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How does population growth affect economic growth and vice versa? An empirical analysis

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Abstract

Purpose – Our paper studies a central issue with a long history in economics: the relationship between population and economic growth. We analyze the joint dynamics of economic and demographic growth in 111 countries during the period 1960–2019.

Design/methodology/approach – Using the concept of economic regime, the paper introduces the notion of distance between the dynamical paths of different countries. Then, a minimal spanning tree (MST) and a hierarchical tree (HT) are constructed to detect groups of countries sharing similar dynamic performance.

Findings – The methodology confirms the existence of three country clubs, each of which exhibits a different dynamic behavior pattern. The analysis also shows that the clusters clearly differ with respect to the evolution of other fundamental variables not previously considered [gross domestic product (GDP) per capita, human capital and life expectancy, among others].

Practical implications – Our results indirectly suggest the existence of dynamic interdependence in the trajectories of economic growth and population change between countries. It also provides evidence against single-model approaches to explain the interdependence between demographic change and economic growth.

Originality/value – We introduce a methodology that allows for a model-free topological and hierarchical description of the interplay between economic growth and population.

Keywords Time series analysis, Non parametric analysis, Minimal spanning tree, Hierarchical tree, Population dynamics, Economic growth

Paper type Research paper

Introduction

A persistent topic in the public discourse revolves around the interplay between population and its impact on economic growth [1]. According to the latest United Nations [2] reports, population growth projections indicate a sustained deceleration followed by successive stability. Nevertheless, the process has been far from consistent across different economies. Vast regions of the globe continue to experience high population growth rates, while contrasting areas are facing stagnant or even declining demographic trends. However, even if these projections materialize, there is no reason to believe that migratory movements will cease, nor for asserting that the population's composition and magnitude will remain static. Until economies achieve a stable population in terms of composition and size, they will encounter potential repercussions on both economic growth and welfare. Said potential effects, along with their magnitude and the mechanisms through which they operate, remain largely uncertain. This paper contributes to the existing empirical literature concerning a

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crucial issue with a rich history within economics: the complex relationship between population and economic growth.

The study of the relations between economic and population growth has a significant history within the field of economics. Population has held a central position in the exploration of economic growth, a role that can be traced back at least to Adam Smith's assertion (Smith (1776) 2010, p. 12) that a nation's wealth should be measured in terms of per capita income rather than aggregate income. Shortly after, Malthus (2018) 2018 proposed his "Population Principle", which postulates that population and aggregate income dynamics are inextricably related in a bidirectional causal relationship. His vision became highly influential in the development of economic theory, and since then, no influential economist studied economic growth without considering population dynamics. Nonetheless, no consensus has emerged on whether population growth is beneficial, neutral, or detrimental to economic growth. Similarly, there is no unanimous agreement on the effects of economic growth on population dynamics. However, this particular aspect or direction of causation has not been extensively explored in the existing literature.

Modern growth theories treat population differently from the classics. Broadly, standard growth models abstract out the role of population by assuming it to be an exogenous variable that expands at a fixed rate.

Solow's model (1956) establishes a connection between population dynamics and economic growth via the population growth rate. The model predicts a negative correlation between population growth rate and per capita income. Over the long term, a higher population growth rate leads to a lower steady-state per capita output. In the short term, a higher population growth rate results in a reduced growth of per capita output during the transition to the new steady-state equilibrium. The model does not differentiate population from labor force, implicitly assuming that both grow at the same rate, or in another manner that keeps the population structure stable. In this setting, the assumption of decreasing marginal returns results in a stable or fixated per capita output. Sustained growth can only be achieved through continuous technological progress.

Certain endogenous economic growth models (Romer, 1986, 1990), posit a positive relation between population and economic growth. In these models, population is not merely a proxy for the labor force, but the source of scientists and innovators. The greater their number, the more technological progress. At the same time, a larger population generates a higher demand for innovative goods, which in turn alters the human capital endowment, resulting in higher productivity (Kuznets, 1967; Kremer, 1993; Simon, 1989). This approach diverges from previous efforts to model economic growth by incorporating controversial "scale effects".

Other theoretical approaches adopt the classic's approach of considering population as an endogenously determined variable. Hansen and Prescott (2002), Irmen (2004), Mierau and Turnovsky (2014), Corchón (2016), and more recently, Bucci *et al.* (2019), among others, have developed models in which the relation between population growth and economic growth is nonmonotonic, with effects that vary in size, sign and direction.

When delving into the empirical literature on the interplay between economic growth and demographic change, there is a pronounced emphasis on both testing for cointegration between these two variables and studying their causal relations. To contextualize our research, the subsequent section offers a representative and updated review of this literature. The primary objective is to highlight the lack of consensus and the extensive range of results, which, in certain instances, present contradictions.

The present work analyzes the hierarchical structure and the dynamic relations between economic and population growth for a large group of countries using a nonparametric approach. The main advantage of this technique is that it allowed us to study and compare the interplay of population growth and economic growth without a predetermined model. The predominant approach of the vast majority of surveyed studies, characterized as *ex ante*, is to begin with a theoretical model (primarily Solow's model) that predicts the influence of population growth on economic growth and then assess this empirically. In contrast, our proposed model will take an *ex post* perspective, employing an inductive approach. In this sense, cluster analysis allows us to categorize the countries within the sample according to the resemblance of their dynamic behaviors.

Our study is limited to considering only the interrelationship between population and economic growth. We did not take into account other relevant variables that affect the relationship, as documented by the analyses of Magazzino and Cerulli (2019), who analyze the links between economic growth, urban population and CO2 emissions or studies on the impact of aging (associated with slower population growth) on productivity and growth (Cristea *et al.*, 2020; Maestra *et al.*, 2023).

The originality of this research derives from its multifaceted objectives. Firstly, it introduces a methodology that facilitates a model-free, topological and hierarchical portrayal of the interplay between economic growth and population. To the best of our knowledge, no prior endeavors in the literature have relied upon this methodology. Secondly, while we refrain from delving into the underlying mechanisms (causes, effects and propagation mechanisms), the proposed procedure indirectly implies the presence of dynamic interdependence in the trajectories of economic growth and population change between countries. Moreover, it offers evidence against approaches centered on singular models for explaining the interdependence between demographic change and economic growth. Furthermore, it provides evidence in support of conceptualizing this relationship as nonlinear and nonmonotonic. This finding has strong implications for policy recommendations. If the relationship is nonlinear, and the sign and direction of the causal relationships change over time, it is necessary to evaluate policies in terms of timeliness and efficiency in order to adapt them to these changes.

This paper is organized as follows. In the next section, we provide a brief review of the empirical literature concerning the relations between economic growth and demographic change. The third section introduces the data and a set of tools that enabled us to conduct the empirical analysis of comparative economic growth without imposing an *ex ante* model. Then, the methodology employed to construct minimum spanning trees (MSTs) and hierarchical trees (HTs) is detailed. We also introduce the concept of regime, analyze symbolic time series and define a distance within this space to measure the degree of similarity among countries. With these tools at our disposal, we then proceed to detect and analyze the global structure, taxonomy and hierarchy within our sample of countries in the fourth section. Lastly, the fifth section presents our concluding remarks.

Population dynamics and economic growth: a review of the empirical literature

The initial research efforts aimed to empirically assess the influence of population change on economic growth were based on correlation analysis. An example of this is provided by Coale and Hover (1958), who studied India and identified a negative relationship between the variables. The authors concluded that rapid population growth constituted an obstacle to economic growth in that country. Interestingly, their conclusions were reversed when studying Mexico between 1955 and 1975 (Coale, 1977). By analyzing six-year periods across 86 different countries, Barlow (1994) found no discernible correlation between the two variables. When incorporating fertility rates into the analysis, the authors were able to uncover a significant adverse relationship between population change and economic growth. The same analysis was subsequently conducted separating countries by income levels. This examination revealed that while the correlation remained negative for both low and high-income countries, it retained statistical significance solely for the former. Additionally, a positive correlation emerged between fertility lagged by one generation and economic growth.

Starting in the late 1960s, a considerable share of the empirical studies consists in cross-country section analysis regressions. The analyses conducted by Kuznets (1967), Thirlwall

(1972), Simon (1989) and Crenshaw *et al.* (1997), among others, did not find evidence of a negative relationship. Their estimations resulted in positive coefficients, although they were not statistically significant. Utilizing fixed-effects modeling (FEM) and random-effects modeling (REM), Kelley and Schmidt (1995) studied 89 countries with populations exceeding one million inhabitants across three different periods: 1960–1970, 1970–1980 and 1980–1990. Their estimation models included population-related variables –such as education and density– as well as economic variables like savings and investment. Their analysis did not uncover evidence supporting a significant impact of population on per capita income during the 1960 and 1970s.

The publication of the Penn tables from the Maddison Project (particularly Maddison, 1995), marked a significant milestone in this field of study. By providing standardized per capita gross domestic product (GDP) statistics across countries, it greatly facilitated comparative analyses of the intricate relationship between population and economic growth. Table 1 summarizes the surveyed empirical literature that has analyzed the connections amongst demographic and economic growth. This summary includes detailed information on the analysis period, sample, method used and main findings.

As shown in Table 1, the described studies attempt to identify the magnitude and direction of the effects between population growth and per capita income growth using different econometric tools and data structures (time series and panel data). These analyses span distinct time periods, consider different groups of countries –including developed and/or developing nations, often examined separately– and control for varying factors (education, health, institutional quality and geography). Despite these efforts, the debate persists. Regarding causality (Granger causality), a diverse range of outcomes is observed.

(1) p $\Rightarrow$ y, unidirectional causality, population growth stimulates economic growth: Darrat *et al.* (1999), Yao *et al.* (2007), Liu *et al.* (2013), Ali *et al.* (2013), Furuoka (2013), Musa (2015) and Sebikabu *et al.* (2020).

(2) y $\Rightarrow$ *p*, unidirectional causality, economic growth stimulates population to grow: Nakibulla (1998).

(3) p $\Leftrightarrow$ y, bidirectional causality, population growth stimulates and is stimulated by economic growth: Garza-Rodriguez *et al.* (2016), Alvarez-Diaz *et al.* (2018) and Furuoka (2018).

(4) Noncausality, population growth neither stimulates nor is stimulated by economic growth: Dawson and Tiffin (1998), Thornton (2001) and Mulok *et al.* (2011).

(5) Mixed results: Jung and Quddus (1986), Kapuria-Foreman (1995), Tsen and Furuoka (2005) and Chang *et al.* (2017).

The reviewed regression analyses, particularly those involving cointegration testing, often presuppose a linear model. This assumption is partly rooted in their utilization of the underlying model (usually Solow's model), which postulates a linear relationship. The goal of these studies is to examine the existence of a linear long-term relation between population and per capita output growth rates. However, a smaller subset of studies employs nonparametric approaches to investigate the dynamic interplay between demographic change and economic growth, often revealing evidence of a nonlinear causal relationship between said variables. Some examples of such studies include An and Jeon (2006) and Azomahou and Mishra (2008). The former examines the data from 25 Organization for Economic Co-operation and Development (OECD) countries over the period 1960–2000 [3].

Their findings depict a dynamic relationship between the two variables that undergoes changes over time. Initially, demographic change exerts a positive impact on economic

Autor	Period	Sample	Estimation method	Findings
Jung and Quddus (1986)	1950–1980	44 countries	Granger Causality test	$p \Rightarrow + y$ $p \Rightarrow - y$ $y \Rightarrow + p$ $y \Rightarrow - p$ Non causality
Kelly and Schmidt (1995)	1960–1970 1970–1980 1980–1990	86 countries	FEM REM	No impact p to y
Kapuria-Foreman (1995)	1961–1991 1961–1990 1953–1989 1951–1990 1953–1989 1961–1991 1949–1991 1952–1991 1961–1990 1961–1990 1951–1990 1958–1990 1961–1990 1952–1990 1948–1986	Nepal India China Ghana Sri Lanka Bolivia Philippines Guatemala Syria Peru Thailand Turkey Chile Argentina Mexico	Granger Causality test	$p \Rightarrow + y$ $p + \Leftrightarrow -^{**} y$ $p - \Leftrightarrow +^{**} y$ $y \Rightarrow - p$ $y \Rightarrow - p$ Noncausality $p \Rightarrow +^{**} y$ $y \Rightarrow - p$ $y \Rightarrow -^{*} p$ Noncausality $p - \Leftrightarrow +^{**} y$ $p - \Leftrightarrow +^{**} y$ Noncausality $p \Rightarrow +^{**} y$
Nakibulla (1998)	1960–1990	Bangladesh	VAR	$y \Rightarrow +p$
Dawson and Tiffin (1998)	1950–1993	India	Cointegration (Johansen	Noncausality
Darrat and Al-Yousif (1999)	1950–1996	20 countries	Cointegration VEC	$p \Rightarrow +^{*} y$
Bloom *et al.* (2000)	1965–1990	70 countries	OLS	$p \Rightarrow y$
Thornton (2001)	1900–1994 1925–1994 1921–1994 1913–1994	Argentina, Brazil Chile, Venezuela Colombia Mexico Peru	Granger Test VAR	Noncausality
Li and Zhang (2007)	1978–1998	China	VI – GMM	$p \Rightarrow - y$
Furuoka (2009)	1961–2003	Thailand	Cointegration (Johansen) VEC	$p \Rightarrow y$
Hasan (2010)	1952–1998	China	VAR VEC	$y \Rightarrow - p$
Choudry and Elhorst (2010)	1961–2003	China India Pakistan	OLS	Effect positive (growth differential pop of working age – total pop) 46% 39% 25%
Mulok *et al.* (2011)	1960–2009	Malaysia	Cointegration (Johansen) VAR, Toda-Yamamoto	Noncausality

(*continued*)

Table 1.
Empirical literature surveyed

Autor	Period	Sample	Estimation method	Findings
Yao *et al.* (2013)	1952–2007	China	Cointegration, VECM	p ⇒ − y
Liu and Hu (2013)	1983–2008	provinces China (panel)	OLS	p ⇒ − y
Musa (2015)	1980–2013	India	Cointegration (Johansen) VEC	p ⇒ +* y
Furuoka (2018)	1961–2014	China	ARDL	p ⇔ y
Tsen and Furuoka (2005)	1950–2000	Japan, Korea, Thailand China, Singapore, Philippines Honk Kong, Malaysia Taiwan, Indonesia	Cointegration (Johansen) VAR	p ⇔ y p ⇒ y y ⇒ p Noncausality
An and Jeon (2006)	1960–2000	25 OCDE countries	cross-country regression nonparametric kernel	relation inverted U-shape
Faria *et al.* (2006)	1950–2000	125 countries	OLS (logy) (logy)2	Africa–Asia U-shape inverted Europe: y ⇒ − p
Yao *et al.* (2007)	1954–2005	Taiwan	Cointegration (Johansen) VAR, Toda-Yamamoto	until 2000 p ⇒ + y until 2005 insignificant
Azamhou and Mishra (2008)	1960–2000	110 countries	GAM non parametric	
Afsal (2009)	1950–2001	Pakistan	OLS	Negative effect (p ⇒ y)
Huang and Xie (2013)	1980–2007	Panel 90 countries	simultaneous ADL	p ⇒ − y
Song (2013)	1965–2009	13 countries Asia	OLS	Negative effect (p ⇒ y)
Ali *et al.* (2013)	1975–2008	Pakistan	ARDL	p ⇒ + y
Chang *et al.* (2017)	1870–2013	Finland, France, Portugal Sweden Canada, Germany Japan Norway Switzerland Austria, Italy Belgium, Denmark, Netherlands UK, US New Zealand	Panel Granger Causality Test	p ⇒ + y y ⇒ − p p ⇔ y Noncausality

Table 1. (*continued*)

Autor	Period	Sample	Estimation method	Findings
Garza-Rodriguez *et al.* (2016)	1962–2012	Mexico	VEC	p ⇔ y
Diep and Hoai (2016)	1990–2013	7 countries Southeast Asia	Panel regression model Structural Equation Model	p ⇔ y
Rahman *et al.* (2017)	1960–2013	USA, UK, Canada China, India, Brazil	Panel cointegration VEC	p ⇒+ y
Chirwa and Odhiambo (2019)	1970–2015 ADL	Zambia	Cointegration (Johansen)	p ⇔ y
Aksoy *et al.* (2019)	1970–2014	21 OECD countries	Panel VAR	p ⇒+ y
Mahmoudinia *et al.* (2020)	1980–2018	57 Islamic countries	Cointegration (Johansen) VEC	p ⇒+ y
Sebikabu *et al.* (2020)	1974–2013	Rwanda	ARDL	Positive effect (p ⇒ y)
Bawasir *et al.* (2020)	1996–2016	10 Middle East countries	OLS	Positive effect (p ⇒ y)
Gatsi and Appiah (2020)	1987–2017	Ghana	ARDL	p ⇒- y
Azam *et al.* (2020)	1980–2020	India	ARDL	p ⇒+ y
Alemu (2020)	1980–2019	Ethiopia	ARDL	p ⇔ y (positive)
Lianos *et al.* (2022)	1820–1938 1950–2016	USA, UK Germany France, Italy	Toda-Yamamoto, Granger, Sims Causality test	p ⇒+ y p ⇔ y y ⇒+ p

Note(s): The table summarizes the results found in the literature review. In the results column, y ⇒ p indicates a unidirectional causal relationship (Granger causality), where per capita income causes population, p ⇒ y indicates population causes per capita income and p ⇔ y indicates a bidirectional causal relationship. The signs + or − and (*), indicate the sign and significance when reported
Source(s): Authors' own elaboration

Table 1.

growth, yet the magnitude of the effect decreases over time and eventually becomes negative towards the end of the period. In other words, the relationship between the variables follows the form of an inverted U-shaped curve. The authors explain this phenomenon by attributing it to the three stages of demographic transitions: (1) high fertility/high mortality, (2) high fertility/low mortality and (3) low fertility/low mortality.

Azomahou and Mishra (2008) present other example of a nonparametric approach. They analyze the same period (1960–2000), but covering a broader range of countries. Their panel includes 110 countries: 24 OECD members and 86 developing countries. Their estimations reveal evidence of a nonlinear relationship between the two variables, as well as "direct" and "feedback" effects of population structure on growth. Furthermore, they affirm that a highly nonlinear demographic structure characterizes age-structured populations and their economic growth, with this nonlinearity potentially acting as a source of growth fluctuations in both OECD and nonOECD countries.

Most of the empirical literature reviewed consists of linear regression models coupled with Granger causality tests (Engle and Granger, 1987). The linearity assumption is rarely discussed and Granger causality tests are frequently misinterpreted. Granger causality analysis is useful for forecasting, but the conclusions that can be drawn about the causal mechanism are limited. The Granger test should serve as a starting point for a more in-depth analysis of the causal relationships between economic and population growth. The capacity to derive conclusions about the causal mechanism, extending beyond temporal precedence, as well as the possibilities for manipulation through political actions, is indeed constrained. On the other hand, the substantial disparities observed in the outcomes of multiple empirical studies focused on the same country, despite the utilization of similar econometric techniques, suggest the presence of a potentially nonlinear underlying cointegration relationship, an aspect not possible to capture through Granger analysis. Among the studies resorting to panel data models, a notable proportion fails to check for homogeneity in the impact of explanatory variables across the different countries. Zooming out from the details, the picture that emerges points to the inadequacy of a single model to explain the dynamic relations between demographic change and economic growth across all countries and/or over long periods. This picture is the starting point of our work. We seek to explore a novel path within the empirical strand of the literature that studies the dynamic relations between demographic change and economic growth, without imposing constraints on the form of these relations or assuming homogeneity in the effects across countries. More specifically, we intend to examine the possibility of multiple patterns in the dynamic relations between these two coexistent variables. With this objective in mind, our pursuit is to identify groups of countries that exhibit internal homogeneity in terms of dynamic relations between demographic change and economic growth, while also maintaining clear distinctions from other groups.

Data and methodology

Data

In this study, population and economic growth dynamics are represented by the evolution of the growth rates of population growth and per capita GDP, respectively. Annual data of per capita GDP (in 2011 constant dollars, PPP [12] adjusted), population and their corresponding growth rates, were obtained from the Penn World Table 10.0 database (Feenstra *et al.*, 2015, available for download at www.ggdc.net/pwt), considered the standard data source when it comes to comparative economic growth. The dataset includes annual data for 111 countries during the period 1960–2019. We sought to find a balance between including as many countries as possible, while covering a period long enough to ensure the robustness of our methods.

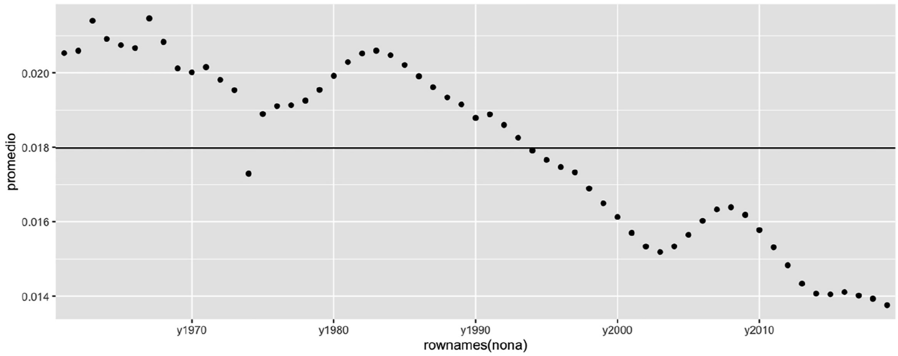
Throughout the period of analysis, aggregate world population exhibits a clear trend. As depicted in Figure 1, the total world population grows at a decreasing rate: slow evolution marked by a consistent trend, with minimal fluctuations in its growth rate. This observation is consistent with the established patterns of the demographic transition. Still, this trend averages out significant disparities between countries in terms of the timing of their demographic transitions and the pace at which each stage passes. These disparities serve as the central focus of this study.

The average growth rates of population and per capita GDP over the analyzed period are remarkably similar: 1.8 and 2.01% respectively, but the similarities end there. Average GDP per capita growth does not show any discernible trend (as seen in Figure 2). Its standard deviation is six times larger than that of the population growth rate, and it exhibits pronounced volatility in the short term. Additionally, its mean inter-annual variation exceeds that of the population growth rate by more than 40 times.

Table 2 provides the most relevant descriptive statistics for the considered variables.

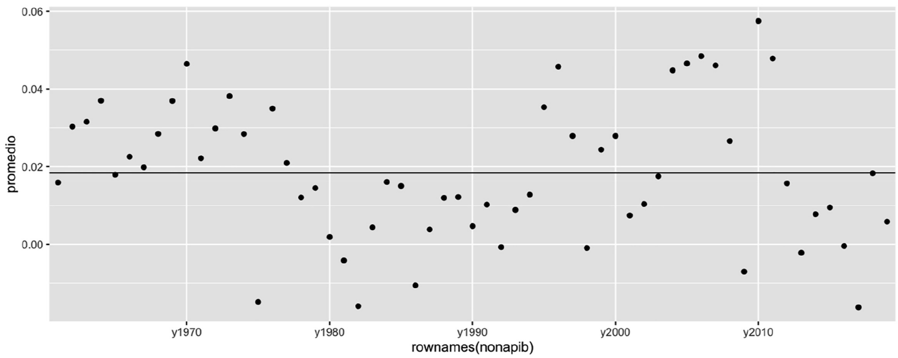
Methodology

This section outlines the methodology applied to compare and analyze the behavioral patterns of different countries from the sample in relation to the variables of economic growth



Source(s): Own calculations based on PTW 10.0

Figure 1. Population growth rate



Source(s): Own calculations based on PTW 10.0

Figure 2. Average GDP per capita growth

Table 2. Descriptive statistics

Growth rate	Mean	SD	Min	$X_{0.25}$	$X_{0.50}$	$X_{0.75}$	Max
Population	1.80%	1.17%	−22.02%	0.93%	1.89%	2.65%	11.76%
GDP per capita	2.01%	6.20%	−59.27%	−0.13%	2.29%	4.59%	42.58%

Note(s): The mean, the variance, the quartiles and the maximum and minimum values of the variables
Source(s): Authors' own calculations based on PTW 10.0

and demographic change. Our approach involved initially studying each variable independently and subsequently repeating the analysis for both variables considered in conjunction. At each step, we obtained a taxonomy and established a hierarchical order among countries, enabling us to assess the degree of similarity in their trajectories. In order to build the taxonomy, we relied on the nearest neighbor clustering procedure, which categorizes time series based on their proximity as determined by a distance function. Two different metrics were used. When analyzing each variable in isolation, we utilized a distance metric introduced by Mantegna (1999), which is founded on a transformation of the Pearson correlation coefficient between two time series, Yi and Yj. For the joint analysis of demographic change and economic performance, we used a metric specifically suited for symbolic sequences.

Except for the metric used to construct the distance matrix, the procedure for grouping and classifying the countries in our sample remains consistent. We followed the same series of steps to investigate the dynamics involving: (1) demographic change, (2) economic growth and (3) both demographic change and economic growth. These steps are as follows: compute the distance matrix, construct the MST, calculate the subdominant ultrametric distance matrix, create the HT and apply a hierarchical clustering stopping rule to determine the optimal number of clusters in the sample.

We started the procedure by building the distance matrix. NxN matrix D, where N is the number of countries and the d_{ij} element is the distance between country i and country j. The second step was to use Kruskal's algorithm to find the MST (Kruskal, 1956). In this regard, we began by sorting all edges (pairs of countries) in the distance matrix according to their weight (distance). Next, we selected the smallest edge and examined whether it formed a cycle with the spanning tree we had built so far. If no cycle was formed, we incorporated the edge into said spanning tree. On the other hand, if a cycle was in fact detected, we discarded the edge. We repeated this process of selecting the smallest edge and checking for cycles until the spanning tree reached V – 1 edges. The result of this process was an MST: a connected edge-weighted graph of the 111 countries within the sample, which highlighted the 110 most pertinent distances and helped us identify which countries had more similar and dissimilar dynamics in terms of one or more variables.

The MST offers an arrangement of countries based on the most relevant connections among each constituent within the group of countries. Any pair of countries is directly connected through one or more vertices, which represent the paths of minimum distance between them.

The third step involves obtaining the clusters. From the MST we obtained the subdominant ultrametric distance matrix D^* (Rammal *et al.*, 1986), whose elements d^*ij are defined as the longest step (maximal distance between connected countries) in the shortest path that connects countries i and j in the MST. Formally, $d^*ij = max(d_{kl})$, in colloquial language "where k and l stand for all nodes connecting i and j (including i and j) in the corresponding MST". Once the values of d^*ij were calculated for every pair of countries, we had all the elements to build the HT.

The HT illustrates how to group countries for a given number of groups. That is, if the objective is to partition the sample of countries into eight groups, the HT determines the allocation of countries into each of these eight groups. To determine the most statistically relevant number of groups –which is the optimal number– we used the pseudo – T^2 (Duda and Hart, 1973) and the C-Kalinski (Calinski and Harabasz, 1974) stopping rules.

The exercise ends with an analysis of group dynamics. To study their evolution, we divide the period of analysis into 27 moving windows of 30 years amplitude. For each window, we repeat the previous exercise, which allows us to study the stability in terms of the composition of each group and to visualize the convergence-divergence between them.

Empirical analysis

This section is divided into two parts. The first part reports the results of the analysis of each variable separately. The second part presents the outcomes derived from analyzing demographic change and economic growth simultaneously.

First exploratory analysis

For the analysis of each variable on its own, we used the distance introduced by Mantegna (1999), which defines the distance based on the Pearson correlation coefficient between two time series, Y_i and Y_j.

$$\rho_{ij} = \frac{\langle Y_i Y_j \rangle - \langle Y_i \rangle \langle Y_j \rangle}{\sqrt{\left(\langle Y_i^2 \rangle - \langle Y_i \rangle^2\right)\left(\langle Y_j^2 \rangle - \langle Y_j \rangle^2\right)}} \tag{1}$$

it defines the distance,

$$\mathrm{d(i,j)} = \sqrt{2\left(1 - \rho_{\mathrm{ij}}\right)} \tag{2}$$

This metric, first introduced by Gower (1966), provided us with a distance between two unidimensional temporal series, where closeness is defined in terms of their co-movements [4]. Applied to our scenario, two countries have similar dynamics in terms of population change when the movements or shifts in their population growth rates resemble each other. For instance, if we have three countries with the following sequences of population growth rates

$$g_A = (0.02, 0.03, 0.01)\, g_B = (0.04, 0.06, 0.02)\, g_C = (0.02, 0.01, 0.0166), \text{then } d(A,B) = 0 \text{ and } d(A,C) = 2.$$

The purpose of this first exercise is to compare the taxonomies of countries arising from the analysis of their population dynamics with those emerging from the analysis of their economic performance. As we delve into our findings, it becomes evident that the results from these to analyses are both qualitatively and quantitatively different.

Population dynamics

In order to compare and analyze the behavior of the countries within the sample in terms of demographic change, we used equation (2) to construct the distance matrix. Then, we applied Kruskal's algorithm to obtain the MST. Figure 3 shows the MST that corresponds to the population growth rate, while Appendix 1 indicates the corresponding country for each code.

Once we calculated the MST, the next step was to build the HT (see Figure). For this purpose, we computed the subdominant ultrametric distance matrix (D^*). The final step was to apply a stopping rule to determine the number of clusters in the sample. Table VII (see Appendix 1) shows the grouping that emerged from this procedure.

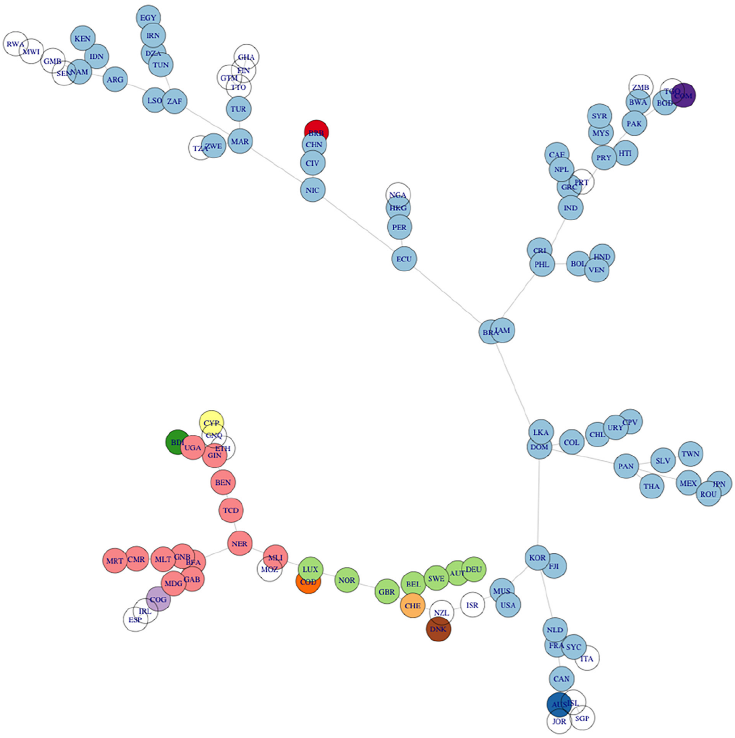
Group 1, the largest cluster, comprises countries from all continents. Group 2 is composed of eight European countries and New Zealand. Group 3 includes several African developing countries.

Growth dynamics

We repeated the same exercise for GDP per capita growth. Refer to Figure 4 for the corresponding MST visualization.

Comparison

A comparative analysis revealed a few interesting results. Firstly, countries exhibit greater similarity in terms of their population dynamics than in relation to their economic growth. This is due to the fact that the global distance (sum of all the distances in the MST [5]) is smaller for the population than for GDP per capita. This observation aligns with our earlier comment regarding the substantial disparity in the behavior of the two series. The population demonstrates a slower pace of change, a distinct long-term trend and less volatility compared to GDP per capita.



Note(s): In light blue the most numerous cluster, in green the cluster formed by a few European countries (mainly), in pink a cluster formed by African countries and the rest of the countries with population dynamics that do not fit the previous patterns

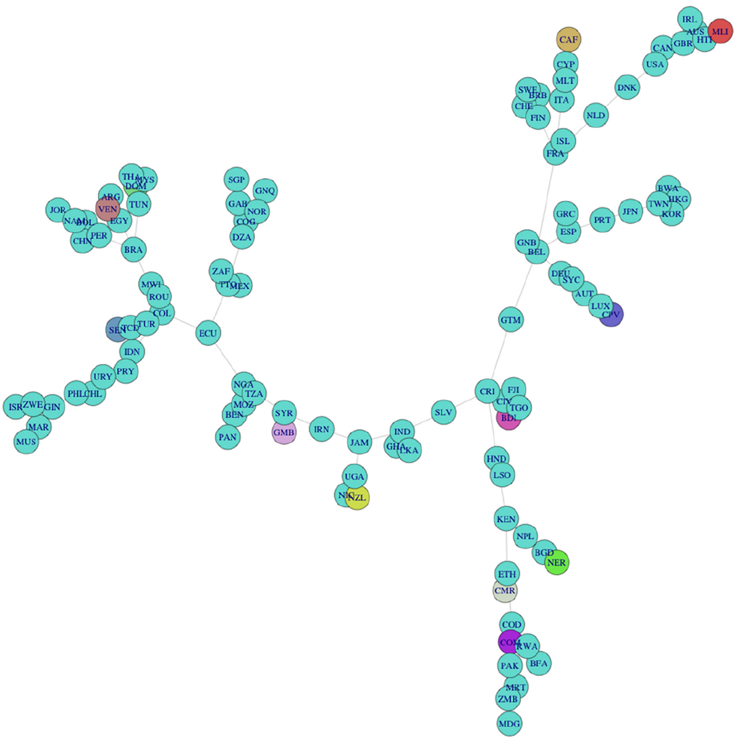
Source(s): Own calculations based on PTW 10.0

Figure 3.
Minimum spanning tree – population

Secondly, there is little correlation in terms of country closeness between the two dimensions. That is, a similar population dynamic between two countries does not necessarily translate into similar economic performance. This can be appreciated in Tables 3 and 4.

Comparing the ten smallest distances in each of the MSTs revealed a notable absence of coincidences, meaning there is minimal overlap among the country-dyads. Furthermore, when considering population, these distances are significantly smaller.

The substantial disparity between the MST and the resultant groupings in each of the preceding exercises serves as an indication of interdependence between these variables. At the same time, this contrast suggests that the functional relationship between them is not unique. In the next section, we repeated the previous exercise considering population and economic growth simultaneously. Our goal was to establish a hierarchical organization and a taxonomy of countries that would enable us to measure the degree of similarity between countries in terms of the co-evolution in time of their population and output per capita. In this joint analysis, our expectation was to find groupings of countries with the same conditions. However, the distance function used so far is limited to univariate time series. Hence, we needed an alternative distance function capable of handling bivariate time series $((g_p, g_y))$. To address this, we introduced the notion of



Note(s): In light blue, the most numerous cluster is the rest of the countries with GDP dynamics that do not fit the previous patterns
Source(s): Own calculations based on PTW 10.0

Figure 4. Minimum spanning tree – GDP per capita growth

Thailand–Panama	0.13	Dominican republic – Korea	0.21
Dominican republic–Panama	0.15	Ecuador–Peru	0.23
Dominican republic–Mexico	0.18	Dominican Republic–El Salvador	0.24
Dominican republic–Brazil	0.19	El Salvador – Taiwan	0.24
Ecuador–Nicaragua	0.19		

Source(s): Authors' own calculations based on the distance function defined in Equation (2)

Table 3. Top 10 distances – population

Belgium–France	0.47	Ecuador–Trinidad and Tobago	0.65
Netherlands–France	0.52	Italy–France	0.66
Austria–Germany	0.53	Hong Kong–Taiwan	0.66
Portugal–Spain	0.56	Japan–Taiwan	0.67
Austria–Portugal	0.61	Finland–Sweden	0.70

Source(s): Authors' own calculations based on the distance function defined in Equation (2)

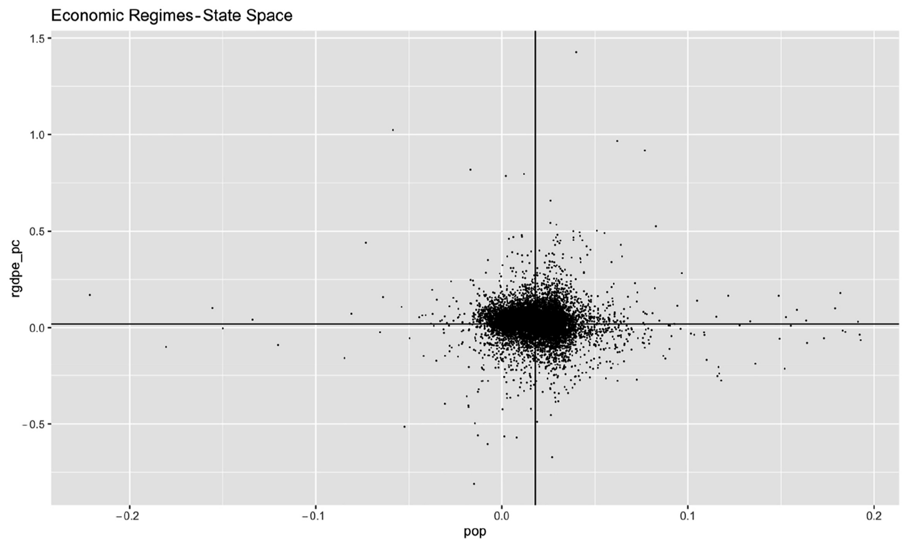
Table 4. Top 10 distances – GDP per capita

regime, which allowed us to define a distance between the dynamic trajectories –in our case bivariate– of different countries.

Symbolic series and regimes

In order to describe the qualitative behavior of the joint evolution of economic and demographic growth, we introduced the notion of regime (Brida *et al.*, 2003; Brida and Punzo, 2003). A regime consists of a range of conditions characterizing the behavior of a system, particularly for the purpose of our research, one that describes the joint dynamics of population and per capita output. These conditions then divide the state space of population and per capita production into regions, each corresponding to a different regime. Each regime represents an explanatory model of the joint performance of population and economic growth distinct from the others. We defined two conditions: one sets a threshold for yearly population change, while the other defines a threshold for the annual change in the rate of per capita GDP growth. As a result, the state space is divided into four regions (refer to Figure 5). If each region corresponds to a different relationship between demographic change and economic performance (a different regime), then a country moving from one region to another implies a structural change in the way population and output per capita relate to each other in that country (a regime switch). It is possible to distinguish two types of dynamics: one within each regime and the other during transitions between regimes. In our analysis, we focused on the dynamics of regimes, aiming to qualitatively describe the evolution of performance in terms of population growth and economic growth as economies progress through successive regimes over the analyzed period. Our interest lies in the sequence of regimes that a country transitions during a certain period of time.

We evaluated the advantages and disadvantages associated with utilizing different thresholds. The evaluation considered the annual average across all nations, the historical average for each country and the overall average for all countries. Nevertheless, it is pertinent to mention that each of these options is accompanied by its own set of drawbacks. Using



Source(s): Own calculations based on PTW 10.0

Figure 5.
Data partition in the state space for the set of 111 countries (population growth rate, growth rate GDP per capita)

different thresholds for each country could appear sensitive at first. Still, the most straightforward operationalization –taking the country's average rate during the period of analysis– would imply forcing every country to transition across all four regimes. Similarly, adopting varying thresholds for each year could be sensitive to fluctuations in global economic conditions, yet it would artificially necessitate having countries on both sides of the thresholds every year. We finally opted for the average change in per capita income and in population during the period of analysis for all countries [6]. The result was the following four-region partition of the state space:

$$R_1 = \{(g_p, g_y) : g_p \geq \mu_p, g_y \leq \mu_y\} \tag{3}$$

Region 1 is characterized by low (below average) economic growth and high (above average) population growth, which could be associated with economies locked in what are colloquially referred to as "poverty traps", as observed in countries such as Senegal or Kenya.

$$R_2 = \{(g_p, g_y) : g_p \geq \mu_p, g_y \geq \mu_y\} \tag{4}$$

In Region 2 we find a virtuous relation between population and economic growth, with both variables surpassing the average growth rates. This pattern is identified as the "demographic dividend capture" regime, exemplified by countries like Egypt.

$$R_3 = \{(g_p, g_y) : g_p \leq \mu_p, g_y \geq \mu_y\} \tag{5}$$

Regime 3 is marked by a population growth rate that unfolds at a slow pace, accompanied with GDP per capita growth that exceeds the average. For instance, this can be observed in a country such as China.

$$R_4 = \{(g_p, g_y) : g_p \leq \mu_p, g_y \leq \mu_y\} \tag{6}$$

Finally, Regime 4 corresponds to an economy where both population and per capita production grow slowly, falling below the average. This scenario is exemplified by countries like Japan.

Figure 6 illustrates, in the space of states, the regimes experienced by Algeria, Mexico, Pakistan and Sweden. As portrayed, there are notable distinctions in the dynamics of these regimes. Algeria and Mexico traverse all four regimes, whereas Pakistan's trajectory includes only regimes 1 and 2 and Sweden encompasses regimes 3 and 4. To account for the short term variations in global economic conditions and minimize the noise characteristic of macroeconomic times series such as output, we filtered the per capita GDP series to smooth its movements.

By framing the problem in the context of multiple regimes that countries transition over time, we gained the flexibility to consider different sequences of dynamic interactions between population and economic performance. An important regime sequence to keep in mind is $R_1 \rightarrow R_2 \rightarrow R_3 \rightarrow R_4$, which captures the stylized facts of the demographic transition theory. In this ideal sequence, countries are able to capture the demographic dividend [7]. Additionally, by capturing the demographic transition theory as a particular case of regime sequences, our framework allowed us to assess the degree to which countries adhere to this stylized pattern.

Table 5 below offers an initial approximation to the characterization of regime dynamics. It shows the percentage of time each country or economy spends in each regime during the period of analysis.

An initial observation reveals a diverse range of behaviors among the countries in our sample, both in terms of the regimes they encounter and the duration they spend within each. Some of them alternated between regimes R_3 and R_4 and never visited R_1 or R_2. Others did the

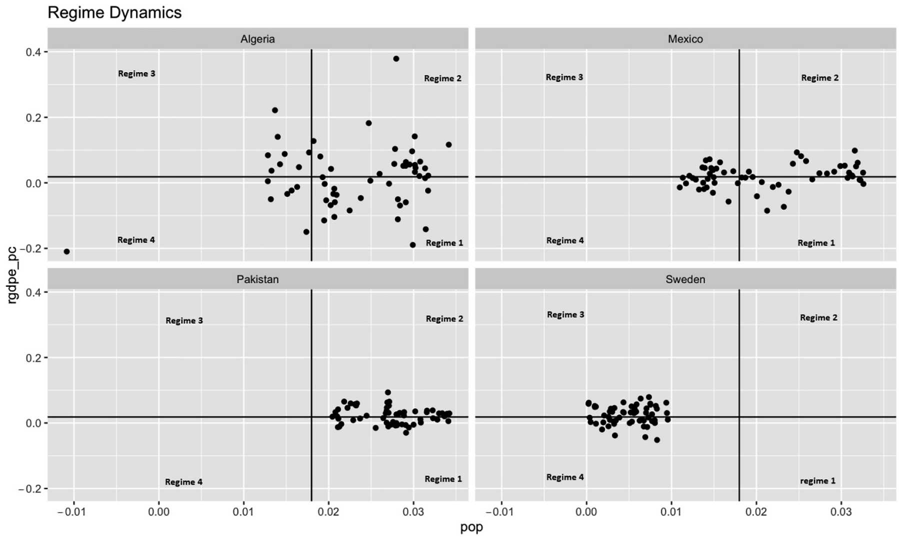


Figure 6.
Dynamics of regimes in Algeria, Mexico, Pakistan and Sweden, in the period 1960–2019

Note(s): Each point of each graph represents a pair (gp, gy) corresponding to each of the four countries in each year between 1960 and 2019. Additionally, the thresholds considered to partition of states space are represented
Source(s): Own calculations based on PTW 10.0

opposite, alternating between regimes R_1 and R_2 and never visiting R_3 or R_4. Another group of countries transitioned through all four regimes. In short, there is not a single pattern but a myriad of them. This first approximation to regime dynamics possesses an important limitation: it leaves aside the order in which countries undergo different regimes, a factor that provides valuable insights into regime dynamics. In particular, this approach overlooks all aspects related to regime transitions. To address this problem we used symbolic series to represent regime dynamics, reducing the information space of the issue but without sacrificing valuable information. If we label each regime R_i with the symbol j, we can substitute the original bivariate time series $\{(g_{1p}, g_{1y}), (g_{2p}, g_{2y}), ..., (g_{Tp}, g_{Ty})\}$ for a sequence of symbols $\{s_1, s_2, ..., s_T\}$ such that $s_t = j$ if and only if (g_p, g_y) belongs to R_j . This Symbolic Series summarizes the most relevant qualitative information on the dynamics of a country's regime [8].

To categorize the 111 countries in terms of their distinct economic-demographic performance, we used the same nonparametric approach applied in the previous section: calculating the distance matrix, constructing the MST, computing the subdominant ultrametric distance matrix, building the HT and applying a hierarchical clustering stopping rule to determine the number of clusters in the sample. As explained in said section, a combined analysis of demographic change and economic performance requires a different metric than the one used to study each of the variables separately. Here, we were addressing regime dynamics represented by symbolic sequences, therefore we needed to measure distances between symbolic sequences.

The distance function we used is simple. Given two countries, we first measured the distance between them every year. There are two possible values for yearly distances: zero if the countries coincide on the same regime or one if they are on different ones. The second step required to get the square root of the sum of all the yearly distances to get the overall distance between the two countries during the entire period.

Table 5. Percentage of time each country or economy spends in each regime during the period of analysis

Country	R_1	R_2	R_3	R_4	Country	R_1	R_2	R_3	R_4	Country	R_1	R_2	R_3	R_4
AFG	39	33	18	11	GAB	77	23	0	0	PER	28	35	19	18
ARG	0	0	60	40	DEU	0	0	63	37	PHL	33	44	23	0
AUS	11	14	35	40	HKG	4	56	36	14	PRT	0	0	68	32
AUT	0	0	70	30	ISL	2	2	56	40	KOR	2	21	58	19
BGD	47	18	25	11	IND	32	33	35	0	GHA	61	37	2	0
BRB	0	0	37	63	IDN	16	33	32	19	GRC	0	0	67	33
BEL	0	0	65	35	IRN	26	28	28	18	GTM	42	58	0	0
BEN	56	44	0	0	IRL	1	9	72	18	GIN	72	11	7	10
BOL	40	33	25	2	ISR	28	44	16	12	GNB	47	23	18	12
BRA	16	33	25	26	ITA	0	0	63	37	HTI	44	9	18	30
BWA	19	51	21	9	GNB	54	46	0	0	HND	61	28	7	4
BFA	47	32	7	14	JAM	5	4	39	52	LKA	23	5	56	16
BDI	53	21	7	19	JPN	0	0	49	51	CHE	0	4	53	44
CPB	9	32	40	19	JOR	54	42	4	0	TWN	0	33	44	23
CMR	60	33	5	2	KEN	63	37	0	0	THA	5	35	46	14
CAN	0	7	54	39	LSO	32	30	26	12	TTO	1	4	46	49
CAF	56	11	18	16	LUX	11	11	51	28	TUR	12	35	33	19
TCD	68	28	2	2	MDG	77	23	0	0	GBR	0	0	56	44
CHL	3	12	46	39	MWI	60	31	4	5	URY	0	0	44	56
CHN	12	14	60	14	MYS	21	61	9	9	ZMB	56	44	0	0
COL	33	26	16	25	MLI	28	49	9	14	ROU	0	2	81	18
COM	56	44	0	0	MLT	0	0	82	18	RWA	28	54	4	14
COG	42	58	0	0	MRT	65	19	14	2	SEN	81	19	0	0
CRI	28	40	26	6	MEX	18	35	16	32	SYC	14	26	42	18
CYP	9	9	61	21	MAR	18	33	21	28	SGP	11	53	32	14
COD	63	37	0	0	MOZ	46	42	2	10	ZAF	39	23	16	23
DNK	0	0	56	44	NAM	53	23	18	7	ESP	0	0	68	32
DOM	28	28	37	7	NPL	30	28	24	18	SWE	0	0	58	42
ECU	51	19	19	11	NLD	0	0	58	42	SYR	44	40	9	7
EGY	30	63	7	0	NZL	0	12	37	61	TZA	42	54	2	2
SLV	12	19	53	16	NIC	42	19	21	18	TGO	56	44	0	0
GNQ	30	39	18	14	NER	88	12	0	0	TUN	14	42	18	26
ETH	46	44	2	8	NGA	49	51	0	0	UGA	54	46	0	0
FJI	12	26	30	32	NOR	0	0	61	39	USA	0	0	58	42
FIN	0	0	60	40	PAK	49	51	0	0	VEN	53	19	14	14
FRA	0	2	56	42	PAN	26	53	19	2	SWE	28	26	21	25
GAB	47	37	14	2	PRY	28	44	18	11					

Source(s): Authors' own elaboration

Given two symbolic series $\{s_{it}\}_{t=1}^{t=T}$ and $\{s_{jt}\}_{t=1}^{t=T}$, corresponding to countries i and j, we define the following distance:

$$d(i,j) = \sqrt{\sum_{t=1}^{T} f\left(s_{it}, s_{jt}\right)} \quad (7)$$

where

$$f(s_{it}, s_{jt}) = \{1\, if\ s_{it} \neq s_{jt}\ 0\, if\ s_{it} = s_{jt}\ \forall\, i \neq j, \forall\, t. \quad (8)$$

Intuitively, the more coincidences two countries have in the same regime, the smaller their distance. When two countries exhibit the exact same sequence of regimes, they reach the minimum possible distance, which is zero. The maximum possible distance is ($\sqrt{T}$) occurring when two countries never coincide on the same regime in any year.

To construct the MST we used Kruskal's algorithm. With its 111 vertices and 110 edges, the resulting weighted graph highlights the most relevant distances for each country. The shortest distance in the MST is $d(Austria, Portugal) = 2.24$, implying that Austria and Portugal had the most similar trajectories in the sample. The second shortest distance is between Belgium and Germany: $d(Belgium, Germany) = 2.45$.

The tree is obtained by joining Austria and Portugal (the shortest distance), then Belgium and Germany (the second shortest distance) and so on. The process continues until all 111 countries are included. Thus constructed, the MST offers an arrangement of the countries where the most relevant connections are taken from each country in the sample. The connections between two countries represent the shortest path between them. Figure 7 shows the resulting tree.

The MST and the matrix D^* allowed us to compute the subdominant ultrametric distance matrix, which is the prerequisite to build the HT. Figure 8 shows the dendrogram that represents the HT obtained.

The HT demonstrates the process of categorizing countries into a specified number of groups. For instance, if the goal is to partition the country sample into eight distinct groups, the HT allocates each country to one of these eight groups. The concluding action involved the application of a hierarchical clustering stopping rule to find the optimal number of groups. The utilization of the C-Kalisky rule resulted in three well-differentiated clusters containing 87 of the 111 countries (approximately 80% of the countries in the sample).

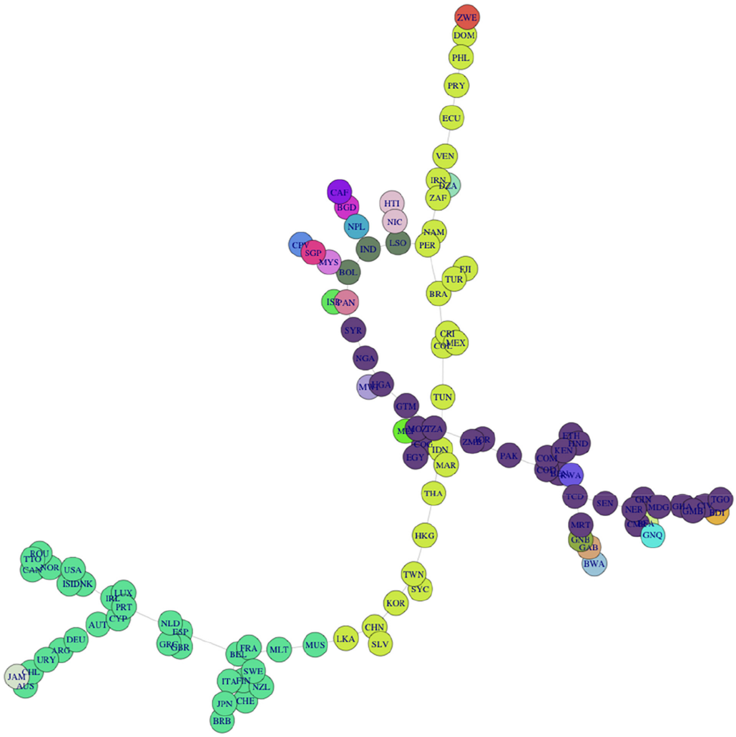
Empirical results

The first group –*mature economies*– contains 32 countries, and it stands out as the most homogeneous of the three. The sum of this group distances in the MST is the smallest one. It includes all 24 of the initial members of the OECD, except for Turkey [9]. NonOECD countries in the group (Argentina, Barbados, Malta, Mauritius, Trinidad and Tobago, Rumania and Uruguay) are currently classified as upper income or upper-middle income countries. Regarding regime dynamics, the common denominator in this group is their nearly exclusive pattern of alternating between regimes R_3 and R_4 during the entire period of analysis. Other countries –such as Canada, Chile, or Trinidad and Tobago– have a short initial phase alternating between regimes R_1 and R_2 (but concentrated in R_2). This alternating pattern lasts for the first decade and a half of the analysis period [10] at most. In brief, this group comprises countries that transitioned from high to low population prior to the period of analysis, with a few cases occurring at the beginning of said period (before the mid-1970s).

Figure 9 shows a plot of the symbolic series of the countries in the first group.

To illustrate this, we calculated the symbolic series for an average country within the group, referred to as the centroid, whose trajectory of regimes can be observed in Figure 10.

Containing 28 countries, the second group –*young economies*– is the most heterogeneous of the three that we obtained. It includes 22 Sub-Saharan African countries, three middle eastern countries (Egypt, Jordan and Syria), two Central American countries (Guatemala and Honduras) and Pakistan. Continuing with the pattern observed in the previous cluster, the distinguishing feature of the countries within this group is their near-exclusive alternation between regimes R_1 and R_2 throughout the analysis period, mirroring the dynamics of the mature economies cluster. Of the 28 countries in this group, 16 of them never visited regimes R_3 and R_4. Mauritania, Mozambique and Syria, are the cases where it would be possible to talk about a short phase in R_3 and R_4: Mauritania experienced this during the 1960s, Mozambique witnessed it in the 1980s and Syria, more recently, within the last decade. The Syrian anomaly has to do with the population displacement resulting from the civil war that started in 2011.



Note(s): In light blue the cluster of mature economies, in yellow that of transition economies, in violet that of young economies, the rest of the countries have trajectories that do not fit the previous patterns

Source(s): Own calculations based on PTW 10.0

Figure 7.
MST

Figure 11 shows a plot of the symbolic series of the countries in the second group.

The trajectory of an average country within the group can be visualized in Figure 12.

Broadly speaking, countries in group 3 –*transition economies*– exhibit two distinct phases. In the first phase, countries alternate between regimes R_1 and R_2, while in the second phase, they shift to alternating between regimes R_3 and R_4. There is variation in terms of the moment when countries switch between phases. The two extreme cases are Korea, which transitioned to the second phase as early as the late 1970s and Philippines, which did not switch phases until the mid-2000s.

There is also variation concerning the proportion of years with above-average economic growth within each phase. To exemplify, during the first phase, the rate is markedly low for Namibia, Venezuela and Ecuador, while Taiwan and Korea boast notably high proportions. What binds the 26 countries forming this cluster is their transition from high to low population growth throughout the analysis period. A substantial portion of these nations managed to harness the demographic dividend over the study's course, a phenomenon seemingly reflected by their time spent in regions R_2 and R_3.

Figure 13 presents a plot of the symbolic series of the countries in the third group.

The trajectory of an average country within the group can be visualized in Figure 14.

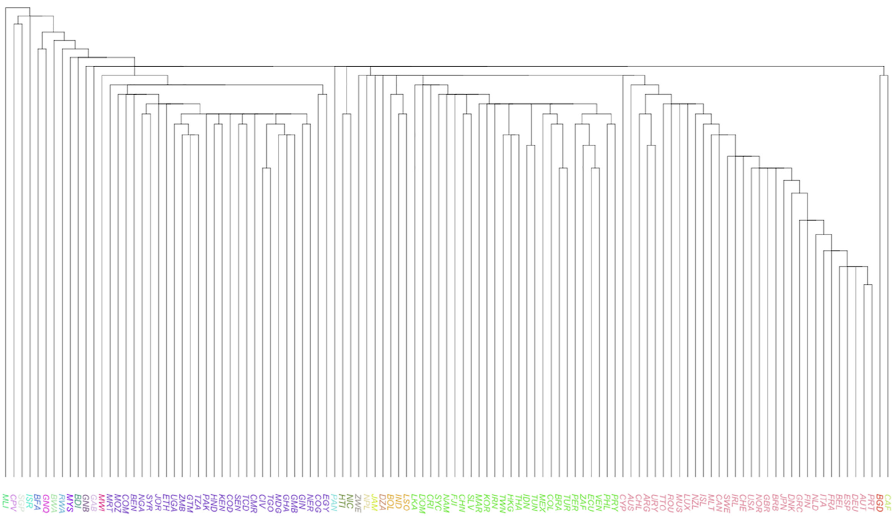


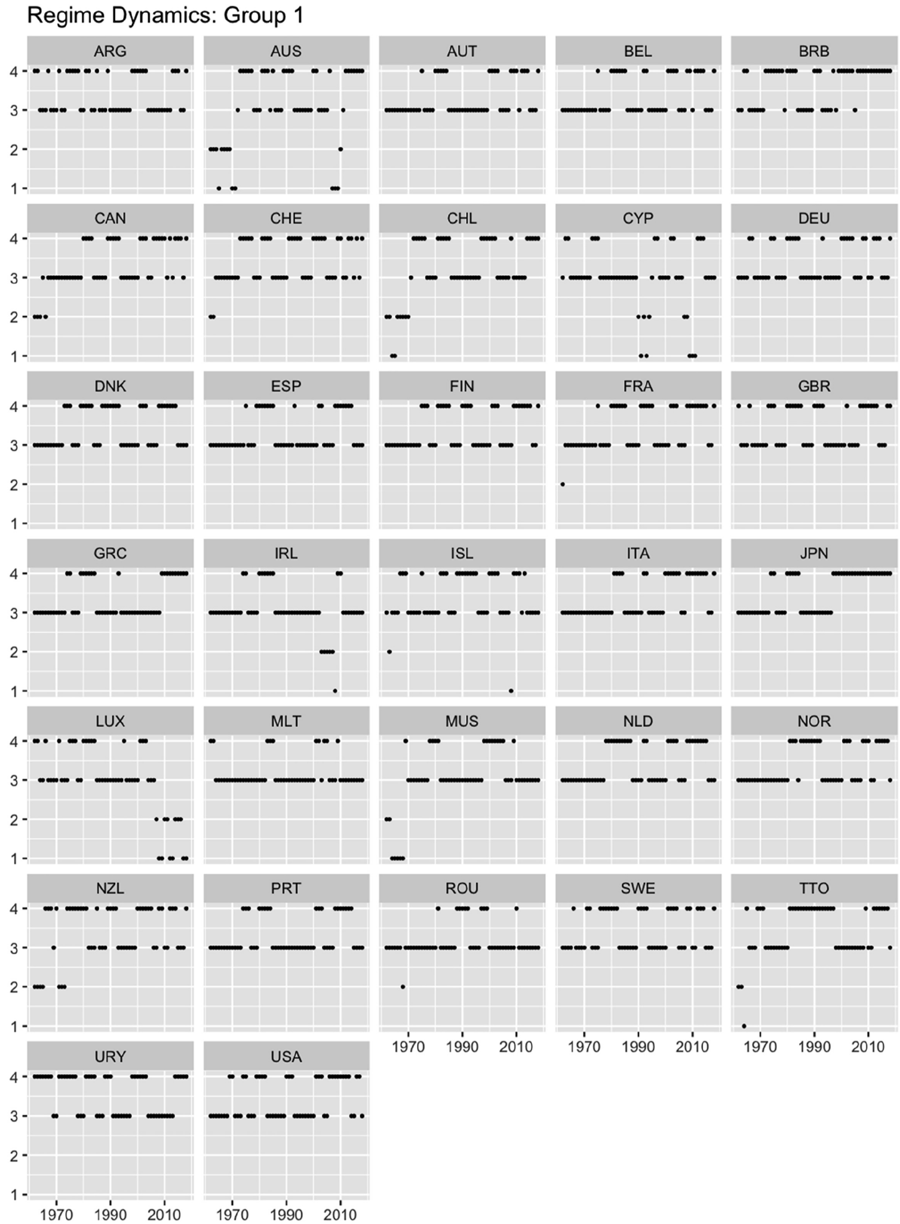
Figure 8.
Hierarchical tree

Source(s): Own calculations based on PTW 10.0

Let's briefly discuss the 25 countries that deviate from the three primary groups and are excluded from the classification. Among them, five constitute two smaller clusters (BOL, IND, LSO, HTI and NIC). The remaining 20 countries, however, do not form any distinct group. Regarding regime dynamics, these countries visit all four of them. Based on the sequence of the two distinct phases identified in group 3, we can distinguish three sub-groups within this default category. The first sub-group comprises 13 countries, distinguished by the absence of clearly distinct phases in which countries alternate across different partitions of the state space. Within this context, a second sub-group emerges, encompassing four countries that exhibit the same dual phases observed in *transition economies*, albeit in reverse order. During the first phase, countries alternate between regimes R_3 and R_4, while in the second phase they switch between regimes R_1 and R_2. Finally, an additional (third) sub-group of eight countries exhibit the same distinct phases as group 3, in the same order. That is, given the way we characterized the three main groups, the dynamic behavior of these eight countries is indistinguishable from the group of *transition economies*.

To conclude this section, we proceed to characterize the three groups with respect to a set of variables closely associated with the two dimensions of our regime dynamics analysis. More precisely, these variables are intertwined within the dynamic system alongside our analysis dimensions. The variables are life expectancy, fecundity, per capita GDP and the human capital index. For instance, both life expectancy and fecundity contribute to determining population growth. Moreover, the literature suggests that these variables are influenced by per capita GDP levels, which, in turn, are shaped by historical growth rates in per capita GDP. Figures 17, 18, 19 and 20 (see Appendix 2) illustrate that the three identified groups can be clearly differentiated based on these supplementary variables. Notably, the figures highlight minimal overlap within the range of variation for these variables and a discernible order across the groups. The predominant commonality among the three groups lies in their shared temporal trend, particularly noticeable in groups 1 and 2: fertility decreases, life expectancy and human capital increases.

In summary, we grouped countries based on their regime dynamics, as captured by symbolic series constructed from considering only population growth rates and per capita



Source(s): Authors' own elaboration

Figure 9.
Regime dynamic group 1, *mature economies*

GDP. Interestingly, we found that these groups also exhibit distinct patterns in relation to other variables that were not initially included in the symbolization process, but are considered relevant in the literature, and in certain instances, even fundamental. The implication here is that the symbolization of two variables reduced enormously the level of

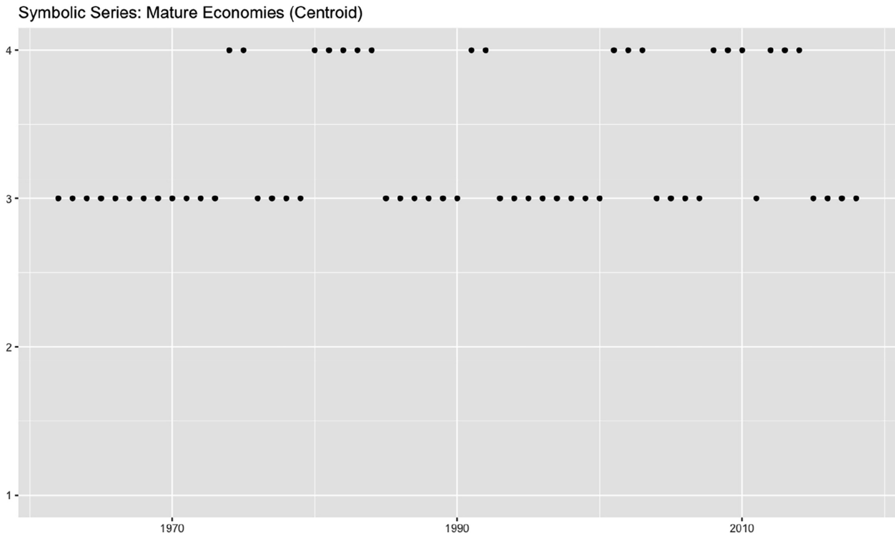


Figure 10.
Regime dynamic for an average country of the group 1, *mature economies*

Source(s): Authors' own elaboration

complexity of a dynamic system involving several variables, while retaining valuable information that enables us to characterize the entire system.

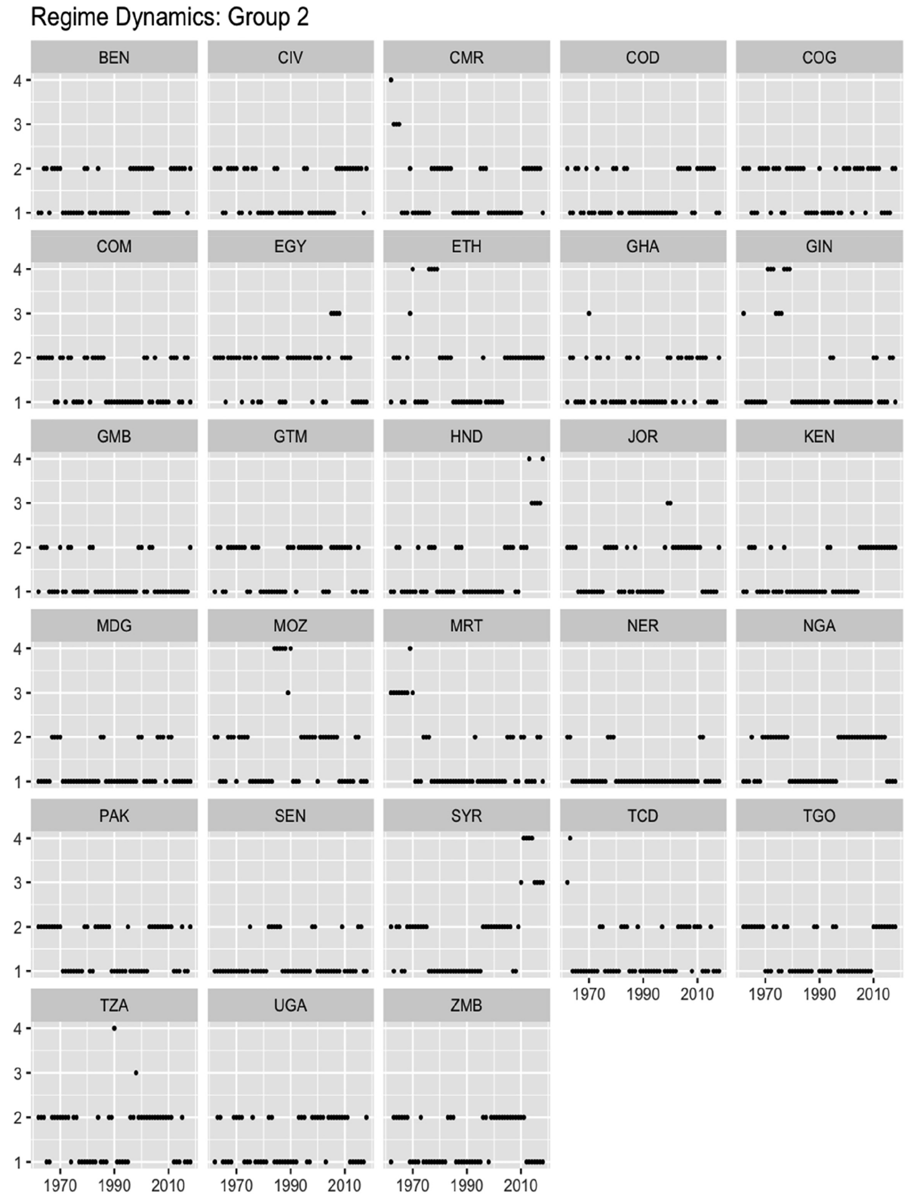
Cluster dynamics, global distance and convergence

In the previous analysis, we discovered information about the dynamics over the entire period. As mentioned earlier, the dynamics of the clusters throughout the considered period are clearly distinct from each other (see Figures 10, 12 and 14). It is possible to observe significant qualitative differences among them.

We conducted an analysis of cluster evolution. Our focus was directed towards investigating the stability of both the quantity and composition within each cluster. Additionally, we aimed to discern whether a trend of convergence could be identified among them, indicating similar dynamics, or conversely, if distinct patterns emerged. To achieve this, we partitioned the analysis period into 30-year timeframes. For each of the 27 windows, we replicated the preceding analysis.

To study whether the countries within the analyzed sample move closer or farther apart over the analysis period, a metric for global distance becomes imperative. Following the methodology employed by Onnela *et al.* (2002), the summation of all MST distances establishes the diameter of each MST, providing insight into the proximity of the countries within the set. The evolution of this global distance in each tree of every time window is depicted in Figure 15, revealing a subtle trend of diminishing distances among the sample countries. This trend suggests an inclination towards increased similarity in their dynamics.

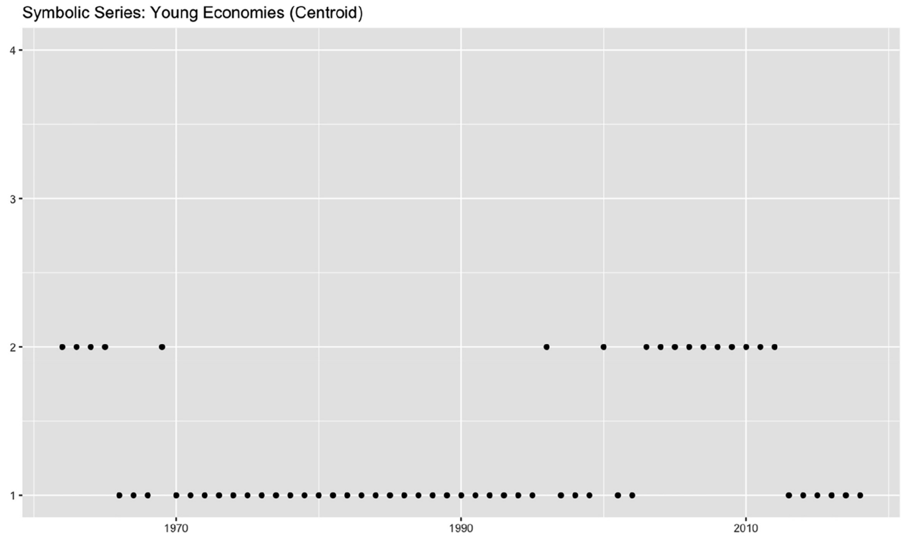
Regarding the stability of group composition, our findings indicate that within the *mature economies* (group 2), all but eight countries (Argentina, Australia, Chile, Mauritius, New Zealand, Romania, Sweden, Trinidad and Tobago and Uruguay) out of the 28 comprising the group, have consistently maintained their positions throughout the analysis period. Notably, these countries primarily encompass European countries and the USA. Argentina, Australia, Chile and Uruguay exhibit similar behavior, consistently moving in tandem and in more recent timeframes, transitioning to the group of economies *in transition*.



Source(s): Authors' own elaboration

Figure 11.
Regime dynamic group 2, *young economies*

In the group *of young economies* (group 3), the behavior has been similar. Its composition has been the most stable, and it is possible to identify 24 countries (out of the 28 that make up the group) that remained together in 25 out of the 27 windows. The country that has stayed the least within the group is Egypt, which has moved away from the group in almost half of



Source(s): Authors' own elaboration

Figure 12.
Regime dynamic for an average country of the group 2, *young economies*

the windows. In no case were any of the countries this group part of either of the other two groups, and they tended to move away.

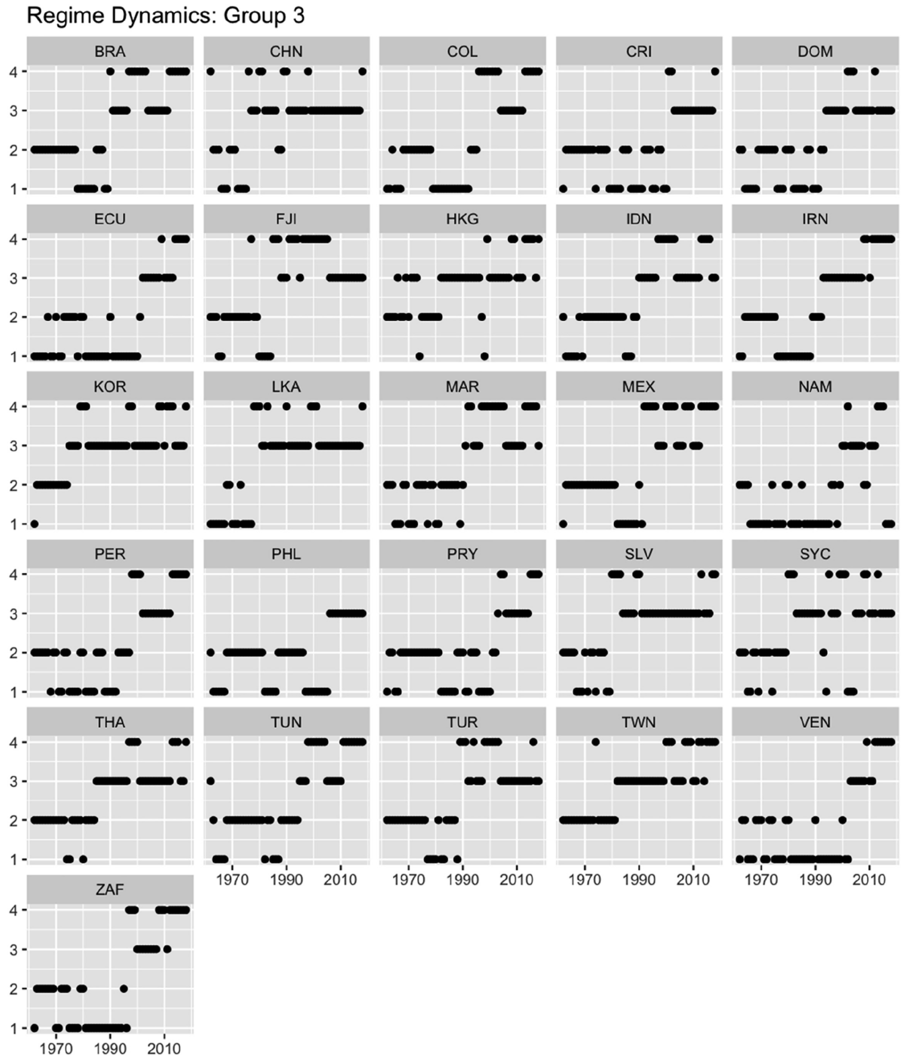
The group of *transition economies* initially includes a small set of countries that remain united throughout the period: Taiwan, Korea, Hong Kong and Thailand. The remaining economies in this group are part of the *young economies* group during the first half of the period and are then added to the *transition economies* group in the second half. In no case do they become part of the *mature economies* group.

The behaviors of Mexico and the Philippines stand out, as in the last eight windows, they tend to move away from the group without joining either of the other two groups. Considering the dynamic behavior of an average country from each cluster, we analyzed the evolution of the distance between them. As portrayed in Figure 16, the results show that the groups have exhibited opposite behaviors. The cluster of *transition economies* is gradually distancing itself from the group of *young economies* and edging closer towards the category of *mature economies*. Concurrently, the gap between *young economies* and *mature economies* remains constant.

Results discussion

The most prominent feature of the partition achieved here is the influence of demographic transition. The clustering that emerges from symbolizing population change and per capita output displays a substantial alignment with the timing of the demographic transition. *Mature economies* encompass countries that had concluded their demographic transition before the analysis period, *transition economies* are those that underwent demographic transition during the analysis period (with the majority experiencing this shift during the final 2 decades of the twentieth century) and *young economies* consist of countries that have yet to undergo a demographic transition.

Interestingly, the taxonomy derived from analyzing population change alone contrasts significantly with the classification derived from the joint dynamics of population and per capita output. In essence, a demographic transition grouping does not arise solely from the



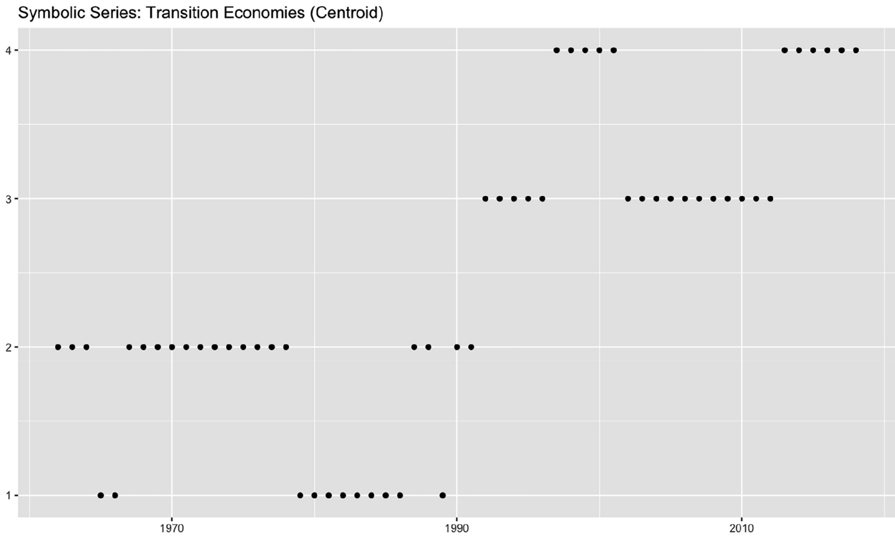
Source(s): Authors' own elaboration

Figure 13.
Regime dynamic group 3, *transition economies*

consideration of population change; it necessitates the inclusion of the interplay between population change and per capita output dynamics. This aligns logically with the understanding that demographic transition encompasses more than just changes in population figures. There are numerous potential explanations for this product.

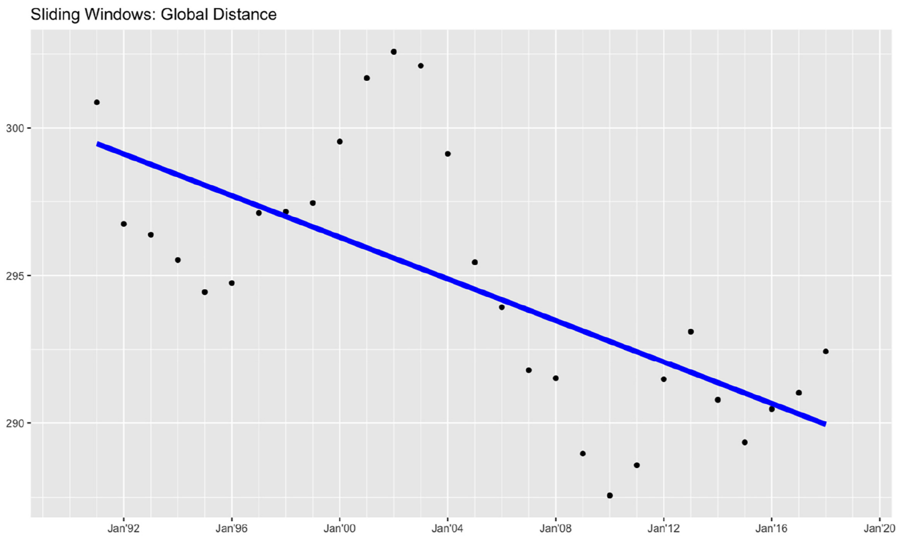
The groupings derived from the similarity in the trajectories of regime change reveal some remarkable facts. First, in addition to the interactions between these variables, the different patterns of behavior reveal functional relationships that vary in sign and magnitude across groups and over time.

This allows us to make some conjectures to explain the diverse and contradictory results found in previous studies. If the relationship between population and economic growth is not



Source(s): Authors' own elaboration

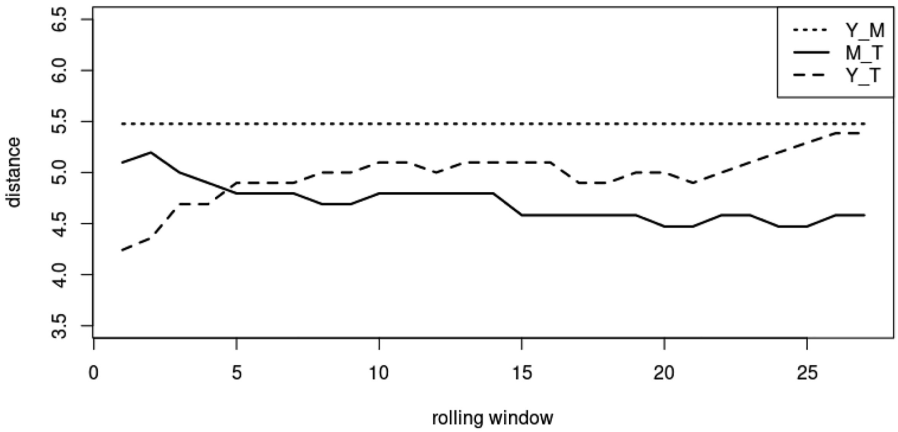
Figure 14.
Regime dynamic for an average country of the group 3, *transition economies*



Source(s): Authors' own elaboration

Figure 15.
Evolution of the diameter of the MST for windows of 30 years

monotonic, case studies of a particular economy could reveal causal relationships with different signs if the time period or the amplitude of the same do not coincide. To illustrate this point, Yao *et al.* (2013) and Rahman *et al.* (2017) analyze the case of China. The former considers the period 1952–2007 and the latter 1960–2013. Both find evidence of a unidirectional causal relationship from population to economic growth, but they differ in the sign. The same observation can be made when looking at the studies by Azam *et al.* (2020),



Note(s): Y_M distance between the cluster of mature economies and young economies, M_T distance between the cluster of mature economies and transition economies, Y_T distance between the cluster of young economies and transition economies
Source(s): Authors' own elaboration

Figure 16. Distance between clusters

Dawson and Tiffin (1998) and Kapuria-Foreman (1995) on India, or by Aksoy *et al.* (2019) and Lianos *et al.* (2022), who focus on OECD countries. Our results allow us to qualify these differences, if the relationship is not linear, the results may differ and will be sensitive to the period of analysis.

At the same time, the marked differences between the groups, both in terms of their regime dynamics and their behavior with respect to human capital or per capita GDP [11], provide an additional explanation for the results reported in the literature. A result that depends on a single model, as is done in standard analyses, has difficulties and obstacles that are difficult to overcome. This idea is reinforced by the analysis of stability, composition and distance between groups. The persistent gap between the group of mature economies (high-income and upper-middle-income countries) and the group of young, low-income, high-growth economies is particularly relevant.

Our results provide evidence of a dynamic interdependence between population and economic growth that is not linear. In terms of causality, the sign, magnitude and direction vary over time and across countries. This has important implications for policy recommendations, design and evaluation. The population control policies pursued in most developing countries may no longer be advisable. In the absence of more in-depth studies of this complex relationship, there is a need for periodic review of these policies, which may become inefficient and have undesirable effects.

Concluding remarks

The study of the interplay between economic and population growth holds a rich historical lineage within the field of economics. However, from a theoretical point of view, there is still no agreement about the scope and channels through which population and economic growth affect each other. Empirical evidence does little to resolve the controversy. Despite the extensive body of studies addressing this topic, no unanimous conclusions have emerged. On the contrary, the results are often contradictory. Given the wide range of findings found within the literature, we have opted to conduct a descriptive and exploratory analysis of the connections between economic and population growth.

In this paper, we have presented a methodology that allowed a model-independent, topological and hierarchical exposition of the intricate relationship between economic growth and population.

By applying clustering techniques and building upon the introduced notion of regime, our objective was to identify groups of countries, each internally homogeneous in terms of the dynamic relations between demographic change and economic growth, while also maintaining clear distinction from the other groups.

Our results show evidence of multiple patterns in the dynamic relations between these two coexistent variables. We identified three distinct groups of countries, each demonstrating a unique dynamic pattern. These countries were classified as *mature economies*, *economies in transition* and *young economies*. The first group comprises mainly OECD countries, characterized by low population growth and robust economic performance, boasting above-average per capita GDP growth rates. In contrast, the *young economies* group, primarily from central Africa, experiences above-average population growth coupled with sluggish economic development. On the other hand, the economies *in transition* group display a distinct pattern set apart from the other two. Initially, its population growth exceeded the average during the first half of the period, only to decline below the average in the latter half. Despite this, its economic performance remains generally above the average.

The methodology enabled the inclusion of additional variables in the analysis, such as life expectancy, fertility, per capita GDP and human capital. This allowed us to compare the impact of these variables on the formation of clusters based on performance changes. The analysis revealed distinct differences among clusters in terms of the trajectories of these variables, thus providing a form of validation for the earlier analysis.

Upon a global examination of the dynamics across all countries in the sample, a subtle tendency towards converging trajectories was observed. Analyzed individually, the dynamics of the three main clusters show that the groups of *young* and *mature economies* are stable in terms of composition.

The *in transition* group initially consisted of a reduced subset of countries, to which those originally part of the *young economies* group were added in the latter half of the period. Towards the end of said period, certain countries from the *in transition economies* group showed a tendency to align with the *mature economies* group, although not vice versa. Analyzing the evolution of the distance between clusters, we observed contrasting dynamics. The *economies in transition* cluster demonstrated a tendency to converge with the *mature economies*, whereas the *young economies* cluster moved away from both the *transition economies* and the *mature economies*.

The evidence provided by our results on interdependence, the variety of ways in which economic growth and population are linked across countries and the changes that occur over time have strong policy implications, especially in terms of their design and evaluation.

Lastly, it is important to highlight certain limitations inherent in the analysis and provide directions for future research. During our investigation, the distinction between natural population growth and the effect of net immigration was not made. This is relevant in light of the fact that the dynamic effects of these two sources of population change exert on output. Incorporating this differentiation stands as a key avenue for future research. Again, the study is exploratory and descriptive; while it provides evidence of interdependence between economic growth and population, it does not allow conclusions to be drawn about causal relationships, nor about the sign or magnitude of possible effects. Another avenue for future research involves conducting a cointegration and causality analysis on the groups derived from countries exhibiting similar dynamics in population and economic growth. This analysis will be based on panel data. Prior to this, an examination of the linearity hypothesis will be undertaken, followed by a comparison of the results with findings from the existing empirical literature.

Notes

1. Biswar, S. (1 may, 2023). Most populous nation: Should India rejoice or panic? *BBC*. Available at: https://www.bbc.com/news/world-asia-india-65322706
   Subramaniam, T. (November 15, 2022). Global population hits 8 billion as growth poses more challenges for the planet. *CNN*. Available at: https://edition.cnn.com/2022/11/15/world/global-population-8-billion-un-intl-hnk/index.html
2. United Nations Department of Economic and Social Affairs, Population Division (2022)
3. In the case of Germany the period of analysis is 1970–2000.
4. See Mantegna and Stanley (1999), chap. 13 for a proof that the function satisfies the distance properties.
5. Following the methodology proposed by Onnela *et al.* (2002), where the sum of the distances, also known as the tree diameter, provides a general measure of the distance between all countries in the sample.
6. The results we got are contingent on the specific thresholds we relied upon. For future research, it would be interesting to explore alternative partitions of the state space and compare the results with the ones obtained here.
7. Given that our framework considers overall population growth without differentiating the effects of birth rates and mortality rates, it's not possible to ascribe the demographic dividend to a single specific regime. That said, in a regime sequence of the type R1 → R2 → R3 → R4, the demographic dividend would be captured somewhere between R2 → R3
8. See Brida *et al.* (2003) for a more detailed exposition of regime dynamics and its symbolic representation. In Brida *et al.* (2011) can be found an empirical analysis on convergence clubs that apply the same approach as the one used in our paper.
9. By initial members, we mean the countries that joined the organization in its first decade or so of existence.
10. Three countries in the group, Australia, Ireland and Luxembourg have some years alternating between R1 and R2 in the final 15 years of the analysis. One possible explanation: the relatively high influx of immigrants during those years. In fact, as a percentage of their population, these are the countries that received the most immigrants in the group during the last 2 decades.
11. To some extent, this is a sign of the robustness of our results.
12. Purchasing Power Parities

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Appendix

The supplementary material for this article can be found online.

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