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Convergence in total greenhouse gas emissions worldwide

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Abstract

This paper examines convergence patterns in total greenhouse gas emissions across 114 countries from 1990 to 2019. Prior research has largely focused on one representative greenhouse gas, carbon dioxide emissions, but our goal is to broaden the study. We use the club convergence test to contrast the null hypothesis of convergence for a pool of data and identify subgroups of convergence. The results reveal different clubs according to the air pollutant considered, indicating the importance of considering a range of air pollutants in convergence analyses. We also explore the main determinants of the observed convergence patterns and estimate various ordinal models. We find that income level, urbanization, natural resources dependency, renewables energy consumption, trade openness, and corruption level all contribute to explain these different patterns. Our determinant analyses especially note the importance of institutional quality. The results are important in reformulating current environmental policies, which are mostly based on the hypothesis of overall convergence, according to the different convergence clubs detected.

Keywords: greenhouse gas emissions, convergence, global analysis, environmental policy, institutions.

JEL Classification: C23, O47, O50, Q53

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1. Introduction

Greenhouse gas emissions are a current threat to sustainable development around the world. As a result, several international agreements have been signed, and policymakers, from both developed and emerging countries are committed to stabilizing greenhouse gas emissions in the current context of climate change. Numerous meetings and conferences have been organized to establish world environmental commitments and mediate global warming. These goals are based on particular assumptions regarding greenhouse gas dynamics and their patterns of behavior. Consequently, testing whether disparities across countries in greenhouse gas emissions have decreased are questions with significant policy implications for international deals.

To better understand the effectiveness of these international commitments, several studies have examined the spatial dynamics of greenhouse gas emissions and, particularly, their convergence behavior. Most climate change models are based on the convergence hypothesis, as well as long-run predictions of emissions made by the International Panel on Climate Change (IPCC). However, the absence of full convergence implies that emission allocation strategies may lead to transfers of resources and relocation of economic activities among countries. If we can identify full convergence among a group of countries in emissions, this would imply that all countries are following the same convergence path in the long-run and current policies are suitable. The presence of divergence would mean that mitigation policies must be modified and should be followed among countries with similar convergence paths, to result in similar outcomes. The importance of emissions convergence has generated a substantial literature during the last decade. Nevertheless, most studies have focused solely on carbon dioxide emissions, a key greenhouse gas from human activities, but only limited attention has been paid to the convergence of total greenhouse gas emissions (Payne et al., 2022).

We contribute to this on-going debate by analyzing greenhouse gas emissions convergence and taking a global perspective. Specifically, the objective of this study is to examine the convergence behavior of greenhouse gas emissions intensity and its potential determinants. In principle, absolute convergence occurs when countries with high initial levels of emissions have a lower emissions growth rate than countries with low initial levels of emissions, reaching a unique steady state in the long-run. Nevertheless, this is a restrictive assumption. In this work we will test for convergence using a methodology that allows us to examine both overall and conditional convergence.

We use the club convergence methodology developed in Phillips and Sul (2007, 2009) because it has well-known advantages over alternative tests, such as cross-sectional or time series approaches. First, this methodology was expressly designed to analyze convergence, and contrasts the null hypothesis of overall convergence, whereas the alternative hypothesis can accommodate to both divergence and club convergence. Convergence clubs are groups of countries that share similar patterns of convergence and are identified by a data-driven algorithm, even if there is no full convergence for the entire sample, grouping regions by unspecified factors. Hence, this approach is more informative than traditional convergence tests, such as stochastic convergence or the traditional cross-sectional approaches of beta- and sigma-convergence, all of which assume a unique equilibrium in the long-run (i.e., a homogeneous type of convergence). Second, this test is independent of stationarity or stochastic properties of the variables under analysis. Finally, the pace of convergence can also be estimated.

Our findings suggest an absence of overall convergence for all greenhouse gas emissions indicators considered, except for carbon dioxide emissions intensity, although the number of clubs differ depending on the pollutant. For the aggregate greenhouse gas emissions, we identify five convergence clubs, whereas for the disaggregation by gas we obtain two convergence clubs in methane emissions and up to four convergence clubs in nitrous oxide emissions. For the determinant analyses, we find that income levels, urban population, natural resources rents, renewable energy consumption, globalization, and corruption are significant predictors of club membership.

The main contributions of this paper are then threefold. First, we study convergence in greenhouse gas emissions, taking a worldwide perspective. The convergence of total greenhouse gas emissions has received very limited attention in the literature, and we investigate the convergence of greenhouse gas emissions in 114 countries, for the first time in the literature, providing new information on a series largely overlooked. From our point of view, this limited literature on greenhouse gas emissions convergence is surprising, as the most important international frameworks on climate change, the Kyoto Protocol and the Paris Climate Agreement, focus on greenhouse gas emissions. Most studies have focused on a single environmental indicator, carbon dioxide emissions traditionally, which represents pollution rather weakly. This is justified by the fact that carbon dioxide is the most representative air pollutant, as it accounts for the largest proportion of greenhouse gas emissions, around 65%. Nevertheless, there are many other

pollutants responsible for climate change and global warming, and we consider it important to adopt a more precise strategy.

Second, the choice of this environmental pressure proxy is directly related to policy implications, and so we pay attention to three distinct air pollutants and components of aggregate greenhouse gas emissions: carbon dioxide, methane, and nitrous oxide emissions, as it is not rational to take only one environmental indicator. This may help planners with useful information in adopting suitable mitigation policies, since overall conclusions could differ, depending on the air pollutant indicator considered.

Third, we offer a detailed view of the convergence process of greenhouse gas emissions around the world, and identify certain characteristics related to club membership, for each gas. To do this, we perform several ordinal models to explore the determinants of the clubs established by the algorithm, taking several factors explicitly into account in the same work. Prior research has omitted this stage (Payne, 2020), leaving it aside for future research, and we think that this generates a very rich framework to suggest different policies aiming at achieving overall convergence in the long run, and improving the current design of environmental policies. All these contributions, along with our global perspective, make our results of general interest for current debates.

The rest of the paper is organized as follows. Section 2 surveys convergence approaches proposed in the literature, together with a review of empirical studies of emissions convergence. Section 3 presents the econometric methodology and the data. Section 4 discusses the main empirical results. Finally, Section 5 concludes.

2. Background

2.1. Convergence approaches

The concept of convergence dates to Solow (1956), who focuses on economic growth dynamics. There are several approaches to testing for convergence from a methodological point of view, which can roughly be divided into four different convergence concepts: beta-convergence, sigma-convergence, stochastic convergence, and club convergence. The notion of beta-convergence dates back to Baumol (1986) and Barro and Sala-i-Martin (1992), and tests whether there is a negative and statistically significant relationship between initial output level and its growth rate. In their original work, Barro and Sala-i-Martin (1992) regress the average growth rate on initial income levels across 48 US states

and find that the whole sample converged. Translated to emissions convergence, beta-convergence would occur when the emissions of those countries with lower initial emissions per-capita levels grow faster than the ones with greater emissions per-capita levels, catching-up with the more polluting countries in the long run.

Additionally, it is important to note that the beta-convergence concept is divided into absolute beta-convergence and conditional beta-convergence, according to whether it depends, or not, on different initial and structural conditions. At this point, conditional convergence assumes different steady states among countries, and can be tested by adding several exogenous variables into the beta-convergence regression. This would imply the existence of multiple steady-state levels according to certain structural characteristics (e.g., government policies, population growth, technology, etc.), which is similar to the club convergence or multiple equilibria notion.

Sigma-convergence, on the other hand, refers to the variability of the variable of interest and can be tested through a dispersion measure, such as the cross-sectional standard deviation or the coefficient of variation (i.e., the ratio of standard deviation to the mean). It exists when there is a negative trend in the dispersion measure of the variable of interest over time. Although the concepts of beta- and sigma-convergence are not identical, it can be demonstrated that these two convergence concepts are similar, since beta-convergence is a necessary but not a sufficient condition for obtaining sigma-convergence. These two standard concepts are based ultimately on cross-sectional techniques and have been exploited in many prior studies, although there are certain underlying concerns (Quah, 1993; Bernard and Durlauf, 1996).

Alternatively, the work of Carlino and Mills (1993) and Bernard and Durlauf (1995, 1996) propose the concept of stochastic convergence, which consists of analysing the time series properties of the data. For example, income stochastic convergence requires that shocks to income relative to the mean are temporary. The existence of a unit root in income relative to the mean implies that this time series is not stationary and shocks have permanent effects, invalidating stochastic convergence. For emissions convergence, the implication is that any shock to emissions per-capita for a given country, relative to the panel average (or to another reference country such as the US) is temporary. Then, a rejection of the null hypothesis of unit root provides evidence of emissions stochastic convergence. However, this theoretical framework is not free from criticism. One drawback of this approach is the well-known structural break problem, as conventional

unit root tests that omit structural breaks in series, such as the Augment Dickey-Fuller test (ADF) or Phillips and Perron (PP) unit root test, lead to a bias against the rejection of a false unit root hypothesis (Perron, 1989). Consequently, practitioners should be aware of this fact in empirical research and use unit root tests that account for structural breaks for accurate predictions. Furthermore, stochastic convergence relies on the selection of reference samples, a too-subjective decision that affects conclusions in general, and particularly in heavily heterogeneous data. On the other, the unit root statistic ultimately tests the null hypothesis of at least unit root, and researchers assume that rejecting this hypothesis is associated with a convergence process, although these hypotheses are not exactly the same.

Finally, the concept of club convergence dates back to Durlauf and Johnson (1995) and Galor (1996). Club convergence refers to the existence of multiple state equilibriums, which depend on initial conditions. Hence, certain groups or countries could be converging, and diverging from each other at the same time. Recently, this notion has received a significant impulse in the convergence literature, due to the development of the Phillips and Sul (2007, 2009) club convergence test, which allows for the identification of convergence clubs by leaving factors unspecified. Initially, Phillips and Sul (2007) use their club convergence test to analyze for convergence in cost-of-living indices among 19 US metropolitan cities, from 1918 to 2002, but now this methodology has been extended to study convergence on other variables.

2.2. Literature on greenhouse gas emissions convergence

Initially, income convergence was tested within the neoclassical growth framework, although the convergence field has attracted considerable research attention among economists, and has been extended to other variables, such as emissions, health, energy, inequality, commodity prices, military expenditures, tourism, labor force participation rates, labor productivity, divorce rates, tax revenues, happiness, COVID-19 infection rates, debt rates, the shadow economy, economic freedom... among others. Hence, the emissions convergence literature is inspired by the economic convergence literature and uses similar methodologies. This literature has grown exponentially in the last decade, and has focused on a variety of air pollutant indicators, time periods, and territories, both at the country and the regional level (i.e., states, regions, provinces). Broadly speaking, we can divide the literature on emissions convergence into two large groups, based on

two predominant pollutant indicators: carbon dioxide emissions (CO₂) and ecological footprint.

For the first group of studies, we can initially refer to Strazicich and List (2003) who study CO₂ emissions convergence for 21 industrialized countries between 1960 and 1997 and obtain evidence of convergence. Later, Aldy (2006) studies the convergence of CO₂ emissions between 1960 and 2000 for 23 OECD countries, but does not obtain evidence of emissions convergence. Westerlund and Basher (2008) test stochastic convergence across 28 countries, both developed and developing, from 1870 to 2002, finding stochastic convergence for the full panel. Through the development of the Phillips and Sul (2007, 2009) methodology, the literature on emissions convergence has experienced a great boom, producing many studies in recent years.

Panapoulou and Pantelidis (2009) were the first to apply this convergence statistic to per-capita CO₂ emissions, using a sample of 128 countries with data from 1960 to 2003. Similarly, Herrerias (2013) finds multiple convergence clubs in CO₂ emissions, in 162 countries from 1980 to 2009. Recently, Haider and Akram (2019a) use the club convergence test for per-capita CO₂ emissions in 53 countries over 1980-2016, obtaining two convergence clubs for total emissions and emissions from natural gas and petroleum use, and identifying three convergence clubs for coal use.

At the regional level, Wang et al. (2014) obtain three convergence clubs for per-capita CO₂ emissions in China for the period 1995-2011, whereas Burnett (2016) tests the convergence in CO₂ emissions among 48 US states for the period 1960-2010. Other studies of carbon dioxide emissions convergence at the regional level in the US include Apergis et al. (2017), Apergis and Payne (2017) and Tiwari et al. (2021). The significant number of studies at the regional level in the US could be justified both from its data availability and from its importance as one of the largest emitters of CO₂ emissions in the world. Ivanovski and Churchill (2020) investigate the convergence process of CO₂ in Australia from 1990 to 2017, identifying one converging club and another diverging club for per-capita CO₂ emissions.

The literature on CO₂ emissions convergence has also looked at developing areas, such as Africa and Latin America. For example, Solarin (2014) examines convergence among 39 African countries, finding evidence of stochastic convergence for 31 countries in CO₂ emissions (i.e., 80% of the sample) and Tiwari et al. (2016) reveal evidence of convergence in CO₂ emissions per-capita in 35 African countries. For studies in Latin

America, Robalino-Lopez et al. (2016) show two convergence clubs for CO₂ emissions in South America during 1980-2010, and Belloc and Molina (2023) identify an absolute convergence process in per-capita CO₂ emissions among 19 Latin American countries during the period 1970-2018.

Another group of studies of emissions convergence has analyzed the ecological footprint, particularly since the recent introduction of the Global Footprint Network (for more details, see <https://www.footprintnetwork.org/>). The underlying idea is that ecological footprints allow consideration of the environmental pressure of human activities in all dimensions, including CO₂ emissions within the carbon footprint (Bilgili and Ulucak, 2018; Ulucak and Apergis, 2018; Solarin et al., 2019; Erdogan and Okumus, 2021; İçik et al., 2021; Tillaguango et al., 2021; Alvarado et al., 2022; Belloc and Molina, 2022). For example, Bilgili and Ulucak (2018) test convergence in the ecological footprint and its components for G20 countries from 1961 to 2014, employing both stochastic and club convergence, and finding no evidence for stochastic convergence and two convergence clubs. Ulucak and Apergis (2018) focus on the ecological footprint per-capita, in 20 European countries over 1961-2013, and find two convergence clubs. Other authors have also examined convergence in ecological footprints for African countries (Ulucak et al., 2020; Belloc and Molina, 2022; Bello et al., 2022), NAFTA countries (Içik et al., 2021), ASEAN countries (Yilanci and Pata, 2020), and the global community (Apaydin et al., 2021; Arogundade et al., 2023).

Nevertheless, although during the last decade there has been an impressive number of studies of emissions convergence, there are still several gaps to be filled. First, prior research has typically focused on per-capita CO₂ emissions, in a restricted geographical context, but these studies ignore the total amount of air pollutants emitted to the atmosphere, that is, the greenhouse gas emissions as a whole. This represents the main interest of international commitments and conventions. Due to the industrial and economic activity of a given country, there could be differences among the air pollutants and all these studies restrict themselves to a specific air pollutant. This could lead to incorrect policy recommendations, since emissions convergence is a concept directly related to the efficacy of current environmental policies, so the choice of the environmental indicator is crucial, although sometimes undervalued. By contrast, we focus on the total greenhouse gas emissions, and we do not restrict our work to a specific gas, nor do we limit our attention to a particular region (e.g., the US, EU, OECD,...).

Finally, the number of studies that pay attention to the club convergence determinants is quite limited and there is much more to be learned about emissions determinants. We also contribute to this line of research.

The only studies, to our knowledge, that examine the convergence of greenhouse gas emissions are El-Montasser et al. (2015), Apergis and Garzón (2020), Presno et al. (2021) and Payne et al. (2022). El-Montasser et al. (2015) investigate convergence of greenhouse gas emissions among the G7 countries for 1990-2011, and they find no evidence for stochastic convergence, using a panel unit root with breaks, while Apergis and Garzón (2020) study greenhouse gas emissions convergence among 19 Spanish regions, from 1990 to 2017, obtaining evidence of four convergence clubs. Presno et al. (2021) focus on greenhouse gas emissions in the EU-28 and identify four convergence clubs from 1990 to 2017, while Payne et al. (2022) study stochastic convergence for per-capita greenhouse gas emissions using yearly time series of 183 countries from 1990 to 2018.

Consequently, the literature review above suggests two large groups of studies, both about carbon dioxide emissions and on the ecological footprint, but only one has examined the convergence of global greenhouse gas emissions, from a stochastic convergence perspective. Our work complements that study, by using the club convergence test and studying the determinants of the club convergence results. Prior studies omitted an analysis of the determinants, which may lead to significant environmental policies to achieve overall convergence in the long-run.¹

3. Methodology and data

3.1. Econometric methodology

To test for the convergence hypothesis of per-capita greenhouse gas emissions, we use the econometric methodology developed by Phillips and Sul (2007, 2009), to test the null hypothesis of convergence for a pool of data and identify convergence club(s) through a clustering algorithm. This approach has been extensively employed to test for convergence and in this section we summarize the methodology.²

¹ For a recent complete review of studies about emissions convergence in the last six years (2018-2023), we refer the reader to Appendix Table 1.

² For a recent review of the state-of-art of this econometric framework, see Tomal (2023).

This methodology is based on a general, non-linear time-varying common factor model and supposes that a group of countries may converge to a common steady state, which differs from that of other groups of countries. Specifically, Phillips and Sul (2007) employ a time-varying common factor model of the variables of interest defined as follows:

$$X_{it} = \delta_{it}\mu_t \quad (1)$$

Where, in our particular case, X_{it} represents either of the four measures of per-capita greenhouse gas emissions, with i denoting the countries ($i = 1, \dots, 114$) and t the timespan ($t = 1990, \dots, 2019$), μ_t a single common trend component in the panel, and δ_{it} a time-varying idiosyncratic factor-loading coefficient. Since δ_{it} cannot be estimated, due to overparametrization, Phillips and Sul (2007) assume the following semi-parametric function for δ_{it} :

$$\delta_{it} = \delta_i + \frac{\sigma_i \xi_{it}}{L(t)t^\alpha} \quad (2)$$

Where δ_i are fixed, $\xi_{it} \sim iid(0,1)$ across i but weakly dependent over t , σ_i is the scale parameter, $L(t)$ is a slowly varying function where $L(t) \rightarrow \infty$ as $t \rightarrow \infty$, and α represents the speed of convergence (the rate at which the cross-sectional variation decays over time to 0).

Under this specification of δ_{it} , the null hypothesis of convergence for all i takes the following form: $H_0: \delta_i = \delta$ and $\alpha \geq 0$, while the alternative hypothesis of the non-convergence for some i takes the form: $H_A: \delta_i \neq \delta$ for all i and $\alpha < 0$.

Phillips and Sul (2007) suggest testing for convergence by testing whether δ_{it} converges towards a constant δ . To test for convergence, they define the relative transition parameter, h_{it} , by modifying Equation (1) and removing the common factor μ_t as follows:

$$h_{it} = \frac{X_{it}}{\frac{1}{N} \sum_{i=1}^N X_{it}} = \frac{\delta_{it}}{\frac{1}{N} \sum_{i=1}^N \delta_{it}} \quad (3)$$

Eq. (3) measures the transition path for per-capita greenhouse gas emissions for the i -th country relative to the panel average at time t . By definition, the cross-sectional mean of h_{it} is equal to 1. The cross-sectional variation of h_{it} is defined as follows:

$$H_t = \frac{1}{N} \sum_{i=1}^N (h_{it} - 1)^2 \quad (4)$$

In the presence of convergence, when t moves towards infinity, δ_{it} converges towards a constant δ , and the relative transition parameter h_{it} converges to unity, so the cross-sectional variation H_t converges to zero.

Formally, Phillips and Sul (2007) test for the null hypothesis of full convergence by estimating the following equation, a simple OLS regression commonly known as the log- t equation:

$$\log\left(\frac{H_1}{H_t}\right) - 2 \log\{\log(t)\} = \alpha + \beta \log(t) + \varepsilon_t, \quad t = [rT], \dots, T \quad (5)$$

Where H_1 measures the variation at the beginning of the sample, and H_t represents the variation for every point over time. Taking the log of $\frac{H_1}{H_t}$, this ratio then measures the distance of the panel from the common limit. The coefficient $\hat{\beta}$ provides a scaled measure of the convergence speed parameter α and, under the null hypothesis of convergence, $\hat{\beta} = 2\hat{\alpha}$. Thus, the null hypothesis of convergence for all i can be tested using the estimated coefficient β by a one-sided t -test of $\beta \geq 0$, against $\beta < 0$.

Under certain regular assumptions, specifically using methods that correct for the presence of heteroskedasticity and autocorrelation for the standard error of the residuals, the null hypothesis of convergence is rejected if the computed one-sided t -statistic for the β coefficient takes a value lower than -1.65 at the 5% level, as this t -statistic follows the standard normal distribution $N(0,1)$. Note that this regression is run after discarding a fraction of the sample ($r > 0$), and in practice this truncation parameter is set to $1/3$ for $T < 50$.

Nevertheless, the rejection of the null hypothesis of full convergence for the whole panel does not rule out the existence of convergence among clubs in the panel, and the alternative can accommodate both club convergence and divergence. If the convergence cannot be verified for the full sample, it should be investigated for the case of clubs. At this point, Phillips and Sul (2007) develop a data-driven algorithm that identifies clubs endogenously, ultimately based on the value of the dependent variable.

The Phillips and Sul (2007) algorithm comprises the following five steps to identify clubs within the panel of countries:

1. *Last observation cross-sectional ordering.* Sorting the N countries in descending order, according to their values in the last period.

2. *Core club formation.* Forming all possible core clubs C_k by selecting the first k highest countries in the panel, for k ($2 \leq k \leq N$). After, run the log t test within each subgroup of size k to see if they can be merged in the same club. Finally, define the core club C^* of size k^* as the club with the maximum value of the log t -statistic, subject to the restriction that it is greater than -1.65 . If this condition does not hold, conclude that there are no convergence clubs in the panel.
3. *Club membership to the core club.* From the remaining $N - k^*$ countries, add regions one by one to the core club C^* and run the log t test. If the test strongly supports the convergence hypothesis (the log t -statistic is greater than a chosen critical value c^* , which in practice is 0 when $T < 50$), include the country in the core club C^* . This is accomplished by adding all countries that strongly support the convergence hypothesis, according to the log t test, and converge to the same equilibrium with C^* . These added countries and the core club form the first convergence club if the log t -statistic is greater than -1.65 . Otherwise, raise the critical value c^* to increase the discriminatory power of the test, and repeat step 3 until the log t -statistic for these countries and the core club is greater than -1.65 .
4. *Recursion and stopping.* For the remaining regions in the sample, if any, run the log t test to see if they are converging (the log t -statistic is greater than -1.65) and form a second convergence club. If the results show convergence, then this group is the second convergence club, and conclude that there are two convergent clubs in the panel. If not, repeat steps 1-3 iteratively for remaining countries to determine if there is convergence. If no core club is found in step 2, then conclude that these countries diverge.
5. *Club merging.* Finally, Phillips and Sul (2009) note that employing a sign criterion in step 3 (t -statistic > 0) and increasing successively the critical value c^* may lead to creating more clubs than actually exist and the last step is club merging which consists of conducting club convergence tests for all pairs of the initial convergence clubs (assuming there are more than one), in order to avoid an over-estimation of the current number of clubs. If the null hypothesis is not rejected (the t -statistic is greater than -1.65), the corresponding clubs can be merged into a larger club. This procedure is repeated until no clubs can be merged, obtaining the final number of clubs.

In our empirical application for per-capita greenhouse gas emissions, we combine the club convergence test with an analysis of the determining factors behind club membership. To do this, we estimate different ordinal models to examine the potential forces behind club membership, according to each pollutant gas, given that the convergence test provides an ordinal rank of the convergence clubs (Bartkowska and Riedl, 2012; Bhattacharya et al., 2020; Ivanovski and Churchill, 2020). Specifically, we estimate the following ordinal model:

$$Y_{it}^* = \alpha_0 + X'_{it}\beta + \Gamma_t + \varepsilon_{it} \quad (6)$$

Where the dependent variable Y_{it}^* refers to the number of clubs identified in the club convergence test (for each gas), α_0 is a constant term, X'_{it} is a vector of determinants, and Γ_t are year fixed effects. ε_{it} is the error term.

3.2. Data

Our primary data are per-capita greenhouse gas emissions, total and disaggregated by air pollutant, drawn from *Our World in Data*, which provides country-level emissions over the period 1990-2019. These data are measured in millions of tonnes, adjusted for population. We supplement this with country-level data drawn from the World Bank's World Development Indicators, the V-Dem Dataset, and the KOF Swiss Economic Institute. Specifically, for the analysis of determinants of club membership, we gather information from GDP (current US\$), urban population (population living in rural areas), natural resources rents (sum of oil rents, natural gas rents, coal rents, mineral rents and forest rents, % of GDP), and renewable energy consumption (% of total final energy consumption) from the World Bank's World Development Indicator database. We also download information from V-Dem Dataset for the regime level of corruption and from the KOF Swiss Economic Institute for the trade globalization level index. Based on data availability for both emissions and explanatory variables, we finally investigate the convergence of greenhouse gas emissions for 114 countries.³ Table 1 reports the summary statistics for greenhouse gas emissions intensity, total and by air pollutant, and the determinants considered in the analyses.

³ We restrict the analysis to the period 1990-2019 because the information on per-capita greenhouse gas emissions is only available for these years. We end with a final sample of 114 countries, mainly due to missing information about determinants. The list of countries is included in Appendix Table 2.

4. Results

4.1. Cross-sectional evidence

In this sub-section, we perform a preliminary investigation of the convergence behavior of the air pollutant series prior to our main analysis through the club convergence test. Specifically, we begin with two simple beta- and sigma-convergence analyses of the time series behavior. In Figures 1 and 2, we display the main cross-sectional results. For the scatter plots in Figure 1, we display pairs of the initial emissions and the average change in emissions between 1990 and 2019, together with the corresponding linear regression fit. The slope coefficients of all figures are negative for all variables considered and suggest a catching-up effect in the world, as the countries with low emissions levels in 1990 have increased their emissions at a larger growth rate, on average, than those with high initial emissions levels, diminishing cross-sectional emissions disparities over time. In Figure 2, we present the evolution of cross-sectional standard deviation of the different greenhouse gases. The time series graphs suggest that the value at the end of the sample is generally smaller than that at the beginning, except for the CO₂ emissions per-capita, suggesting a sigma-convergence process of these air pollutants, as the dispersion has declined across countries throughout the time period.

4.2. Club convergence results

To explore convergence of the greenhouse gas emissions, we perform the club convergence test separately by gas. Table 2 reports the results from the club convergence test for per-capita greenhouse gas emissions. We employ the log t -test to test the overall convergence hypothesis for the whole sample. The coefficient \hat{b} -0.7312 for the whole sample, and the t -statistic is -422.5453, much less than the critical value of -1.65 at the 5% level. This suggests that the null hypothesis of overall convergence is clearly rejected, and that the per-capita greenhouse gas emissions do not converge as a whole. With panel overall convergence and a common pattern of behavior rejected by the data for total greenhouse gas emissions intensity, club convergence may still exist. When we run the club convergence algorithm, we identify five final convergent clubs, indicating that the per-capita greenhouse gas emissions have some club convergence characteristics.

We describe the specific, final club memberships in Table 2. The first club contains 33 countries, with the log t -statistic of 11.3471 (and greater than -1.65). The countries in this first club include Algeria, Argentina, Australia, Bahrain, Barbados, Bolivia, Botswana, Canada, China, Guyana, Ireland, Japan, Libya, Maldives, Mauritius, New Zealand, Oman, Paraguay, Peru, Qatar, Saudi Arabia, Seychelles, Singapore, South Africa, South Korea, Thailand, Trinidad and Tobago, Turkey, United Arab Emirates, United States, Uruguay, Vietnam and Zimbabwe. The second club is the largest and has 48 countries, namely: Albania, Angola, Austria, Bangladesh, Belgium, Brazil, Cameroon, Central African Republic, Chad, Colombia, Cyprus, Denmark, Dominican Republic, Ecuador, Egypt, France, Gabon, Germany, Greece, Guinea, Honduras, Iceland, India, Indonesia, Italy, Jordan, Laos, Lebanon, Malaysia, Malta, Mexico, Morocco, Nepal, Netherlands, Nicaragua, Norway, Pakistan, Panama, Papua New Guinea, Philippines, Poland, Portugal, Spain, Switzerland, Tunisia, United Kingdom, Vanuatu and Zambia.

The third club has 17 countries and the log t -statistic of 2.0570. The countries in this club include Benin, Bulgaria, Burkina Faso, Eswatini, Ethiopia, Guatemala, Guinea-Bissau, Jamaica, Kenya, Mali, Mauritania, Niger, Senegal, Sri Lanka, Sudan, Sweden and Tanzania. The last two clubs consist of 9 and 7 countries, respectively. Chile, Costa Rica, Djibouti, Haiti, Lesotho, Madagascar, Nigeria, Sierra Leone and Uganda belong to the fourth club, and Burundi, Comoros, Gambia, Ghana, Malawi, Rwanda and Togo are in the fifth club.

As shown in Table 2, the speed of convergence varies between the five clubs. Convergence occurs at a rate of -0.1560% for club one, 0.0024% for club two, 0.0543% for club three, 0.0260% for club four and 1.3135% for club five, which is increasing faster than the other clubs. Figure 3 displays the average values for per-capita greenhouse gas emissions among the clubs detected. Since the algorithm sorts the countries in descending order, Club 1 exhibits the greatest value of greenhouse gas emissions per-capita at the end of the time period, while the ratio for Club 5 is the lowest.⁴

Table 3 illustrates the results of the club convergence test for per-capita carbon dioxide emissions. Results from the log- t test for the entire panel indicates a non-rejection of the null hypothesis of convergence, since the t -statistic is 17.620, greater than -1.65. All countries follow the same convergence path in per-capita carbon dioxide emissions and

⁴ We have calculated the transition paths for the estimated clubs in Appendix Figure 1.

the null hypothesis of full convergence is not rejected at the 5% level, suggesting that these countries are converging to the same steady state in carbon dioxide emissions intensity. Specifically, the estimated value of the $\hat{\beta}$ parameter is 0.6978, suggesting that these countries are converging at a rate of 0.3489%.

For per-capita nitrous oxide emissions, Table 4 reports the results of the club convergence test across the full sample. The null hypothesis of full convergence is rejected by the data, since the t -statistic is -7.6301, which is lower than the critical value at a 5% significance level, indicating an absence of overall convergence for this specific pollutant, and that nitrous oxide intensity does not converge to the same steady state. Thus, convergence should be identified across subgroups (if any). To do this, we perform the clustering algorithm and, after running club merging test across initial clubs detected, we obtain four convergent clubs and one diverging club. The first club includes 64 countries, the second club is 31 countries, club 3 has 8 countries, and club 4 has 5. The remaining countries represent the diverging club that does not converge to the same steady state as the others. Figure 4 shows the time series evolution of the nitrous oxide emissions per-capita for each club.

The main empirical results of the club convergence for the per-capita methane emissions are shown in Table 5. For the overall sample, the coefficient $\hat{\beta}$ is negative and the log t -statistic value is -9.832, much less than -1.65, suggesting that the convergence hypothesis is rejected for the full sample. Thus, per-capita methane emissions do not converge as a whole in the sample. Consequently, we test for the presence of club convergence. After running club merging test, we obtain two convergence clubs. Club 1 contains the smallest number of countries, 11 countries, while Club 2 is formed by the 103 remaining countries. Specifically, Club 1 contains Australia, Barbados, Chad, Libya, New Zealand, Oman, Paraguay, Qatar, Trinidad and Tobago, United Arab Emirates and Uruguay. Club 2 contains Albania, Algeria, Angola, Argentina, Austria, Bahrain, Bangladesh, Belgium, Benin, Bolivia, Botswana, Brazil, Bulgaria, Burkina Faso, Burundi, Cameroon, Canada, Central African Republic, Chile, China, Colombia, Comoros, Costa Rica, Cyprus, Denmark, Djibouti, Dominican Republic, Ecuador, Egypt, Eswatini, Ethiopia, France, Gabon, Gambia, Germany, Ghana, Greece, Guatemala, Guinea, Guinea-Bissau, Guyana, Haiti, Honduras, Iceland, India, Indonesia, Ireland, Italy, Jamaica, Japan, Jordan, Kenya, Laos, Lebanon, Lesotho, Madagascar, Malawi, Malaysia, Maldives, Mali, Malta, Mauritania, Mauritius, Mexico, Morocco, Nepal,

Netherlands, Nicaragua, Niger, Nigeria, Norway, Pakistan, Panama, Papua New Guinea, Peru, Philippines, Poland, Portugal, Rwanda, Saudi Arabia, Senegal, Seychelles, Sierra Leone, Singapore, South Africa, South Korea, Spain, Sri Lanka, Sudan, Sweden, Switzerland, Tanzania, Thailand, Togo, Tunisia, Turkey, Uganda, United Kingdom, United States, Vanuatu, Vietnam, Zambia and Zimbabwe. The graphical evolution of the average values for methane emissions intensity appears in Figure 5.

All in all, we perform the club convergence test for different greenhouse gas emissions and obtain evidence of different convergence processes. For per-capita carbon dioxide emissions, the null hypothesis of overall convergence is not rejected, suggesting a common pattern of behavior across these 114 countries and giving support to common environmental policies. However, for total greenhouse gas emissions intensity we find 5 different convergence clubs. For nitrous oxide emissions intensity, our results indicate four convergence clubs, while for methane emissions intensity two results are identified.⁵

4.3. Determinants of club convergence

In this section, we estimate ordered probit regressions for the previously identified clubs in per-capita greenhouse gas and nitrous oxide emissions, and for the clubs detected in per-capita methane emissions, we estimate a linear probability model (Club 1 is labelled as 0, and Club 2 is labelled as one) in order to interpret the estimates directly as marginal effects. Specifically, we investigate country-specific conditions and certain structural characteristics that might explain the convergence clubs identified in the previous section. This is important in identifying certain convergence drivers behind our main results.

The probit regressions for per-capita greenhouse gas emissions are displayed in Table 6, together with the associated marginal effects. The results suggest that all structural characteristics included are indeed statistically related to club membership and are significant predictors of the club outcomes previously identified by the club convergence test. With these estimates, we can obtain an overall perspective of the characteristics of the countries in each club.

⁵ In Appendix Table 3, we report the club convergence results (for the full sample) using an alternative truncation parameter, as suggested by Kwak (2022). The results are completely robust to this alternative parameter.

The estimated coefficient for the income level is -0.499, statistically significant at the 1% level. Regarding the total urban population, we obtain an estimate of 0.449, also statistically significant at the 1% level. For total natural resources rents, the coefficient is -0.029, statistically significant at the 1% level, for renewables energy consumption the coefficient is 0.024, whereas for the KOF trade globalization index the coefficient equals to 0.123. Finally, for the regime corruption index, we obtain an estimate of -0.953, also statistically significant at the 1% level.

In the next five columns of Table 6, we calculate the average marginal effects on the probability of belonging to each club. For these estimates, we obtain a clear dichotomy, at least from a qualitative point of view, from the probability of belonging to Club 1, vs. Clubs 3, 4 and 5. Specifically, the income level, the natural resources rents, and the corruption level are related to an increase in the probability of belonging to Club 1, whereas these variables are negatively associated with the probability of belonging to Clubs 3, 4 and 5. On the other hand, the urban population, renewables energy consumption, and trade openness are positively related to the probability of belonging to Clubs 3, 4 and 5, and negatively related to Club 1.

The results of the ordered probit model for per-capita nitrous oxide emissions appear in Table 7, together with the average marginal effects. For this club classification, we find that the income level, natural resources rents, renewables energy consumption, and regime corruption level are variables that are significantly correlated with club membership, at standard levels of significance. Specifically, we find that countries in Club 1 have greater levels of income and renewable energy consumption, while they have lower natural resources rents and levels of corruption, relative to Clubs 2, 3 and 4.

We display the linear probability model results in Table 8 for the convergence clubs identified in methane emissions intensity. In this case, all the variables are significantly related to the probability of belonging to the two clubs. Specifically, compared to Club 1, income level and natural resources rents are negatively related to the probability of belonging to Club 2, while urban population, renewables energy consumption, globalization, and corruption are positively related to the probability of belonging to Club 2 in per-capita methane emissions.

5. Concluding remarks and policy implications

This paper examines convergence in global greenhouse gas emissions from 1990 to 2019, studying total greenhouse gas emissions and its disaggregation by air pollutants. We differ from prior research by taking a global perspective. Whereas prior research has focused on an indicator of greenhouse gas emissions, mainly carbon dioxide emissions (given its contribution to total greenhouse gas emissions), we consider in the same work a range of environmental indicators. The existence of convergence is a crucial concern in order to support current environmental policies and climate predictions. The methodology used in this paper allows us to test this hypothesis for a pool of data and, whether it is rejected, to identify subgroups of countries that are following the same converging path.

Our results suggest different results according to the pollutant indicator considered. Specifically, for the total amount of greenhouse gas emissions intensity we obtain evidence for five convergence clubs, suggesting that these countries are not converging as a whole. When we consider the disaggregation, we obtain different results. Specifically, for carbon dioxide emissions intensity, we obtain evidence of overall convergence, whereas for per-capita nitrous oxide emissions and methane emissions, from four to two clubs are obtained. We do not limit the club convergence results and we pay attention to how certain structural characteristics explain club membership, through the estimation of ordinal models. Thus, we combine the club convergence results with an analysis of the determinants that may predict the probability of belonging to a given club. The results from the ordinal models suggest the importance of income level, urban population, renewables energy consumption, natural resources, trade openness, and corruption as key predictors of club membership.

All these results have significant implications for current environmental policies. Specifically, our finding of convergence clubs for total greenhouse gas emissions intensity suggests implementing different environmental policies, according to the clubs detected, to achieve overall convergence in the long run. This suggests that current environmental policies, implemented through the Kyoto Protocol and the Paris Climate Agreement, should be reformulated, as a common environmental policy to reduce disparities in greenhouse gas emissions does not fit with our results. Nevertheless, these climate agreements appear to be effective in the reduction of carbon dioxide emissions' disparities. Our results also suggest the importance of taking into account a range of environmental indicators in convergence analyses and given the specificity of each air

pollutant, separate policies should be pursued across them. Planners should consider our determinants analyses to achieve overall convergence. Specifically, for greenhouse gas emissions intensity, the main determinant appears to be institutional quality, and policymakers should aim to improve governance structures and transparency to enhance credibility, to implement environmental policies, and converge with the lowest emissions intensity clubs. Countries should also diversify their energy mix against an economic structure dependent on natural resources.

Several avenues emerge for future research from this study. Future research should deepen our understanding of convergence of greenhouse gas emissions by studying convergence at the sectoral level. Specifically, our literature review indicates that only a small number of studies have investigated greenhouse gas emissions convergence at the sectoral level. Another avenue for future research is to analyze whether COVID-19 has affected the convergent behavior of these series, when data become available. Finally, extending the analysis to study convergence at different regional levels is extremely encouraged.

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Table 1. Summary statistics

	Mean	Std. Dev.	Minimum	Maximum
<i>Main variables</i>				
Per-capita GHG emissions	7.592	8.070	0.032	62.035
Per-capita CO2 emissions	4.658	6.988	0.019	66.817
Per-capita CH4 emissions	1.787	2.233	0.078	14.553
Per-capita NO2 emissions	0.635	0.801	0.000	6.270
<i>Determinants</i>				
GDP (/1,000,000)	412,869.900	1,517,644.000	168.879	21,400,000.000
Urban population (1,000,000)	24.059	68.596	0.028	848.983
Natural resources rents	6.724	9.502	0.000	66.060
Renewable energy consumption	38.878	31.700	0.000	97.510
Corruption level	0.477	0.307	0.002	0.967
KOF Trade Globalisation level	50.286	18.157	13.151	96.770
Number of observations	3,420			
Number of countries	114			

Figure 1. Beta-convergence analysis

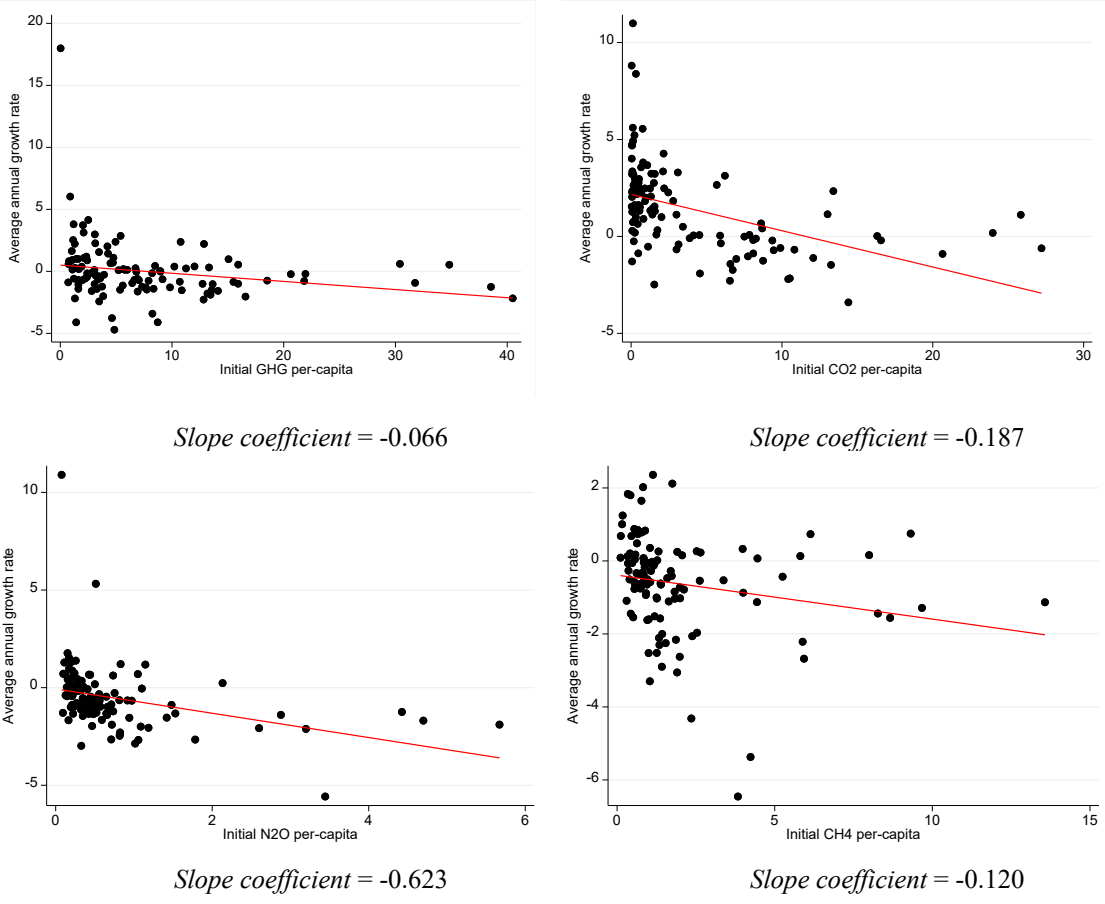


Figure 2. Sigma-convergence analysis, cross-sectional standard deviation

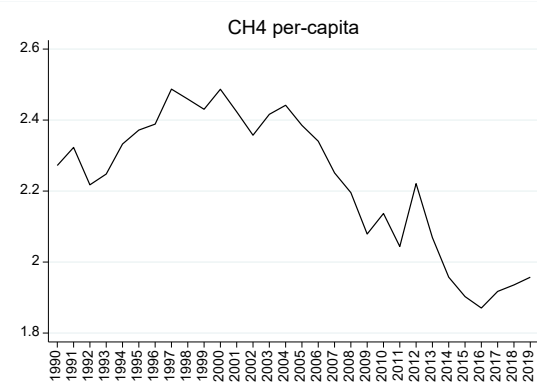
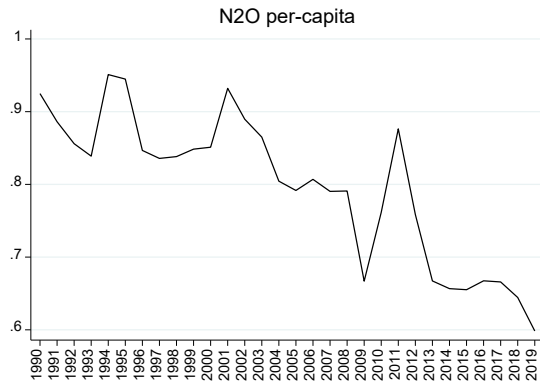
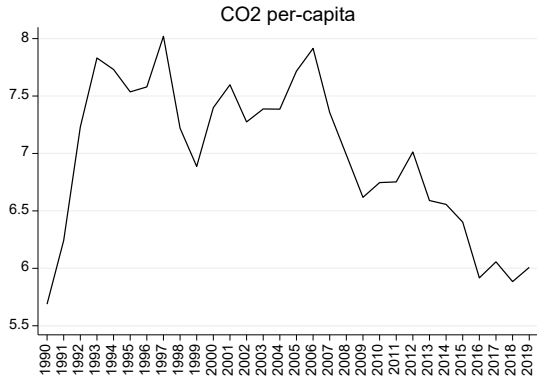
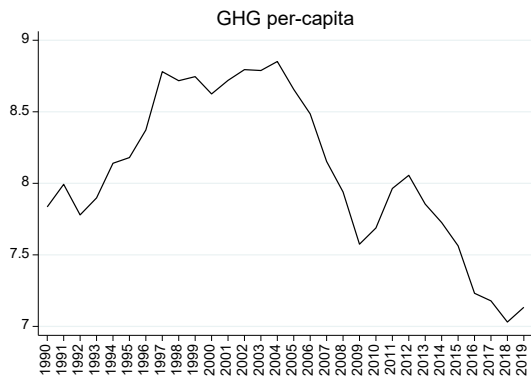


Table 2. Convergence analysis, per-capita greenhouse gas emissions

Group	Countries	\hat{b} coefficient	log t -statistic	$\hat{\alpha}$
All	Full sample	-0.7312	-422.5453**	-0.3656
Club 1 [33]	Algeria, Argentina, Australia, Bahrain, Barbados, Bolivia, Botswana, Canada, China, Guyana, Ireland, Japan, Libya, Maldives, Mauritius, New Zealand, Oman, Paraguay, Peru, Qatar, Saudi Arabia, Seychelles, Singapore, South Africa, South Korea, Thailand, Trinidad and Tobago, Turkey, United Arab Emirates, United States, Uruguay, Vietnam, Zimbabwe	0.3121	11.3471	0.15605
Club 2 [48]	Albania, Angola, Austria, Bangladesh, Belgium, Brazil, Cameroon, Central African Republic, Chad, Colombia, Cyprus, Denmark, Dominican Republic, Ecuador, Egypt, France, Gabon, Germany, Greece, Guinea, Honduras, Iceland, India, Indonesia, Italy, Jordan, Laos, Lebanon, Malaysia, Malta, Mexico, Morocco, Nepal, Netherlands, Nicaragua, Norway, Pakistan, Panama, Papua New Guinea, Philippines, Poland, Portugal, Spain, Switzerland, Tunisia, United Kingdom, Vanuatu, Zambia	0.0047	0.0989	0.00235
Club 3 [17]	Benin, Bulgaria, Burkina Faso, Eswatini, Ethiopia, Guatemala, Guinea-Bissau, Jamaica, Kenya, Mali, Mauritania, Niger, Senegal, Sri Lanka, Sudan, Sweden, Tanzania	0.1086	2.0570	0.0543
Club 4 [9]	Chile, Costa Rica, Djibouti, Haiti, Lesotho, Madagascar, Nigeria, Sierra Leone, Uganda	0.0520	1.2559	0.0260
Club 5 [7]	Burundi, Comoros, Gambia, Ghana, Malawi, Rwanda, Togo	2.6270	1.0548	1.3135

Notes: ** indicates rejection of the null hypothesis of absolute convergence (the critical value is -1.65 at the 5% significance level). Numbers in brackets stand for the number of countries within a given club. Convergence clubs denote the final clubs after running club merging tests developed in Phillips and Sul (2009).

Figure 3. Average values by final clubs, per-capita GHG emissions

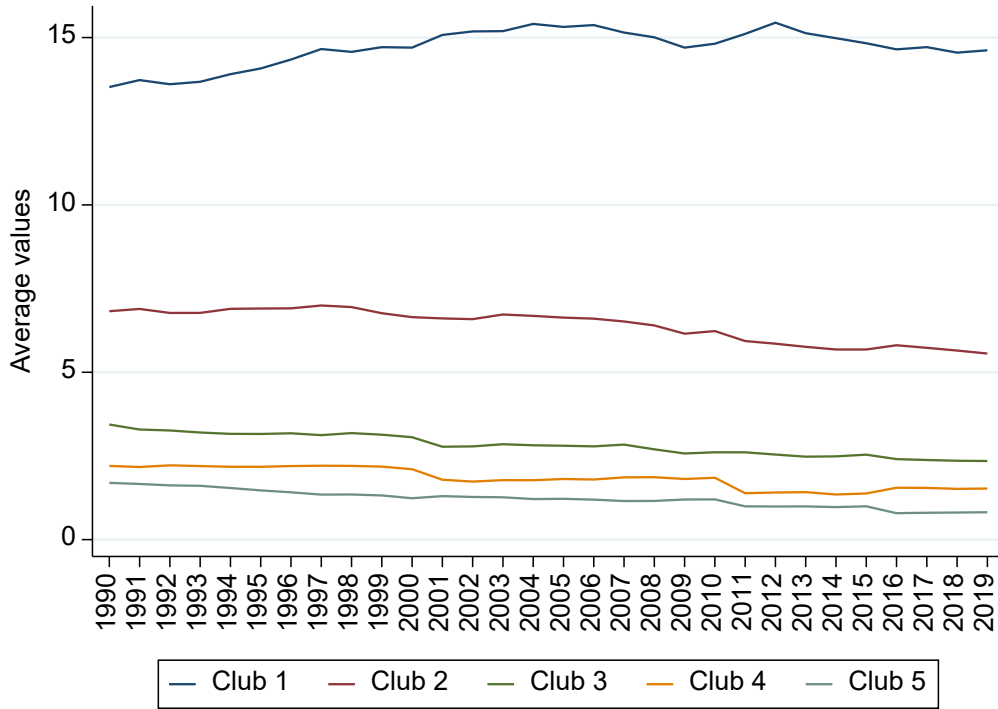


Table 3. Convergence analysis, per-capita CO2 emissions

Group	Countries	\hat{b} coefficient	log t -statistic	$\hat{\alpha}$
All	Full sample	0.6978	17.6205	0.3489

Table 4. Convergence analysis, per-capita N2O emissions

Group	Countries	\hat{b} coefficient	log t -statistic	$\hat{\alpha}$
All	Full sample	-0.2331	-7.6301**	-0.11655
Club 1 [64]	Albania, Angola, Argentina, Australia, Austria, Belgium, Benin, Bolivia, Botswana, Brail, Bulgaria, Burkina Faso, Cameroon, Chad, Chile, China, Colombia, Costa Rica, Denmark, Djibouti, Ecuador, Ethiopia, France, Gambia, Germany, Ghana, Greece Guinea, Guinea-Bissau, Guyana, Honduras, Iceland, Ireland, Italy, Jamaica, Japan, Kenya, Laos, Madagascar, Malaysia, Mali, Mauritania, Netherlands, New Zealand, Nicaragua, Niger, Norway, Papua New Guinea, Paraguay, Poland, Singapore, South Korea, Spain, Sudan, Sweden, Switzerland, Tanzania, Turkey, United Kingdom, United States, Uruguay, Vanuatu, Zambia, Zimbabwe	0.1826	4.0187	0.0913
Club 2 [31]	Algeria, Cyprus, Dominican Republic, Egypt, Eswatini, Gabon, Guatemala, Indonesia, Lesotho, Libya, Malawi, Mexico, Morcco, Nepal, Oman, Pakistan, Panama, Peru, Portugal, Qatar, Saudi Arabia, Senegal, Sierra Leone, South Africa, Thailand, Togo, Trinidad and Tobago, Tunisia, Uganda, United Arab Emirates, Vietnam	0.4339	19.1882	0.21695
Club 3 [8]	Bangladesh, Burundi, Haiti, India, Lebanon, Mauritius, Nigeria, Rwanda	0.5836	20.5336	0.2918
Club 4 [5]	Bahrain, Barbados, Jordan, Philippines, Sri Lanka	0.9354	19.5986	0.4677
Diverging [4]	Canada, Central African Republic, Comoros, Malta			

Notes: ** indicates rejection of the null hypothesis of absolute convergence (the critical value is -1.65 at the 5% significance level). Numbers in brackets stand for the number of countries within a given club. Convergence clubs denote the final clubs after running club merging tests developed in Phillips and Sul (2009). Maldives and Seychelles are excluded due to missing data.

Figure 4. Average values by final clubs, per-capita N2O emissions

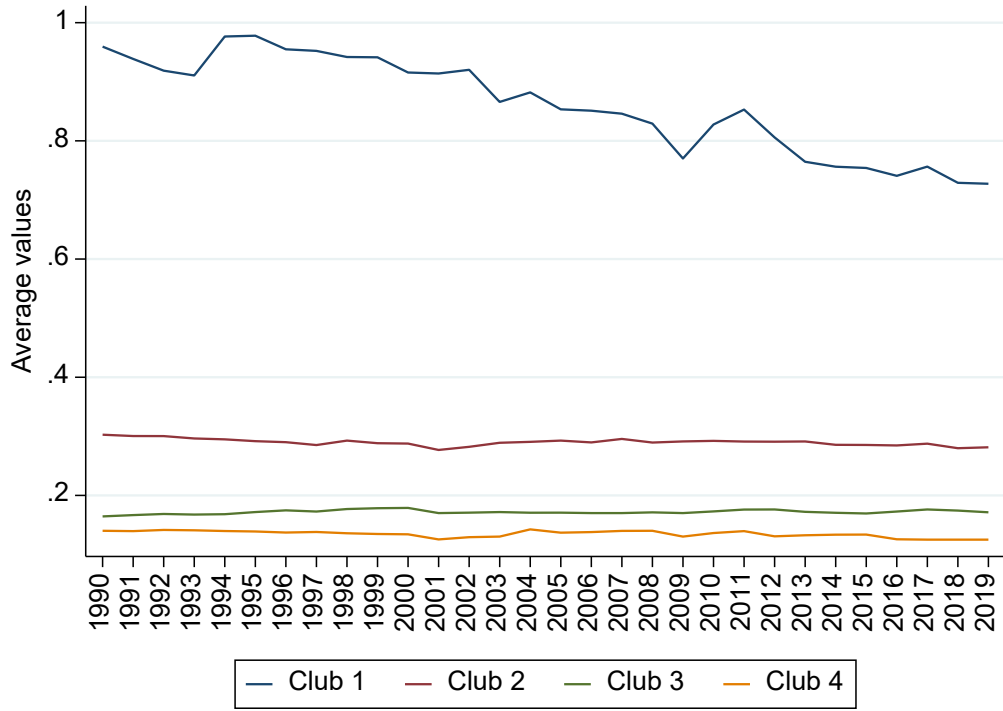


Table 5. Convergence analysis, per-capita CH4 emissions

Group	Countries	\hat{b} coefficient	log t -statistic	$\hat{\alpha}$
All	Full sample	-4.4526	-9.8320**	-2.2263
Club 1 [11]	Australia, Barbados, Chad, Libya, New Zealand, Oman, Paraguay, Qatar, Trinidad and Tobago, United Arab Emirates, Uruguay	0.2452	4.6675	0.1226
Club 2 [103]	Albania, Algeria, Angola, Argentina, Austria, Bahrain, Bangladesh, Belgium, Benin, Bolivia, Botswana, Brazil, Bulgaria, Burkina Faso, Burundi, Cameroon, Canada, Central African Republic, Chile, China, Colombia, Comoros, Costa Rica, Cyprus, Denmark, Djibouti, Dominican Republic, Ecuador, Egypt, Eswatini, Ethiopia, France, Gabon, Gambia, Germany, Ghana, Greece, Guatemala, Guinea, Guinea-Bissau, Guyana, Haiti, Honduras, Iceland, India, Indonesia, Ireland, Italy, Jamaica, Japan, Jordan, Kenya, Laos, Lebanon, Lesotho, Madagascar, Malawi, Malaysia, Maldives, Mali, Malta, Mauritania, Mauritius, Mexico, Morocco, Nepal, Netherlands, Nicaragua, Niger, Nigeria, Norway, Pakistan, Panama, Papua New Guinea, Peru, Philippines, Poland, Portugal, Rwanda, Saudi Arabia, Senegal, Seychelles, Sierra Leone, Singapore, South Africa, South Korea, Spain, Sri Lanka, Sudan, Sweden, Switzerland, Tanzania, Thailand, Togo, Tunisia, Turkey, Uganda, United Kingdom, United States, Vanuatu, Vietnam, Zambia, Zimbabwe	2.2301	33.1670	1.11505

Notes: ** indicates rejection of the null hypothesis of absolute convergence (the critical value is -1.65 at the 5% significance level). Numbers in brackets stand for the number of countries within a given club. Convergence clubs denote the final clubs after running club merging tests developed in Phillips and Sul (2009).

Figure 5. Average values by final clubs, per-capita CH4 emissions

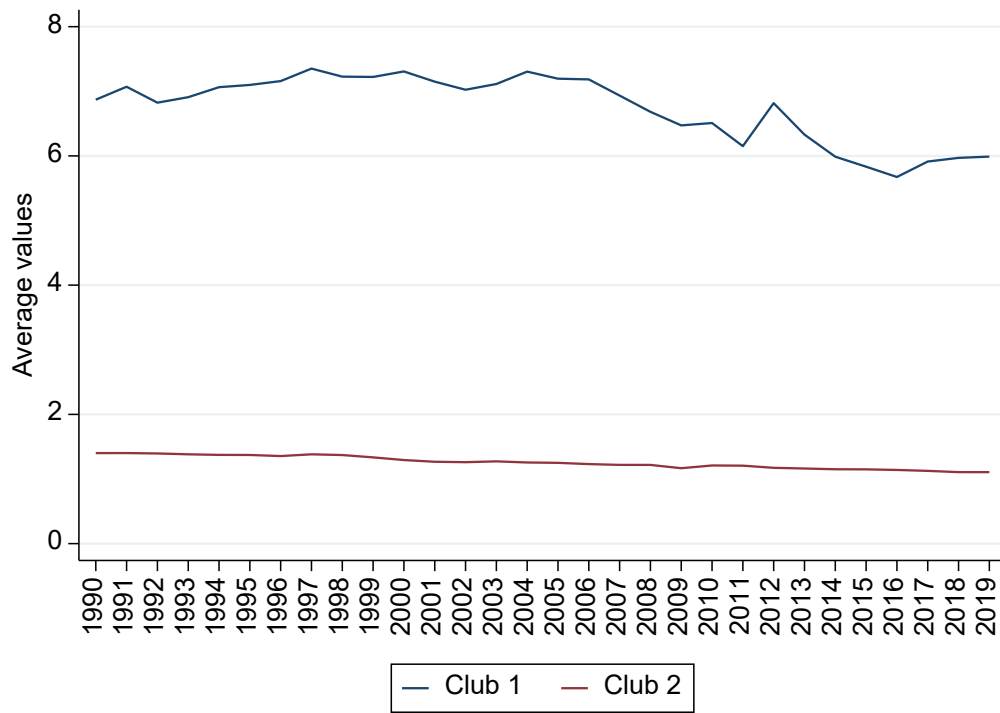


Table 6. Ordered probit estimates, per-capita GHG emissions

Explanatory variables	(1)	Marginal effects				
		Club 1 (2)	Club 2 (3)	Club 3 (4)	Club 4 (5)	Club 5 (6)
Log of Income	-0.499*** (0.031)	0.121*** (0.007)	-0.001 (0.002)	-0.040*** (0.003)	-0.034*** (0.003)	-0.046*** (0.003)
Log of Urban	0.449*** (0.033)	-0.109*** (0.008)	0.001 (0.001)	0.036*** (0.003)	0.030*** (0.003)	0.041*** (0.003)
Natural resources rents	-0.029*** (0.002)	0.007*** (0.001)	-0.000 (0.000)	-0.002*** (0.000)	-0.002*** (0.000)	-0.003*** (0.000)
Renewables energy consumption	0.024*** (0.001)	-0.006*** (0.000)	0.000 (0.000)	0.002*** (0.000)	0.002*** (0.000)	0.002*** (0.000)
KOF Trade Index	0.012*** (0.002)	-0.003*** (0.000)	0.000 (0.000)	0.001*** (0.000)	0.001*** (0.000)	0.001*** (0.000)
Regime corruption level	-0.953*** (0.105)	0.231*** (0.025)	-0.002 (0.003)	-0.076*** (0.009)	-0.065*** (0.008)	-0.088*** (0.010)
Year F.E.	Yes					
Log Pseudo-Likelihood	-3,780.034					
Pseudo R-squared	0.198					
Number of observations	3,420					
Number of countries	114					

Notes: Ordered probit estimates in Column (1). Marginal effects in Columns (2-6). Robust standard errors in parentheses.
*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Table 7. Ordered probit estimates, per-capita N2O emissions

Explanatory variables	(1)	Marginal effects			
		Club 1 (2)	Club 2 (3)	Club 3 (4)	Club 4 (5)
Log of Income	-0.082** (0.035)	0.029** (0.012)	-0.014** (0.006)	-0.007** (0.003)	-0.008** (0.003)
Log of Urban	-0.012 (0.039)	0.004 (0.014)	-0.002 (0.007)	-0.001 (0.004)	-0.001 (0.004)
Natural resources rents	0.004** (0.002)	-0.001** (0.001)	0.001* (0.000)	0.000** (0.000)	0.000** (0.000)
Renewables energy consumption	-0.011*** (0.001)	0.004*** (0.000)	-0.001*** (0.000)	-0.001*** (0.000)	-0.001 (0.000)
KOF Trade Index	-0.004* (0.002)	0.001* (0.001)	-0.001* (0.000)	-0.000* (0.000)	-0.000* (0.000)
Regime corruption level	1.251*** (0.105)	-0.442*** (0.035)	0.210*** (0.018)	0.115*** (0.011)	0.117*** (0.012)
Year F.E.	Yes				
Log Pseudo-Likelihood	-3,057.895				
Pseudo R-squared	0.060				
Number of observations	3,240				
Number of countries	108				

Notes: Ordered probit estimates in Column (1). Marginal effects in Columns (2-5). Robust standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Table 8. OLS estimates, per-capita CH4 emissions

Explanatory variables	(1)
Log of Income	-0.068*** (0.006)
Log of Urban	0.103*** (0.007)
Natural resources rents	-0.011*** (0.001)
Renewables energy consumption	0.002*** (0.000)
KOF Trade Index	0.006*** (0.000)
Regime corruption level	0.150*** (0.027)
Constant	0.592*** (0.087)
Year F.E.	Yes
R-squared	0.246
Number of observations	3,420
Number of countries	114

Notes: OLS estimates. Robust standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

APPENDIX

Appendix Table 1. Literature review on emissions convergence

Authors	Period	Countries	Variables	Testing approach	Main findings
Bilgili and Ulucak (2018)	1961-2014	G20 countries	Ecological footprint and its components	Stochastic and club convergence	No stochastic convergence, two convergence clubs
Churchill et al. (2018)	1900-2014	44 countries	CO2 emissions per-capita	Stochastic convergence	97.73% of the sample is stochastic convergent
Liu et al. (2018)	2003-2015	285 Chinese cities	SO2 and industrial soot emissions	Club convergence test	Four and three convergence clubs
Presno et al. (2018)	1901-2009	28 OECD countries	CO2 emissions per-capita	Stochastic convergence	Mixed results
Ulucak and Apergis (2018)	1961-2013	20 EU countries	Ecological footprint per-capita	Club convergence test	Two convergence clubs
Yu et al. (2018)	1995-2015	24 industrial sectors in China	CO2 emissions intensity	Beta-convergence and club convergence test	Beta-conditional convergence and three convergence clubs
Emir et al. (2019)	1990-2016	28 EU countries	CO2 emissions intensity	Club convergence test	Multiple convergence clubs
Haider and Akram (2019b)	1961-2014	77 countries	Ecological and carbon footprint per-capita	Club convergence test	Two convergence clubs
Hamit-Haggar (2019)	1990-2014	Canadian provinces and territories	GHG emissions per-capita	Club convergence test	Multiple convergence clubs
Morales-Lage et al. (2019)	1971-2018	27 EU countries	Sectoral CO2 emissions per-capita	Club convergence test	Mixed results
Solarin (2019)	1961-2013	27 OECD countries	Ecological and carbon footprint per-capita, CO2 emissions per-capita	Stochastic convergence	Mixed results
Solarin et al. (2019)	1961-2014	92 countries	Ecological footprint and its components	Club convergence test	Multiple convergence clubs
Ozcan et al. (2019)	1961-2013	113 countries	Ecological footprint per-capita	Stochastic convergence	Stochastic convergence for all high-income countries, and for the half of the low-income and upper-middle income countries, stochastic divergence for the lower-middle income countries

Apergis and Garzón (2020)	1990-2017	Spanish regions	GHG emissions per-capita	Club convergence test	Four convergence clubs
Apergis and Payne (2020)	1971-2014	NAFTA	CO2 emissions intensity, energy intensity, the carbonization index	Stochastic convergence, sigma-convergence, club convergence test	NAFTA has not changed the convergence behavior
Bhattacharya et al. (2020)	1990-2014	70 countries	Consumption-based and territory-based carbon emissions	Club convergence test	Two and three convergence clubs
Churchill et al. (2020)	1921-2014	17 emerging countries	CO2 emissions per-capita	Stochastic convergence	64.71% of the sample is stochastic convergent
Fallahi (2020)	1850-2013	Nine global regions	CO2 emissions	Stochastic convergence	Stochastic divergence
Ivanovski and Churchill (2020)	1990-2017	Australian regions	CO2, CH4, N2O emissions per-capita	Club convergence test	Multiple convergence clubs
Solarin and Tiwari (2020)	1850-2005	32 OECD countries	Sulphur dioxide emissions	Stochastic convergence	Stochastic convergence
Ulucak et al. (2020)	1961-2014	23 Sub-Saharan African countries	Ecological footprint and its components	Club convergence test	Multiple convergence clubs
Yilanci and Pata (2020)	1961-2016	ASEAN-5	Ecological footprint per-capita	Stochastic convergence	80.77% of the sample is stochastic convergent
Akram and Ali (2021)	1980-2017	93 countries	GHG emissions of agriculture	Club convergence test	Five convergence clubs
Apaydin et al. (2021)	1980-2016	130 countries	Ecological footprint per-capita	Club convergence test	Five convergence clubs
Cialani and Mortazavi (2021)	1970-2018	28 EU countries	CO2 emissions per-capita	Club convergence test	Five convergence clubs
Erdogan and Okumus (2021)	1961-2016	89 countries	Ecological footprint per-capita	Stochastic convergence, club convergence test	Stochastic divergence, multiple convergence clubs
Erdogan and Solarin (2021)	1960-2016	151 countries	CO2 emissions per-capita	Stochastic convergence	Mixed results in different income levels
Haider et al. (2021)	1990-2017	172 countries	Biomass material footprint	Club convergence test	Six convergence clubs
İçik et al. (2021)	1961-2016	NAFTA/USMCA countries	Ecological footprint per-capita	Stochastic convergence	48.08% of the sample is stochastic convergent

Marrero et al. (2021)	1990-2014	22 European countries	Road transport CO2 emissions per-capita	Club convergence and stochastic convergence	Overall convergence
Matsuki and Pan (2021)	1907-2011	7 developing countries of Asia	CO2 emissions per-capita	Stochastic convergence	71.43% of the sample is stochastic convergent
Nazlioglu et al. (2021)	1960-2016	OPEC countries	CO2 emissions per-capita	Stochastic convergence	Stochastic divergence
Payne and Apergis (2021)	1972-2014	65 developing countries	CO2 emissions per-capita	Stochastic convergence, club convergence test	Stochastic convergence, multiple convergence clubs
Solarin et al. (2021)	1750-2019	G7 countries	NO _x emissions at the aggregate and sectoral level	Stochastic convergence	Mixed results
Tiwari et al. (2021)	1976-2014	50 states of the US	CO2 emissions	Stochastic convergence, club convergence test	Stochastic divergence, four convergence clubs
Belloc and Molina (2022)	1970-2018	39 African countries	Ecological footprint per-capita	Club convergence test	Two convergence clubs
Bello et al. (2022)	1973-2018	49 African countries	Ecological footprint per-capita	Stochastic convergence	77.55% of the sample is stochastic convergent
Çelik et al. (2022)	1961-2017	ECCAS and ECOWAS countries	Ecological footprint per-capita	Stochastic convergence	Stochastic convergence
Dogah and Churchill (2022)	1960-2018	7 ASEAN member states	CO2 emissions per-capita from coal, oil, natural gas and cement production	Club convergence test	Multiple convergence clubs
Fernández-Amador et al. (2022)	1997-2014	66 countries	Production-based and consumption-based CH4 emissions	Conditional beta-convergence	Conditional convergence
Mikael and Heshmati (2022)	1960-2016	39 American countries	CO2 emissions	Club convergence test	Two convergence clubs for CO2 emissions per-capita and four convergence clubs for CO2 emissions intensity
Payne et al. (2022)	1990-2018	183 countries	GHG emissions per-capita	Stochastic convergence	No convergence
Solarin et al. (2022a)	1871-2014	37 countries	CH4 emissions	Stochastic convergence	Most of the OECD countries fail to convergence
Solarin et al. (2022b)	1750-2019	37 OECD countries	Ammonia emissions at the aggregate level, by	Stochastic convergence	Stochastic divergence

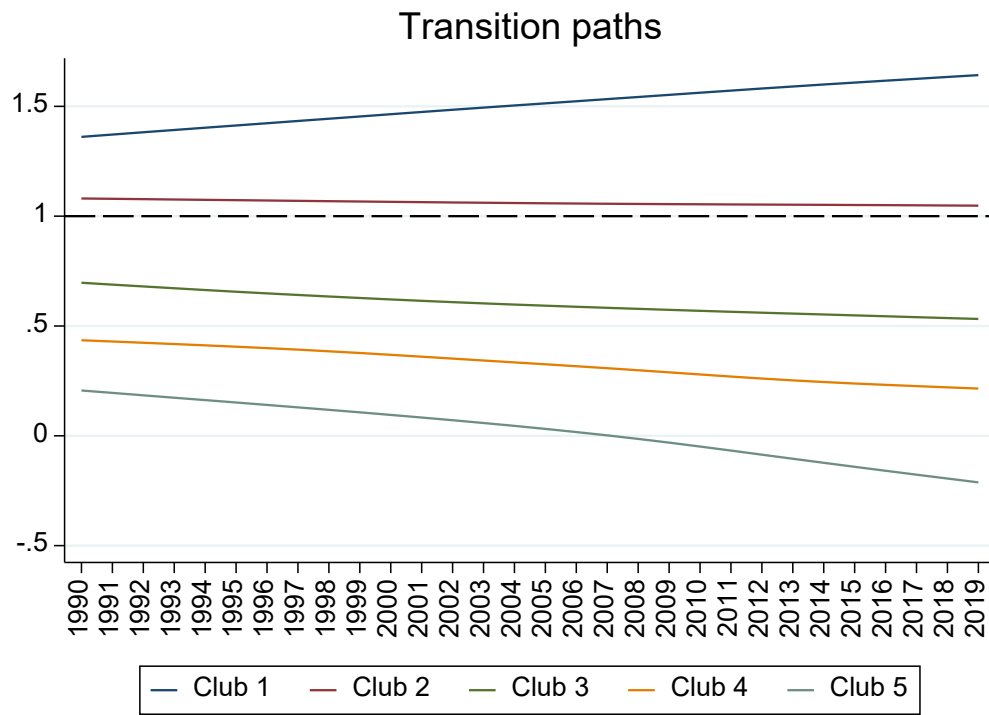
			sector, and by fuel source		
Yilanci et al. (2022a)	1961-2016	G7 countries	CO2 emissions and ecological footprint per-capita	Stochastic convergence	Stochastic convergence
Yilanci et al. (2022b)	1968-2017	ECOWAS countries	Ecological footprint per-capita	Stochastic convergence	Stochastic convergence
Akram et al. (2023)	2003-2019	16 Indian states	CO2 emissions	Club convergence test	Three convergence clubs
Arogundade et al. (2023)	1990-2017	181 countries	Ecological footprint per-capita	Club convergence test	Multiple convergence clubs
Bayraktar et al. (2023)	1992-2017	BRICS-T countries	Ecological footprint per-capita	Stochastic convergence	40% of the sample is stochastic convergent
Bektaş and Ursavaş (2023)	1981-2015	OECD countries	Ecological footprint per-capita	Club convergence test	Two convergence clubs
Solarin (2023)	1820-2019	20 OECD countries	Non methane volatile organic compound emissions per-capita	Beta, sigma and stochastic convergence	Stochastic convergence both at aggregate and disaggregate levels
Yilanci and Abbas (2023)	1961-2018	BASIC countries	Ecological footprint per-capita	Stochastic convergence	Stochastic short-run convergence for all countries and for India and South Africa in the long-run

Appendix Table 2. List of countries included in each continent

Continent	Countries
Africa [42]	Algeria, Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Central African Republic, Chad, Comoros, Djibouti, Egypt, Eswatini, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Libya, Madagascar, Malawi, Mali, Mauritania, Mauritius, Morocco, Niger, Nigeria, Rwanda, Senegal, Seychelles, Sierra Leone, South Africa, Sudan, Tanzania, Togo, Tunisia, Uganda, Zambia, Zimbabwe
Asia [25]	Bahrain, Bangladesh, China, Cyprus, India, Indonesia, Japan, Jordan, Laos, Lebanon, Malaysia, Maldives, Nepal, Oman, Pakistan, Philippines, Qatar, Saudi Arabia, Singapore, South Korea, Sri Lanka, Thailand, Turkey, United Arab Emirates, Vietnam
Australia and Oceania [4]	Australia, New Zealand, Papua New Guinea, Vanuatu
Europe [20]	Albania, Austria, Belgium, Bulgaria, Denmark, France, Germany, Greece, Iceland, Ireland, Italy, Malta, Netherlands, Norway, Poland, Portugal, Spain, Sweden, Switzerland, United Kingdom
Latin American and the Caribbean [21]	Argentina, Barbados, Bolivia, Brazil, Chile, Colombia, Costa Rica, Dominican Republic, Ecuador, Guatemala, Guyana, Haiti, Honduras, Jamaica, Mexico, Nicaragua, Panama, Paraguay, Peru, Trinidad and Tobago, Uruguay
North America [2]	Canada, United States

Notes: Numbers in brackets stand for the number of countries within a given continent.

Appendix Figure 1. Transition paths per-capita GHG emissions



Appendix Table 3. Robustness check, $r = 1/10$

Variable	\hat{b} coefficient	log t -statistic
Per-capita GHG emissions	-0.8053	-37.1567**
Per-capita CO2 emissions	0.6978	17.6205
Per-capita N2O emissions	-0.5479	-7.1946**
Per-capita CH4 emissions	-2.8767	-8.5998**

Notes: ** indicates rejection of the null hypothesis of absolute convergence (the critical value is -1.65 at the 5% significance level).