Historical Pathways of National Research and Development Systems in OECD Countries

Trayectorias Históricas de los Sistemas Nacionales de Investigación y Desarrollo en los Países de la OCDE

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Research and development (R&D) is crucial for promoting knowledge generation as well as the acquisition of new knowledge, so as to enable the development of new products, processes, or services, and improve the existing ones. In this vein, countries make decisions to increase and sustain their innovation efforts and focus on public R&D expenditures. This paper seeks to analyse the pathways of national R&D systems of OECD countries. For this purpose, we conducted a descriptive and exploratory analysis for the period of 2000-2021. We used innovative effort variables, such as R&D intensity, as well as patents as an output variable. The sample consisted of 37 OECD countries, divided into five quintiles according to productivity performance during the study period. The results highlight cases of R&D systems that made a significant leap in productivity during the study period; however, the results also identify cases where a higher R&D intensity does not translate into substantial improvements in productivity. This confirms that innovation is a complex phenomenon where there is not always a guarantee of a positive linear relationship between innovative effort and scientific/technological performance.

Keywords: R&D Systems, Innovation, Scientific Productivity, R&D Intensity, OECD

La investigación y desarrollo (I+D) es crucial a la hora de promover la generación y adquisición de nuevos conocimientos, permitir el desarrollo de nuevos productos, procesos o servicios y mejorar los existentes. En esta línea, los países toman decisiones para incrementar y sostener su esfuerzo de innovación, centrándose en el gasto público en I+D. Este artículo busca analizar las trayectorias de los sistemas nacionales de I+D de los países de la OCDE. Para ello se realizó un análisis descriptivo y exploratorio en el período 2000-2021. Se utilizaron variables de esfuerzo innovador, como la intensidad de I+D, y la variable de producción: patentes. La muestra estuvo compuesta por 37 países de la OCDE, divididos en 5 quintiles según el desempeño de la productividad durante el período de estudio. Los resultados destacan casos de sistemas de I+D que han dado un salto significativo en productividad; pero también casos en los que una mayor intensidad de I+D no se traduce en mejoras sustanciales de la productividad. Esto confirma que la innovación es un fenómeno complejo en el que no siempre se garantiza una relación lineal positiva entre el esfuerzo innovador y el desempeño científico/tecnológico.

Palabras clave: Sistemas de I+D, Innovación, Productividad Científica, Intensidad de I+D, OCDE

1. Introduction

Economic development and technological innovation do not occur in isolation but are part of a broader historical context and process. In short, "History matters" (Crafts & O'Rourke, 2014). From this approach, it is important to analyse countries' research and development (R&D) systems as complex processes of historical development that are affected by many actors.

The result of innovation that is beneficial to society is higher productivity, which has the potential to improve people's lives. In addition, many variables measure the level of innovation and R&D effort (e.g., R&D expenditure and patents). These variables belong to important sectors of society that interact and give rise to R&D systems; namely: innovative companies, public administration, universities, non-governmental organisations (NGOs), and collaborative networks. Various variables are sector-specific; others overlap and interact with all sectors. The result is that the innovation ensuing from formal scientific research is not a linear process, but rather a systemic one where different actors and sub-systems interact with one another.

Academic literature shows that one of the most recognised determinants of countries' economic growth is innovation. Authors such as Schumpeter (1939), Solow (1956), Abramovitz (1956), Griliches (1986), Fagerberg (1988), Freeman (1994), Pradhan *et al.* (2020), and Hausman (2022) consider innovation as a key factor for development. Other authors such as Freeman (1987), Porter (1990), and Nelson (1993) point out that new and advanced technologies are an important determinant of the competitive position of a country or region. It follows then that a country must incorporate innovation in order to generate a better competitive position and sustainable economic growth in the long run (Gutierrez, 2018).

This knowledge has prompted countries to steadily increase their innovative efforts, especially in public R&D spending. However, given the budgetary and financial constraints of governments, it is important to allocate resources efficiently as well as increase the innovative drive in order to optimise results and minimise costs. These aspects highlight the need for public and private actors to spend R&D resources efficiently, an important aspect for decision-makers and those responsible for managing countries' scientific and technological policies (Gutierrez, 2018).

The current global context must be added to the aforementioned analysis, as the international discussion on the future of science, technology, and innovation policies is affected by the COVID-19 pandemic and the climate and environmental crisis. Therefore, the factors that will shape the future of science, technology, knowledge, and innovation (STKI) include the uneven effects of the R&D crisis across sectors, the accelerated adoption of digital tools and techniques, and the changes in the openness, inclusiveness, and agility of research and innovation ecosystems. STKI policies could undergo deep changes as resilience, environmental sustainability, and inclusion become more prominent on political agendas. This crisis could also stimulate experimentation with new tools, policy approaches, and governance models (OECD, 2021a).

Given this complexity, there are many paths a country can take in developing its economy, science, and technology. This paper seeks to analyse the pathways of the national R&D systems in OECD countries while attempting to answer the following research questions:

What have the historical pathways of the main STKI systems been like in the last 20 years?

Is there a significant correlation between expenditure in R&D and productivity?

In this sense, the study aims to explore the long-run relationships among input variables of the innovation process, particularly those that reflect R&D efforts, as well as output variables (e.g., productivity), through the analysis of their historical trajectories for developed and emerging countries.

A characterisation of the various evolutionary paths that OECD countries traverse in the development of their STKI systems may help orient emerging economies that need to design public policies to stimulate R&D and economic growth that are specific to their own needs and growth paths. The latter is of particular interest to Latin American countries such as Peru with developing R&D systems that require references and action guides for both their scientific and technological policy and for defining their economic development strategy. The differences in innovative activity between developed and developing countries underscore the need for further exploration to understand the traditional concept of innovation systems in developing nations (Kasych & Vochozka, 2017).

In section 2, a review of the academic literature is included to visualise the state of the art in the development and evolution of international R&D efforts and results. The review includes the proposal of secondary information sources and databases from different official national and international sources.

Section 3 describes the methods used. In the descriptive analysis, productivity is used as an output variable, and a selection of explanatory variables is used to characterise the pathways adopted by OECD countries in developing their R&D systems over a 20-year period. In addition, an Engle-Granger test for cointegration is used to complement the descriptive analysis.

Section 4 presents the results and section 5 the conclusions.

2. Literature Review

The paper that lays the foundations for the conceptual framework of this study is that by Schot and Steinmueller (2018). These authors conducted a qualitative comparative analysis of three frameworks for understanding the role of innovation policy: the economic growth approach, the innovation system approach, and the transformative change approach.

With a systemic approach to countries, Fagerberg and Srholec (2017) measured their technological, educational, and social capabilities as well as their correlation with economic development. They conducted a factorial analysis, followed by a linear regression of factors with four development variables. The dependent variables were Gross Domestic Product (GDP), GDP per capita, national income adjusted for the use of capital and natural resources, and life expectancy at birth. The main finding of this paper is that technological and social capability variables predict growth not only in GDP but also in other variables adjusted for sustainability and welfare, such as life expectancy and the use of natural resources.

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Navarro *et al.* (2009), classified 188 European regions (EU-25) based on an innovation typology. They used factor analysis (PCA) and cluster analysis. Their findings include: 1) policies to promote innovation need to be tailored to each region, considering their specific value; 2) policies must be accompanied by complementary investments (e.g., in education and training) to generate the right conditions for innovation to happen; 3) the proposed typology can serve as a guide for other regions as well as stage progression.

Coccia (2010) and Rehman *et al.* (2020) analysed the relationship between public and private investment in R&D by using different econometric methodologies. While the former analysed the impact of both investments on productivity growth, the latter analysed the impact on national innovative processes. Both studies point out the complementary nature of the two sources of investment and the importance of an efficient R&D system for this relationship to reach its full potential.

A specific paper on the return to public R&D expenditure is that by Goñi and Maloney (2017). They carried out a quantitative panel analysis using a production function, finding that the return to public R&D is an inverted U-shape. Their results highlight the importance of complementary factors to R&D, such as education (systemic approach) and the use of historical data (1960-2010), and they encourage technology transfer from abroad (as the upward part of the curve). This inverted U-shaped relationship between technological progress and economic growth is found in the case of China, revealing a need to shift the technological progress approach from imitation to innovation, Zhou *et al.* (2021).

Coccia (2009) estimated the return of total R&D spending on productivity growth in a sample of European countries plus Japan and the US, finding that spending between 2.3% and 2.6% of GDP maximises the long-run impact on productivity growth.

In terms of comparative studies among countries, the OECD report (2021b) R&D Intensity as a Policy Target - Lessons from 11 International Case Studies stands out. The report reinforces the idea that there is no optimal level of R&D expenditure, that the R&D effort is highly concentrated within the countries, and there are pros and cons of having R&D target policies. The comparative analysis uses key variables such as private R&D investment, public R&D investment, economic sectors, and R&D expenditure as a percentage of GDP adjusted to the productive structure, size of the companies, and weight of multinational companies in national innovation processes. The report also provides country case studies and STI policy briefs. Two cases of interest are highlighted: South Korea, whose R&D expenditure is not tied to performance targets; and Sweden, where an increased R&D expenditure has not brought about the expected development of high-tech products.

In the same vein of cross-country comparisons, Parrilla *et al.* (2015) carried out a benchmarking analysis between the German and US experience in STI. They used variables such as the level of public and private cooperation applied to research and support for innovation; the educational system and training of the workforce; the weight of the manufacturing sector in the national economy; regional R&D collaboration; the use of institutional intermediaries to avoid market failures in R&D; and the use of incentive-based investments. A qualitative analysis concludes that, though exporting the elements of the German STI system is a complex undertaking, three key features help to achieve success:

regional cooperation among system actors, the existence of institutional intermediaries to drive markets, and incentive-based investments.

Finally, Navarro *et al.* (2016) diagnosed the R&D deficit in Latin America and the Caribbean, by looking at the experience of the Inter-American Development Bank (IDB) and its contribution to progress. They reviewed the literature and used variables such as cooperation between actors of the STI system: universities, firms, and government; the rate of basic and applied research; and the rate of graduates from technical versus professional careers. The main conclusion of their study is that the problem in Latin America lies in low private investment in R&D. They highlighted the coordination between academia and industry, the research in applied and basic science, and technical and professional education, using Finland, Israel, and South Korea as examples.

All these studies show the complexity involved in studying the innovation phenomenon at a national level and how national R&D systems are configured and obtain different results. From this point of view, it is important to take a historical look at these systems, based on certain individual variables, and compare their different trajectories.

The main hypothesis of the study is that although there are short-run relationships between individual variables that account for R&D effort (R&D expenditure) and innovative results (patents) and economic growth as final economic results (GDP per capita), these relationships weaken in the long run, making it difficult to visualise clear causalities, revealing the complexity and multifactorial aspect of the innovative process and the development of national R&D systems. In this sense, firms and governments of different countries and groups spend a sizeable amount of their earnings on R&D activities to create new products and obtain patents for them. The short-run motive is to get patents, and the long-run motive is to influence the income growth of the countries. The empirical findings so far are sceptical of the effects of R&D spending.

Chandra Das (2020) investigated the long-run associations and short-run dynamics among R&D spending, number of patents, and per capita income growth in a panel of countries for the period 1996–2017, observing that R&D spending, number of patents, and per capita income growth have no long-run equilibrium relations but in the short-run, income growth and number of patents are a cause of R&D spending. However, there is weak causation from patents and R&D spending to income growth rates.

On the other hand, Nair *et al.* (2020) found that the intensification of R&D and the information and communication technology (ICT) infrastructure have been regarded as important drivers for sustained economic growth across the globe. The empirical results show that both R&D and ICT infrastructure development contribute to long-run economic growth in the OECD countries. The short-run dynamics show that complex inter-relationships between these variables exist.

An interesting exercise is the one performed by Ahmad (2021), who examined the non-linearity and asymmetries of innovation activities in thirty-six OECD countries for the period 1981-2019. The impulse response function and historical decompositions were estimated to check the cyclical property of innovation activities (R&D expenditures, residential patents, non-residential patents, and international collaboration in technology development) during booms and recessions. The impulse response function provided three important results. First, R&D expenditure moves pro-cyclically in response to gross domestic product (GDP), exports, imports, and gross fixed capital formation in both boom and recession periods. Second, the findings suggest that patents (residential and non-residential) move pro-cyclically in response to GDP, exports, imports, labour force, R&D expenditures, and gross fixed capital formation shocks in boom and recession periods. Third, variables including R&D expenditures, GDP, exports, labour force, imports, and gross fixed capital formation shocks significantly affect residential and non-residential patents during boom and recession periods across the sampled OECD states. Fourth, the results also suggest that international collaboration in technology development moves pro-cyclically in response to GDP, R&D expenditures, exports, imports, labour force, and gross fixed capital formation shocks in boom and recession periods.

A second hypothesis relates to the existence of similar R&D system trajectories, which allows us to speak of groups or clusters of countries that describe similar trajectories and whose results are similar. Yoruk *et al.* (2023) found a significant association between growth dynamics and country-level specific technology clusters that are driven by the ongoing ICT-based technological revolution and enable nanotechnology, biotechnology, and automation tools. Heterogenous trajectories in technological profiles allow them to distinguish between more productive and less productive technology upgrading profiles at different income levels.

Finally, Lee *et al.* (2021) used US patent data of 32 to 35 economies to measure, classify, and analyse the evolution and performance of their respective national innovation systems (NIS) or technology clubs, with a focus on those economies that sustained growth beyond the middle-income stage. The NIS is measured in terms of five variables, namely, knowledge localisation, technological diversification, cycle time of technologies, originality, and decentralisation. Cluster analysis identifies five major NIS clusters that are either balanced or imbalanced in terms of the relative values of the five NIS variables. Growth equation regressions confirm two pathways to achieve catching up towards high-income status. One pathway has been identified for Ireland, Spain, Hong Kong, and Singapore, which all belong to the balanced and mixed NIS cluster and have been joined recently by India and Russia, thus achieving "balanced catching-up." The other pathway has been identified for Korea and Taiwan, which create imbalanced and catching-up clusters and have recently been joined by China. In contrast to these two groups, they have also identified the trapped NIS consisting of those economies perceived to be stuck in the middle-income trap, such as Brazil, Argentina, Chile, Mexico, South Africa, Malaysia, and Thailand. Compared with the trapped NIS with exactly opposite attributes, the imbalanced and catching-up NIS is characterised by the short cycle time of technologies, low originality, high localisation, and high diversification. By contrast, the balanced and catching-up group is characterised by all of these NIS variables that are balanced at intermediate values.

3. Method

Based on the literature, we consider an innovation system as a process of inputs and outputs that involve different actors, such as firms, universities, and public agencies. The inputs are human and capital resources, and output can be well measured by patents and productivity. Patents are an output of the national innovation system and productivity is an output of both the NIS and the economy as a whole. In a market economy, the principal agents are firms since they are the main producers of goods and services. Patents enable firms to obtain a temporary monopoly and economic profits from their R&D investments, greater than those achievable in competitive markets with homogeneous goods. In turn, greater profits of innovative firms eventually result in greater productivity for the economy as a whole, which thus increases living standards in the long run.

We obtained official panel data for countries and years from the OECD website, and extracted variables that, based on the literature, we consider most representative of the aforementioned inputs and outputs.

Table 1 summarises the variables used in this study, together with their roles in the R&D system, definitions, and units of measure.

Table 1. Variables of the study

Nº	Variable	Role in R&D	Definition	Unit of Measure
1	R&D Intensity	Input of STI System	R&D Expenditure/GDP	Percentage
2	Private R&D Funding as % of GDP	Input of STI System	Private Spending in R&D/GDP	Percentage
3	Patent Applications per Million Inhabitants (EPO + USPTO)	Output of STI System	$\frac{\text{Patents}}{\text{Population}} \times 1{,}000{,}000$	Patents per Million Inhabitants
4	Productivity	Output of Economy	Hourly Income per Worker	US$ PPP / hour

Source: OECD dataset and World Bank dataset, 2023

We provide an explanation for the variables used and the rationale for their selection.

R&D Intensity is defined as the proportion of a firm's revenue invested in R&D activities and is thus a measure of the innovative effort expended by a firm, based on its size. At the country level, it is total expenditure on R&D as a percentage of GDP.

Private R&D Funding as % of GDP is a measure of the innovative effort expended by the private sector of a country or region, as opposed to the above general R&D intensity which refers to the private and public totals. This variable is important because it is an indicator of the effectiveness of R&D investment. Firms are the principal actors in an innovation system, and they are compelled to justify investments with concrete returns in profits for their shareholders, whereas public agencies' accountability is sometimes less stringent.

Patent Applications in OECD countries are usually processed by the two principal patent offices in industrialised countries: the European Patent Office (EPO) and the United States Patent Office (USPTO). Patents are the direct result of innovative activities before profits can be accrued. The concrete deliverable end-product of applied R&D is a patent. The patent then enables the firm to enjoy a temporary monopoly on the products derived from it. Therefore, patents are a good measure of the output of an innovation system.

Productivity is an output of the entire economy. In the long run, innovation should give rise to increased productivity of the economy (i.e. better products in less labour time), which results in a greater quality of life for the population.

With the clean data, we carried out the following two sets of activities:

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1. Descriptive and exploratory analysis
2. Engle-Granger test for cointegration

We conducted a descriptive and exploratory analysis for the 2000–2021 period, which has a reasonably complete time series of data for each of the variables included in the analysis. The sample consisted of a panel dataset of 37 OECD countries[1]. We divided these countries into five quintiles according to their growth in productivity during the study period. We then analysed the countries grouped into these five productivity growth quintiles in terms of each of the four variables specified in Table 1.

In addition, we performed an Engle-Granger test for cointegration among three pairs of variables to verify if there is a linear relation among them that is not spurious. This is important because, with time-series data, apparent well-fitting linear regression models can actually be spurious, as Granger and Newbold demonstrated in their seminal paper of 1974.

The three pairs of variables chosen for the Engle-Granger test were:

1. R&D intensity – Patents
2. Patents – Productivity
3. R&D intensity - Productivity

The intensity of R&D is an input for the R&D system and patents are an output. Productivity redounds in increased living standards. This is the rationale for choosing these three pairs of variables.

The steps of the Engle-Granger test are:

1. Test each variable for stationarity with the augmented Dickey-Fuller test.
2. Run a linear regression and compute the Durbin-Watson statistic for each country.
3. Perform a linear regression with all the data (all countries) and evaluate the residuals for stationarity.

The results of the test are displayed in the results section.

4. Results

4.1. Exploratory Quantitative Analysis

Table 2 shows the five quintiles of productivity growth. Quintile 5 consists of the countries that grew most in productivity between 2000 and 2021, at an average annual rate of 3.8% - 7.0%. Quintile 1 grew the least: -0.4% - 0.6%.

[1]Country Codes: AUT Austria, BEL Belgium, CAN Canada, CHI Chile, COL Colombia, CR Costa Rica, CZE Czech Rep., DEN Denmark, EST Estonia, FIN Finlandia, FRA France, GER Germany, GRE Grece, HUN Hungary, ICE Iceland, IRE Ireland, ISR Israel, ITA Italy, JAP Japan, KOR Korea, LAT Latvia, LIT Lithuania, LUX Luxembourg, MEX Mexico, NETH Netherlands, NZ New Zealand, NOR Norway, POL Poland, POR Portugal, SLVK Slovak Republic, SLVE Slovenia, SPA Spain, SWE Sweden, SWI Switzerland, TUR Turkey, UK United Kingdom, USA United States.

Table 2. Countries grouped into quintiles by average productivity growth rate between 2000 and 2021 (USD PPP/Hour)

Quintile	Average Annual Growth Rate	Countries
1	-0.4% - 0.6%	Netherlands, Italy, Luxembourg, Greece, Mexico
2	0.7% - 1.0%	Germany, Portugal, Finland, France, Belgium, United Kingdom, Spain, Norway
3	1.0% - 1.6%	Sweden, Australia, Denmark, Austria, New Zealand, Switzerland, Japan, Canada
4	1.8% - 3.2%	Czech Republic, Hungary, Chile, Iceland, Slovenia, Colombia, Israel, United States
5	3.8% - 7.0%	Latvia, Ireland, Lithuania, Korea, Estonia, Slovakia, Poland, Costa Rica

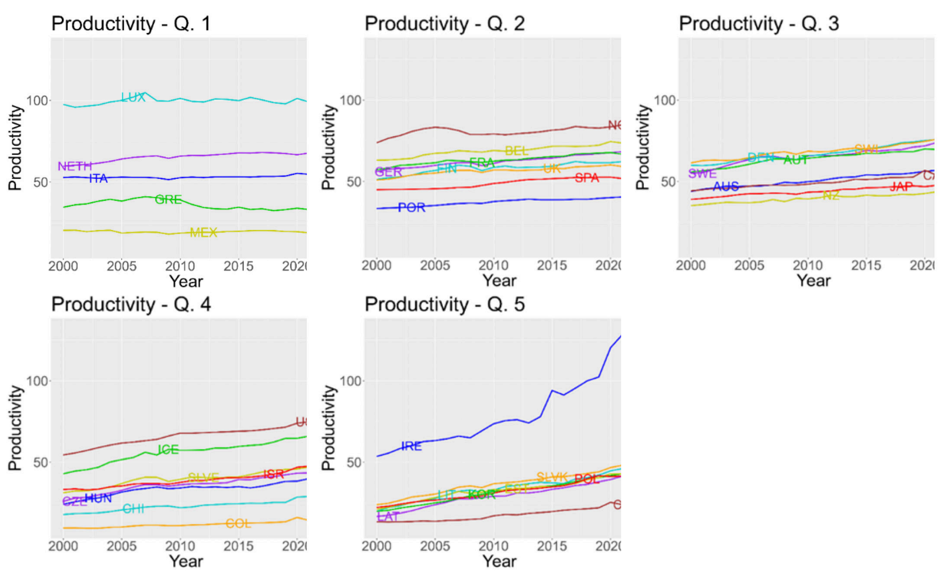
Source: Compiled by the authors, based on the World Bank database

The growth pathways of the different countries are shown in Graphic 1. For this variable only, the steepness of the pathways clearly coincides with the quintile. The case of Ireland is remarkable, as it shows the second highest growth (only behind Latvia), but also a much higher level of productivity than any other country within Quintile 5. Latvia has an even higher productivity growth than Ireland but from a lower level. At the other extreme (Quintile 1), some countries have had insignificant or negative growth, from Luxembourg at an elevated level, to Mexico at one of the lowest levels.

Overall, productivity in OECD countries has experienced heterogeneous growth over the past 20 years. Some countries have shown a steady increase in their productivity, whereas others have stagnated.

It is important to note that there are significant differences between OECD countries in terms of their economic structure, natural resources, level of development, and government policies, among other factors. These differences can influence the evolution of productivity in each country.

Graphic 1. Country Pathways in Productivity by Quintile – 2000 to 2021



Source: Compiled by the authors, based on OECD data

R&D Intensity

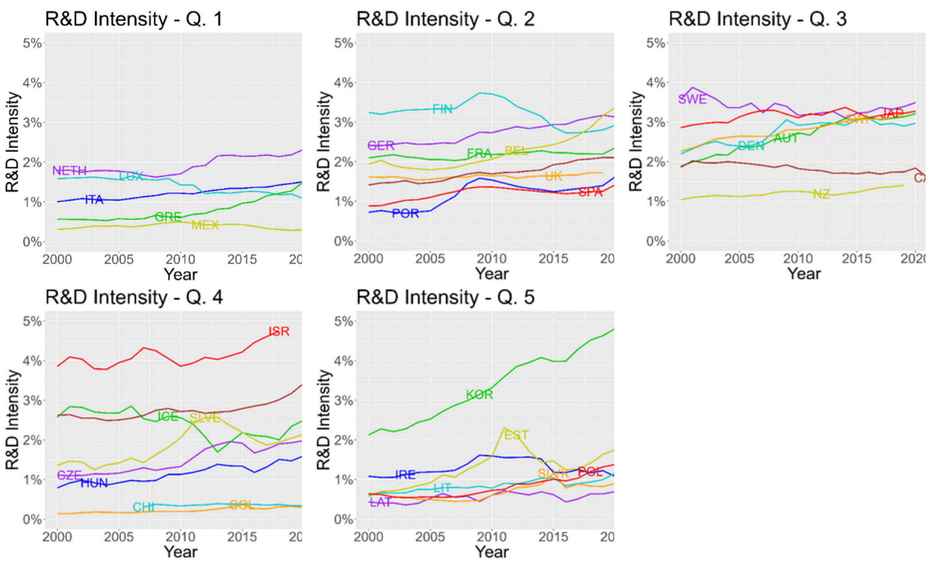
Global investment in research and development (R&D) grew faster than the world economy between 2014 and 2018, registering an increase of 19%. However, 63% of this growth comes from just two countries: China and the US, the two largest economies in the world. China alone accounts for 44% of this increase. Thus, spending on R&D remains highly concentrated: 93% is contributed by the G20 member countries (UNESCO, 2021). This is partly confirmed by the fact that only one in five countries invests more than 1% of its GDP in R&D. In Latin America and the Caribbean, with the exception of Brazil, no country exceeds this threshold, and in contrast to the rest of the world. Investment between 2015 and 2018 fell from 0.69% to 0.62% (UNESCO, 2021).

There are some studies on convergence in the R&D expenditure among countries. For example, Blanco et al. (2020) examine the convergence of R&D expenditure in the European Union (EU28) over the period 2004–2015. The results show convergence in total expenditure, due to the behaviour of the business and higher education sectors, despite the divergence of the public sector. However, notable differences are evident between EU15 and EU13 countries. The business sector is the main driver of R&D convergence in the EU15, while in the EU13 this role is assumed by public expenditure.

When analysing the effort in R&D, Graphic 2 shows different behaviours within each productivity growth quintile. Korea and Israel stand out, as they have increased their R&D intensity steadily throughout the period. Likewise, Quintile 4 is quite diverse: while most countries spent more than 1.5% of their GDP on R&D in the last year, Chile and Colombia never exceeded 0.5% throughout the period.

In general, the graphic displays little correspondence between R&D intensity and productivity growth. Quintile 5 has countries with both high and low R&D intensity. Likewise, quintile 2 also shows significant heterogeneity. Only quintile 1, with the lowest productivity growth, also has significantly and consistently low R&D intensity.

Graphic 2. Country Pathways in R&D Intensity by Quintile – 2000 to 2021



Source: Compiled by the authors, based on OECD data

R&D Private Funding

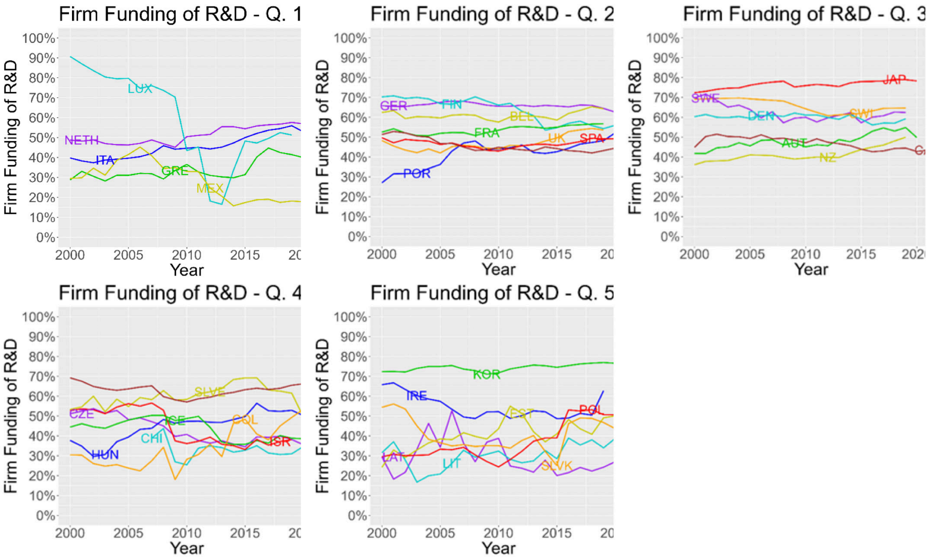
Private financing of R&D, provided mainly by companies, is a variable that allows for understanding the effort made in innovation in each R&D system. However, it is a variable that critically depends on the incentive structure existing in the economy. In particular, the various incentive schemes, tax subsidies (additivity and complementarity), credits, and tax rebates largely explain the differences that exist in this regard between the various countries. Klassen *et al.* (2004), provided evidence on the impact of tax incentives and financial constraints on corporate R&D expenditures decisions comparing the USA and Canada, estimating that the Canadian credit system induces on average $1.30 of additional R&D spending per dollar of taxes forgone, while the U.S. system induces on average $2.96 of additional spending. Other research studies indicate reversed causality. For example, Cheng *et al.* (2021), using a large US sample, found a significant and positive relation between patents and corporate tax planning, and the effect is incremental to the effect of R&D on tax planning. They also found that patents are not associated with tax planning for domestic firms, but their association with tax planning is concentrated in multinational firms, which can shift domestic income to low-tax countries.

Oswald *et al.* (2002), for the case of UK firms, showed that the accounting method affects the amount that firms invest in R&D. On the other hand, Curtis *et al.* (2020) for USA firms documented strong evidence of a declining relation between R&D and future profitability, which coincides with a number of important economic changes, including a significant increase in R&D spending. They identified several contributors to this decline, including changes in the nature and riskiness of R&D projects and a shift in the types of firms undertaking R&D. They also demonstrated variation in the implications of R&D for future profitability, consistent with diminishing marginal returns to R&D investments.

Leung & Sharma (2021) investigated the mediating role of innovation performance in the effects of R&D intensity and R&D internationalisation on firm performance, using data from privately owned firms listed on the Shanghai and Shenzhen stock exchanges. Their results showed a negative effect of R&D intensity on short-run (profitability) and a positive effect on long-run (firm value) financial performance but no significant effect on export (sales) performance. The innovation performance (number of patents) partially mediates the impact of R&D intensity and R&D internationalisation on firm performance and these effects vary based on firm age and size.

In our data, unlike the previous variable, the change in the private sector's share of R&D funding is quite steady within each quintile. Quintile 1 is the exception, in which Luxembourg and Mexico exhibit quite dramatic reductions. The share of business in R&D in Luxembourg has significantly dropped, and it did not exceed 20% in Mexico in recent years. It is worth mentioning the case of Asian countries, Japan and Korea, whose private sectors sustain more than 70% of R&D over time (Graphic 3).

Graphic 3. Country Pathways in Private Funding of R&D as % of Total by Quintile – 2000 to 2021

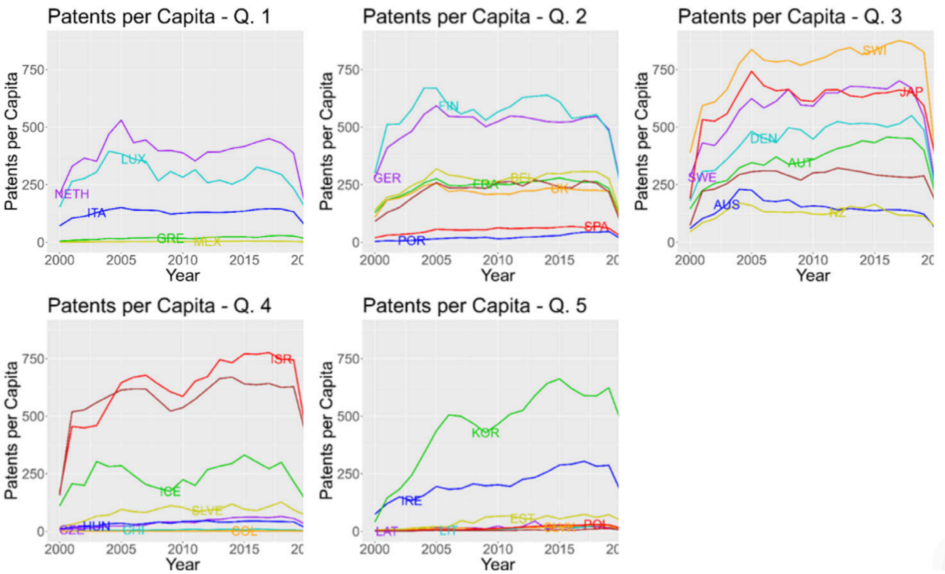


Source: Compiled by the authors, based on OECD data

Patents

Various countries stand out in each quintile when analysing patents. This is the case for Luxembourg, Switzerland, Japan, Germany, Finland, the United States, Israel, Korea, and Ireland (Graphic 4). In addition, the number of patents exhibits heterogeneity and extremes of high and low values in each quintile.

Graphic 4. Country Pathways in Patents by Quintile – 2000 to 2019

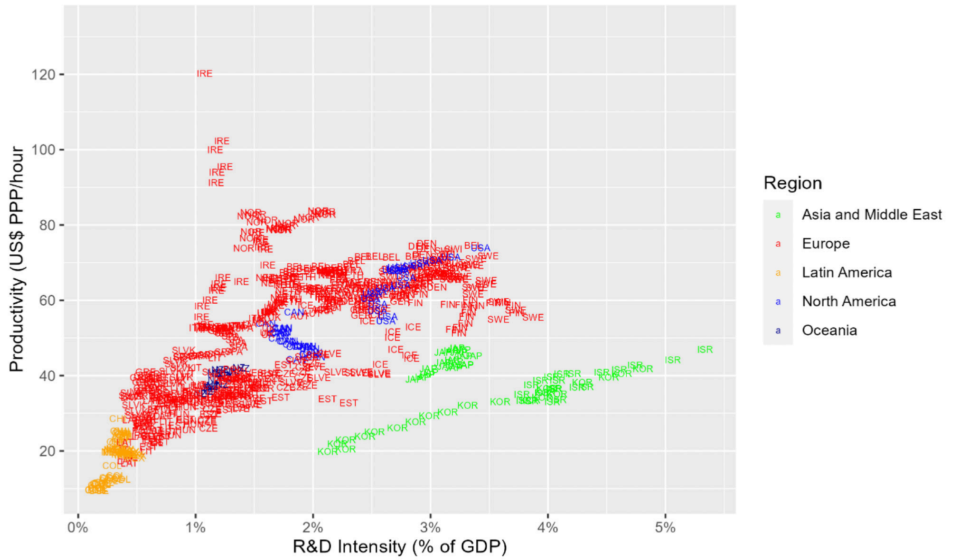


Source: Compiled by the authors, based on OECD data

R&D Intensity and Productivity

Graphic 5 is a scatterplot of countries, where each point is a country and is represented by its 3-letter code. On the x-axis is R&D intensity and on the y-axis is productivity. The region of each country is represented by a colour. The legend of regions and colours is in the graphic.

Graphic 5. Correlation between Productivity and R&D Intensity with Panel Data (Country and Year)



Source: Compiled by the authors, based on OECD data

What is noticeable is that the countries exhibit clear clusters by region, instead of the regions being homogeneously mixed throughout the plot. Therefore, each region occupies a distinct area in the intensity-productivity space and thus exhibits a clear behaviour in terms of these two variables. Asia (green) displays high investment in R&D but low productivity, towards the lower right corner; Europe (red) and North America (blue) have higher productivity and also higher intensity in the middle of the plot; Oceania (dark blue) lower R&D intensity than Asia but similar productivity; and Latin America (orange) low performance in both variables, shown in the lower left corner.

In addition, it might be tempting to infer from the plot that there is a linear relationship between R&D intensity and productivity. However, caution is required here because the data is from a panel, and therefore the relationship may be spurious, as discussed in the next section.

4.2. Engle-Granger Test

To find evidence to support a relationship between R&D investment and productivity, a linear regression could be carried out between both variables, using dummy variables by country to control for each country's fixed effects. Even if the relationship is not linear, it would be reflected in the significance of the coefficients of a linear regression.

However, a linear regression with high R2 between two time-varying variables may well be spurious, as Granger and Newbold (1974) clearly demonstrated in their seminal paper. The Engle-Granger test can rule out spurious relationships by detecting cointegration between variables (Enders, 2008). Therefore, we performed an Engle-Granger test for each country. No cointegration was found in 35 out of the 37 countries, indicating that there is no significant linear relationship between R&D investment and productivity. The lack of such a linear relationship could be consistent with the aforementioned phenomenon of scientific research being less and less disruptive (Park *et al.*, 2023), and raises interest in further research on this trend, as well as the need to model the impact of R&D on productivity by incorporating complementary factors, such as education, scientific and technological infrastructure, the quality of the private sector and the overall functioning of the national R&D system (Goñi & Maloney, 2017).

The results of the Engle-Granger tests for all pairs of variables and all countries show that for almost all combinations of variables and countries, the variables are not cointegrated. We do not show the Durbin Watson statistics and p-values here for space reasons, but instead show a summary for each variable pair in Table 3. Except for a few exceptions, there is generally no real linear relation between the three pairs of variables.

Table 3. Summary of results of Engle-Granger test

Variable Pair	Nº of Countries with Cointegration	% of Countries with Cointegration
R&D Intensity – Productivity	2	5.4%
R&D Intensity – Patents	3	8.1%
Productivity – Patents	1	2.7%

Source: Compiled by the authors, based on OECD data

Notwithstanding, it is important to point out that the Engle-Granger test only rules out linear relationships. There may well be a non-linear relationship. However, to the best of our knowledge, there is not yet an econometric test to detect any type of relationship among a set of variables.

5. Conclusions

This research included a descriptive and exploratory analysis of the pathways of national R&D systems for the 2000-2021 period in 37 OECD countries using individual variables. One of the most significant findings is that there are R&D systems that have made a major leap in productivity during the study period. Ireland and the Baltic countries stand out in this regard. Other interesting cases are Korea and Israel, which have increased their R&D intensity steadily throughout the period, although this has not translated into outstanding productivity. The opposite cases are Ireland and Luxembourg, with a relatively low R&D intensity but high productivity. Although Korea and Israel have experienced significant capital accumulation, they reflect complex phenomena that do not guarantee a positive linear relationship between innovative effort and productivity.

It is worth mentioning the case of the Asian countries Japan and South Korea, whose private sectors have been supporting more than 70% of R&D over time, and also stand out in terms of the number of patents (i.e., applied research). In addition to the fact that productivity in the most advanced economies has been stagnating for years (Graphic 1), innovation seems to have also stagnated in global terms.

Contrary to a standard perspective, there is no discernible linear relationship between R&D intensity and productivity. However, this may be due to insufficient data, or the fact that the relationship may be non-linear or require the simultaneous interaction of several variables, given the complexity of R&D systems. More research needs to be done in this regard.

The main contribution of this study, given its exploratory scope, is the quantitative description of the trajectories of R&D systems for a sample of OECD countries based on a series of individual variables that reflect the efforts and results of national innovation processes. How these differ and reflect phenomena that would require a more specific study on the existence of regional agglomerations and the non-linearity between input and output variables in the description of the innovation phenomenon at the national level.

The latter is of the greatest relevance for policymakers in emerging countries considering, on the one hand, the systemic and non-linear nature of the innovation process, which means that the design of scientific and technological policy must incorporate high degrees of flexibility and levels of openness, as well as adaptation to changes and new realities; and, on the other hand, that the impact assessment must consider periods that allow the effective deployment of the R&D effort, as well as its contribution to economic development.

Limitations of this research include the fact that it is confined to a merely descriptive analysis, without delving into causal relationships through multivariate models. Moreover, the analysis does not incorporate context variables to indicate structural differences between countries, nor does it specify the science and technology policies that have shaped the pathways described by each R&D system.

Future research should focus on studying the systemic impact that R&D has on economies, incorporating complementary variables such as the quality of education or technological infrastructure, and importantly their interaction with the standard innovation variables, in order to discern those public policies that make the innovative effort more effective and that translate into productivity improvements.

Author's role:

CGR: conceptualization, methodology, investigation, writing – original draft preparation, writing – review and editing

JSU: investigation, data curation, writing – original draft preparation, writing – review and editing

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