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Club convergence of sustainable development: fresh evidence from developing and developed countries

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Abstract

Sustainability is a process that characterizes in a broad sense a nation's ecological performance and may display a time-varying pattern. Such dynamic trajectories may vary among different countries and prompt not only intriguing questions on space–time convergence but also on the possibility of club convergence. The scope of this study is to investigate the long-run convergence pattern of 137 countries, as presented by their sustainable development index (SDI) over the period 1990–2019. The statistical–econometric analysis used to identify convergence across (groups of) countries is based on the advanced Phillips and Sul (JAE 24:1153–1185, 2009; ECTA 75:1771–1855, 2007) method. The empirical findings from our study allow us to identify two SDI convergence clubs of countries. The first and the biggest club includes mainly the developing African and Asian countries; whereas, the second club includes many OECD countries including *inter alia* the US, Canada, and Australia. Our analysis brings to light that the transition paths of these two clubs show a significant divergence pattern; this a-symmetry calls also into question the effectiveness of global green policies, such as the clean development mechanism as foreseen in the Kyoto protocol.

Keywords Climate change · Club convergence · Developed and developing countries · Ecological footprint · SDI · Sustainability

JEL Classification C23 · Q5 · Q56

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1 Introduction

Sustainable development has gained a lot of attention in recent years all over the world, as it is increasingly seen as a necessary response to the environmental crisis. Sustainable development "*refers to a process of change in which the exploitation of resources, the direction of investments, the orientation of technological development, and institutional change are all in harmony and enhance both current and future potential to meet human needs and aspirations*" (United Nations 1987).

The importance of sustainable development is immense, as it is essential for protecting the environment and ensuring that resources are used efficiently and effectively. The first step toward achieving sustainable development is a (global and local) recognition of the need for change. By understanding the current environmental crisis, the long-term effects of current development practices, and the potential for a more sustainable future, individuals and organizations can focus on exploring effective ways to reduce the negative impacts of resource exploitation and use (Van den Bergh 2018).

Additionally, by focusing on sustainable development, individuals and institutions can help create a better future for generations to come. Sustainable development can help to reduce poverty, improve health, and increase access to resources. Furthermore, it can promote sustainability assessment using renewable energy sources, reduce greenhouse gas emissions, and increase the global economy (Sala et al. 2015). Therefore, sustainable development is essential for preserving the environment, creating a better future, and ensuring that resources are used efficiently and effectively. Ultimately, sustainable development is an important tool for protecting our planet and ensuring a favorable quality of life.

To give an example of its importance, it is noteworthy to highlight that the European Union (EU) has agreed on a wide range of policies, regulations, and investments designed to transform various sectors of the economy and society to be more sustainable and environmentally friendly. This initiative better known as the "*European Green Deal*" (EGD) aims to transform the EU countries into a fair and prosperous society, with a modern, resource-efficient, and competitive economy where by 2050, (1) there are no net emissions of greenhouse gases; (2) economic growth is decoupled from resource use; and (3) no person and no place is left behind.

It is thus obvious that the EGD covers economic, societal, and environmental challenges that Europe must overcome by 2050. These challenges are also met in the pursuit of making viable economic growth socially equitable and environmentally bearable, which captures the three pillars of Sustainable Development. From this perspective, the EGD is closely related to the 17 Sustainable Development Goals (SDGs) adopted by the United Nations (UN) General Assembly on 25 September 2015 as part of the 2030 Agenda for Sustainable Development. The 17 SDGs reflect a broad and ambitious plan of action for people, the planet, prosperity, peace, and partnership. Therefore, they are in line with the most common definition of sustainable development, according to which development is sustainable if "*it meets the needs of the present without compromising the ability of future generations to meet their own needs*" (United Nations 1987; Koundouri et al. 2021).

An important tool used to measure sustainable development is the ecological footprint, which measures the amount of land and sea area required to sustainably support a population's resource consumption and waste absorption (WWF 2016). This tool provides a measure of sustainability and can allow people to better understand their relationship to the environment. Consequently, sustainable development strategies seek to reduce the ecological footprint of current economic activities, thus allowing for economic growth while also protecting the environment.

The goal of this study is to investigate the convergence/divergence patterns of the sustainable development index (SDI) in a sample of 137 countries regardless of their development level. For this reason, we have included a representative global sample of developed and developing or emerging economies (e.g., Latin American, Asian, European countries, etc.) to find possible convergence clusters using the well-established Phillips and Sul (2007, 2009) statistical methodology (P–S).

The study which is closest to ours is the one by Sueyoshi and Wang (2020). Sueyoshi and Wang (2020) conduct a two-step analysis. In the first step, they construct two sustainable development metrics using data envelopment analysis (DEA) with two outputs—GDP (desirable output) and carbon emissions (undesirable output); one index where economic performance is given more weight and one index where environmental protection is the priority. In the second step, they perform a club convergence analysis by applying the P–S algorithm. However, their analysis ignores important variables capturing both development and sustainability aspects, such as years of schooling, life expectancy, and material footprint leading to the identification of more convergence clubs (four clubs when economic performance is prioritized and three clubs when environmental protection is given more weight). These variables are included in the sustainable development index used in our analysis, thus enhancing the robustness of our findings. Furthermore, in contrast to Sueyoshi and Wang (2020), we additionally attempt to identify the driving factors behind the formation of the convergence clubs.

This study has important novelties. First, it utilizes the P–S algorithm to trace if there exists a global convergence trend in the sustainable development mechanism or separate (distinct) club formations (clusters) among the sample countries that call for a more customized and direct environmental policy. Second, this study attempts to disentangle the driving factors of the SDI among the formulated club clusters based on the P–S algorithm; while, it tries to assess the effectiveness of prevailing climate change agreements. Third, linking the results drawn from the empirical analysis to the country level could be beneficial for government officials and policymakers to develop efficient policies for the accomplishment of the sustainable development goals (SDGs) by 2030, particularly for those countries with high incomes (developed countries). This connection could provide an opportunity for decision-makers to gain insight into strategies that could most effectively bring about desired sustainable outcomes (see also Tsani et al. 2020).

The remaining part of the study is structured as follows. Section 2 describes the sample and the variables used in the empirical analysis, alongside the econometric methodology. The next section proceeds with a discussion of the empirical results, while Sect. 4 concludes the paper by suggesting useful policy implications and avenues for future research.

2 Material and methods

To measure the progress in sustainable development, in recent years the sustainable development index (SDI) has been developed as a measurable tool. It is a composite index that measures social, economic, and environmental sustainability and considers the interactions between them (United Nations 2020). The SDI enables countries to assess their progress, identify areas of improvement, and develop policies to better promote sustainable development. By providing a holistic view of the progress in sustainable development, the SDI helps countries to identify and address many sustainable development issues they may face.

Building on the previously developed human development index (HDI), the sustainable development index (SDI) incorporates the environmental implications of the anthropocene era (see Pinar et al. 2022; Alexander et al. 2018; Hickel 2020 for further details). The SDI utilizes each country's human development score, which considers factors like life expectancy, education, and income, and divides it by their ecological overshoot. Ecological overshoot signifies the extent to which a nation's consumption-based CO_2 emissions and material footprint exceed their equitable share of planetary boundaries. Countries that excel in human development while operating within or near planetary boundaries will achieve higher scores on the SDI. The SDI aims to tackle the challenge of balancing human development with ecological sustainability. Nations that attain high levels of human development while maintaining low ecological footprints will rank more favorably on the SDI; whereas, countries with low human development or significant negative ecological impact alongside high human development will rank lower (Hickel 2020). Clearly, there can be substantial variations among countries in terms of their SDI rankings.

2.1 Sample and data

The sample includes annual data for 137 developed and developing countries drawn from the sustainable development index website over the period 1990–2019.[1] The sustainable development index developed by Hickel (2020) presents a thought-provoking alternative to the sustainable development scores provided by the United Nations Development Programme (UNDP). Unlike the UNDP's approach, which often relies on a combination of economic, social, and environmental indicators, Hickel's index challenges the dominant paradigm by focusing on more nuanced and holistic measures of sustainability. Hickel's framework delves deeply into the systemic imbalances between developed and developing nations, scrutinizing the impact of global economic structures, ecological footprints, and social equity. By emphasizing the importance of decoupling economic growth from environmental degradation and addressing underlying power dynamics, Hickel's index offers a fresh perspective on what constitutes genuine and lasting sustainable development. While both approaches share the goal of

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[1] The data used in this study can be downloaded from the sustainable development index website: https://www.sustainabledevelopmentindex.org/time-series.

Table 1 Descriptive statistics. Source: data retrieved from the sustainable development index website

Variables	N	Mean	Std. Dev.	Min.	Max.
Sustainable development index (SDI)	4110	0.569	0.170	0.0850	0.850
Human development variables					
Life expectancy (in years) (*le*)	4110	68.83	9.801	26.20	84.60
Expected years of schooling (*eysch*)	4110	12.12	3.347	2.100	23.30
Mean years of schooling (*mysch*)	4110	7.514	3.190	0.300	14.20
Gross National Income per capita, PPP (constant 2017 USD) (*gni*)	4110	17,722	19,434	420	104,640
Ecological variables					
CO_2 emissions (metric tons per capita) (*co2*)	4110	5.303	6.419	0	52.71
Material footprint (metric tons per capita) (*mfoot*)	4110	12.18	11.94	0.0400	78.19

For more information about the components and the construction of the SDI, see Hickel (2020)

improving human well-being and environmental health, the divergence lies in their methodologies and underlying philosophies, sparking important conversations about the multifaceted nature of development in an interconnected world.

The sustainable development index (SDI) can be computed by comparing two key indicators: (1) A "*development index*" derived from the human development index (HDI), which incorporates factors such as life expectancy (in years), educational attainment (represented by expected and average years of schooling), and income (measured by per capita Gross National Income); and (2) an "eco*logical impact index*" that assesses the extent to which a country's consumption-based CO_2 emissions (measured in tons) and material footprint (measured in tons) surpass its per capita allocation of planetary boundaries.

The material footprint indicator (MFI) is a quantitative measure utilized to assess the overall mass of materials extracted and consumed by a country, encompassing biomass, minerals, fossil fuels, and construction materials. The significance of this indicator arises from the fact that material extraction from both terrestrial and marine ecosystems can give rise to various concerns, including land-use alterations, chemical pollution, biodiversity decline, and other matters addressed within the framework of planetary boundaries. Although the MFI does not directly measure ecological impact, it is widely accepted and has strong empirical evidence backing its use as a proxy for this purpose (see among others Krausmann et al. 2009).

Table 1 presents the summary statistics. The table reveals that the SDI has an average value of 0.569 units; whereas, this variable has the lowest variance depicting a standard deviance equal to 0.170 compared with the rest of the sample variables. For the human development variables, the average life expectancy of the sample countries is approximately 69 years, the average expected years of schooling is 12.12 years, and the average years of schooling is 7.514 years. The gross national income per capita averages about 17,722 USD. For the ecological variables, it is evident that the average CO_2 emissions in the sample countries are equal to 5.3 metric tons per capita, and the average material footprint is 12.18 metric tons per capita ranging from 0.04 to 78.19.

2.2 Methodology

Based on recent similar studies on club convergence (Eleftheriou et al. 2022; Kerner and Wendler 2022; Cuestas et al. 2021; Polemis et al. 2021; Eleftheriou and Polemis 2020; Ulucak and Apergis 2018) we rely on the Phillips and Sul (2007, 2009) methodology (P–S) to explore possible convergence clusters. The P–S algorithm assesses the quantitative divergence between consecutive variables (elements), without relying on any assumptions about the stationary or non-stationary trends of the stochastic process (Eleftheriou et al. 2022; Burnett 2016).

The P–S club clustering methodology is a powerful tool that can be used to identify “clubs” of countries that share similar characteristics and are thus likely to behave similarly (Ulucak and Apergis 2018). The methodology supports that countries that share a similar level of development are likely to have similar policy preferences and objectives and that these shared preferences and objectives can be used to group them into distinct “clubs.” It uses a combination of statistical methods to identify clusters of countries. It combines cluster analysis, which uses data from a variety of sources to identify clusters of countries that share similar characteristics, with a multidimensional scaling technique, which assesses the distance between countries in terms of their similarities and differences.

This combination allows us to identify clusters of countries that are distinct from one another in terms of their characteristics, but that still share certain similarities. Once the clusters have been identified, we can then analyze the policy preferences and objectives of the countries within each cluster. This analysis is important as it can provide useful insights into the likely behavior of the countries within a particular cluster.

While there is a ‘wealth’ of techniques in the empirical literature of club convergence (see among others Christopoulos et al. 2022), the P–S approach appears to have several attractive features compared with other convergence methodologies [a detailed overview of the advantages of the P–S methodology can be found in Apergis et al. (2013)]. First, the fact that the theoretical foundations of the P–S test are not based on growth theory (e.g., β-convergence), extends its applicability to the study of economic variables other than output. Second, the endogenous identification of the existence of convergence clubs by the P–S methodology eliminates any bias caused by the a priori determination of regional clusters. Third, the P–S algorithm does not suffer from small-sample issues as opposed to the unit root and cointegration testing. Fourth, unlike traditional time series convergence methodologies (see Phillips and Sul 2009), the P–S test is appropriate in the case of temporal transitional heterogeneity (time-varying speed of convergence). Finally, the P–S methodology enables the identification of the members of each convergence club as opposed to the models of distribution dynamics [see Kounetas et al. 2021. For a more thorough treatment of distributional dynamics methodology, see also Quah (1996)].

The P–S approach employs a one-sided t test to examine the null hypothesis of convergence across all countries in our dataset, contrasting it with the alternative hypothesis of non-convergence for certain countries. The null hypothesis is deemed inconclusive when the t-value exceeds -1.65 at the 5% significance level. In cases where sample convergence is rejected, the Phillips and Sul (2007) algorithm is utilized to identify potential convergence clubs. Additionally, we ascertain the presence of additional convergence clubs by employing the aforementioned Phillips and Sul (2009) procedure and calculating the corresponding transition paths. A more detailed description of the methodology applied in our analysis is presented in the following paragraph.

The P–S methodology can be described as follows. Let X_{it} denote the SDI of country i at time t, and

$$X_{it} = \delta_{it}\mu_t, \tag{1}$$

where δ_{it} is the idiosyncratic component measuring the deviation of the SDI of each country from the common trend μ_t. The abovementioned idiosyncratic component is equal to (for more details on how δ_{it} is defined, see Phillips and Sul (2007), pp. 1772–1773):

$$\delta_{it} = \delta_t + \sigma_i \xi_{it} L(t)^{-1} t^{-a}, \tag{2}$$

where σ_i are idiosyncratic scale parameters, ξ_{it} is an independently and identically distributed random variable across the cross-section dimension i with zero mean and unit variance (but weakly dependent over t), $L(t)$ denotes a slowly varying function with $L(t) \rightarrow \infty$, when $t \rightarrow \infty$, and δ_i is a time-invariant fixed value. Phillips and Sul (2007) propose an algorithm for testing if all i's converge to single steady-state or multiple ones in terms of the variable of interest (SDI in our analysis). Specifically, the null hypothesis H_0: $\delta_i = \delta$ and $a \geq 0$ of convergence for all countries against the alternative one H_A: $\delta_i \neq \delta$ (for all i) or $a < 0$ of non-convergence for some countries is tested (for more details about the testing procedure see Phillips and Sul (2007), pp. 1788–1789 and Phillips and Sul (2009), p. 1168) through the following specification:

$$\log\left(\frac{H_1}{H_t}\right) - 2\log L(t) = \hat{c} + \hat{b}\log t + \hat{u}_t, \tag{3}$$

for $t = [rT], [rT]+1, \ldots, T$ with some $r > 0$, N denotes the number of countries, T the number of years, $H_t = (1/N)\sum_{i=1}^{N}(h_{it}-1)^2, h_{it} = \frac{X_{it}}{N^{-1}\sum_{i=1}^{N} X_{it}} = \frac{\delta_{it}}{N^{-1}\sum_{i=1}^{N}\delta_{it}}$, $L(t) = \log(t)$, $\hat{b} = 2\hat{a}$, where $\hat{a}$ is the least-squares estimate of a under the null hypothesis, (H_0) and u_t are weakly dependent, zero mean errors. As in Phillips and Sul (2007, 2009), we set r equal to 0.3. P–S conducted extensive Monte Carlo simulations to show that this value of r gives satisfactory results in terms of both the power and the size properties of the test (see Phillips and Sul 2007, pp. 1802–1803). The null hypothesis of sample convergence is rejected if $t_{\hat{b}} < -1.65$, where $t_{\hat{b}}$ is the t-statistic of $\hat{b}$ of a one-sided heteroskedasticity and autocorrelation consistent t test. If the null hypothesis is rejected, a further test for the existence of convergence clubs is conducted. This test consists of the following four steps (for more details, see Phillips and Sul (2007), pp. 1800–1801):

(i) First, the last period SDI values of all the countries included in our sample are sorted in descending order,
(ii) Second, the core club is formed by starting from the k highest-ordered countries ($2 \leq k \leq N$) and calculating the corresponding convergence t-statistic (t_k) based on (3). The size of the club k is determined by maximizing the t-statistic of (3) for $t_k > -1.65$,
(iii) Third, from the countries not included in the main core club, we add one country at a time to this core club and estimate (3). The new country is included in the convergence club if the corresponding t-statistic is greater than zero,
(iv) Fourth, a club is formed from all the countries failing to be included in the core club from the stage (iii). Equation (3) is estimated for this newly formed club. If the convergence criterion is not met, all the previous steps are repeated to determine whether that club can be divided into convergence clubs. If there is no k satisfying the convergence criterion in the second step, then we conclude that these countries diverge.

At this point, we should note that the use of a conservative sieve criterion regarding the t-statistic in the third step of the above four-step club clustering process may overestimate the number of convergence clubs. Therefore, following Phillips and Sul (2009), we conduct club merging tests using (3). Furthermore, it should be mentioned that the existence of a wide sample or the use of a conservative critical value may lead to the identification of many identical convergence clubs by the P–S methodology. To tackle this issue, Von Lyncker and Thoennessen (2017) proposed a merging technique that is robust to the above over-identification problem. However, the fact that the P–S cluster algorithm identifies only two clubs (see Table 2), implies that the results generated by both tests (the one proposed by Lyncker and Thoennessen (2017) and the P–S algorithm) will be eventually the same.

3 Results and discussion

Table 2 reports the results of the primary club clustering algorithm based on Phillips and Sul (2007). As it is evident from panel A, the results indicate rejection of the null hypothesis (convergence) for the full sample since the t-statistic is smaller (-17.1359) than the critical value (-1.65) at a 5% level of statistical significance. This means that we must deduce whether there are distinct convergence formations (clubs) within the 137 sample counties. It can be shown that there are two convergence clubs consisting of a different number of countries (see also Fig. 1). This happens since the value of the convergence coefficient ($\log t$) in each club now exceeds the critical value of the convergence test statistic (-1.65) based on the one-sided hypothesis testing. This results in the acceptance of the null hypothesis (convergence) at a 5% level of statistical significance. Apart from the SDI, we have

Table 2 Club convergence of sustainable development index (SDI) (1990–2019)

	Panel A: Phillips and Sul (2007)			Panel B: Phillips and Sul (2009)		
	log *t*	*t*-stat	New club	Final club	log *t*	*t*-stat
Full sample	− 1.0158 (0.0593)	− 17.1359**				
Club 1 [Afghanistan, Albania, Algeria, Argentina, Armenia, Bahrain, Bangladesh, Barbados, Belize, Benin, Bolivia, Brazil, Bulgaria, Burundi, Cambodia, Cameroon, Central African Republic, Chile, China, Colombia, Congo, Costa Rica, Croatia, Cuba, Côte d'Ivoire, Dem. Rep. of the Congo, Dominican Republic, Ecuador, Egypt, El Salvador, Eswatini, Fiji, France, Gabon, Gambia, Ghana, Greece, Guatemala, Guinea, Haiti, Honduras, Hungary, India, Indonesia, Iran, Iraq, Ireland, Israel, Italy, Jamaica, Jordan, Kenya, Kyrgyzstan, Laos, Latvia, Lesotho, Libya, Malawi, Malaysia, Mali, Malta, Mauritania, Mauritius, Mexico, Moldova, Mongolia, Morocco, Mozambique, Myanmar, Namibia, Nepal, Nicaragua, Niger, Pakistan, Panama, Papua New Guinea, Paraguay, Peru, Philippines, Poland, Portugal, Romania, Russian Federation, Rwanda, Samoa, Sao Tome and Principe, Senegal, Serbia, Sierra Leone, South Africa, Spain, Sri Lanka, Syria, Tajikistan, Tanzania, Thailand, Togo, Trinidad and Tobago, Tunisia, Turkey, Uganda, Ukraine, United Kingdom, Uruguay, Venezuela, Viet Nam, Yemen, Zambia, Zimbabwe] (club 1 mean SDI = 0.6107)	− 0.088 (0.0543)	− 1.619		Club 1	− 0.088 (0.0543)	− 1.619

Table 2 (continued)

	Panel A: Phillips and Sul (2007)			Panel B: Phillips and Sul (2009)		
	log *t*	*t*-stat	New club	Final club	log *t*	*t*-stat
Club 2 [Australia, Austria, Belgium, Botswana, Brunei Darussalam, Canada, Cyprus, Denmark, Estonia, Finland, Germany, Iceland, Japan, Kazakhstan, Korea, Kuwait, Lithuania, Netherlands, New Zealand, Norway, Qatar, Saudi Arabia, Singapore, Slovakia, Sweden, Switzerland, United Arab Emirates, United States of America] (club 2 mean SDI = 0.4087)	− 0.185 (0.1277)	− 1.446		Club 2	− 0.185 (0.1277)	− 1.446

log *t* = estimated convergence coefficient; *t*-stat = convergence test statistic. The convergence test statistic is distributed as a simple one-sided *t* test with a critical value of − 1.65. Standard errors are reported in parentheses

**denotes rejection of the null hypothesis (convergence) at 5% level of statistical significance. The estimation was performed with the use of the STATA codes provided byDu (2017)

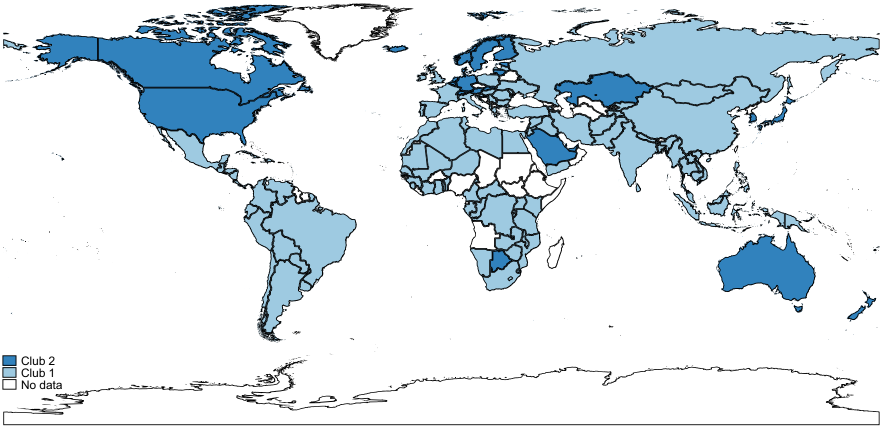

Fig. 1 Map of SDI convergence clubs

attempted to use two other indicators, namely the happy planet index available from the New Economics Foundation and the CPIA policy and institutions for environmental sustainability rating index drawn from the World Bank, as robustness checks. However, the limited time span covering nearly 15 years and the number of missing values in both indicators prevented us from the relevant testing.

Club 1 consists of 109 countries (Afghanistan, Albania, Algeria, Argentina, Armenia, Bahrain, Bangladesh, Barbados, Belize, Benin, Bolivia, Brazil, Bulgaria, Burundi, Cambodia, Cameroon, Central African Republic, Chile, China, Colombia, Congo, Costa Rica, Croatia, Cuba, Côte d'Ivoire, Dem. Rep. of the Congo, Dominican Republic, Ecuador, Egypt, El Salvador, Eswatini, Fiji, France, Gabon, Gambia, Ghana, Greece, Guatemala, Guinea, Haiti, Honduras, Hungary, India, Indonesia, Iran, Iraq, Ireland, Israel, Italy, Jamaica, Jordan, Kenya, Kyrgyzstan, Laos, Latvia, Lesotho, Libya, Malawi, Malaysia, Mali, Malta, Mauritania, Mauritius, Mexico, Moldova, Mongolia, Morocco, Mozambique, Myanmar, Namibia, Nepal, Nicaragua, Niger, Pakistan, Panama, Papua New Guinea, Paraguay, Peru, Philippines, Poland, Portugal, Romania, Russian Federation, Rwanda, Samoa, Sao Tome and Principe, Senegal, Serbia, Sierra Leone, South Africa, Spain, Sri Lanka, Syria, Tajikistan, Tanzania, Thailand, Togo, Trinidad and Tobago, Tunisia, Turkey, Uganda, Ukraine, United Kingdom, Uruguay, Venezuela, Vietnam, Yemen, Zambia, Zimbabwe). This club includes mainly the developing and emerging countries, while Club 2 consists of the rest 28 countries (Australia, Austria, Belgium, Botswana, Brunei Darussalam, Canada, Cyprus, Denmark, Estonia, Finland, Germany, Iceland, Japan, Kazakhstan, Korea, Kuwait, Lithuania, Netherlands, New Zealand, Norway, Qatar, Saudi Arabia, Singapore, Slovakia, Sweden, Switzerland, United Arab Emirates, and the USA). This specific club includes mainly developed countries such as the USA, Canada, Australia, Sweden, and the United Arab Emirates among others with a relatively high score on the HDI but a low score on the ecological impact index.

After a careful inspection of Fig. 1, we argue that there is no strong evidence of spatial spillover effects for club 2. We notice that some Central and Northern

European countries such as Germany, Denmark, Austria, Belgium, and Sweden are included in the same club with the USA, Saudi Arabia, and Australia. The common feature for these countries except for the high development level is the low score attributed to their ecological impact index (CO_2 emissions and material footprint). On the other hand, spatial proximity patterns are most evident in club 1, where certain African developing countries coincide with other contingent European and Asian countries.

The analysis of the speed of convergence among the two primary clubs reveals some important findings. Club 1 has a negative value of $a = -0.044$, indicating a higher adjustment speed to convergence than club 2. The latter exhibits a smaller (negative) value of $a = -0.0925$, meaning that the countries included in the specific club formation are moving toward each other slowly in relative terms (Polemis et al. 2022). These findings suggest that the speed of convergence among the two primary clubs seems to vary to some extent, with club 1 recording the highest speed of convergence. This finding unravels the existence of heterogeneity among the sample countries. This could be the effect of certain disparities in socioeconomic characteristics such as income or population density or could be the result of different ecological and environmental policy goals.

The convergence merging club algorithm of Phillips and Sul (2009) is not able to merge the two (primary) detected clubs into one since the null hypothesis cannot be rejected in both formations (see panel B in Table 2).

In Table 3, the essential tests for comparing the means of the two convergence clubs are conducted, considering both homogeneous and heterogeneous covariance matrices (the test produces the same results, in terms of significance, under both homogeneous and heterogeneous covariance matrices). The results reveal that the null hypothesis of equal means is rejected with a statistical significance level of 1% for all the variables in the sample, across both formation clubs. To ensure the reliability of our findings, we have conducted two additional tests: the two-sample Wilcoxon rank-sum (Mann–Whitney) test and the two-sample nonparametric test for equality of medians. These tests provide further support and confirmation of our earlier findings (for brevity, the results of the two tests are available from the authors upon request).

As it is evident from the relevant table, the magnitude of the driving factors (components) of the SDI differs substantially between the two identified clubs, revealing heterogeneity in terms of human development and ecological impact assessment among the sample countries. If we look at the ecological footprint of the two formulated clusters, as it is expressed by the two proxy variables (CO_2 emissions and material footprint), we see that club 1 performs better than club 2. This happens since the magnitude of the mean value in club 2 is nearly four times larger than its counterpart indicating worse ecological performance. On the contrary, countries that form club 1, seem to lag in terms of the human development components (e.g., life expectancy, expected and mean years of schooling, and gross national income) compared to the other club.

To further test the robustness of the results in Table 3, we estimate logit specifications, using as a dependent variable a binary indicator taking the value of 1 if a country belongs to convergence club 1, and 0 otherwise. In each specification,

Table 3 SDI driving factors

Driving factor	Convergence club	Mean value
Human development factors		
Life expectancy (in years)	1	66.804***
	2	76.710***
Expected years of schooling	1	11.304***
	2	15.273***
Mean years of schooling	1	6.7201***
	2	10.602***
Gross national income per capita, PPP (constant 2017 $)	1	10,819.03***
	2	44,596.38***
Ecological development factors		
CO_2 emissions (metric tons per capita)	1	3.0693***
	2	13.996***
Material footprint (metric tons per capita)	1	7.8589***
	2	29.001***

The mean value of each driving factor for each SDI convergence club is reported

***indicates the rejection of the null hypothesis of equal means at 1% significance level

we use as an explanatory variable each of the SDI components reported in Table 1, averaged over the sample period for each country. The findings, which are reported in Table 4, corroborate the results presented in Table 3.

Lastly, Fig. 2 provides the transition paths of the two (final) estimated convergence clubs. As it is evident, from the inspection of the relevant figures, there is an increasing trend of the SDI regarding the transition path of club 1 ("leaders") during the whole sample period (1990–2019). This finding reflects the good ecological performance of many (developing) countries that fall within planetary boundaries compared with the wealthier nations (see club 2) following an inverse (downward) trend. The decreasing trend of the transition path in club 2 ("laggards") is more pronounced after the Kyoto Protocol ratification (1997–2008) which after a short period of recovery (2008–2009) bounces back.

The difference in terms of the SDI trend between the two identified clubs is less prominent, even after the first three years of the Kyoto protocol ratification (1997–2000); whereas, the divergence pattern is striking henceforth and deepens after the Paris Accord (December 2015). The intense divergence pattern of the SDI between the two clubs ("leaders" and "laggards") unfolds significant efficiency issues of the national binding climate agreements such as the Paris Accord or Kyoto protocol. Regarding the first legally binding climate agreement back in 1997 (Kyoto protocol), we observe that one of the three implementation mechanisms was the clean development mechanism. The clean development mechanism (CDM) first introduced in the Kyoto protocol (December 1997), enables countries that have commitments to reduce or limit emissions (Annex B

Table 4 Logit regression results—robustness test

Variables	Coefficients	Marginal effects	Coefficients	Marginal effects	Coefficients	Marginal effects	Coefficients	Marginal effects	Coefficients	Marginal effects	Coefficients	Marginal effects
mean_le	− 0.253*** (0.0794)	− 0.0303*** (0.00603)										
mean_eysch			− 0.763*** (0.128)	− 0.0776*** (0.00759)								
mean_mysch					− 0.776*** (0.165)	− 0.0824*** (0.00909)						
mean_gni							− 0.000122*** (2.04e−05)	− 8.70e−06*** (7.19e−07)				
mean_co2									− 0.471*** (0.124)	− 0.0330*** (0.00306)		
mean_mfoot											− 0.335*** (0.0613)	− 0.0187*** (0.00106)
constant	19.85*** (6.028)		11.65*** (1.873)		8.401*** (1.710)		4.364*** (0.589)		4.834*** (0.957)		7.368*** (1.230)	
Observations	137		137		137		137		137		137	
Pseudo-R2	0.275		0.360		0.351		0.513		0.542		0.648	
Log-likelihood	− 50.33		− 44.37		− 45.01		− 33.79		− 31.80		− 24.43	
Chi-squared	10.13		35.42		22.10		35.56		14.36		29.88	
Prob. Wald	0.00146		2.66e−09		2.59e−06		2.47e−09		0.000151		4.59e−08	

Dependent variable = binary variable taking the value of 1 if country *i* belongs to convergence Club 1 (see Table 2) and 0 otherwise. *mean_le* = sample period average of *le* for country *i*; *mean_eysch* = sample period average of *eysch* for country *i*; *mean_mysch* = sample period average of *mysch* for country *i*; *mean_gni* = sample period average of *gni* for country *i*; *mean_co2* = sample period average of *co2* for country *i*; *mean_mfoot* = sample period average of *mfoot* for country *i*. See Table 1 for variable abbreviations. Robust standard errors are reported in parentheses

$^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$

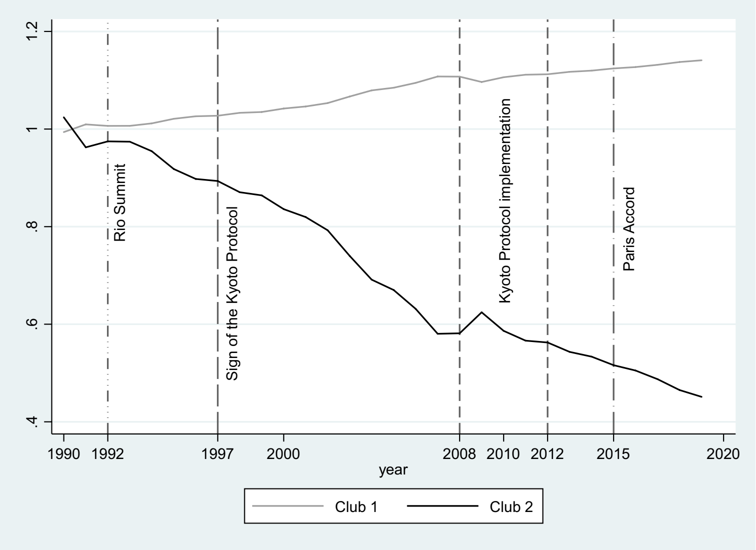

Fig. 2 Transition paths

Parties) to undertake emission reduction initiatives in developing nations. This mechanism is widely regarded as a pioneering global environmental investment and credit scheme, providing a standardized emissions offset instrument in the form of certified emission reduction (CERs).

However, based on the findings of the present study, it seems that this mechanism had only a transitory effect on the convergence of the SDI between the two clubs mostly evident at the early stages of the Kyoto protocol implementation (2008–2009). In other words, the "clean" investments of the richer (developed/industrialized) countries targeted at the poorer (developing) ones do not allow them to meet or limit their emission reduction targets, as was primarily set by the Kyoto protocol. On the other hand, the developing countries (club 1) seem to have benefited from this mechanism which fostered sustainable development and emission reductions at a faster pace than the developed countries (club 2).

All in all, the empirical findings of this study, show that there are distinct convergence clubs formed around distinct equilibrium points among the sample countries, particularly after the Kyoto Protocol was ratified (the late 1990s). This divergence can be attributed to the diverse ecological footprints of the sample countries, mainly due to their varying environmental policies for carbon dioxide mitigation and climate change. This result validates our prior conclusion that there is a diversified distribution of sustainability levels among countries and years, which supports a recent study by Polemis et al. (2021) regarding the eco-efficiency convergence patterns in the OECD countries.

4 Conclusions and policy implications

The present study attempts to analyze the convergence pattern of the sustainable development index across 137 countries from 1990 to 2019, using the Phillips and Sul (2007, 2009) approach. The results indicate the formation of two convergence clubs. The first club, the largest one, consists mainly of developing African and Asian countries; while, the second club includes most of the developed countries studied, such as the US, Canada, and Australia. The transition paths reveal a significant divergence pattern between the two clustering clubs, suggesting important implications for climate policy to achieve the United Nations' Sustainable Development Goals.

Drawing upon our empirical findings, we contend that the SDI fosters a fresh perspective on progress in the twenty-first century, one that aligns with the ecological well-being of our planet. At the apex of the SDI, rankings are countries characterized by high human development and minimal ecological impact. Conversely, those with low human development and substantial ecological impact, as well as those with high human development coupled with a significant ecological footprint, find themselves at the lower end. Effectively implementing the SDI necessitates substantial advancements in human development for less affluent nations while ensuring their ecological footprint remains within sustainable thresholds. Similarly, wealthier nations must strive to either sustain or elevate human development levels while actively reducing their ecological impact to sustainable levels. For the developed countries, we argue that they must strive to ensure that human development continues to progress, while drastically reducing its ecological footprint to a sustainable level. Therefore, for developed countries, a comprehensive approach that integrates climate action into broader sustainable development strategies is crucial. Governments, in collaboration with the private sector and civil society, need to implement policies that address climate change challenges while promoting economic growth, social equity, and environmental sustainability. Aligning climate policies with broader sustainable development goals can ensure a holistic approach to addressing environmental, social, and economic challenges. Policies should encourage and incentivize the transition to renewable energy sources (e.g., solar, wind, and hydroelectric power). Moreover, their governments can promote research and development in green technologies to drive innovation and enhance energy efficiency by focusing *inter alia* on sustainable natural resource management to prevent over-exploitation and degradation of ecosystems.

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Declarations

Conflict of interest All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript. All authors declare that the research does not involve human participants, or animals.

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