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Climate Change:
North & South EU Economies. An application of dynamic asymmetric panel data models

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Abstract

This paper investigates the effect of climate change on economic growth, using nonlinear dynamic panel methods, for 15 countries of European Union (EU), by the period 1981-2019. Specifically, it is examined the impact of temperature, precipitation and CO_2 emissions on economic growth. So, ARDL (Autoregressive Distributed Lags) methods were employed, overcoming cross-dependency and also considering linearity and nonlinearity. In results is showed that economic growth has positive nonlinear relationship with long-run temperature, but in short-run they have a symmetric negative association. Moreover, precipitation has long-run negative and a short-run positive relationship with economic growth. However, when CO_2 emissions are added, then precipitation has a positive effect on economic growth, but all others except from temperature increase, become insignificant. Finally, actions should be taken for more stable climate conditions and consistent environmental policies by EU countries.

Keywords: Asymmetries · Climate change · European Union· Economic Growth · Dynamic Panel data · Pollution

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1. Introduction

It is an indisputable fact that production and economies are affected by climate conditions, from the very first years of human existence. Especially, in Europe's economic history, the utilization of land and agricultural had played crucial role in human development and surviving. For example, harsh fluctuations on temperature or water availability could lead to reduced harvest, and thus, increased mortality rates (Erdkamp et al. 2021). Although, even in modern economies of European Union (EU), production of vital agricultural goods is expected to be negatively affected by climate change (Knox et al. 2016). This is an alarming fact, because it could possibly drive into market equilibrium collapse, raising up socioeconomic crises (EEA 2021).

Nowadays, reduction of carbon dioxide pollution as a result of climate change is a crucial objective in European Union, accompanied by plethora of environmental policies (Cifuentes-Faura 2022). For instance, "European Climate Law" (2021/1119) is targeted in limiting levels of net greenhouse gas emissions by at least 55% in 2030, compared to ones of 1990, and finally achieving net zero levels by 2050, in a cost-effective way (European Climate Law 2021). Synergy in this attempt between European Union and United Nations in Tokyo Protocol (1998) and Paris Agreement (2015) is also remarkable. The governance quality of each EU country is still found as a key factor for the efficiency of environmental policy applications (Apergis & Garćıa 2019).

Despite the environmental awarness of EU policies, it is widely accepted that European continent is more and more affected by climate chage. For example, Pfeifer et al. (2019) found that heat shocks, summer precipitation extremes, higher summer temperatures and greater differences between day and night temperatures are dealt in highly populated European regions. Additionally, there are concerns about increased greenhouse emmisions in the future by the high economic European activity, unless drastic ecological measures are taken in supply chain (Giannakis & Zittis, 2021).

Taking into account these, an effort is made in this study for a dynamic contribution in resolving this problematic situation, by the investigating the effect of climate change on economic growth at EU level. Both symmetric and asymmetric dynamic panel methods are employed, considering for cross-dependency, so the impact of temperature, rainfall and CO_2 emissions per capita on economic growth be addressed. In results is showed that economic growth has positive relationship with long-run temperature in a nonlinear way, but in short-run they have a symmetric negative association. Precipitation has long-run negative and a short-run positive relationship with economic growth. However, when CO_2 emissions are added, precipitation has a positive effect on economic growth, but all others except from temperature increase, become insignificant. Finally, actions should be taken for more stable climate conditions and consistent environmental policies by EU countries.

In Section 2, some fundamental previous works about the effect of climate change on economic growth are presented. Then, in Section 3, the strategy of the empirical models is showed and in Section 4 we have the outcome. Finally, in Conclusion the basic results and methods of the work are discussed.

2. Literature view

One of the most fundamental recent studies on this field was done by Dell et al. (2008). Specifically, was used annual data for 50 years in worldwide panel data in order to examine the effect of temperature and precipitation on economic growth, using dynamic methods. In conclusion was deducted that temperature increase has little effect on economic growth for financially sounded countries, but negative effect, reduced output level and growth rate, and also economic and political problems for the poor ones.

In more recent literature, like Burke et al. (2015), is figured out a nonlinear effect of temperature on economic growth, using nonlinear fixed-effects (FE) models. Characteristically, productivity was found to be maximized in temperature of 13 °C and harshly diminished for greater ones. This association is international since 1960 and irrelevant from agricultural activities or development of the countries. Future predictions that were made, showed only a slight increase of temperature and more inequal income distribution, and so they were interpreted as over-optimistic.

The effect of climate change in three tourism-based countries of Mediterranean Basin: Greece, Spain, and Turkey, was explored by Du & Ng (2018), employing Ordinary Least Squares and Quantile regression methods. In particular, it was denoted that the negative footprint of temperature increase in these specific countries is greater in comparison with G-7 and a group of developing countries. As a result, it is ended up a need of international collaboration for these three countries, so as to overcome the negative reverberations of climate change for their economies.

Heterogeneous dynamic models were applied by Sequeira et al. (2018) and was revealed that increasing temperature has not reduced economic growth for about last 50 years, in international level. It should be noted that special attention was paid on the global correlated effects between countries. Lastly, it was infered that lower income countries and countries with hot and temperate climate are in benefit of precipitation increaments. Nevertheless, a negative outcome from rises of temperature was showed for the first ones and from the increments of precipitation in the countries with colder climate.

One other study in the effects of climate on economic growth, focused mainly on precipitation, was done by Kotz et al. (2022). For this reason, 1,554 regions globally were analyzed for a period of 40 years. Specifically, the distribution of rainfall at several timeframes and their macroeconomic effects. From econometric aspect, panel regional and annually FE regressions were estimated. Eventually, that daily rainfall extremes produced from human activities have dentrimental negative impacts on worldwide economies. Therefore, the need for re-evaluate of the disadvantages of climate change is recognized.

In addition, numerous surveys on this field were concentrated in Africa and Sub-Saharan countries, employing panel Autoregressive Distributed Lags (ARDL) methods. For example, in work of Lanzafame (2012) analyzed the effect of temperature and precipitation on economic growth for Africa continent, using data from 1962 to 2000 for 36 African countries. It was observed low significance of precipitation on economic growth and vulnerability on weather changes. Hence, corrective measures are needed to be taken in these cases.

Later, a nonlinear impact of temperature on economic growth of Sub-Saharan countries was identified by Alagidede et al. (2016). In more detail, the relationship between GDP per capita and temperature could be described by a “Laffer curve” (curve with the shape of inverted latin letter U), where economic growth is increased for temperatures below 24.9 °C, but downturned for ones above that value.

Into the bargain of climate change discussion, effect of CO_2 emmisions is also a main determinant factor of economic growth. Although, the way of that influence is an object of dispute across scientific community. As a common part of all the researches is observed the requirement for environmentall policies by all economic members and in all sectors.

The impact of carbon emmisions on GDP was explored by Aslan et al. (2021), using panel quantile regression for 17 Mediterranean countries. Specifically, it was revealed that for low levels of economic growth could be escorted countries by low CO_2 pollution, accomplishing sustainability. However, this outcome was insignificant for higher levels of growth. Also, was noticed a two-way dependency between CO_2 emmisions and GDP.

Besides, the paper of Hongxing, et al. (2021) analyzed the interaction between economic growth, energy consumption, urbanization, trade, and CO_2 pollution in 81 Belt and Road Initiative (BRI) countries, for period 1990-2018. Particullary, with the use of Pooled Mean Group (PMG) estimations was found that contribution significance of all other magnitudes on economic growth are different across geographical regions. Additionally, from causality tests, CO_2 emissions was found as one of the variables responsible for the economic growth. In the end, it was recognized the need for fiscal policies from governments that motivate bussinesses and dwellers in “green” practices and for the use of renewable energy resources.

In the paper of Iqbal et al. (2022) the influence of CO_2 pollution, renewable energy and a group of economic variables on GDP, for BRICS countries from 2000 to 2018 was researched. More clearly, PMG, Mean Group (MG), FMOLS and DOLS were applied, depicting a positive long-run effect of the two environmentall variables on economic growth. Therefore, encourage for renewable energy sources consumption should be given in these countries.

The effect of a group of pollution and economic variables (including carbon emmissions) on economic growth, was analyzed by Yiew, et al. (2021) for G-20 countries, from 1995 to 2014. By the use of PMG and FMOLS estimations, was confirmed the positive influence of pollutions on economic growth, while CO2 pollution had the greatest impact on it. Eventually, the necessity of environmental policies for pollution diminution was declared, as essentiall act against climate change.

The work of Balsalobre-Lorente & Leitão (2020) examined the relationship between renewable energy, trade, CO_2 emissions and international tourism on economic growth for the panel of EU-28, from 1995 to 2014. In the econometric methods utilized were included FMOLS, DOLS and FE methods, showing a positive association among CO_2 pollution and economic growth. Finally, the requirement for more intense policies for achieving sustainability in EU is resulted.

Additionally, the nexus between renewable, non-renewable energy consumption, CO_2 pollution, and economic growth for 26 countries of EU, for period 1990-2018, was analyzed by Asiedu et al (2021). In this work were revealed a significant positive correlation among CO_2 emmissions and economic growth. A negative impact of these emmissions on economic growth was found from the use of FMOLS and DOLS models. Moreover, results of Granger causality tests that were implemented had been interpreted as inconsistent.

3. Data

The examined sample consists of 15 European countries, for period 1981 – 2019. So, this is a panel data sample with N = 15 cross-sections and T = 39 years (balanced panel data), in total 585 observations.

Specifically, as economic variable, per capita GDP was computed, by using real GDP per country and corresponding population, downloaded from *Penn World Table version 10.0*. Per capita GDP is considered as an index of economic productivity, for each country. In addition, as emissions data was employed CO_2 per capita emissions, on production basis, harvested from *Our World in Data* sector named *CO_2 and GHG Emissions*.

As climatic data, were used 2m temperature above the surface level and total precipitation, taken from the *ERA5-Land monthly averaged data from 1981 to present*, downloaded from *Copernicus climate change service* in 0.1 x 0.1 gridded resolution (about 11.1 km x 11.1 km area grid cells). This is a re-analysis data-set in which are contained modeled and real observations, offering accurate past climate data. Note that temperature converted from Kelvin to Celsius degrees by subtracting by 273.15 and precipitation from monthly average in m to total monthly precipitation in mm by multiplying by month's days x 1000.

These climatic variables were averaged in year level and then weighted by the population distribution of each country, as proposed by Dell et al. (2008). For gridded population was used data from the *Gridded Population of the World project*, versions *1*, *3* and *4*, provided by *Socioeconomic Data and Applications Center* (SEDAC) of NASA.

3.1. Data presentation

Annual average temperature maps for years 1985, 2000 and 2015 for 6 selected countries of this sample, covering the most of Europe's climate zones[1] are presented in Fig. 1 (Appendix B). In all of them, the temperature increase is rough, but differences from 1985 to 2000 are more violent than the ones from 2000 to 2015. Specifically, in Fig. 1.a temperature change is presented for 2 North European countries: United Kingdom -oceanic climate country- and for Sweden -sub-Arctic climate except from humid continental climate at the South. Here, the temperature increase is intense for Central and Southern England and London of United Kingdom. The same goes for Scandinavian Mountains and at

[1] For more about recent Köppen climate classifications see Beck et. al (2018).

the South of Sweden. Moreover, The Fig. 1.b depicts temperature maps for 2 countries of central Europe: France -mainly oceanic climate with Mediterranean at the South shore- and Germany -oceanic climate at the West and humid continental climate at the East. In these, it is clear that only Massif Central and North Pyrenees of France and German Alpes remain unchanged from temperature increase, although the other regions are struck by highly crescent temperatures. Especially, France's South shore is about 15 Celsius Degrees (°C) in 2015. Lastly, the Fig. 1.c presents 2 South European countries: Italy -mainly Mediterranean climate with humidly subtropical climate at the North- and Greece -mainly Mediterranean climate with steppe climate at the North-East. In this case, the already hot regions become hotter and Northern Italy and Greece is reached even 15 Celsius Degrees (°C) in 2015.

The Fig. 2.a (Appendix B) illustrates real GDP per capita (in log scale), respectively, of these 6 countries for the period for analysis. In all graphs a positive trend is observed. Additionally, the Fig. 2.b (Appendix B) displays the temperatures of the same countries (in log scale and weighted by population), for the whole sample period. In this variable are distinguished consecutive rises and falls, but with a slight positive trend. Subsequently, the Fig. 2.c (Appendix B) visualizes the corresponding graphs of precipitation (rainfall). In these, it is shown some symmetry in their progress, but it is also represented as more stable.

The Fig. 2.d depicts graphs of per capita CO_2 production (in log scale). Here, negative trend is all countries. However, Italy and Greece (which belong to the South Europe) have upward trend about until mid-00's and from then the per capita emission output is diminished too. The different process of these two countries was allowed by Kyoto Protocol, as they had low production and emission level (United Nations, 1998). But, when high levels of pollution were reached, then it was needed to be taken for more strict environmental measures too.

The Fig. 4 (Appendix B) drawn boxplots of the same data. Specifically, in most of them the mean (red dot) is very close to the median of the boxplot, indicating a possible normal distribution in them and no severe skewness is observed. Moreover, the number of outliers in the majority of the boxplots is very small or non-existing, underlining that the most of the observations are associated with the boxplot values. Additionally, in boxplots of real GDP per capita and per capita CO_2 (Fig.s 4.a and 4.d, respectively) is shown more variability, than the ones of temperature and precipitation (Fig.s 4.b and 4.c).

3.2. Descriptive Statistics

The Table 1 (Appendix A) presents the basic descriptive statistics of the data that were depicted in the 3.1 (all in logarithmic scale). Here, normal distribution is followed by the most variables for each country. Exceptions are the temperatures of France, Germany, Italy and Greece and precipitation of Greece and per capita CO_2 production of United Kingdom, where null hypothesis of normal distribution is rejected.

4. Framework and Models

4.1. Theoretical framework

For this study is utilized the Cobb-Douglas relationship that was implied in the paper of Lanzafame (2012), augmented by the effect of CO_2 emissions per capita on real GDP. Therefore:

$$\boldsymbol{Y_{it} = A_i\, Temperature_{it}^{a}\, Rainfall_{it}^{\beta}\, (CO_2E)_{it}^{\gamma}\, L_{it}\, e^{\varepsilon_{it}}} \quad \textbf{(1)},$$

Where real GDP is represented by Y, temperature by Temperature, precipitation by Rainfall, CO_2 emissions per capita by CO_2E, total population of country by L and A is technology level of each country (which is assumed as constant). So, for $\boldsymbol{y_{it} = Y_{it}/L_{it}}$, where y is real GDP per capita, relationship (1) could be transformed as:

$$\boldsymbol{y_{it} = A_i\, Temperature_{it}^{\alpha_i}\, Rainfall_{it}^{\beta_i}\, (CO_2E)_{it}^{\gamma_i}\, e^{\varepsilon_{it}}} \quad \textbf{(2)},$$

By transforming (2) in log form, the result is:

$$\boldsymbol{log(y_{it}) = log(A_i) + \alpha_i \, log(Temperature_{it}) + \beta_i \, log(Rainfall_{it}) + \gamma_i \, log(CO_2E_{it}) + \varepsilon_{it}} \quad \textbf{(3)},$$

And for reasons of abbreviation, (3) will be written as:

$$\boldsymbol{GDPPC_{it} = k_i + \alpha_i \, Temp_{it} + \beta_i \, Rain_{it} + \gamma_i \, CO2_{it} + \varepsilon_{it}} \quad \textbf{(4)},$$

With log(y) relabeled as GDPPC, log(A) as k, log(Temperature) as Temp, log(Rainfall) as Rain and CO_2E as CO2.

4.2. Exploratory of Cross-Dependence and Stationarity

First and foremost, Cross-Dependence is needed to be tested. So, because of the large dimensions of the sample, Cross-Dependence test of Pesaran (2004) is utilized. Then, for testing the stationarity of the data, both cross-independed and cross-depended unit roots are deployed. First, Levin et al. (2002) (or LLC), Im et al. (or IPS) and Fisher-type panel ADF and PP unit root tests (Maddala & Wu 2002; Choi 2001) are performed. No cross-dependency is assumed between the countries of each variable in these tests. Note that common unit root process is supposed in LLC test and an individual one is considered in the other three. Moreover, as optimal lag length for the test was set by Schwarz information criteria. Secondly, Cross-Section IPS (CIPS) of Pesaran (2007) unit root is used, so as to test for stationarity under the presence of dependency between countries. Here, ADF lag selection was decided via Akaike Information Criterion (AIC).

4.3. Panel Cointegration Tests

In order to acquire a comprehensive view of the examined data, Pedroni (1996) and Kao (1999) panel cointegration tests are conducted. Both of these two tests are based on Engle-Granger (1987) cointegration tests. Here, it should be underlined that Panel ARDL Models are equipped with their specialized cointegration tests.

4.4. Model specification

Due to the large dimensions of the panel data, (the number of periods is larger than number cross-sections) for the results of stationarity tests in the following section, the Pooled Mean Group/ARDL methods are preferred, according to Asteriou et al. (2020), who used these methods, with data with similar behavior. Moreover, other ARDL methods, like Mean Group and Dynamic Fixed Effects, are based on large N asymptotics and so inconsistent estimations could be produced by their use in a medium N sample like this. So, Pooled Mean Group method is supposed to be more consistent than the others, capturing also short-run heterogeneity and long-run homogeneity of the variables slopes and synthesizing both pooling and averaging (Pesaran et al. 1999; Favara 2003).

4.4.1. Panel ARDL Model

The panel Autoregressive Distributed Lags models are used in the absence of cointegration of other tests, I(1) depended variable and mixed stationarity -I(0) and I(1)- independed variables, as proposed by Pesaran et al. (1999). This dynamic model is based on the idea that the value of depended variable in each specific is affected by its previous values, the independed variables and their lags.

In the case of this study, it could be depicted by transforming (4) as:

$$\boldsymbol{GDPPC_{it} = k_i + \sum_{j=1}^{p} a_{ij} GDPPC_{i,t-j} + \sum_{j=0}^{q} b_{ij} Temp_{i,t-j} + \sum_{j=0}^{q} c_{ij} Rain_{i,t-j} + \sum_{j=0}^{q} d_{ij} CO2_{i,t-j} + \varepsilon_{it}} \quad \textbf{(5)},$$

Also, i = 1,...,15 indicates each of the 15 countries, p the number of GDPPC lags used and q the number of lags of independed variables. It should be noted that the optimum number of lags is selected using AIC.

For estimating the short-run coefficients, the Error Correction form of this model is conducted. In this case, the short-run model is the (5) estimated in first differences and augmented by the residuals of the (5):

$$\boldsymbol{\Delta GDPPC_{it} = k_i + \varphi_i\left(GDPPC_{i,t-j} - \theta_1 Temp_{i,t-j} - \theta_2 Rain_{i,t-j} - \theta_2 CO2_{i,t-j}\right) + \sum_{j}^{p-1} \lambda_{ij}\Delta GDPPC_{i,t-j} + \sum_{j}^{q} \lambda'_{ij}\Delta Temp_{i,t-j} + \sum_{j}^{q} \lambda''_{ij}\Delta Rain_{i,t-j} + \sum_{j}^{q} \lambda'''_{ij}\Delta CO2_{i,t-j} + \varepsilon_{it}} \quad \textbf{(6)}$$

Or, by expanding the parenthesis:

$$\boldsymbol{\Delta GDPPC_{it} = k_i + \varphi_i GDPPC_{i,t-j} - \gamma_i Temp_{i,t-j} - \gamma'_i Rain_{i,\ t-j} - \gamma''_i CO2_{i,\ t-j} + \sum_{j}^{p-1} \lambda_{ij}\Delta GDPPC_{i,t-j} + \sum_{j}^{q} \lambda'_{ij}\Delta Temp_{i,t-j} + \sum_{j}^{q} \lambda''_{ij}\Delta Rain_{i,t-j} + \sum_{j}^{q} \lambda'''_{ij}\Delta CO2_{i,t-j} + \varepsilon_{it}} \quad \textbf{(7)}$$

Where $\boldsymbol{\theta_1}$and $\boldsymbol{\theta_2}$ are estimations of (7) of the independed variables and $\boldsymbol{\gamma_i = \varphi_i * \theta_1}$ and $\boldsymbol{\gamma'_i = \varphi_i * \theta_2}$**.** Note that $\boldsymbol{\varphi_i}$ represents the speed of adjustment of short-run variables to the long-run relationship. Hence, a negative and statistically significant $\boldsymbol{\varphi_i}$ signals cointegration of the variables. But, in case that this coefficient is statistically insignificant, then there is no long-run cointegration in the model. Moreover, the long-run coefficients should be tested via Wald test whether their coexistence is statistically significant and so they indeed have a simultaneous impact on depended variable.

4.4.2. Panel ARDL Model Augmented with Common Correlated Effects

In ARDL model in (5), it is assumed cross-section independency of the variables. As a result, in the presence of cross-dependency, computing inconsistent and biased estimators. Hence, one solution of this problem was presented by Pesaran (2006), by using Common Correlated Effects procedure. According to this methodology, there are some unobserved factors that could be approximated by augmenting (5) with the cross-sectional averages of the depended and independed variables. Furthermore, the estimators produced from this model are correct even in the existence of autocorrelation in its residuals (Pesaran 2006). Unfortunately, none economic interpretation of these averages could be extracted.

Therefore, adding cross-sectional averages in (5) for each used variable there is:

$$\boldsymbol{GDPPC_{it} = k_i + \sum_{j=1}^{p} a_{ij} GDPPC_{i,t-j} + \sum_{j=0}^{q} b_{ij} Temp_{i,t-j} + \sum_{j=0}^{q} c_{ij} Rain_{i,t-j} + \sum_{j=0}^{q} d_{ij} CO2_{i,t-j} + \beta_i \sum_{j=0}^{p} \overline{GDPPC}_t + \beta'_i \sum_{j=0}^{q} \overline{Temp}_t + \beta''_i \sum_{j=0}^{q} \overline{Rain}_t + \beta'''_i \sum_{j=0}^{q} \overline{CO2}_t + \varepsilon_{it}} \quad \textbf{(8)}$$

4.4.3. Panel Nonlinear ARDL model

This model is based on the hypothesis that the result on the depended variable would be different from the increase and from the decrease of one independed variable, as it was proposed by Shin et al. (2014). In order to avoid multicollinearity problems, the increase and the decrease of the target-variable -here temperature- are expressed as:

$$\boldsymbol{Temp^{+}_{i,t}} = \sum_{j=1}^{t} \boldsymbol{\Delta Temp^{+}_{t}} = \sum_{j=1}^{t} \mathbf{max}(\boldsymbol{\Delta}\mathbf{Temp}_{\boldsymbol{t}}, \mathbf{0}) \quad \mathbf{(9)}$$

$$\boldsymbol{Temp^{-}_{i,t}} = \sum_{j=1}^{t} \boldsymbol{\Delta Temp^{-}_{t}} = \sum_{j=1}^{t} \boldsymbol{min}(\boldsymbol{\Delta}\mathbf{Temp}_{\boldsymbol{t}}, \mathbf{0}) \quad \mathbf{(10)}$$

Therefore, the model (5) is converted into:

$$\boldsymbol{GDPPC_{it}} = \boldsymbol{k_i} + \sum_{j=1}^{p} \boldsymbol{a_{ij} GDPPC_{i,t-j}} + + \sum_{j=0}^{q} \boldsymbol{b_{ij} Temp^{+}_{i,t-j}}$$
$$+ \sum_{j=0}^{q} \boldsymbol{b'_{ij} Temp^{-}_{i,t-j}} + \sum_{j=0}^{p} \boldsymbol{c_{ij} Precip_{i,t-j}} + \sum_{j=0}^{p} \boldsymbol{d_{ij} CO2_{i,t-j}} + \boldsymbol{\varepsilon_{it}} \quad \mathbf{(11)}$$

It should be underlined that Wald test must be performed in this case, both in the short and in the long horizon, in order to confirm the existence of asymmetry.

5. Results

5.1. Basic Tests

First issue needed to be examined are cross dependence between countries, for each variable. In Table 2 (Appendix A) strong evidence of statically cross-correlation for all variable is presented. This is a highly expected result, because of the geospatial and time aggregated nature of the data.

The outputs of both cross-independed and depended unit root tests are presented in Tables 3 and 4 (Appendix A), respectively. By the highest majority of them, it is agreed that GDP per capita and CO_2 emissions are stable in first differences, I(1), but temperature and rainfall are stationary at levels, I(0).

Continuing the analysis, no cointegration is showed by Pedroni and Kao cointegration tests in Table 5. Hopefully, it is not problematic, as long as special cointegration tests are available for panel ARDL methods.

5.2. Estimated models

In all cases there were estimated using two different groups of independed variables. In the first one, per capita GDP is affected only by temperature and rainfall. But, in the second one CO_2 effect is included too. Additionally, as first step in all estimations trend and intercept included. However, if trend was statistically insignificant, it was removed from the model. Thereafter, in case that intercept was statistically insignificant, it was abstracted from the model too. Additionally, Wooldridge autocorrelation test for the residuals is included for every model, as it was proposed by Wooldridge (2010). Moreover, lag selection performed by using AIC.

5.2.1. ARDL models

In Table 6 (Appendix A) the results of basic ARDL model without and with including CO_2 variable presented. In the long run and in both cases, GDP per capita is significantly and positively affected by an increase in temperature, but without CO_2 add the rainfall is insignificant and with it is acquired a significant positive effect. Additionally, the existence of long-run impact for these two models is verified by the Wald test. It should be noted that standard errors of the coefficients become lower when including CO_2 emissions, indicating more consistent coefficients when pollution is added. Moreover, both speeds of adjustment are significant, but their magnitude is higher when including CO_2 (22.3% versus 3.7%).

In the short-run, economic growth is positively influenced by its past values in both models. In addition, real GDP per capita is negatively affected by temperature when not adding CO_2 emissions, but this impact is not significant with the presence of CO_2 pollution. Reversely, influence of rainfall is insignificant, but when emissions included gets significant with positive impact on economic growth. Moreover, pollution is seemed to have positive effect on economic growth.

Besides, residuals are characterized by stationarity and Wooldridge no autocorrelation, pointing out no spurious results in both models. But, cross-dependence is statistically significant, showing that the results are awkward. Despite these issues, higher AIC is resulted when including CO_2.

5.2.2. ARDL-CCE Models

In Table 7 (Appendix A) the results of ARDL models when including Common Correlated Effects without and with adding CO2 variable are summarized. Specifically, in the long-run, rain has a significant increment effect on per capita GDP, but temperature is insignificant when abstracting CO_2 and has a significant negative effect on growth when adding the emissions' impact. Additionally, CO_2 seems to have a positive impact on economic growth. Note that the long-run impact of each of these groups of variables is significant. In addition, in both models cointegration is statistically significant, but its speed is higher in the one without CO_2 (14% against 7.5%).

In the short-run, economic growth seems to be promoted by its preview values, but when adding pollution's impact, a negative effect is appeared too. Also, a negative impact of temperature on real GDP per capita is observed when CO_2 emissions are omitted. Nevertheless, all other short-run influences in both models are statistically not significant.

At the same time, the errors produced from both models are corrected in their cross-correlation (as expected), are not time-correlated and they are stable. Besides these, higher AIC is returned putting in emissions' effect, than omitting it.

5.2.3. NARDL Models

The Table 8 (Appendix A) illustrates results of Nonlinear ARDL models. In the long-run, temperature decrease is statistically significant and has a negative impact on economic growth of the countries. But the temperature increment has a positive effect on GDP per capita only in the absence of CO_2; otherwise, this effect becomes insignificant. Additionally, a positive effect on economy is expected to come up when emissions' levels are increased. Furthermore, speed of adjustment is significant for both cases, although that it is faster when including emissions' effects (7.9% versus 21.8%). Moreover, the standard errors of coefficients are greater when excluding impact of emissions, showing that a more consistent model is resulted by its existence.

However, for both cases in the short-run, the hypothesis of symmetry cannot be rejected. Besides, temperature decrease is significant with a positive impact on economic growth. Although, when including emissions temperature's rise and fall and rainfall become insignificant, but emissions' variable is significant with positive effect on economic growth. In addition, the depended variable is positively associated with its previous values in the two models. However, when adding CO_2 emissions, a positive trend is resulted, but a negative one is occurred when it is omitted.

It should be highlighted that residuals of both models are outlined by cross-sectional dependency, stationarity and no autocorrelation. Although, AIC is greater when CO_2 pollution is included.

5.2.4. NARDL-CCE Models

The Table 9 (Appendix A) presents the outputs for Nonlinear ARDL models, applying Common Correlated Effects. In this specific occasion the results when including CO_2 emissions and excluding them are much different.

On one hand, without CO_2 variable and in the long-run, a temperature increase shock results in higher GDP per capita, but a decrease has a higher (in absolute values) negative impact on economic growth. It is needed to be highlighted that the existence of this asymmetry is supported by the corresponding Wald test. Furthermore, an increase in rainfall has negative effect on economic growth. Moreover, a significant speed of adjustment is indicated by the cointegration term and is equal to 5.6% Also, the past lags of economic growth have a positive impact on GDP per capita. In the short-run and without adding CO_2 emission effect, both rise and fall of the temperature are statistically significant and show a negative impact on economic growth, but symmetric (according to Wald test).

On the other hand, if CO_2 emissions are included, they have positive association with economic growth, which is significant in the long-run but insignificant in the short-run. Besides, a significant and positive effect of rainfall on depended variable is observed both in the short and the long run. Temperature increase has positive and significant effect on economic growth, but its fall is insignificant. Adjustment term is statistically insignificant and so no cointegration is accomplished and the null of asymmetry for short and long run is rejected.

Lastly, it should be underlined that errors produced from both models are neither cross nor time correlated and they are stable. Despite these, AIC is higher on model without CO_2.

6. Conclusion

The Fig. 4 (Appendix B) illustrates the econometric methodology that was followed in this work. First, in this large dimension panel dataset the cross-dependency for all variables was tested. Then, because cross-correlation existed, the rational was to test 2^{nd} Generation Unit Root tests for stability testing, revealing a depended variable stable in first differences and all the independed variables at levels and first differences. So, nonlinear/asymmetric ARDL method was attempted. By performing Wald tests, a long-run asymmetry found, accepting nonlinearity. All other models were showed for the sake of completeness.

The Table 10 (Appendix A) depicts the summary of models presented, with their AIC sorted in increasing order. According to this, the Nonlinear ARDL model which counts for CCE seems to have the best adjustment from all other models. It should be noted that all the models with CCE included are higher in classification, probably because of the correction of cross-dependency in the errors.

This work is deduced that economic growth is increased by temperature rise, but decreased by a temperature fall with more impact in growth (in absolute terms). Therefore, past works about the existence of a nonlinear relationship between economic growth and temperature (Burke, et al., 2015; Alagidede, et al., 2016) are certified. Nevertheless, in the short-run, a symmetric negative impact of temperature on economic growth was observed, with only temperature fall is significant and beneficial. Moreover, lower real GDP per capita is resulted by a rainfall increasement, which is reasonable, as long as this magnitude is weighted by population and therefore extreme rainfall could be responsible for natural disasters in towns. This negative association is also depicted in some of the most recent literature views (Kotz, et al., 2022).

Every time that CO_2 emissions were included, a positive relationship with economic growth, occured in harmony with previous literature (Balsalobre-Lorente & Leitão 2020; Yiew, et al. 2021; Hongxing, et al. 2021; Iqbal et al. 2022). However, a concern is that temperature and rainfall decrease turn into insignificant when pollution is joined in the model and that lower AIC.

Based on the aforementioned, it is an indisputable fact that actions of acquiring a more environmentally "friendly" policy should always be one of the prime goals of European Union, despite the great steps that have been made since its establishment. That, not only because a more stable climate is needed inside EU borders (Fagerberg et al. 2016), but also climate change caused from developed countries encloses a "moral hazard", damaging the undeveloped ones (Tietenberg & Lewis 2012). In conclusion, a more stable climate is preferred, because the position of poor countries gets even worse when global temperature is increased (Dell et al. 2008; Lanzafame 2012; Sequeira et al. 2018) and the short-run situation of EU itself.

In the selected NARDL-CCE model, 3 lags for the climate variables as regressors were chosen by AIC (Table 9, Appendix A). From this, it could be extracted that every time economic growth is directly influenced by climate information of the past 3 years. Consequently, every time environmental policy applied, should be consistent at least for 3 years, so the results of this policy can be observable. Although, due to the distributed lags nature of the model, it would certainly take even more years of consequent "green policies" to create a sustainable economic growth in EU.

Appendix A

Significant in *=1%, **=5%, *=10% level**

Real GDP per capita (log scale)	UK	Sweden	France	Germany	Italy	Greece
Mean	10.453	10.573	10.489	10.600	10.533	10.135
Median	10.525	10.597	10.552	10.643	10.573	10.157
Maximum	10.707	10.878	10.693	10.852	10.684	10.438
Minimum	10.020	10.240	10.203	10.267	10.251	9.930
Std. Dev.	0.213	0.203	0.153	0.178	0.130	0.155
Skewness	-0.551	-0.034	-0.498	-0.412	-0.937	0.422
Kurtosis	1.983	1.552	1.873	2.080	2.711	2.030
Jarque-Bera	3.653	3.413	3.671	2.479	5.848*	2.685

(a)

Temperature (log scale)	UK	Sweden	France	Germany	Italy	Greece
Mean	2.272	1.882	2.440	2.243	2.624	2.750
Median	2.277	1.915	2.442	2.261	2.633	2.747
Maximum	2.439	2.141	2.588	2.416	2.796	2.928
Minimum	2.129	1.412	2.310	2.050	2.477	2.559
Std. Dev.	0.069	0.171	0.066	0.094	0.055	0.057
Skewness	-0.257	-1.083	-0.108	-0.360	0.151	-0.202
Kurtosis	2.690	3.726	2.554	2.449	4.894	6.403
Jarque-Bera	2.272	1.882	2.440*	2.243*	2.624*	2.750*

(b)

Precipitation (log scale)	UK	Sweden	France	Germany	Italy	Greece
Mean	4.275	4.130	4.302	4.312	4.412	3.953
Median	4.281	4.150	4.321	4.304	4.410	3.940
Maximum	4.538	4.376	4.521	4.535	4.746	4.183
Minimum	3.989	3.794	4.068	4.001	4.215	3.523
Std. Dev.	0.123	0.120	0.124	0.129	0.134	0.150
Skewness	-0.324	-0.654	-0.217	-0.434	0.520	-0.900
Kurtosis	2.977	3.626	1.852	3.063	2.574	3.790
Jarque-Bera	0.684	3.420	2.449	1.231	2.054	6.278*

(c)

Per Capita CO_2 (log scale)	UK	Sweden	France	Germany	Italy	Greece
Mean	2.173	1.792	1.888	2.420	1.968	2.054
Median	2.262	1.847	1.939	2.403	1.989	2.094

Maximum	2.363	2.120	2.131	2.600	2.154	2.333
Minimum	1.701	1.432	1.604	2.129	1.717	1.640
Std. Dev.	0.190	0.183	0.132	0.125	0.134	0.199
Skewness	-1.293	-0.643	-0.701	-0.143	-0.290	-0.490
Kurtosis	3.330	2.359	2.632	2.195	1.803	2.177
Jarque-Bera	11.042***	3.355	3.412	1.186	2.878	2.659

(d)

Table 1: Descriptive statistics for 6 selected countries

Variable	**CD-TEST**
GDPPC	60.764***
Temp	46.274***
Rain	14.440***
CO2	31.312***

Table 2: CD tests

Levels	**Constant**	**Constant & Trend**	**Constant**	**Constant & Trend**	**Constant**	**Constant & Trend**	**Constant**	**Constant & Trend**
Test\Variable	**LLC**		**IPS**		**FISHER-ADF**		**FISHER-PP**	
GDPPC	-6.322***	-0.798	-1.483	2.041	38.939	14.977	45.874**	6.386
Temp	-14.468***	-17.315***	-10.458***	-13.056***	160.889***	194.443***	157.828***	206.909***
Rain	-22.014***	-20.197***	-20.521***	-19.025***	356.594***	306.379***	412.381***	685.827***
CO2	2.307	2.485	3.573	5.130	14.331	7.033	16.729	7.991
1st Differences								
GDPPC	-9.545***	-8.728***	-9.930***	-8.841***	154.191***	128.846***	153.544***	178.485***
Temp	-	-	-	-	-	-	-	-
Rain	-	-	-	-	-	-	-	-
CO2	-19.029***	-19.568***	-19.082***	-20.231***	319.037***	372.347***	333.368***	879.612***

Table 3: Unit root tests (cross-indipendency assumed)

Levels	Constant	Constant & Trend
Test\Variable	**CIPS**	
GDPPC	-2.129	-2.113
Temp	-4.187***	-4.309***
Rain	-5.187***	-4.803***
CO2	-1.898	-2.253
1st Differences		
GDPPC	-2.977***	-3.193***
Temp	-	-
Rain	-	-
CO2	-4.008***	-3.422***

Table 4: Unit root tests (cross-dependency assumed)

	Intercept		Trend & Intercept	
	t-statistic	**(Weighted)**	**t-statistic**	**(Weighted)**
Panel v-Statistic	-3.555	-3.315	11.436***	11.553***
Panel rho-Statistic	3.306	2.038	2.487	2.318
Panel PP-Statistic	3.474	1.327	1.654	1.214
Panel ADF-Statistic	3.358	1.210	2.122	1.536
Group rho-Statistic	3.696		3.194	
Group PP-Statistic	3.176		1.723	
Group ADF-Statistic	3.012		1.493	
Kao	-0.832			

Table 5: Cointegration tests

		ARDL	ARDL (CO2)
Long – Run	Temp	1.547*** (0.271)	0.131*** (0.049)
	Rain	0.098 (0.166)	0.099*** (0.028)
	CO2	-	0.377*** (0.020)
Short – Run	Cointegration Term	-0.037*** (0.006)	-0.223*** (0.021)
	Δ(GDPPC(-1))	0.348*** (0.048)	0.372*** (0.043)
	Δ(Temp)	-0.023* (0.012)	0.001 (0.012)
	Δ(Rain)	-0.002 (0.003)	-0.010** (0.005)
	Δ(CO2)	-	0.132*** (0.041)
	Constant	0.237*** (0.036)	1.933*** (0.183)

	Trend	-	0.004*** (0.000)
	Number of observations	555	555
	AIC	-4.681	-4.883
	Wald test	16.872***	122.653***
	CD-test	31.673***	24.364***
	WD-AR(1)	1.072	0.673
	Residuals	I(0)	I(0)

Table 6 *ARDL models with and without including impact of CO2 (standard errors in parentheses)*

		ARDL - CCE	**ARDL (CO2) – CCE**
Long – Run	Temp	0.000 (0.050)	-0.370*** (0.040)
	Rain	0.194*** (0.038)	0.196*** (0.039)
	CO2	-	0.061* (0.034)
Short – Run	Cointegration Term	-0.140** (0.060)	-0.075*** (0.026)
	Δ(GDPPC(-1))	0.647*** (0.077)	0.682*** (0.098)
	Δ(GDPPC(-2))	-0.133 (0.086)	-0.206** (0.080)
	Δ(GDPPC(-3))	0.162** (0.080)	0.032 (0.061)
	Δ(Temp)	0.022** (0.038)	0.004 (0.033)
	Δ(Temp (-1))	0.016 (0.039)	0.035 (0.031)
	Δ(Temp (-2))	0.015 (0.032)	0.034 (0.026)
	Δ(Temp (-3))	-0.035** (0.014)	-
	Δ(Rain)	-0.002 (0.018)	-0.002 (0.013)
	Δ(Rain(-1))	-0.005 (0.008)	0.008 (0.010)
	Δ(Rain(-2))	-0.017 (0.014)	-0.007 (0.006)
	Δ(Rain(-3))	-0.019 (0.013)	-
	Δ(CO2)	-	-0.011 (0.029)
	Δ(CO2(-1))	-	0.064 (0.042)
	Δ(CO2(-2))	-	0.001 (0.039)
	Constant	-0.061** (0.027)	–
	Number of observations	525	525

	AIC	-5.524	-5.478
	Wald test	13.220***	1038.517***
	CD-test	0.445***	-0.332***
	WD-AR(1)	1.184	0.312
	Residuals	I(0)	I(0)

Table 7 *ARDL-CCE models with and without including impact of CO2 (standard errors in parentheses)*

		NARDL	**NARDL (CO2)**
Long – Run	$Temp^{+}$	1.730*** (0.315)	0.197 (0.058)
	$Temp^{-}$	0.614* (0.317)	0.131** (0.065)
	Rain	0.009 (0.082)	0.083*** (0.028)
	CO2	-	0.366*** (0.023)
Short – Run	Cointegration Term	-0.079*** (0.016)	-0.218*** (0.023)
	Δ(GDPPC(-1))	0.343*** (0.048)	0.376*** (0.043)
	$\Delta(Temp^{+})$	-0.038 (0.024)	0.016 (0.020)
	$\Delta(Temp^{-})$	-0.059** (0.025)	-0.017 (0.028)
	Δ(Rain)	0.003 (0.004)	-0.006 (0.005)
	Δ(CO2)	-	0.129*** (0.042)
	Constant	0.800*** (0.157)	1.975*** (0.207)
	Trend	-0.001*** (0.000)	0.003*** (0.000)
	Number of observations	555	555
	AIC	-4.820	-5.005
	Wald test Short-Run	0.316	0.636
	Wald test Long-Run	18.147***	1.333
	CD-test	29.980***	23.720***
	WD-AR(1)	0.770	0.428
	Residuals	I(0)	I(0)

Table 8 *NARDL models with and without including impact of CO2 (standard errors in parentheses)*

		NARDL - CCE	NARDL (CO2) - CCE
Long – Run	$Temp^{+}$	1.435*** (0.159)	0.215* (0.126)
	$Temp^{-}$	1.818*** (0.195)	-0.098 (0.147)
	Rain	-0.448*** (0.064)	0.088* (0.047)
	CO2	-	0.604*** (0.049)
Short – Run	Cointegration Term	-0.056** (0.028)	-0.030 (0.020)
	Δ(GDPPC(-1))	0.435*** (0.091)	0.382*** (0.063)
	Δ(GDPPC(-2))	-0.042 (0.075)	-0.091** (0.042)
	Δ(GDPPC(-3))	0.030 (0.040)	0.027 (0.040)
	$\Delta(Temp^{+})$	-0.115* (0.063)	-0.006 (0.022)
	$\Delta(Temp^{+}(-1))$	-0.075 (0.056)	0.010 (0.032)
	$\Delta(Temp^{+}(-2))$	0.067 (0.069)	-
	$\Delta(Temp^{-})$	-0.160* (0.093)	0.010 (0.035)
	$\Delta(Temp^{-}(-1))$	-0.026 (0.064)	-0.036 (0.031)
	$\Delta(Temp^{-}(-2))$	-0.023 (0.041)	-
	Δ(Rain)	0.031*** (0.011)	0.015* (0.008)
	Δ(Rain(-1))	0.018 (0.009)	0.012* (0.007)
	Δ(Rain(-2))	0.002 (0.008)	-
	Δ(CO2)	-	0.036 (0.032)
	Δ(CO2(-1))	-	0.045 (0.033)
	AIC	-5.991	-5.603
	Trend	0.001*	
	Number of observations	525	525
	Wald test Short-Run	0.040	0.836
	Wald test Long-Run	10.222***	84.721***
	CD-test	-0.359	0.744
	WD-AR(1)	-0.600	1.019
	Residuals	I(0)	I(0)

Table 9 *NARDL-CCE models with and without including impact of CO2 (standard errors in parentheses)*

Rank	Model	AIC
1st	NARDL-CCE	-5.991
2nd	NARDL(CO2)-CCE	-5.603
3rd	ARDL-CCE	-5.524
4th	ARDL(CO2)-CCE	-5.478
5th	NARDL(CO2)	-5.005
6th	ARDL(CO2)	-4.883
7th	NARDL	-4.820
8th	ARDL	-4.681

Table 10: AIC model selection

Appendix B

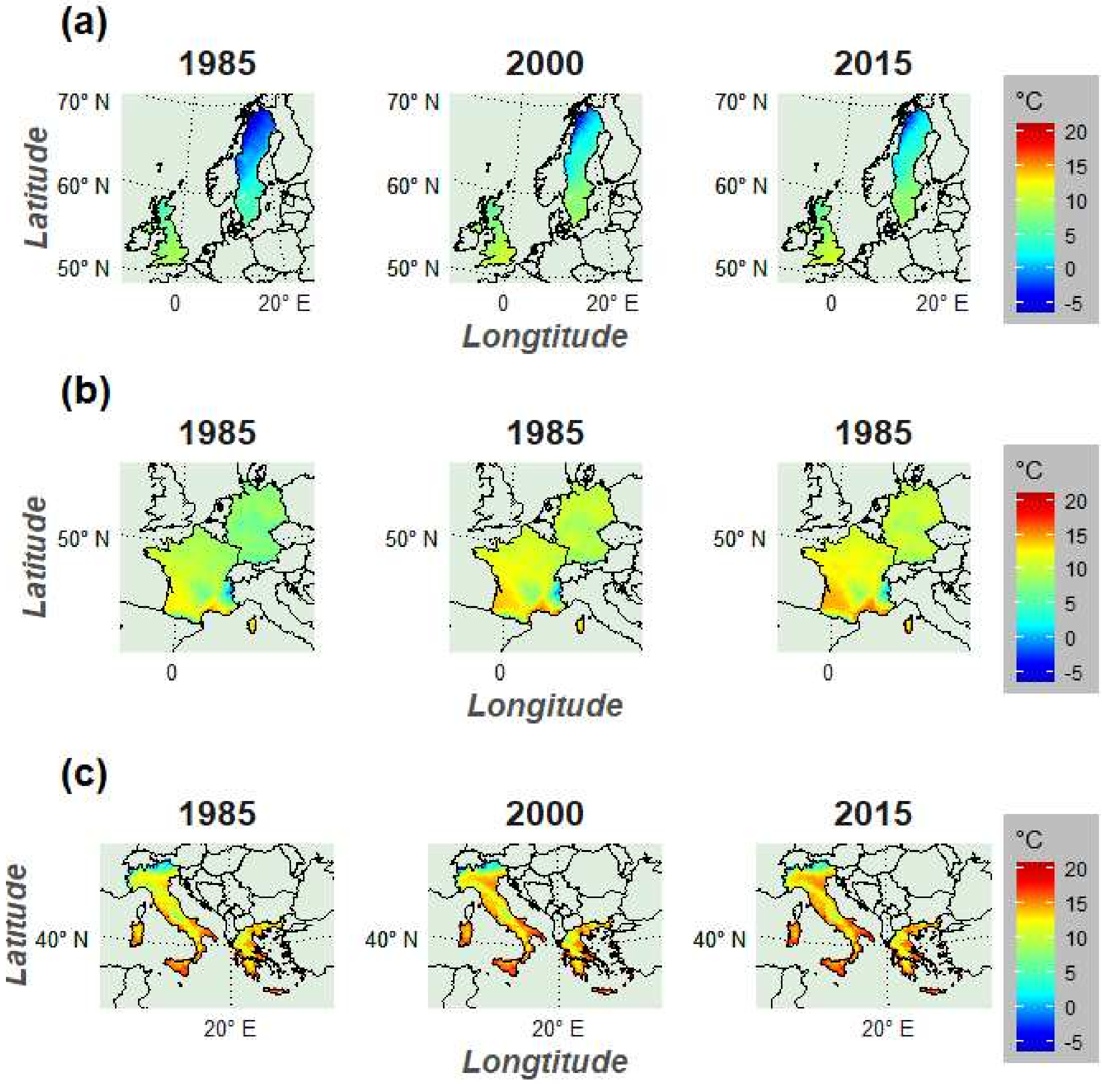

***Fig. 1** Temperature maps of 1985, 2000 and 2015, for **(a)** UK and Sweden, **(b)** France and Germany and **(c)** Italy and Greece*

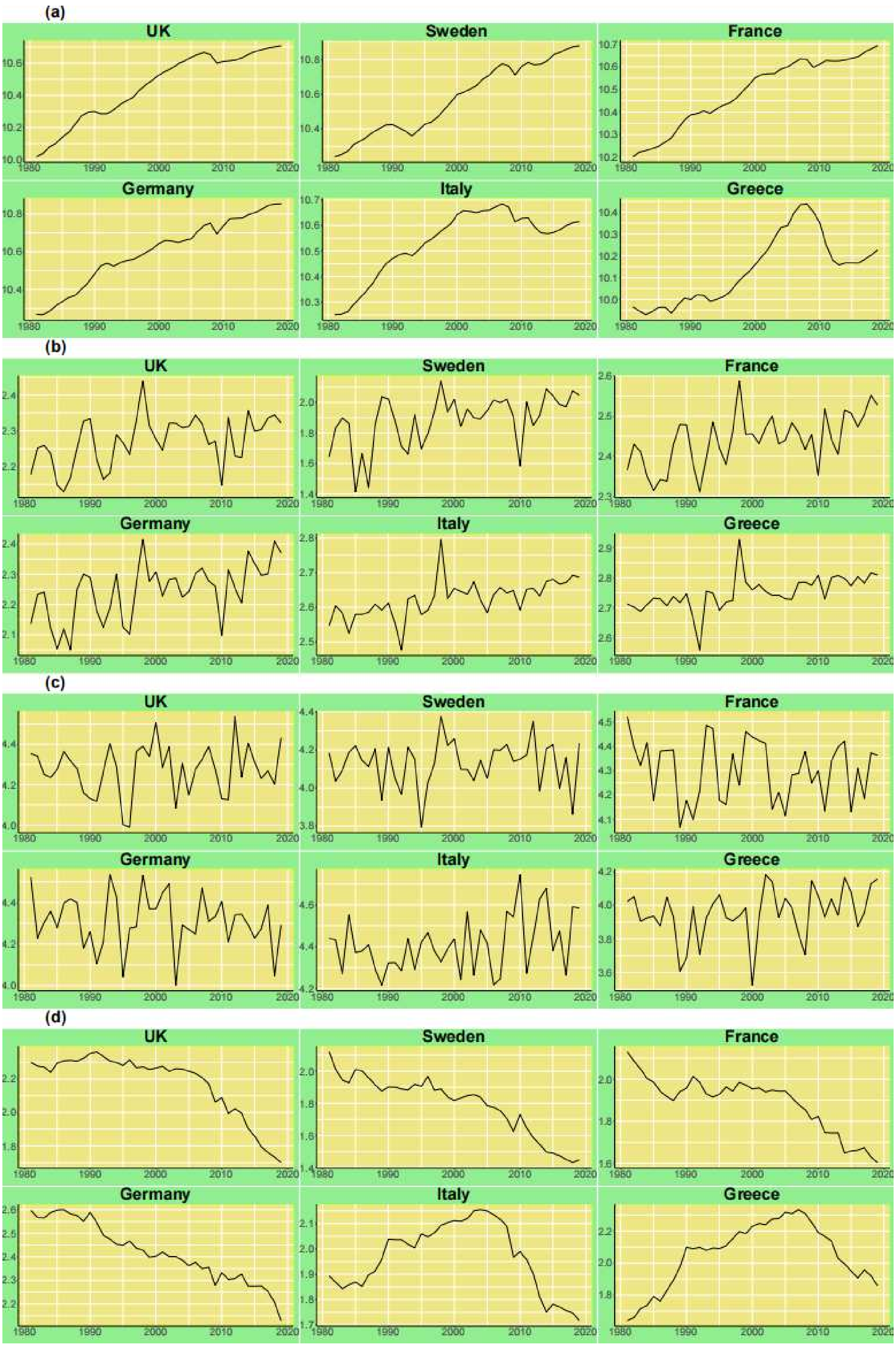

Fig. 2 Line graphs of **(a)** GDP per capita (in log scale), **(b)** temperature (in log scale and weighted by population), **(c)** rainfall (in log scale and weighted by population) and **(d)** CO_2 emissions per capita (in log scale) , for 6 selected countries

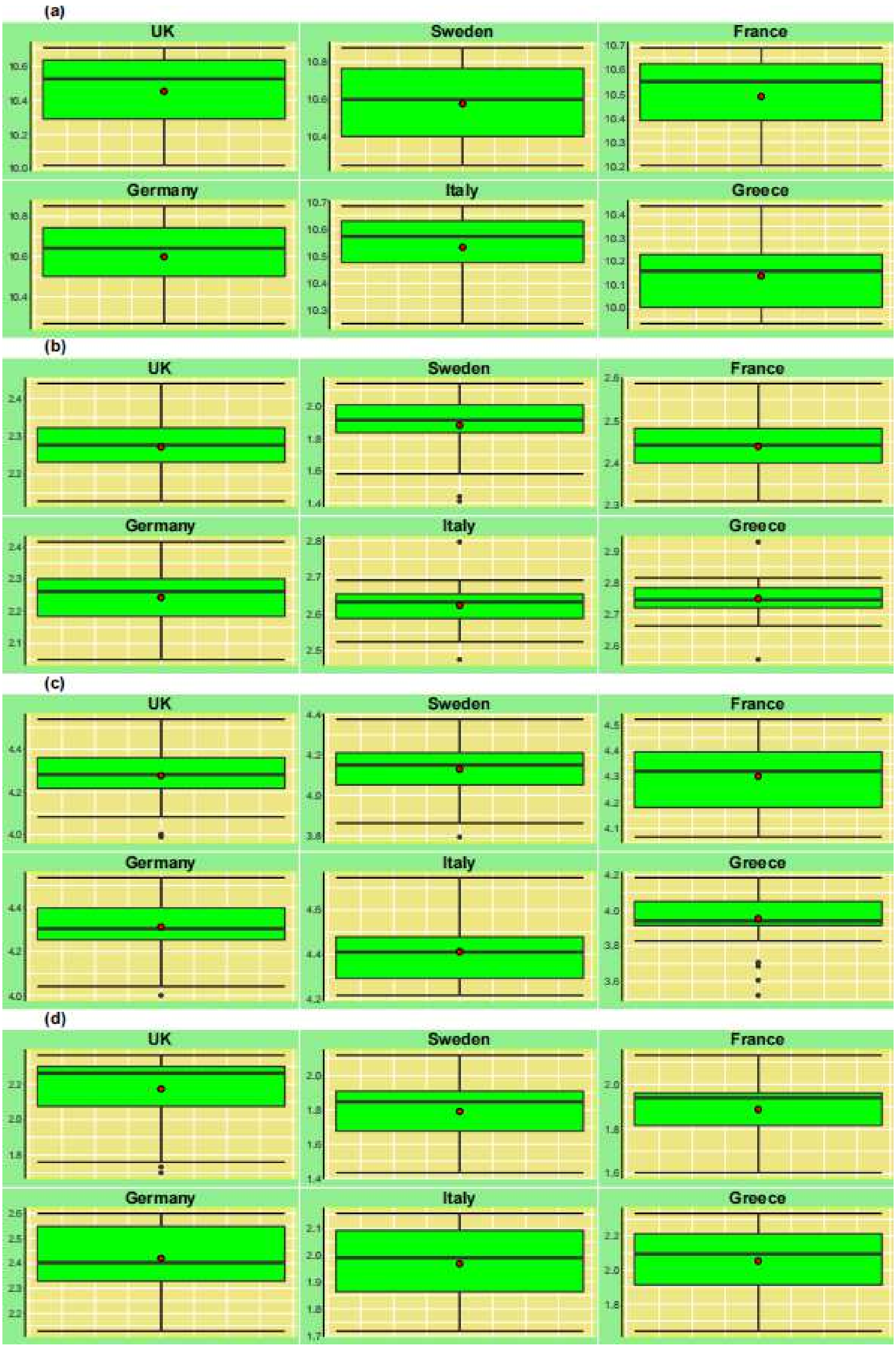

Fig. 3 Boxplots *of **(a)** GDP per capita (in log scale), **(b)** temperature (in log scale and weighted by population), **(c)** rainfall (in log scale and weighted by population) and **(d)** CO_2 emissions per capita (in log scale), for 6 selected countries*

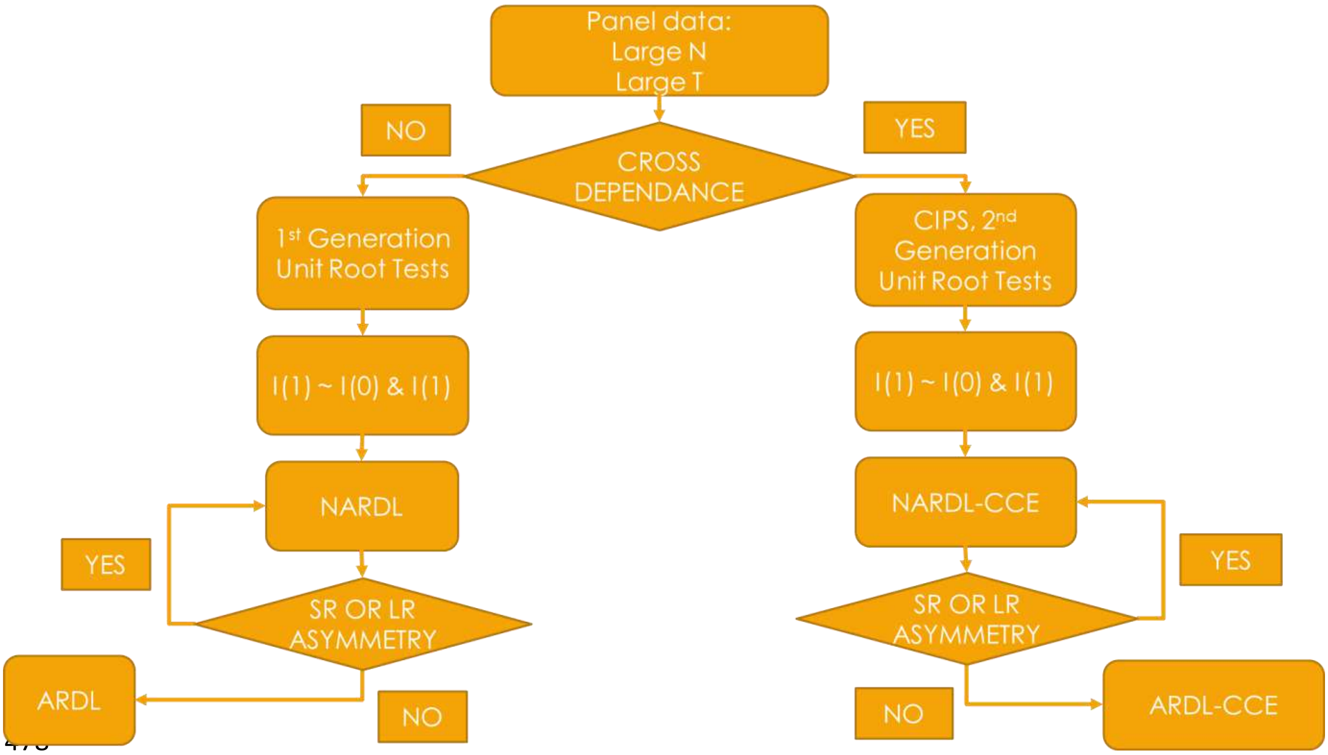

Fig. 4 *Econometric methodology framework*

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Ethical Approval

Not applicable

Consent to Participate

Not applicable

Consent to Publish

Not applicable

Availability of data and materials

Data, coding, command line text and graphs are available upon request