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New insights on the environmental Kuznets curve (EKC) for Central Asia

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Abstract

We estimate the environmental Kuznets curve (EKC) for Central Asia by allowing for the possibility of linear, U-shaped and N-shaped forms, and considering the impact of ecological footprint, climate change adaptation and energy consumption. We employ a fully modified ordinary least squares framework for cointegrating polynomial regressions, and include obtained long-run relations in a panel Vector Error Correction model. The findings suggest that the linear EKC form is more coherent for Central Asia compared to the N-shaped EKC form. We link this to the fact that the Central Asian countries are in the first stage of the EKC. We observe that Gross domestic product, ecological footprint, energy consumption and climate change adaptation positively impact carbon dioxide emissions in the long-run. Moreover, there is bidirectional causality from GDP and climate change adaptation to CO_2 emissions, while causality is unidirectional between emissions and energy consumption.

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1 Introduction

In 2015, the Central Asian (CA) countries ratified the Paris Climate Change Agreement, at the 21st UN Climate Change Conference held in Paris. Kazakhstan and Turkmenistan endorsed it in 2016, Tajikistan in 2017, Uzbekistan in 2018 and Kyrgyzstan in 2019 (Konurbaeva et al. 2022). While efforts have been made to shift from non-renewable to renewable energy sources, the share of renewable energy in total energy consumption has not increased by much: Uzbekistan's renewable energy consumption share in total energy consumption is 2.52%; the figure is 3.90% for Kazakhstan, and 0.01% for Turkmenistan; in Kyrgzstan and Tajikistan the renewable energy consumption share is around 28% and 30%, respectively. The total greenhouse gas emissions of these five Central Asian nations are 470.47 million-tonnes of CO_2, which is equivalent to approximately 1% of world total global emissions. Given this dependency on fossil fuels, CO_2 emissions in the region remain high. Therefore, CA remains the most vulnerable to the adverse effects of climate change (Konurbaeva et al. 2022).

While it is important for this region to complete the transition to clean energy approaches, the transition should not conflict with economic development. Thus, we analyze the interdependence between economic growth and carbon emissions by means of the environmental Kuznets curve (EKC) for CA. The EKC, based on Kuznets (1955), postulates that in early phases of economic growth environmental degradation increases, leading to a fall in environmental quality. However, beyond a certain threshold level of income per capita, environmental degradation will fall with increasing economic growth, producing an inverted U-shaped relation between environmental degradation and per capita income; see, among others, Grossman and Krueger (1991), Shafik and Bandyopadhyay (1992), and Panayotou (1993).

We address the following research questions. First, we investigate if the EKC for Central Asia is linear, quadratic, or cubic? To the best of our knowledge, previous studies have not undertaken linear and non-linear estimation of the EKC for this region neither have they considered polynomial cointregration. This is particularly relevant as neglecting potential non-linearities can lead to misleading inference. Second, in addition to GDP per capita, we investigate how additional environmental variables including energy consumption, ecological footprint, and the Notre Dame Global Adaptation Index (ND-GAIN) affects CO2 emissions. More recently, the ecological footprint of Wackernagel and Rees (1996), Wackernagel (2002), is accepted as a more comprehensive indicator of the demand for and supply of nature, while the ND-GAIN index takes into account the susceptibility and preparedness of nations to global climate change.[1] Only few studies consider these variables, and none has focused on

[1] See Sect. 3 for additional details on the variables we include in our study.

the Central Asian countries. The inclusion of these factors is expected to provide a more comprehensive understanding of the factors influencing CO_2 emissions and will shed light on the form of the Kuznets curve for CA countries.

The majority of studies which examine the EKC for CA, focus on energy factors, ignoring environmental factors, for example, Zhang (2019), and Salahodjaev et al. (2022). Although Ansari et al. (2020) include ecological footprint in their study, they use this variable as the dependent variable. However, ecological footprint also represents the absorptive capacity of the environment and can give us another way of linking the ecological footprint to EKC: the lower the ecological footprint the better the environmental ability in effectively absorbing carbon dioxide emissions. Furthermore, this study also employs, the climate change adaptation (GAIN) index as the more adaptation actions, the more resistant a country is to climate change. Finally, we use the recent contribution of De Jong and Wagner (2022) and estimate our model accounting for the possible presence of squared and cubic GDP terms in the EKC. To the empirical ends, the analysis uses a panel fully modified ordinary least squares (FMOLS) framework for cointegrating polynomial regressions, a vector error correction (VECM) and cointegration methodology. The findings reveal that compared to the U- and N-shaped EKC relations, the linear association is more coherent for the Central Asian countries when employing energy and environmental variables (ecological footprint and climate change adaptation).

The paper proceeds as follows. Section 2 reviews the literature. Section 3 presents the data and methodology. Section 4 provides the empirical results and Sect. 5 concludes.

2 Literature review

The EKC is based upon the Kuznets curve proposition (Kuznets 1955) according to which, there is an inverted U-shaped relationship between income inequality and per capita income; see Dinda (2004) for a comprehensive review of the literature. Many studies have investigated the association between environmental quality and per capita income. These studies have found, evidence of different forms of the EKC: U (Lantz and Feng 2006), inverted *U* (Selden and Song 1994; Sabir and Gorus 2019; Destek and Sarkodie 2019),*N* (Awan and Azam 2022; Allard et al. 2018; Aljadani et al. 2021; Onafowora and Owoye 2014) and inverted *N* (Bekhet and Othman 2018; Özokcu and Özdemir 2017). This evidence suggests that the association between GDP per capita and the environment might be both be time-varying (Farooq and Dar 2022). As stated above, an inverted U-shaped relation would suggest that, in the first stage, environmental degradation increases with economic growth, but once a certain level of income is reached, economic growth allows for environmental remediation in the second stage. A U-shaped curve would suggest the converse, where the first stage refers to an increase in economic growth, leading to a fall in environmental degradation, but beyond a certain level of income, environmental pollution would start to rise in the second stage. This could take place in the event that technological development does not keep pace with the rise in income or environmentally friendly policies are not implemented as an economy develops (Shafik and Bandyopadhyay 1992). The N-shaped EKC hypothesis is consistent with the inverted U-shaped curve in the first and second stages. In the second stage, there is a technological effect as policymakers focus on reducing pollution levels (Di Vita 2008; Koilo 2019; Porrini 2016). In the third stage however, there is a technological obsolescence effect if technological progress does not keep up, leading to a deterioration of the environment with income again (Zhang 2021). The inverse N-shaped EKC is similar to the U-shaped curve in the first and second stages. If technological development keeps pace, and governments design environmentally friendly policies, the third stage would lead to a fall in environmental degradation as income increases.

The EKC has been empirically tested for many countries using different methodologies. The studies of Usama et al. (2020), Saidi and Mbarek (2016), Tiwari et al. (2013), Shahbaz et al. (2012), Acaravci and Ozturk (2010), Jaforullah and King (2017) among others, employ an Autoregressive Distributed Lag (ARDL) methodology. Usama et al. (2020) examine the effects of renewable energy and non-renewable energy consumption on CO_2 emissions for Ethiopia. They find that both renewable and non-renewable energy reduce Ethiopia's CO_2 emissions. The unexpected results for non-renewable energy on CO_2 emissions are attributed to the fact that the share of non-renewable energy in the aggregate energy consumption of Ethiopia becomes insignificant exhibiting continuous decline in the last three decades. The results support the existence of the EKC hypothesis. Saidi and Mbarek (2016) testing the EKC for a group of emerging economies over 1990–2013, find no existence of an EKC. Investigating the EKC for India over 1966–2011 employing the ARDL methodology, Tiwari et al. (2013) find support for the hypothesis. Shahbaz et al. (2012), similarly, testing the EKC for Pakistan over 1971–2009, find the existence of an EKC. Acaravci and Ozturk (2010) in a study of the EKC for Europe over 1960–2005, find a long-run relationship between the variables and the existence of a EKC for Denmark and Italy. Jaforullah and King (2017) show that Itkonen's (2012) conclusions are sensitive to the form of the relationship assumed between energy consumption and income. They find that the presence of an energy consumption variable in a model of CO_2 emissions can lead to volatility in the coefficients, which can potentially change their magnitude and sign.

In their studies, Ang (2007), Pao and Tsai (2011), Itkonen (2012) and Jebli and Kahia (2020) employ a Vector Error Correction Model (VECM) to estimate the Kuznets curve. More specifically, Ang (2007) investigates the relationship between pollutant emissions, energy consumption, and output for France, using cointegration and vector error-correction methodology. The results indicate the existence of a long-run relationship between these variables for the period 1960–2000. Economic growth is found to have a causal effect on the growth of energy consumption and pollution in the long run. Pao and Tsai (2011) test the EKC for the BRIC nations over 1992–2007, using the VECM and Granger causality methods and find support for the EKC. Itkonen (2012) argues that most empirical findings with regard to the Carbon Kuznets Curve (CKC) where carbon emissions initially increase with economic growth and then reverse, is due to model misspecification associated with the econometric methodologies used and database definitions. Therefore, he argues that results are often biased to support the existence of a CKC. He finds a long-run relationship between these variables over the period 1960–2000, and that economic growth has a causal effect on the growth of energy use and growth of pollution in the long run. Jebli and Kahia (2020) examine the interdependence between CO_2 emissions, economic growth, energy generation, and renewable energy for a panel of 65 countries by applying a VECM to test for causality. The empirical results suggest a bidirectional causality between CO_2 emissions and non-renewable energy, but only in the short-run with unidirectional causality running from CO_2 emissions to renewable energy.

The studies by Dogan and Seker (2016), Baek (2015), Osabuohien et al. (2014), Hamit-Haggar (2012), Wen et al. (2021), Salazar-Nunez et al. (2022) apply FMOLS and DOLS methods to test the EKC. Examining these studies in greater detail, in a study of the effect of renewable and non-renewable energy, real income, and trade openness on CO_2 emissions for the existence of an EKC for the European Union over the 1980–2012 period, Dogan and Seker (2016), find a long run relation between CO_2 emissions, renewable and non-renewable energy, GDP and trade using the FMLOS and DOLS techniques. In a study over 1980–2009 for 12 countries, using the DOLS and FMOLS methodology, Baek (2015) does not find the existence of a EKC but that nuclear energy reduces CO_2 emissions. Osabuohien et al. (2014) also employing the panel DOLS method for a group of African countries over 1995–2010, find support for the existence of an EKC. Hamit-Haggar (2012), similarly, find evidence of a EKC and for Canada over the 1990–2007 period using FMOLS and cointegration methods. Wen et al. (2021) examine the effect of globalization, non-renewable energy consumption, and economic growth on CO_2 emissions for a group of South Asian economies over 1985–2018. Using a fully modified ordinary least square (FMOLS) technique, they find that non-renewable energy consumption increases environmental pollution. Moreover, the results confirm the EKC hypothesis for the South Asian region; where at the early stages of development, as economic growth increases, environmental pollution also increases, but begins to fall with the increase in economic growth after a threshold point. Salazar-Nunez et al. (2022) explore the short- and long-run relationship among consumption of renewable and non-renewable energies, economic growth, and CO_2 emissions in Mexico through a FMOLS approach. Their findings indicate that the reduction of CO_2 emissions is primarily due to the use of renewable energies in the short run, while in the long run it is not observed that CO_2 emissions decrease. Starting from a methodological point of view, Wagner (2015) and De Jong and Wagner (2022) challenge the literature on the EKC when quadratic and cubic terms are included. They show that appropriate estimation methods, a corrected version of FMOLS, must be used for proper evaluation of the existence of the EKC. By contrasting the standard FMOLS with their proposal, they show the empirical evidence on the EKC are much weaker.

Some studies, for example, Halkos (2003), Li et al. (2016), use the Generalized Method of Moments (GMM) estimator in the estimation of the EKC hypothesis. More precisely, Halkos (2003) tests the inverted U-shaped relationship between environmental damage from sulfur emissions and economic growth in the case of 73 OECD and non-OECD countries for 31 years (1960–1990) using the GMM estimator and finds support for the EKC while it is not achieved with a random effects model. Li et al. (2016) examine the effect of economic growth on various kinds of pollutant emissions with the GMM estimator, using a panel of 28 provinces of China from 1996 to 2012.

When examining the studies on the Central Asian countries, we note that only Zhang (2019) and Ansari et al. (2020) focuses on these countries. More specifically, Zhang (2019), employing FMOLS, DOLS, OLS estimations, find no support for an inverted U-shaped EKC, but results confirm the validity of a U-shaped EKC. Ansari et al. (2020) applying the PMG estimator to examine the EKC for West-, Central-, South-, East-and Southeast Asian countries over the period 1991 to 2017, find the existence of an inverted U-shaped EKC for the Central Asian countries.

There are other studies, for instance, Apergis and Payne (2010) and Salahodjaev et al. (2022) that include the five Central Asian countries in panel data models. More specifically, Apergis and Payne (2010), employing a panel vector error correction model for eleven countries of the Commonwealth of Independent States, over the 1992–2004 period find that in the long-run, energy consumption has a positive and statistically significant impact on carbon emissions and that real output exhibits an inverted U-shaped pattern associated with the EKC hypothesis. Salahodjaev et al. (2022) find the existence of an inverted-U shaped relationship for Europe and Central Asia, over the period 1990–2015, applying the GMM estimator. Therefore, our study will provide a further contribution to the scarce literature on the Central Asian countries.

3 Data and methodology

3.1 Data

To empirically examine the relationship between carbon dioxide emissions, gross domestic product, ecological footprint, climate change adaptation initiatives and energy consumption, we build a panel dataset for the Central Asian Countries. Specifically, we consider the following countries, Uzbekistan, Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, during the period 1995–2018.[2] In our analysis, CO_2 emissions, measured in tons, are used as the reference variable, while GDP (USD), ecological footprint (global hectare-gha per person), climate change global adaptation initiative index (by Notre Dame) and energy consumption per capita [measured in kilowatt-hours (kWh)], are used as variables related to emissions and relevant for the estimation of the EKC.

Economic growth in CA has led to high energy use and rising CO_2 emissions due to the region's heavy reliance on fossil fuels causing energy consumption to be high. Possible barriers to climate change adaptation in CA could also be explained by backward and outdated technology (Gómez et al. 2015; Karimov et al. 2013). Activities such as deforestation, soil erosion and combustion of carbon-based fuels are major sources of carbon dioxide (CO_2) emissions in CA (Ali et al. 2019; Ahmed et al. 2015; Abbas et al. 2020). Ecological footprint which measures the demand and supply of nature using existing technology and is accepted as a more comprehensive indicator of environmental change, could also influence this relation. Consequently, we postulate that the joint effect of climate change adaptation, ecological footprint, and

[2] Data after 2018 are not fully available and we thus preferred to limit the analyses to 2018.

carbon-based energy consumption factors on CO_2 emissions need to be incorporated in the EKC relation for Central Asia. Moreover, according to the previous discussion, we expect a positive impact of the mentioned variables on CO_2 emissions.

Data for CO_2 emissions and energy consumption per capita were obtained from Our World in Data (https://ourworldindata.org/), while GDP data was obtained from Macrotrends (https://www.macrotrends.net/). Furthermore, data for ecological footprint were downloaded from the Global Footprint Network (https://www.footprintnetwork.org/) and the $GAIN$ (Global Adaptation Initiative) index was obtained from the Notre Dame Global Adaptation Initiative (https://gain.nd.edu/our-work/country-index/). All data are available at the annual frequency. Table 1 provides definition and sources of the variables.

Table 2 reports the descriptive statistics for the variables. We observe that, on average 78.19 tons of CO_2 has been emitted during the period 1995–2018 in Central Asian countries. The GDP is on average equal to 32.53 billion USD. The $GAIN$ (Global Adaptation Initiative) index for climate change is 46.12 on average for each country. Regarding energy, on average each person consumes 23.89 kilowatt-hours of energy. Ecological footprint is 2.72 hectare per person in the Central Asian region during the period covered. The standard deviations of CO_2 and GDP is large implying that both of them are more spread out from the mean. Standard deviations of the $GAIN$ and EC are also high, whereas the data for EF are clustered around the mean as it is relatively small and close to zero. The coefficients of variations report that standard deviation of CO_2 is nearly equal to the mean, while the standard deviation of GDP is about 1.5 times larger than the mean. The standard deviation of the $GAIN$, is 0.1 the amount of the mean. Standard deviations of both the EC and EF are 0.6 the amount of their means. Data for all variables are positively skewed, $GAIN$, EC and EF are platykurtic while CO_2 and GDP are leptokurtic. The Jarque–Bera normality test indicates that all variables are not normally distributed.

3.2 Methodology

The study examines the validity of the EKC hypothesis for Central Asia employing energy and climate change factors as additional variables in the long-run relation. To investigate the long-run equilibrium, we might consider a Panel Vector Error Correction Model, taking the following general representation:

$$\Delta \boldsymbol{Y}_{i,t} = \boldsymbol{\alpha}\left(\boldsymbol{\beta}' \boldsymbol{Y}_{i,t-1}\right) + \boldsymbol{\Gamma} \Delta \boldsymbol{Y}_{i,t-1} + \boldsymbol{\varepsilon}_{i,t} \tag{1}$$

where $Y_{i,t}$ is a country-specific vector of modelled variables including $CO_{2,i,t}$, $GDP_{i,t}$, $GAIN_{i,t}$, $EC_{i,t}$, $EF_{i,t}$, $\varepsilon_{i,t}$ is the model error and might be further detailed with the specification of unobserved heterogeneity, and Δ is the first difference operator. In addition, we introduce a single lag given our focus is on yearly data and the limited size of our sample.[3] Furthermore, we highlight that the short-term parameters Γ, the adjustment coefficients α, and the cointegrating equation coefficients β are constant across all subjects (countries) of our sample. Finally, we note that the term

[3] In the empirical analyses we will justify this choice with appropriate model specification tools.

Table 1 Definition and sources of the variables

Variable	Description and unit	Sources	Online link
CO_2	Carbon dioxide (CO_2) emissions in million tons from fossil fuels and industry. Land use change is not included	Our World in Data	https://ourworldindata.org/
GDP	Gross domestic product in billion USD	Macrotrends	https://www.macrotrends.net/
EF	Ecological footprint measured in global hectares (gha) per person. A measure of how much area of biologically productive land and water an individual, population, or activity requires to produce all the resources it consumes and to absorb the waste it generates, using prevailing technology and resource management practices	Global Footprint Network	https://www.footprintnetwork.org/
$GAIN$	Global Adaptation Initiative Index by Notre Dame. The ND-GAIN Country Index is composed of two key dimensions of adaptation: vulnerability and readiness. The higher the index is, the better the adaptation for climate change is	Notre Dame Global Adaptation Initiative	https://gain.nd.edu/our-work/country-index/
EC	Energy consumption[a], including both renewable and non-renewable energy per capita in kilowatt-hours (kWh). Energy use not only includes electricity, but also other areas of consumption including transport, heating and cooking	Our World in Data	https://ourworldindata.org/

[a]As our energy consumption data is aggregated data which includes both renewable and non-renewable energy consumption, we assume that it has a positive impact on emissions. This is a consequence of the fact that the share of non-renewable energy, with very high emissions is predominant in Central Asian countries. Non-renewable energy consumption share in total energy consumption was 97.4% in 2020 for Uzbekistan (Our World in Data—https://ourworldindata.org/). This figure was 96.1% for Kazakhstan (Our World in Data) and 99.9% for Turkmenistan (Our World in Data). In the case of Kyrgyzstan in 2018 this amount was 91.2%, and in Tajikistan the figure was 60% in 2019 (International Energy Agency 2022)

Table 2 Descriptive statistics

	CO_2	GDP	$GAIN$	EC	EF
Mean	78.19	32.53	46.12	23.89	2.72
Median	49.77	9.91	44.62	20.19	2.19
Maximum	317.28	236.63	57.7	62.04	6.78
Minimum	1.88	0.86	39.33	7.33	0.79
SD	83.75	51.58	4.74	14.27	1.71
Coefficient of variation	1.07	1.58	0.1	0.59	0.62
Skewness	1.06	2.34	0.55	0.79	0.57
Kurtosis	3.27	7.88	2.18	2.69	1.9
Jarque–Bera	23.11	229.66	9.43	13.27	12.49
P value	0.00	0.00	0.00	0.00	0.00
Sample size ($T \times N$)	120	120	120	120	120

in parentheses, $\boldsymbol{\beta}'\boldsymbol{Y}_{i,t-1} = \boldsymbol{\mu}_t$, is also called the cointegration residual or error correction term. We observe that, from an economic perspective, the parameters in the $\beta\prime$ vector are also defined long-run multipliers. Notably, a two-step estimation approach might be used (Sims 1980), where in a first stage the long-run parameters, that is the $\boldsymbol{\beta}$ vector, are estimated by appropriate methods (for instance Dynamic OLS or Fully Modified OLS), then the cointegration residuals are evaluated and, given their stationarity, the short-term dynamic parameters and the adjustment coefficients are estimated by least squares methods. Such a two-step procedure allows for the specification of more flexible long-run equations.

In the empirical analysis, we will evaluate the existence of unit roots for the variables of interest and the occurrence of cointegration among them. Specifically, we consider panel unit root tests to verify the presence of unit roots in our variables: we use the Levin, Chin & Chu t*-test (Levin et al. 2002) (for common unit root process), the Im, Pesaran and Shin W-stat (Im et al. 2003), the ADF—Fisher Chi-square (Maddala and Wu 1999), and the PP—Fisher Chi-square (Choi 2001) (for individual unit root process) tests. We also apply the Fisher (or combined Johansen) cointegration test to identify the existence of a long-run relationship among the studied variables. Furthermore, we complement our analyses with the Dumitrescu and Hurlin causality test (Dumitrescu and Hurlin 2008) which is used to examine the causality relations existing between the variables.

From a theoretical point of view, and coherently with the previously cited literature, we might postulate the existence of a single long-run relationship, associated with the Empirical Kuznets Curve. Consequently, if this claim is supported by the data, we will specify the following long-run equation, representing the EKC curve with parameters common to all Central Asian countries

$$\begin{aligned} CO_{2,i,t} = \delta_0 + \beta_2 GDP_{i,t} + \beta_3 GDP_{i,t}^2 + \beta_4 GDP_{i,t}^3 \\ + \beta_5 GAIN_{i,t} + \beta_6 EC_{i,t} + \beta_7 EF_{i,t} + \mu_{i,t} \end{aligned} \qquad (2)$$

where we included an intercept, this to be coherent with the presence of a trend in the variables in levels (and where we set the usual normalization with $\beta_1 = 1$ in the vector $\boldsymbol{\beta}\prime$), and the residual is the error correction term. Furthermore, differently from the general Panel VECM structure, we also include the squared and cubed GDP levels, which allow a more detailed evaluation of the EKC for Central Asia. In fact, the cointegration Eq. (2) will allow for three possible specifications, the presence of only the linear GDP impact, or the more flexible EKC specifications that can be obtained with the introduction of the quadratic or cubic form; we notice this is a very common specification in the literature, as we previously argument. From a methodological point of view, Eq. (2) is also called Cointegrating Polynomial Regression, as one of the explanatory variables appear in the level as well as with powers. Several papers have been using standard estimation approaches and cointegration tests for the evaluation of the EKC as described by Eq. (2). However, these results might be impacted by the existence of the polynomial terms; see Wagner (2015) and Wagner and Hong (2016).

For estimation of the model we follow a two-step procedure mentioned above. At first, we estimate the cointegration relation of Eq. (2). However, the presence of powers of *GDP* precludes the use of the standard Fully Modified Least Squares put forward by Phillips and Hansen (1990). Wagner and Hong (2016), from the methodological point of view, and Wagner (2015), covering also the empirical aspect, provide an interesting analysis of the consequences of using an inappropriate estimation method: in summary, the overconfidence in the existence and relevance of the EKC. Therefore, we adopt the recent estimator introduced by De Jong and Wagner (2022): they generalized to the panel setting the work of Wagner and Hong (2016).[4] The interpretation of the estimated coefficients will allow a first evaluation of the EKC existence for Central Asia. In a second step we proceed to estimation of the adjustment coefficients and of the short-term dynamics, giving us additional insights on the adjustment of the variables after deviations from the EKC-implied equilibrium. In this case we apply a Panel VECM model of Eq. (1). This approach was put forward by Sims (1980), introducing the estimated error correction term as an explanatory (stationary) variable. Therefore, we estimate the following specification in first differences:

$$\Delta \boldsymbol{Y}_{i,t} = \boldsymbol{\alpha}\widehat{\mu}_{i,t-1} + \boldsymbol{\Gamma}\Delta \boldsymbol{Y}_{i,t-1} + \boldsymbol{\varepsilon}_{i,t} \tag{3}$$

where the equation of CO_2 reads as

$$\begin{aligned}\Delta CO_{2,i,t} =\ & \alpha_1\hat{\mu}_{i,t-1} + \gamma_{1,1}\Delta CO_{2,i,t-1} + \gamma_{1,2}\Delta GDP_{i,t-1} + \gamma_{1,3}\Delta GAIN_{i,t-1} \\ & + \gamma_{1,4}\Delta EC_{i,t-1} + \gamma_{1,5}\Delta EF_{i,t-1} + \varepsilon_{1,i,t}\end{aligned} \tag{4}$$

and the other equations have a similar structure. For this second stage, our interest will be focused on the adjustment coefficients as well as on the relevance of the various variables in the short-term dynamic model. Full model results will also be read in combination with the causality test outcomes previously mentioned.

[4] The specification of Cointegrating Polynomial Regressions has an impact also on cointegration testing. However, Panel versions of the tests provided in Wagner and Hong (2016) is not available. We further discuss this issue in the empirical section.

4 Empirical results

We first consider the unit root tests on the variables of interest, which are reported in Table 3. For CO_2, GDP, $GAIN\ EC$ and EF we have clear empirical evidence of the presence of a unit root. Both the t* statistic of Levin et al. (2002), the W-stat of Im et al. (2003), the ADF-Fisher-Chi-square and the PP-Fisher-Chi-square are coherent in detecting a unit root. All the variables are stationary once taken in first differences.

Given the evidence that the integration order of the variables is one, we proceed with the evaluation of the presence of cointegration by using the Fisher (combined Johansen) cointegration test. The results are reported in Table 4.

The test results highlight an incoherence between the two test statistics, as only the trace test suggests the existence of a cointegration relation among variables. We link this result to the limited time sample of our dataset and therefore, despite the incoherence of the two Johansen-type tests, we read the evidence reported as mildly supporting the existence of cointegration among the variables, and allowing for this, we proceed with the estimation of the Panel VECM model.

Before model estimation, we analyze the causality between the variables in our panel by means of the Dumitrescu-Hurlin causality test. We run the test both on the series in levels and first differences. Table 5 contains the results. When focusing on the causality among the series in levels, we observe that GDP has a unidirectional causal effect on CO_2 emissions, an aspect which is in line with the Kuznets Curve for Central Asia. Moreover, CO_2 emissions have a bidirectional causal relation with both climate adaptation and energy consumption, but not with ecological footprint. All variables except ecological footprint have a causal effect on CO_2 emissions, a relevant element for the specification of a Panel VECM model where variable relations in levels and first order differences can both be captured. Furthermore, climate adaptation has a bidirectional causal effect with GDP, and a unidirectional effect on energy consumption. Finally, GDP has a bidirectional causal relation to ecological footprint, while it shows a unidirectional causal effect to energy consumption.

Results are quite different when focusing on the first differences. In fact, we note only two cases where causality is detected, from GDP to CO_2 e and from CO_2 e to EF. There two findings are in line with the expectation that as the change in economic growth impacts carbon emissions that these in turn, will affect ecological footprint. Overall, the causality analysis shows evidence of much stronger links in levels which might be associated with the existence of cointegration and with the possibility of rewriting model (1) by exploiting the level relationships among variables (Lütkepohl 2005).

Table 6 reports the estimated coefficients of the cointegrating Eq. (2), for three different choices of the impact of GDP (linear, quadratic and cubic). We remind that we estimate the parameters adopting the panel FMOLS estimator introduced in the recent contribution of de Jong and Wagner (2022),[5] leading to a more appropriate evaluation of the parameters and of their significance in the presence of panel cointegrating

[5] Given the limited sample, and differently from De Jong and Wagner (2022), we use a pooled estimate the contemporaneous and long-run variance matrices required for the evaluation of the Panel FMOLS estimator.

Table 3 Unit root tests

	CO_2		GDP		$GAIN$		EC		EF	
	Level	1st Dif	Level	1st dif	Level	1st dif	Level	1st dif	Level	1st dif
Null: Unit root (assumes common unit root process)										
Levin, Lin & Chu t*	0.99	0.00*	0.83	0.00*	0.94	0.00*	0.67	0.00*	0.37	0.00*
Null: Unit root (assumes individual unit root process)										
Im, Pesaran and Shind W-stat	1.00	0.00*	0.99	0.00*	0.95	0.00*	0.94	0.00*	0.74	0.00*
ADF-Fisher-Chi-square	0.97	0.00*	0.99	0.00*	0.95	0.00*	0.90	0.00*	0.68	0.00*
PP-Fisher-Chi-square	0.97	0.00*	0.99	0.00*	0.94	0.00*	0.89	0.00*	0.63	0.00*

For all tests (Levin, Lin & Chu t*, Im, Pesaran and Shind W-stat, ADF-Fisher-Chi-square, PP-Fisher-Chi-square) we report only the p values. Lags have been selected using the SIC (lag was set to 1 in all cases, and only the individual intercept has been considered). The null hypothesis is the presence of a unit root. We denote by * the rejection of the null at the 1% confidence level

Table 4 Johansen Fisher Panel cointegration test

Hypothesized No. of CE(s)	Fisher stat.* (from trace test)	Prob	Fisher stat.* (from max-eigen test)	Prob
None	59.11	0.00***	52.74	0.00***
At most 1	19.98	0.02**	11.90	0.29
At most 2	12.65	0.24	10.83	0.37
At most 3	7.64	0.66	8.31	0.59
At most 4	7.04	0.72	7.04	0.72

The table shows the trace and maximum eigenvalue tests of Johansen Fisher for panel cointegration and their p-values. The null hypothesis is associated with the cointegration ranks (i.e., the number of cointegrating relations) reported over the rows of column 1. Asterisks represent statistical significance, *** at 1% level, ** at 5% level and * at 10% level. We set the lag to 1 using SIC

Table 5 Dumitrescu Hurlin panel causality tests

Null hypothesis	Level	First diff
GDP does not homogeneously cause CO_2	0.00***	0.08*
CO_2 does not homogeneously cause GDP	0.12	0.27
$GAIN$ does not homogeneously cause CO_2	0.00***	0.56
CO_2 does not homogeneously cause $GAIN$	0.05*	0.99
EC does not homogeneously cause CO_2	0.02**	0.92
CO_2 does not homogeneously cause EC	0.00***	0.20
EF does not homogeneously cause CO_2	0.77	0.48
CO_2 does not homogeneously cause EF	0.60	0.01**
$GAIN$ does not homogeneously cause GDP	0.00***	0.60
GDP does not homogeneously cause $GAIN$	0.00***	0.74
EC does not homogeneously cause GDP	0.11	0.31
GDP does not homogeneously cause EC	0.00***	0.35
EF does not homogeneously cause GDP	0.00***	0.20
GDP does not homogeneously cause EF	0.00***	0.43
EC does not homogeneously cause $GAIN$	0.68	0.78
$GAIN$ does not homogeneously cause EC	0.00***	0.36
EF does not homogeneously cause $GAIN$	0.32	0.17
$GAIN$ does not homogeneously cause EF	0.48	0.46
EF does not homogeneously cause EC	0.81	0.69
EC does not homogeneously cause EF	0.46	0.92

The table reports the p-values for the Dumitrescu Hurlin panel causality test. Asterisks represent statistical significance ***, ** and * for 1%, 5% and 10% levels, respectively. Optimal lag has been selected using SIC

Table 6 FMOLS estimation results of cointegration equation

Variables	Dependent variable = $\boldsymbol{CO_2}$ (carbon dioxide) emissions		
	Testing the relation between $\boldsymbol{CO_2}$ and GDP	Testing U-shaped Kuznets curve	Testing N-shaped Kuznets curve
EF	7.95* (4.48)	6.97 (4.53)	6.74 (4.37)
$GAIN$	4.94*** (1.56)	4.73*** (1.58)	4.63*** (1.51)
EC	0.85** (0.43)	0.82* (0.43)	0.82** (0.41)
GDP	0.33*** (0.08)	0.36*** (0.09)	0.37*** (0.12)
GDP^2		-8.81×10^{-4} (6.48×10^{-4})	-9.09×10^{-4} (8.11×10^{-4})
GDP^3			4.72×10^{-7} (1.30×10^{-5})

Standard errors are in parentheses. Asterisks represent statistical significance ***, ** and * for 1%, 5% and 10% levels, respectively

polynomial regressions. The estimations in column 1 confirm the existence of a long-run association between the variables: with the coefficients statistically significant, in particular *GDP* and *GAIN*. In addition, in all specifications EF, $GAIN$, EC variables positively impact CO_2 emissions. More specifically, an increase in ecological footprint (EF) and higher energy consumption (EC) is associated with larger CO_2 emissions in the long-run. Regarding the climate change adaptation ($GAIN$) index, it has a positive relation with CO_2 emissions. However, if we look at the GDP coefficient, it is positive and always significant if we limit our interest only to the linear impact. When introducing higher order impact, that is, the quadratic and cubic effects, the associated coefficients are not statistically significant.

This evidence seems to suggest that the EKC is linear in Central Asia.[6] This is in contrast with the several empirical analyses supporting the existence of non-linear EKC curves; see, for instance, Awan and Azam (2022), Allard et al. (2018), Aljadani et al. (2021), Onafowora and Owoye (2014) found N-shaped EKC relation, whereas Bekhet and Othman (2018), Özokcu and Özdemir (2017) discovered an inverted N-shaped EKC association.

[6] A KPSS-Shin type test for cointegrating polynomial regression, similar to that in Wagner and Hong (2016), is not available for panel data. However, exploiting the pooling in contemporaneous and long-run variance matrices estimation (see Footnote 5), we use the KPSS-Shin cointegration test for time series data (Wagner and Hong 2016). The test statistic equals 0.0537 for the linear model, while it moves to 0.2937 and 0.3372 for the squared and cubic cases, respectively. We detect cointegration for the linear and quadratic cases only. Critical values have been obtained using the code available in M. Wagner website, https://www.aau.at/en/economics/quantitative-economics/team/univ-prof-dipl-ing-dr-techn-martin-wagner/; last access, November 2022. We are indebted to M. Wagner for making available the code for FMOLS estimation and cointegration testing under polynomial regression. Combining this finding with the fact that the most appropriate specification is the linear one, our findings are coherent with those based on standard cointegration tests and reported above.

Table 7 The results of VECM model – adjustment coefficients

Estimated alphas (p values)	
CO_2	– 0.114** (0.056)
EF	0.008*** (0.002)
GAIN	– 0.007 (0.005)
GDP	0.178** (0.081)
EC	0.006 (0.023)

Standard errors are in parentheses. Asterisks represent statistical significance ***, ** and * for 1%, 5% and 10% levels, respectively

We proceed to the evaluation of the VECM model, Eq. (3), for the linear case only, given the previous evidence. We report only the adjustment coefficients, showing the impact of the disequilibrium (the error correction term) on the series' first differences in Table 7.

Notably, the signs of the adjustment coefficients are in line with expectations. We observe that a negative disequilibrium leads to an increase in carbon emissions. Remarkably, this is coherent with the evidence of the cointegration Eq. (2) and the estimated coefficients (Table 6).[7] The occurrence of a disequilibrium also leads to adjustments in ecological footprint, and, with a reduced significance, on economic growth. A disequilibrium originates when variables deviate from their long-run values, leading to a not null residual in the cointegration equation; the disequilibrium might be related to an increase in GDP (negative disequilibrium), or for improvements in the ecological footprint (a drop in *EF* and a subsequent positive disequilibrium). The adjustment mechanism we identify suggests that the main variables responding to the disequilibrium are the emissions, the economic growth and the ecological footprint. The latter is particularly relevant as further strengthen and support the introduction of further drivers of the environmental dimension in the EKC, not restricting interest to the CO_2 emissions. Therefore, our approach, while on the one hand identifies the existence of a long-run equilibrium condition (the linear EKC curve), on the other hand provides a rational for the causality induced by a disequilibrium. Overall, the empirical evidence validates the causality mechanism implicitly relating the EKC and the extended set of variables we consider, including the climate change ($GAIN$) index, energy consumption (EC) and ecological footprint (EF).

The empirical evidence is thus coherent with the existence of a linear relationship between the variables, that is, the linear EKC. This is in contrast with the expectation of having a U-shaped or N-shaped curve (inverse or not), but we might postulate a

[7] We note that in Eq. (2) coefficients are reported on the right hand side and to identify the impact of a change in one of the variables of interest on the disequilibrium (the cointegration residual), we have to express the disequilibrium as a function of all variables, leading to a change in the coefficients sign.

reason supporting our evidence. As we are considering the CA countries, we have to consider the development level of these countries as a relevant factor, see Fig. 1. If we compare the GDP (Macrotrends) of the CA countries we observe that Kazakhstan reaches 190.81 billion US dollars in 2021, while Uzbekistan reaches 69.24 billion US dollars. Kyrgyzstan and Tajikistan shows a very similar pattern with GDP values equal to.54 and 8.75 billion US dollars, respectively; and finally, Turkmenistan GDP reaches a value of 45.23 billion US dollars in 2019. The countries show evidence of relevant differences in GDP. Furthermore, if we focus on their level of economic development, we might argue that the CA countries are on a path of medium-long term economic growth, and might thus all be located at the beginning of the EKC. This claim is in line with the graphical evidence in Fig. 1 where the linear relationship between CO2 emissions and GDP emerges in a clear way.

5 Conclusion

This study is a pioneer in investigating the linear and non-linear EKC relation for Central Asia considering ecological footprint, climate change adaptation and energy consumption. The empirical analysis tests for a linear, U and N-shaped Kuznets curve by adopting for model estimation a recent methodological contribution by De Jong and Wagner (2022), which is appropriate when a long-run relation, like the EKC, includes powers of a non-stationary variable (the GDP). Our findings reveal evidence of a linear Kuznets relation between carbon dioxide emissions, and gross domestic product. There is no evidence of a U-shaped or N-shaped Kuznets relation for Central Asia. The empirical evidence suggests that the countries' path to economic development severely impact the evaluation of the EKC. In fact, the estimates and the graphical analyses provide stronger support for a linear EKC. The linearity might not be surprising as it might be interpreted as an evidence of all countries being in the first phase of the N-shaped and U-shaped curve, which might be locally approximated by a linear relationship. These results are consistent with that of Bekhet and Othman (2018) for Malaysia. Many EKC studies show that the income–environmental degradation relationship is influenced significantly by government policies (Dinda 2004). The Central Asian countries: Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan have made significant progress in achieving economic growth based on natural capital, and the governments of these countries have committed to promoting efficient technologies to provide a cleaner environment (World Bank 2022). For example, the World Bank together with the Korea Green Growth Trust Fund and supported by the Korea Green Growth Trust Fund (KGGTF) and Nationally Determined Contributors Support Facility is working with Kazakhstan, the Kyrgyz Republic, and Uzbekistan to develop a circular economy approach to promoting a greener environment (World Bank 2022). Thus, this would explain the second stage of the N-shaped EKC curve obtained by our results.

The long-term results of the linear estimation show evidence of the relevant role of ecological footprint, climate change adaptation and energy consumption on CO_2 emissions. In the long-run, adaptation strategies might not be so effective to reduce or absorb CO_2 emissions because of the positive relation. Adaptation strategies mostly

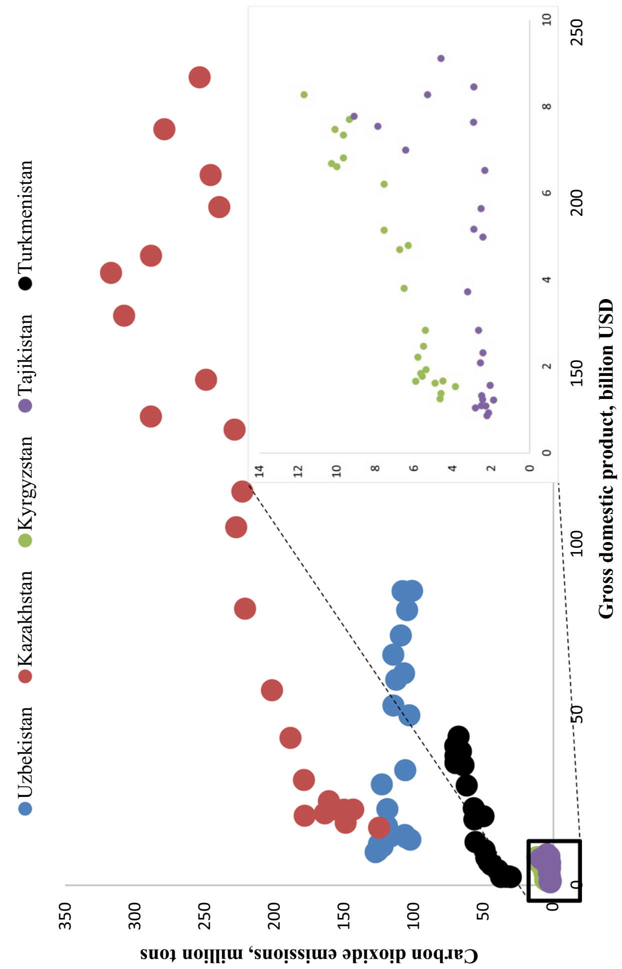

Fig. 1 The relation between GDP and CO_2 emissions for CA countries. The figure reports the relation between the GDP (bottom axis) and the CO2 emission (left axis). We denote countries with different colors. Due to the heterogeneity in the GDP size, we zoomed the area including Kyrgyzstan and Tajikistan

focus on investing on infrastructure, education, and innovation. The positive impact of energy consumption can be explained by the fossil fuel related energy consumption in Central Asia which increase CO_2 emissions.

However, the regions endorsement of the Paris Climate Agreement and initiatives taken by the governments of the countries to increase energy efficiency, suggest that they are on the right track towards reducing CO2 emissions.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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