

$$lnCO2_{2it} = \beta_0 + \beta_1 lnGDP_{it} + \beta_2 lnAGR_{it} + \beta_3 lnWATER_{it} + \beta_4 lnENG_{it} + \beta_5 lnELC_{it} + \beta_6 lnTO_{it} + \varepsilon_{it} \quad (3)$$

where t represents the time; i indicates the cross-section (1 . . . 2, . . . 3 . . . . N developing countries); and ε is the residual term. The coefficients $\beta_1,\ \beta_2,\ \beta_3,\ \beta_4,\ \beta_5,\ \beta_6$ symbolize the relationship between endogenous and exogenous variables in natural logarithms.

3.3. Estimation Methodologies

3.3.1. Panel Unit-Root Tests

In the initial stage of the econometric analysis, to verify that the data set has stationarity characteristics, different panel unit root tests are used. As each panel unit root test has various statistical drawbacks regarding size and power features, this research employs three kinds of unit root tests to establish the order of integration of series: [84,85] and the Fisher-PP and Fisher-ADF tests [86,87]. To determine whether the first hypothesis, which presupposed the presence of a unit root in the panel data in the time series, is correct, the aforementioned tests have been carried out. Accordingly, the equitation IPS panel unit root tests, when applying the overall method, can be given as:

$$\Delta y_{i,t} = \alpha_0 + \beta_i y_{i,t-1} + \sum_{j=1}^{P} k_i \Delta y_{i,t-1} + \varepsilon_{i,t-1} \tag{4}$$

In Equation (4), y_{it} represents the series for country i in the panel over period t; Δ is the first difference operator; $P = 0$ for all i, which is the null hypothesis; and $P = 0$ for at least one i, the alternative hypothesis which is non-existent for a unit root.

3.3.2. Specification of Panel ARDL (PMG) Model

The pooled mean group (PMG) model that was firstly developed [85] to calculate the short-run and long-run estimates of the effect of the employed explanatory variables on the dependent variable. The PMG makes it possible for the short-term parameters to discriminate between the groups, but it assumes that the long-term coefficients are the same for each group. To make matters even more intriguing, the PMG can be used in situations in which the employed variables are either I (1) or I (0). In the end, the Hausman poolability test is employed to determine whether the practice of pooling long-term coefficients is efficient and acceptable. Taking into consideration an ARDL(p,q) model, in which the lag order of the response variable is indicated by the variable p, and the lag order of the independent variables is indicated by the variable q, the expression of the model may be written as follows:

$$\begin{aligned} lnCO_{2,i,t} = \mu_{it} &+ \sum_{j=1}^{p} \varphi_{i,j} lnCO2_{i,t-j} + \sum_{j=1}^{q} \delta_{ij} lnGDP_{i,t-j} + \sum_{j=1}^{q} \delta_{ij} lnAGR_{i,t-j} + \sum_{j=1}^{q} \delta_{ij} lnWATER_{i,t-j} \\ &+ \sum_{j=1}^{q} \delta_{ij} lnENG_{i,t-j} + \sum_{j=1}^{q} \delta_{ij} lnELC_{i,t-j} + \sum_{j=1}^{q} \delta_{ij} lnTO_{i,t-j} + \varepsilon_{it} \end{aligned} \tag{5}$$

where i represents countries (1, 2, 3 … 20); t is the year (1992–2020); j is the optimum time lag; and μ_{it} is a fixed effect.

The short-run relationship with error correction models is written as follows:

$$\begin{aligned} lnCO_{2,i,t} = \mu_i + \quad & \varphi_i (lnCO_{2,t-1} - \delta_{1i} lnGDP_t - \delta_{2i} lnAGR_t - \delta_{3i} lnWATER_t - \delta_{4i} lnENG_t - \delta_{5i} lnELC_t - \delta_{6i} lnTO_{6t}) \\ & + \sum_{j=1}^{p} \varphi_{i,j} lnCO2_{i,t-j} + \sum_{j=1}^{q} \delta_{ij} lnGDP_{i,t-j} + \sum_{j=1}^{q} \delta_{ij} lnAGR_{i,t-j} \\ & + \sum_{j=1}^{q} \delta_{ij} lnWATER_{i,t-j} + \sum_{j=1}^{q} \delta_{ij} lnENG_{i,t-j} + \sum_{j=1}^{q} \delta_{ij} lnELC_{i,t-j} + \sum_{j=1}^{q} \delta_{ij} lnTO_{i,t-j} \\ & + \mu_{it} \end{aligned} \tag{6}$$

3.3.3. FMOLS and DOLS Long-Run Estimators

The Fully Modified Least Square, abbreviated as FMOLS, is a technique to carry out the most effective method of cointegrating regression analysis [88]. However, the heterogeneous FMOLS estimator has been utilized for the panel cointegration regression in this investigation [89] since it has the benefit of removing endogeneity bias as well as serial correlation. FMOLS is the optimal method for the panel that has heterogeneous cointegration [90].

Taking into consideration the fact that a panel FMOLS estimation for the coefficient β of model 2 is

$$\beta^{*}_{NT} - \beta = \left\{ \sum_{i=1}^{N} L_{22i}^{-2} \sum_{i=1}^{T} \left(x_{it} - x^{*}_{it} \right)^{2} \right\} \sum_{i=1}^{N} L_{11i}^{-1} L_{22i}^{-1} \left\{ \sum_{i=1}^{T} \left(x_{it} - x^{*}_{i} \right) \mu^{*}_{it} - T\sigma^{*}_{i} \right\} \tag{7}$$

where,

$$\mu^{*}_{it} = \mu_{it} - \frac{M_{21i}}{M_{22i}} \Delta x_{it},\ \sigma_i = F_{21i}\Omega^{0}_{21i} - \frac{M_{21i}}{M_{22i}} \left(F_{22i} + \Omega^{0}_{22i} \right) \tag{8}$$

and M_i is the lower triangulation of Ω_i.

The Dynamic OLS estimator has the same asymptotic distribution as that of the panel FMOLS estimation derived [91]. Both the DOLS and FMOLS estimations are performed as shown to confirm the consistency of the outcome.

3.3.4. Juodis, Karavias and Sarafidis (2021) Granger Non-Causality Test

We also perform Granger non-causality tests [92] to examine the sign and the type of temporal relation between CO_2 emissions, economic growth, agriculture, water, energy and trade openness.

We consider the following specification:

$$lnCO_{2i,t} = \varphi_{0,i} + \sum_{p=1}^{p} \varphi_{p,i} lnCO_{2i,t-p} + \sum_{q=1}^{Q} \beta_{q,i} x_{i,t-p} + \varepsilon_{i,t} \tag{9}$$

for i = 1, N and t = 1, T. Without loss of generality and for ease of exposition, $x_{i,t}$ is assumed to be a scalar. The parameters $\varphi_{0,i}$ denote the individual-specific effects; $\varepsilon_{i,t}$ are the errors; $\varphi_{p,i}$ denote the heterogeneous autoregressive coefficients; p = 1, P and $\beta_{q,i}$ are the heterogeneous feedback coefficients or Granger causality parameters.

The null hypothesis that $x_{i,t}$ does not Granger-cause $lnCO_{2i,t}$ can be formulated as a set of linear restrictions on the parameters in Equation (9):

$$H_0 : \beta_{i,t} = 0$$

$$H_1 : \beta_{p,i} \neq 0$$

Failure to reject the null hypothesis can be interpreted as $x_{i,t}$ does not Granger-cause $\text{lnCO}_{2i,t}$. The same applies when $x_{i,t}$ is a k × 1 vector of regressors.

4. Empirical Results

Firstly, unit root and cointegration tests have been conducted extensively before examining the relationship between the variables in the area of our interest by employing panel ARDL. Table 4 summarizes the findings of stationarity tests performed by utilizing variety of techniques, namely, the augmented dickey fuller (ADF), Phillips Perron (PP) and IPS tests. The findings provide evidence that the variables in our paper are stationary either at their level or first level. Therefore, it can be concluded that the panel ARDL model can be utilized in our analysis.

Table 4. Panel Unit Root tests.

	Fisher-Type Tests				IPS Test	
	Fisher ADF Statistics		Fisher-PP Statistics			
	I(0)	I(1)	I(0)	I(1)	I(0)	I(1)
$\ln CO_2$	6.1427	57.9795 ***	10.2413	85.9605 ***	−2.4397 ***	−5.4896 ***
GDP	4.7553	52.4932 ***	0.2920	28.3205 ***	−5.2704 ***	−1.6087 **
lnagriculture	14.0404	46.3537 ***	14.4270	124.6767 ***	0.8348	−5.7529 ***
lnlevofwater	17.9404 **	50.9431 ***	10.4234	57.3955 ***	1.1062	−4.4619 ***
lnenergy	20.4985 **	75.6571 ***	50.5401 ***	69.2403 ***	−2.8629 ***	−4.2897 ***
lnfenergy	12.2603	75.5989 ***	14.6722	132.0359 ***	−2.7732 ***	−5.6403 ***
lntrade	9.8814	51.4519 ***	12.4277	94.3563 ***	−0.8764	−4.9880 ***

Note: Standard errors in parentheses: *** $p < 0.01$, ** $p < 0.05$. For the Im–Pesaran–Shin (IPS) test, t-bar test statistics values are shown. For the Fisher-type tests, inverse chi-squared test statistics are presented.

To verify the long-term relationship between variables, the Pedroni panel cointegration technique is used. The cointegration findings that are provided in Table 5 provide evidence that there is a long-term link between the variables, since the *p*-values reject the null hypothesis that there is no long-term relationship between the variables.

Table 5. Pedroni Cointegration test results.

Within-Dimension		
	Statistic	*p*-value
Panel v-Statistic	−2.0091 ***	0.0223
Panel rho-Statistic	1.5452 ***	0.0111
Panel PP-Statistic	−0.7160	0.2370
Panel ADF-Statistic	−1.1488	0.1253
Between-Dimension		
	Statistic	*p*-value
Group rho-Statistic	1.8060 ***	0.0355
Group PP-Statistic	−1.8377 ***	0.0331
Group ADF-Statistic	−1.0976	0.1362

Note: Standard errors in parentheses: *** $p < 0.01$.

Long-Run Results

We have used PFMOLS and PDOLS analyzes to get the long-term coefficients of the variables after validation of the long-term correlation between the variables. The outcomes of PFMOLS and PDOLS, which are displayed in Table 6, indicate that a 1% growth in the economies of the economies that are the focus of the research generates a 0.604% and 0.726% rise in the amount of CO_2 emissions, correspondingly. The results are in line with the findings [93–98]. Whilst, based on the results of panel DOLS and FMOLS, it can be concluded that agricultural value-added has a negative effect on CO_2 emissions over the long term. An increase of each percentage point in the value created by agriculture potentially leads to a decline in CO_2 emissions of 0.762% and 0.419%, correspondingly. This demonstrates that the influence of value-added agriculture on lowering CO_2 emissions may progressively be recognized over the course of time, as shown by the fact that. Agriculture has the potential to both store carbon and lower its overall carbon footprint if it adopts more modern management and technological practices [16,18,56]. The findings of our paper are supported by scholars [33,99–101]. The next variable, water productivity, has a positive and statistically significant relationship with CO_2 emissions, at a 1% significance level. In theory, effective water resource management and productivity can result in decreased emissions [102].

Table 6. Panel FMOLS and DOLS models estimation results.

Variables	DOLS	FMOLS
lnGDP	0.652 ***	0.544 ***
	(0.0288)	(0.0500)
lnAGR	−0.762 ***	−0.419 **
	(0.146)	(0.174)
lnWATER	0.435 ***	0.125
	(0.131)	(0.161)
lnENG	0.500 ***	0.0129
	(0.160)	(0.214)
lnELC	0.558 ***	0.418 ***
	(0.0632)	(0.0824)
lnTO	−0.672 ***	−0.706 ***
	(0.115)	(0.143)
Observations	96	101
R-squared	0.984	0.963

Standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$.

The energy consumption and electricity generated from oil, gas and coal were shown to have a positive and significant impact on CO_2 emissions by the coefficient values of 0.500 and 0.558 of the DOLS model. The estimated outcomes showed that a 1% increase in energy consumption causes an increase in CO_2 emissions in Central Asian countries. The authors of [103–106] claimed that the increase in CO_2 emissions is attributable to a 1% rise in the amount of energy used. The findings of panel ARDL, which are given in Table 7, have also supported the results of panel DOLS and FMOLS, accordingly.

Table 7. Panel ARDL model, PMG technique.

Variables	Long-Term	Kazakhstan	Kyrgyz Republic	Tajikistan	Turkmenistan	Uzbekistan
__ec		−0.628 **	0.00775	−0.997 ***	0.0380 *	0.0328
		(0.252)	(0.0511)	(0.148)	(0.0220)	(0.134)
D.lnGDP		−0.264	0.663 **	0.519 **	0.0764 *	−0.661
		(0.319)	(0.310)	(0.240)	(0.0390)	(0.966)
D.lnAGR		−0.266 **	−0.0544	−0.0724	−0.00125	0.139
		(0.114)	(0.189)	(0.0995)	(0.0115)	(0.147)
D.lnWATER		−0.0662	−0.105	2.279	0.607 ***	0.723
		(0.156)	(0.544)	(1.699)	(0.196)	(1.441)
D.lnENG		0.301	1.369 ***	0.822 ***	0.971 ***	0.487 *
		(0.274)	(0.124)	(0.257)	(0.0434)	(0.249)
D.lnELC		0.983 **	0.00489	−0.0324	33.91 **	−0.377
		(0.408)	(0.0549)	(0.0272)	(16.60)	(0.364)
D.lnTO		0.0430	0.0914	−0.000571	−0.0110	−0.0247
		(0.0968)	(0.128)	(0.0796)	(0.0183)	(0.102)
lnGDP	0.484 ***					
	(0.0578)					
lnAGR	−0.503 ***					
	(0.139)					
lnWATER	−0.439					
	(0.286)					
lnENG	0.847 ***					
	(0.139)					
lnELC	0.154 ***					
	(0.0278)					
lnTO	−0.224 ***					
	(0.0781)					
Constant		−3.921 *	0.0341	−6.367 ***	0.254	0.245
		(2.065)	(0.335)	(2.112)	(0.171)	(0.801)
Observations	97	97	97	97	97	97

Standard errors in parentheses.*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Trade openness has a negative sign and is statistically significant at the 1% level. This finding suggests that liberalized trade is associated with better environmental conditions (i.e., decreases CO_2 emissions). As shown by the coefficient value by panel DOLS, FMOLS and ARDL approaches, a 1% increase in trade openness results in a 0.672%, 0.706% and 0.224% reduction in CO_2 emissions, respectively. Because of the increased rivalry brought about by trade liberalization, domestic manufacturers are now more likely to adopt cutting-edge equipment in an effort to reduce manufacturing costs per unit of output, which in turn reduces carbon waste and emissions [107–109]. In the short run, we analyze the country specific relationship between CO_2 emissions and independent variables. There is a positive correlation between economic growth and CO_2 emissions in Kyrgyz Republic, Tajikistan and Turkmenistan, whilst agriculture has a negative and statistically significant connection with CO_2 emissions in only Kazakhstan. In Turkmenistan, water productivity has a positive and significant connection with CO_2 emissions. Interestingly, energy consumption is positive and statistically significant at 1% level in Kyrgyz Republic, Tajikistan, Turkmenistan and Uzbekistan, while electricity from oil, gas and coal is positive and statistically significant at the 5% level in Kazakhstan and Turkmenistan.

We also performed the Granger non-causality test [92] to examine the causality direction. Table 8 summarizes the findings of this investigation. According to the findings of the Granger non-causality test that are shown in Table 8, quite several associations have been found to be as follows: we find at the 1% level of significance that there is bidirectional causation between $\ln CO_2$ and other variables (lnGDP, lnAGR, lnWATER), and unidirectional causality from lnENG and lnELC to $\ln CO_2$. In addition, there is no evidence that indicates a nexus between the liberalization of trade and the deterioration of the environment.

Table 8. Juodis, Karavias and Sarafidis (2021) Granger non-causality test results.

Test Statistics	HPJ Wald Test	Coefficient	Prob.
lnGDP does not Granger-cause $\ln CO_2$	29.817045 ***	0.1709876 ***	0.0000
$\ln CO_2$ does not Granger-cause lnGDP	47.105256 ***	−0.179036 ***	0.0000
lnAGR does not Granger-cause $\ln CO_2$	63.039461 ***	−0.7809887 ***	0.0014
$\ln CO_2$ does not Granger-cause lnAGR	34.481617 ***	−0.041358 ***	0.0042
lnWATER does not Granger-cause $\ln CO_2$	8.3430113 ***	−0.4575799 ***	0.0039
$\ln CO_2$ does not Granger-cause lnWATER	13.615436 ***	0.0710439 ***	0.0002
lnENG does not Granger-cause $\ln CO_2$	65.762049 ***	−1.313412 ***	0.0000
$\ln CO_2$ does not Granger-cause lnENG	2.5654612	0.1313206	0.1092
lnELC does not Granger-cause $\ln CO_2$	177.43993 ***	−0.3573938	0.0000
$\ln CO_2$ does not Granger-cause lnELC	0.09616554	0.0351109	0.7565
lnTO does not Granger-cause $\ln CO_2$	0.67881694	0.0451014	0.4100
$\ln CO_2$ does not Granger-cause lnTO	1.3098619	0.0429897	0.2524

Standard errors in parentheses: *** $p < 0.01$.

To get more precise and accurate information regarding the findings of the Panel FMOLS, DOLS and ARDL techniques, we construct a graphical illustration (Figure 1). In this graph, blue lines indicate positive and statistically significant at 1% level, whilst red lines are negative ones.

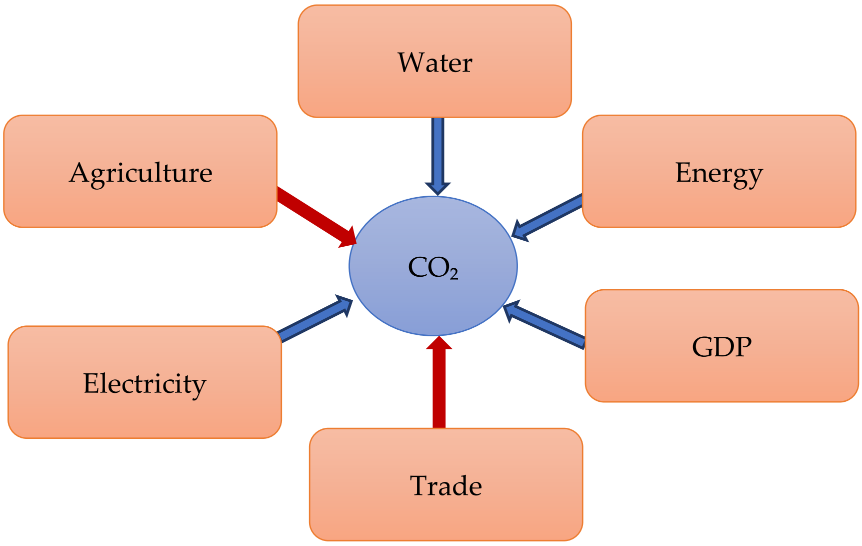

Figure 1. Graphical representation of the findings of Panel Data Models. Note: Blue sign is for positive and statistically significant at 1% level; Red sign is for negative and statistically significant at 1% level.

Figure 2 shows the graphical representation of the findings of Granger non-causality test which can be seen in Table 8. According to the graph, agriculture, water and GDP have bi-directional causality on CO_2 emissions, whilst energy has unidirectional relationship with CO_2 emissions. Interestingly, electricity production from oil, gas and coal and trade openness have no causal relationship with CO_2 emissions in the countries under the study when all countries are treated as a group.

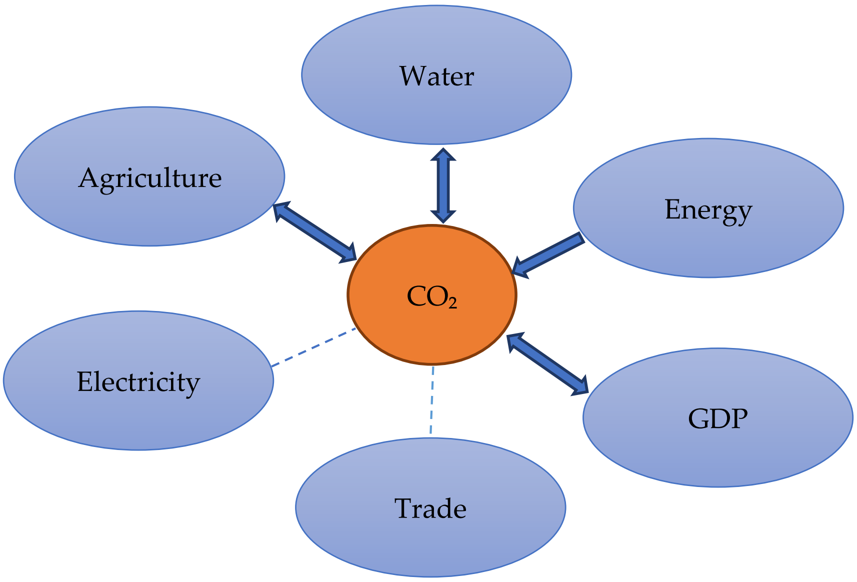

Figure 2. Graphical representation of Granger non-causality test results. Note: ⇔—means bi-directional causality; ⇐—means unidirectional causality; —-—means no causality.

Furthermore, we employ Granger non-causality test to further check if there is a strong causality between CO_2 emissions and dependent variables in this study. When we rank the CO_2 emitters by country (Table 9), it can be shown that the main emitters of CO_2 are energy and electricity from oil, gas and coal. In Kyrgyz Republic, CO_2 emissions are mainly caused by agriculture, energy, water and electricity from oil, gas and coal. In the case of Tajikistan, GDP and electricity from oil, gas and coal are the ones which generate CO_2 emissions.

Table 9. Juodis, Karavias and Sarafidis (2021) Granger non-causality test results by countries.

Kazakhstan	**HPJ Wald Test**	**Coeff.**	**Prob.**
GDP-CO_2	24.924641 ***	0.2442349 ***	0.0000
Agriculture → CO_2	35.594333 ***	−0.6423979 ***	0.0000
Water → CO_2	10.534225 ***	0.4054786 ***	0.0012
Energy → CO_2	18.018716 ***	1.734604 ***	0.0000
Electricity from oil, gas, and coal → CO_2	6.47384 ***	2.339287 ***	0.0109
Trade → CO_2	3.3811766 **	−0.1676981 **	0.0659
Kyrgyz Republic	**HPJ Wald Test**	**Coeff.**	**Prob.**
GDP-CO_2	32.874327 ***	0.6220052 ***	0.0000
Agriculture → CO_2	61.170693 ***	9.494256 ***	0.0000
Water → CO_2	80.119141 ***	2.917541 ***	0.0000
Energy → CO_2	49.775664 ***	3.182574 ***	0.0000
Electricity from oil, gas, and coal → CO_2	29.763587 ***	0.4218315 ***	0.0000
Trade → CO_2	54.601792 ***	1.005915 ***	0.0000
Tajikistan	**HPJ Wald Test**	**Coeff.**	**Prob.**
GDP-CO_2	19.093867 ***	0.3717678 ***	0.0000
Agriculture → CO_2	10.044585 ***	−0.2268042 ***	0.0000
Water → CO_2	2.5430826	−0.7768634	0.1108
Energy → CO_2	17.633354 ***	−1.024879 ***	0.0000
Electricity from oil, gas, and coal → CO_2	47.522853 ***	0.2429706 ***	0.0000
Trade → CO_2	45.1325353	−0.1325353	0.3669
Turkmenistan	**HPJ Wald Test**	**Coeff.**	**Prob.**
GDP-CO_2	5.311809 ***	−0.1491076 ***	0.0212
Agriculture → CO_2	0.84441843 ***	−6.83907 ***	0.0009
Water → CO_2	0.1578529	0.1858017	0.6911
Energy → CO_2	6.6229458 ***	1.360706 ***	0.0101
Electricity from oil, gas, and coal → CO_2	0.33449237 ***	65.41621 ***	0.5630
Trade → CO_2	0.41130557	−0.0300651	0.5213
Uzbekistan	**HPJ Wald Test**	**Coeff.**	**Prob.**
GDP-CO_2	23.621855 ***	−0.1234307 ***	0.0000
Agriculture → CO_2	0.20574869 ***	−4.4622 ***	0.0085
Water → CO_2	2.6526705	0.4455153	0.1034
Energy → CO_2	9.9312233 ***	0.4170792 ***	0.0016
Electricity from oil, gas, and coal → CO_2	27.857949 ***	1.515818 ***	0.0000
Trade → CO_2	5.7874141 ***	0.1169658 ***	0.0161

Standard errors in parentheses: *** $p < 0.01$, ** $p < 0.05$.

5. Discussion

The Aral Sea's compounding risk scenarios must be taken into account in shaping solutions for climate change adaptation. It is evident that upstream countries (Tajikistan and Kyrgyzstan) mostly focus on water for energy generation while downstream countries discharge water from neighbors for irrigation purposes. At the national level, adaptation and resilience measures must incorporate climate change scenarios in short- and long-term plans [13]. Research on climate resilient development in the Aral Sea region is in its nascent stage which should be focused on the mitigation and resilience approaches to deal with the negative consequences of human made environmental catastrophe in the Aral Sea region.

The Sustainable Development Goals (SDGs) must be attained, and five important adaptation methods for the transboundary risk in CA are suggested: (1) improved dryland agriculture crop production, (2) more robust new infrastructure, (3) improved water resource management, (4) green infrastructure, nature-based solutions and (5) strengthened multi-hazard risk assessment and early warning systems [5,19].

In order to deal with climate fluctuations in agricultural fields, climate smart agriculture (CSA) offers adaptable, society-oriented approaches and solutions. This holistic approach also ensures food security [16]. For instance, Hungary has used a variety of climatic adaptation strategies, including water supply management, particularly in times of scarcity [61]. Because of CSA success stories in industrialized nations, policymakers in Central Asia should create comparable plans to advance CSA in the region.

6. Policy Recommendations

This research has contributed to the existing literature by examining the connectivity of energy, agriculture, water, economic development and CO_2 emissions in Central Asian countries to provide more insight to policymakers. First, this article discovers that energy consumption and economic growth have a substantial and statistically significant effect on CO_2 emissions. Consumption, urbanization and industrialization have been major contributors to the region's overall economic development during the last several decades. Non-renewable energy sources have been relied upon heavily to provide the energy necessary to meet this rising demand. As a result, increases in both economic development and CO_2 emissions have occurred simultaneously throughout Central Asia. Central Asia's energy strategy should prioritize diversifying the region's energy supply and boosting the use of renewable energy.

Second, the findings suggest that agriculture has a detrimental and statistically significant impact on the level of carbon dioxide released into the atmosphere. Thus, governments in Central Asia must give top priority to the growth of their agricultural sectors and guarantee that this development considers environmental quality to the greatest extent possible. The rise in agricultural value-added, which is regarded to be the growth of the agriculture sector, is inextricably related to the advances in technical capabilities. As a result, the production of value-added goods in the agricultural industry is intrinsically linked to the use of technology, often known as digital agriculture. Using digital technology in agriculture, these countries have the potential to improve not just the value of their agricultural products but also the quality of their local environment. Thus, technological assistance for agricultural producers, as well as expenditures in research and development (R&D) by governments and financial incentives for such work, is a crucial instrument. In addition, it is advantageous for the agricultural producer to make use of technology and to be periodically guided towards the appropriate production and management approaches.

Finally, the results show an adverse relationship between trade openness and CO_2 emissions in Central Asia. To a large extent, the inverse link between economic openness and carbon emissions may be rationalized by pointing to the impacts of technological advancement. Governments in Central Asia should foster preferential trade policies, with a special focus on technological value addition. This may be nurtured via reciprocal trade liberalization and the elimination of trade restrictions. Furthermore, trade openness, in the long run, encourages a virtuous cycle that is good for the economy. This cycle helps the economy by creating job possibilities, easing capital flows and encouraging a competitive atmosphere.

Based on the aforementioned literature review, data analysis and metric calculations, the following future scenarios can be recommended to stakeholders and policy makers:

1. Climate migration is a potential threat resulting from the unsustainability of available resources (water, energy) and industries (agriculture, economy, environment) in Central Asia. The agricultural productivity of cultivated land has decreased because of salt and dust being transported when the northeastern winds blow. As a result of increased health hazards, inadequate nutrition and unemployment, the Aral Sea's degraded water resources are also having a negative socioeconomic impact on the local population. Salinity-related losses are thought to reach more than USD 2 billion annually, or 5% of Central Asia's GDP [2]. Rural populations with fragile ecological and socio-economic conditions will start moving to places offering sustainable economic and ecological conditions.
2. Smart and water management strategies should be urgently introduced for CA countries. With almost 2000 m^3 per person in 2025, Central Asia will have the highest water withdrawal rates globally [17]. More than 65 percent of the water used in

Central Asian nations is used by the agriculture sector where Uzbekistan is a dominant consumer (56 km^3) followed by Turkmenistan (28 km^3) [2]. Water quality and quantity are expected to continue to decline over the next ten years, so Uzbekistan needs to come up with a water management plan that uses as little water as possible for cotton cultivation [3]. To prevent an excessive amount of water from being wasted, for instance, irrigation management should be improved, and irrigation limitations should be established. It is important to encourage the development of crop types that can resist drought and save water. By implementing above mentioned policies, countries located in Central Asia can tackle the Aral Sea dilemma which is seen as an upcoming disaster for the surrounding locals.

7. Conclusions

The main aim of this paper is to examine the dynamic relationship between economic growth, agriculture, water, energy consumption, trade openness and environmental degradation in Central Asian countries, namely, Kazakhstan, Kyrgyz Republic, Tajikistan, Turkmenistan and Uzbekistan, from 1992 to 2020 by employing dynamic panel data models, including Panel DOLS, FMOLS, Panel ARDL (PMG approach) and Granger non causality tests to see the short and long run nexus between the variables under the investigation. After confirming the level of stationarity and long run cointegration of variables, we proceed to analyze the variables. The findings of Panel DOLS and FMOLS reveal that there is a positive long-term impact of economic growth, water productivity, energy consumption and electricity production from oil, gas and coal on CO_2 emissions in Central Asia at the 1% significance level (Table 6). Specifically, a 1 percent rise in economic growth, agriculture, water productivity, energy consumption and electricity production from oil, gas and coal led to 0.652, 0.435, 0.500 and 0.558 percent increases, correspondingly. These results, additionally, are confirmed by the results of the Panel ARDL, PMG approach. Agriculture value added and trade openness have a negative and statistically significant influence on CO_2 emissions at the 1% significance level. A 1% rise in agriculture and trade openness is responsible for 0.762 and 0.672% decline in CO_2 emissions, respectively. Country-specific short-run coefficients from Panel ARDL reveal that energy consumption is the main driver for rise in the level of CO_2 emissions in the countries under the study. Furthermore, Granger non-causality test is conducted to see the relationship between variables. According to the results of non-causality test, there is a bidirectional connection between CO_2 and economic growth, between CO_2 and agriculture and between CO_2 and water productivity, whilst energy consumption and electricity production from oil, gas and coal have unidirectional causality with CO_2 emissions.

Scientific novelty of the paper is that this is the first interdisciplinary and empirical paper integrating six variables in the case of five CA countries. The findings can be used to strengthen regional integration in CA, to forecast future regional development scenarios and strategies, to improve transboundary resource sharing mechanisms and to minimize potential conflicts and threats resulting from water deficiency, energy default, food safety, climate change and environmental degradation. Indeed, technological developments and adaptations of climate-resilient practices can give us better results to deal with climate change. The most important thing is that all stakeholders involved must come together to develop a comprehensive strategy to combat climate change and its detrimental repercussions.

Besides, this paper has several shortcomings. Researchers might analyze the current situation of environmental degradation in Central Asia by including several indicators which affect the level of CO_2 emissions, namely, FDI, urbanization, industrialization and democratization in the future. Additionally, cutting edge time series methodologies can be applied to country-level data by expanding the time span.

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