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Knowledge gaps in Latin America and the Caribbean and economic Development

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Abstract

An economy based on primary products is present in most countries in Latin America and the Caribbean. These remain focused on the export of unprocessed materials and goods, with little added value from knowledge and technology, which creates a development gap with technologically advanced countries and regions. By using a set of 5 quantitative indicators, we provided a novel assessment of growth gaps in the production of knowledge across world regions. Our study interpreted growth curves in terms of their essential constituent components (i. e. size, tempo, and intensity). Latin America and the Caribbean remains a region with average or below-average performance for most indicators of knowledge and most components of growth. The region shows a relatively large intensity for growth in patent applications, high-tech exports, and scientific publications, and this may have to do with recent investment in R&D by some Latin American countries. Although education gaps are slightly closing, research and technological gaps, measured by patent applications and scientific publications, are widening and driving up the resulting gaps in economic growth. Our study adds to other assessments of growth gaps in establishing the existence of an increasing divide between Latin America and the Caribbean and the developed world regions. We also propose strategy recommendations in the context of the current observed gaps in the production of knowledge. Bridging knowledge gaps represents a historical imperative and an unavoidable condition for the economic and social progress of the Latin American region. Therefore, active domestic public policies are urgently needed, along with international agreements that contribute to democratizing access to knowledge and technology.

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1. Introduction

How far is the Latin American region from other parts of the world in terms of development in knowledge? Can the historical trajectory of development in knowledge across world regions be measured in terms of how growth curves differ in growth rate, timing, and magnitude? How could such perspective raise further awareness on increasing gaps and ever more difficult catch-up? We address these issues, centered around Latin America and the Caribbean (LCR), to show new evidence on the extent of these gaps and set new parameters and perspectives that could help develop further strategies to overcome an increasing divide.

Knowledge, technology, and innovation have been at the core of the evolution of the world economy and the growth of international economic activity for the last 50 years (Andersson et al., 2016). However, LCR struggles to realize a progressive shift of its economy from the production of simple goods, which are labor or natural resource-intensive, to complex goods, which are often technologically intensive and with demanding capital (Lavopa & Szirmai, 2018). The gap between North and South in several industries remains unmistakably persistent (Fu et al., 2011).

The specialization in primary exports, the absence of internal policies to promote economic development, and the asymmetry in access to knowledge are all factors that perpetuate the historical dependence of LCR in aspects related to the economy, science, and technology (Childs & Hearn, 2017; Hurtado, 1977; Ponce et al., 2018). Most LCR nations currently base their economy on primary products, that are focused on the export of unprocessed materials and goods, with little added value coming from knowledge, and technology (Brock, 1981; Carvalho & Flórez-Flórez, 2014).

The industrial revolutions of the 18th and 19th centuries were social, economic, and scientific processes that occurred mainly in Europe and North America and resulted in an increased demand for raw materials from LCR; consequently, these industrial revolutions intensified the economic model based on the exports of primary goods for most countries in LCR (Arocena et al., 2015). For LCR, the implications of the third technological revolution, and by homology, the currently fourth revolution (Schwab, 2017), included the loss of economic and productive autonomy, a widening of the income gap with technologically advanced countries, technological unemployment, regressive income distribution, concentration of power in large technological and transnational corporations, and an imbalance of the external sector of the regional economy (Gallopín, 1992).

Neotechnological approaches, particularly within the theory of technological gaps (Hufbauer, 1966; Posner, 1961), justify comparative advantages based on the ability that countries have to innovate (Bayraktutan & Bıdırdı, 2018; Soete, 1981). This, in turn, results in international trade patterns. Thus, for authors such as Krugman et al. (2014), the goal is to export goods produced with high levels of productivity and import goods with less efficient production processes. This competitive market logic could keep LCR stagnant in the production of raw materials since the primary export sector would become the critical component of accumulation and innovation capacity (Bayraktutan & Bıdırdı, 2018; Sunkel, 1987). The international insertion of LCR countries as producers of raw materials would entail an obstacle to the reduction of knowledge gaps. This would be in line with the statement of Cardoso and Faletto (1969), that technological dependence was due to the concentration of production processes in industrialized countries (Hidalgo & Hausmann, 2009). Thus, the specialization patterns of the countries in LCR are perpetuated; particularly as its production is mostly based on the abundance of natural resources and a low-skilled workforce (Sun et al., 2019). Such asymmetry in production patterns in LCR, between LCR and more economically and technologically advanced regions, would not stimulate the diversification of production towards greater technological use (Deacon, 2011; Henri, 2019); especially, when considering phenomena such as the commodities boom of the early 21st century (Gudynas, 2009).

The classic models of economic development have included, as main drivers for development, not only the differences in resource endowments but also different elements that affect production factors (Solow, 1956; Zhao, 2019). Productivity depends on the application of knowledge and technology to the productive sector (Barro & Sala-i-Martin, 2003). Ideas and creativity (also known as technology, innovation, and knowledge) are an essential part of processes generating value (Solow, 1956), they are at the heart of the industry and business, and their importance has increased dramatically over time (Andersson et al., 2016). The neoclassical growth theory proposes that gaps in per capita income across countries should converge over time because the development of poor countries is not restricted only to the adoption of new technologies, as are high-income countries, but also by catching up with the leading economies through the shift from low to high-productivity sectors (Gollin et al., 2014). However, convergence between rich and poor countries, as expected by neoclassical growth theory, lacks evidence (Fukase & Martin, 2020). If anything, the prevalent form of economic growth since the 19th century has been one of increasing and unrelentless income divergence, with initially poorer countries growing much slower that more advanced countries (Fukase & Martin, 2020; Pritchett, 1997).

More specifically, countries diverge in economic development in the same measure they diverge in knowledge and the production of technology. Divergence in economic performance across countries and regions depends on the realization of structural change and technological catch-up within the economic systems; the former component is understood as the relocation of labor from the traditional sector to a modern part of the economy (Lavopa & Szirmai, 2018). In terms of demography and the distribution of population, the increasing divergence of per capita income levels responds mostly to differences between population growth and labor force growth; in this sense, long-term economic growth strongly depends on the relationship between labor force growth and the amount by which population growth exceeds labor force growth, as a dependency ratio (Sheehey, 1996). However, the transition to a developed modern sector by itself is not a unique condition for economic development and the reduction of the technological gap, as it also requires a process of absorption of technological knowledge (Lavopa & Szirmai, 2018).

Knowledge is stimulated by endogenous development (Lucas, 1988; Romer, 1986), where economic growth is driven by technological improvements that respond to internal potentials and investment decisions in R&D in different countries (Solow, 1956; Zhao, 2019). Even culture and society, considered as environments for innovation, are decisive in reinforcing generational patterns that usually deepen pre-established gaps in the ability to innovate and develop knowledge (Bell et al., 2019). Crucial for learning and innovation, as components of economic development, are cultural conventions that foster the informal and free exchange of ideas and knowledge; thus, social rules, common language, tacit knowledge or "learning by doing", physical proximity and interaction between business parties, trust, honesty, and individual freedom are all part of agglomerated production systems (Kesidou & Romijn, 2008).

Therefore, the generation of knowledge responds to investment in R&D, while the volume of ideas depends directly on the number of researchers or human capital in the modern sector that can freely interact within and among the production systems (Romer, 1990; Wu et al., 2019). However, for developing countries, technological innovation and economic development have been until the start of the 21st century based mostly on passive assimilation, learning, imitation, and adaptation of imported new technologies from developed regions of the world (Kesidou & Romijn, 2008). This system of exogenous influence is not enough in terms of crucial knowledge necessary for technological innovation, as diffusion of knowledge in developing countries does not flow as easily as in the developed ones and may be associated with the "enormous technological gaps" that this region suffers from (Kesidou & Romijn, 2008).

Knowledge gaps are accentuated in recent decades due to the increasing speed in knowledge generation and technological change (Moore, 1965; Roser & Ritchie, 2019). The progress of science, as measured by the number of publications, has experienced yearly growth rates of between 8% and 9% since the Second World War, meaning only 9 years are needed for the body of global knowledge to be doubled (Bornmann & Mutz, 2015). This rapid accumulation of knowledge and information increasingly makes the scientific activity a central axis of social and economic development (Berman, 2014); but, at the same time, it is the cause of what Fochler (2016) calls "epistemic capitalism" or the accumulation of capital through the act of conducting research inside or outside the academy (Rikap & Harari-Kermadec, 2019). By the year 2014, the US and China represented 36% of all the publications in science and engineering (2.3 million as a world total); while Germany, India, Japan, and the United Kingdom contributed with a share between 16% and 20% of all the publications, which is about 100,000 publications each (White et al., 2017). According to Scimago Journal & Country Rank for the year 2019, the list of productivity by country reported a total of 177,784 publications from LCR countries, with Brazil accounting for more than half that figure. This value represents only 26.2% of the production in the USA. It also reported China, for the first time, as the leading country by the number of publications, overtaking the USA.

Education, understood as a fundamental right (Black, 2019), is a significant component when conducting regressions on the determinants of economic growth (Mankiw et al., 1992); particularly, when measured through academic achievements or quality of the received education (Delgado et al., 2012; Hanushek & Woessmann, 2008). Although econometric models trying to establish a causal relationship between education and economic growth face considerable problems in the design and application of linear models and mathematical relations, a recent analysis suggested that there is "fairly strong empirical support" that quality of education has a sizable effect or even decisive role on economic growth (Boccanfuso et al., 2015; Glewwe et al., 2014). However, the cognitive abilities of secondary education students in Latin America remain consistently in the last positions in standard measurements such as PISA (Hanushek & Woessmann, 2008; OECD, 2016), which is considered as a factor that explains, in a nonnegligible and statistically significant way, the gap in technological and economic growth for Latin American countries (Hanushek & Woessmann, 2016).

The historical condition of human capital, measured through the quality of education in decades and centuries, has a long-term effect, with per capita patent applications and current GDP per capita as the two most significant historical factors that explain regional disparities (Diebolt & Hippe, 2019). In general, "the knowledge capital of nations" is singularly necessary as a condition for economic growth and is an essential ingredient for the presence of innovative entrepreneurs and their products, which indirectly stimulate economic growth and development through technological innovation processes (Diebolt & Hippe, 2019; Hanushek & Woessmann, 2015). However, for countries to catch-up along the widening technological gap, new knowledge must not only flow from the international strongholds of technological productivity and knowledge to a few isolated centers in developing countries; it must instead be widely diffused and absorbed throughout the national production systems (Kesidou & Romijn, 2008).

According to the OECD (OECD, 2018), boys and girls entering now the education system will conclude their secondary education in 2030. This generation will face complex social, economic, and environmental challenges as adults (Collin, 2019); Besides, they will need more technological and scientific knowledge, with new skills that allow them to work in jobs that do not yet exist, use technologies that are not yet invented and solve problems that are yet to arise (Ingerman & Collier-Reed, 2011; Stone, 2017). Society is facing changing scenarios that require creative solutions and sustained investments to stimulate the generation of knowledge and innovation in LCR, as a mechanism to break the known barriers that the current specialization in commodities represents for the economy of the region.

Since the beginning of the 21st century, LCR has significantly increased investments in education, research, and development, as a percentage of GDP (Medina-Jerez, 2018; Neidhöfer et al., 2018); However, certain indicators perform far below what is needed to accomplish the UN 2030 Agenda (Acerenza & Gandelman, 2017; Castellani et al., 2019). These gaps not only remain over time, but some of them also increase between world regions (Altinok et al., 2018). A very recent analysis on 182 countries, on the last 50 years of data from the Penn World Table database, and a review of global literature on the subject, concluded that there are broad consensus and evidence of no absolute convergence in per capita incomes across countries (Johnson & Papageorgiou, 2020). The injection of greater economic resources, technology acquisition, or linear transfer of knowledge and innovation does not necessarily reduce knowledge gaps (Hanushek, 2006; Marchand & Weber, 2020; OECD, 2012). Technology can even deepen gaps and inequality if not properly implemented with development in mind (Forestier et al., 2002; Kharlamova et al., 2018). Increasing use of external knowledge is often accompanied by a parallel decrease of R&D activities in industry and private firms (Fu et al., 2011). Thus, when an improved indigenous capability to access innovation and knowledge and higher levels of human capital accumulation are simultaneously combined, it is possible to foster a catch-up process in the technological and knowledge gaps and accelerate economic convergence (Fu et al., 2011; Perez-Trujillo & Lacalle-Calderon, 2020).

Our study is a contribution to understanding gaps in knowledge through an assessment of the historical accumulated difference and the constituent components of growth in the production of knowledge. We present an assessment of the current gaps for growth in knowledge and how these patterns could be understood in terms of components of growth (i.e., size, tempo, and intensity). We provide a diagnosis of the observed trends in the growth curves of each world region and suggest possible alternatives to reduce the currently increasing divide. When we refer to "development" we do it in the context of the growth curves presented in this study and focused mostly on the issue of catch-up among world regions. Although much has been said of the increasing divide between nations and regions, our work in measuring and understanding the current gaps between world regions is a novel quantitative approach with new insights; in the hope of contributing to rising further awareness and perspectives on this global issue (Anand & Segal, 2017).

2. Materials and methods

Our analyses were partly made on the Systema Globalis data set, which is a collection of harmonized and manually curated statistics, and freely available from the Open Numbers community (open-numbers.github.io), which is moderated by the Gapminder Foundation (gapminder.org). Open Numbers compiles all public statistics, from hundreds of sources, and includes local and global information on social, economic, and environmental aspects. Systema Globalis includes hundreds of sources from historians, public agencies, and commercial companies (open-numbers.github.io). Our analyses on Systema Globalis included the largest possible extent of time, whenever available. World Bank regions were used as references for regional growth and were defined as North America (NA), Europe & Central Asia (ECA), Middle East & North Africa (MNA), East Asia & Pacific (EAP), Latin America & Caribbean (LCR), South Asia (SAR), and Sub-Saharan Africa (SSA). Additionally, data was obtained from World Development Indicators of the World Bank (World Bank, 2020) and (Inklaar et al., 2018; Lall, 2000). The datasets for this study and their detailed descriptions are available in Mendeley Data (Jarrin, Cango, Ramos-Martin, & Falconí, 2020).

We used a total of six data matrices, consisting of 1) income per person (GDP per capita, PPP inflation-adjusted), 2) the number of patent applications by residents and non-residents per million inhabitants, 3) high-tech exports in thousands of millions of 2010 US dollars, 4) total government expenditure on education per capita in 2010 US dollars, 5) the number of scientific and technical journal articles per million inhabitants, and 6) research and development expenditure per capita in 2010 US dollars. The correction by the number of inhabitants was made by the authors. The selection of these matrices, as proxies for knowledge, was based on the Knowledge Assessment Methodology by the World Bank (Chen & Dahlman, 2005; Robertson, 2009) and the knowledge indicators used in the Global Innovation Index for 2019 (Cornell University - INSEAD - WIPO, 2019). We referred to these six parameters as indicators of knowledge and used short names for each one.

Gaps across regions were measured as the accumulation of differences in growth curves through time; the integration of curves was based on the trapezoid rule with base points on the x-axis, as implemented in the *trapz* function of the *pracma* package in R (Borchers, 2019). The R built-in function *aov* was used for an orthogonal type III analysis of covariance (ANCOVA) (R Core Team, 2018) to test for differences across world regions. Time is a common variable used in growth trends, and this was considered as a continuous cofactor in the linear models, with world regions as the discrete predictor. After the applied ANCOVAs, the *multcomp* package was used for a Tukey multiple comparisons of world region means and associated boxplot graphs (Hothorn et al., 2008). Tukey tests considered the effect of the covariate and the interaction term. Box plot graphs were based on the linear predictor (region by time) and any significant interaction terms. However, because of limited and patchy data (such as for expenditure on education), or strong interaction terms, we suggest caution at the moment of establishing groupings by the Tukey tests. Packages broom (Robinson & Hayes, 2019) and *tidyverse* (Wickham et al., 2019) were used for manipulating original matrices and tabulating estimated results.

Growth curve analysis allowed us to understand the patterns of growth across regions in contrast to the estimated average. By the method of "SuperImposition by Translation And Rotation", implemented in the package *sitar* (Cole, 2019), an average, shape-invariant, single-fitted growth curve model was obtained (i.e. regression spline). This fitted model was a cubic regression spline, which required an optimized number of degrees of freedom. The latter was determined by exploring a range of degrees of freedom (1–100) and their effect on the model's Akaike information criterion (AIC). By spatially matching growth curves for each region to the average growth curve, three parameters, estimated as region-specific random effects, were extracted from growth curve analysis: 1) size was the difference in mean growth (shifts along the vertical axis of curves concerning the estimated average growth), 2) timing (or tempo) was the region's year at peak growth velocity, compared to the average, or the year when a region was growing the fastest (i.e. shifts along the horizontal axis of curves to the mean), and 3) intensity was growth rate compared to the average, or the steepness of each curve (i.e. compression of the time axis to the mean) (Cole et al., 2010). To fit a regression spline, transformations to natural logarithms were necessary for the indicators of knowledge that refer to the number of scientific publications, patent applications, and expenditure on R&D. Figures were constructed in *ggplot2* (Wickham, 2016) and *GGally* (Schloerke et al., 2018). All analyses were made in R version 3.5.0 (R Core Team, 2018).

Ideally, particular World Bank regions could have distinct growth patterns, some with large size and intensity (large growth over the average and at high rates), or others with small size but large tempo (small growth over the average, but with marked growth at later stages). In terms of the correlations among size, tempo, and intensity of growth, each scatterplot tile was divided into cartesian quadrants that were centered at the origin. Quadrants allowed for differentiation among groups of regions and their trends of growth. How these patterns of size, tempo, and intensity in growth defined the different regions provided us with insights into the observed gaps of either economic or knowledge growth.

The components of growth (size, tempo, and intensity) were then compared across World Bank regions and indicators of knowledge through the analysis of heatmaps and hierarchical clustering (unweighted pair group method with arithmetic mean, UPGMA).

Package *superheatmap* (Barter & Yu, 2017) was used for such comparisons. Values for each indicator of knowledge were normalized to unit standard deviation to enable contrasts on the heatmaps. Our discussion was centered around LCR and, in comparison, to all other world regions. We first applied our approach to income per person, and then expanded this approach to the previously mentioned indicators of knowledge.

3. Results

Based on differences between means, four groups of regions are possible to define in the long-term trend observed for economic growth. Being the region with the fastest and largest growth in the last two centuries, NA is the reference for most comparisons. ECA and MNA are the pair with the second-largest growth. EAP remains just above the pair with the lowest growth overall, which is SA and SSA. The former three pairs of regions show no significant differences (P >

0.99) in long-term growth after a fixed-effects ANOVA (F = 65.71, df = 6, P < 0.001), followed by a Tukey multiple comparison of means. All other Tukey comparisons are significant (P < 0.001). Four regions remain on or below the mean trend in economic growth (i.e., SSA, SAR, LCR, and EAP), and three regions above (NA, ECA, and MNA) (Fig. 1). With NA as the reference for largest growth, the estimated gaps in economic growth, integrated through the last two centuries, show that LCR maintains a gap of 70%; only SA and SSA remain further below with gaps of 87% and 89% respectively (Fig. 1). Mean growth, as represented in Fig. 1 corresponds to 25 degrees of freedom, which was the model with the lowest AIC value.

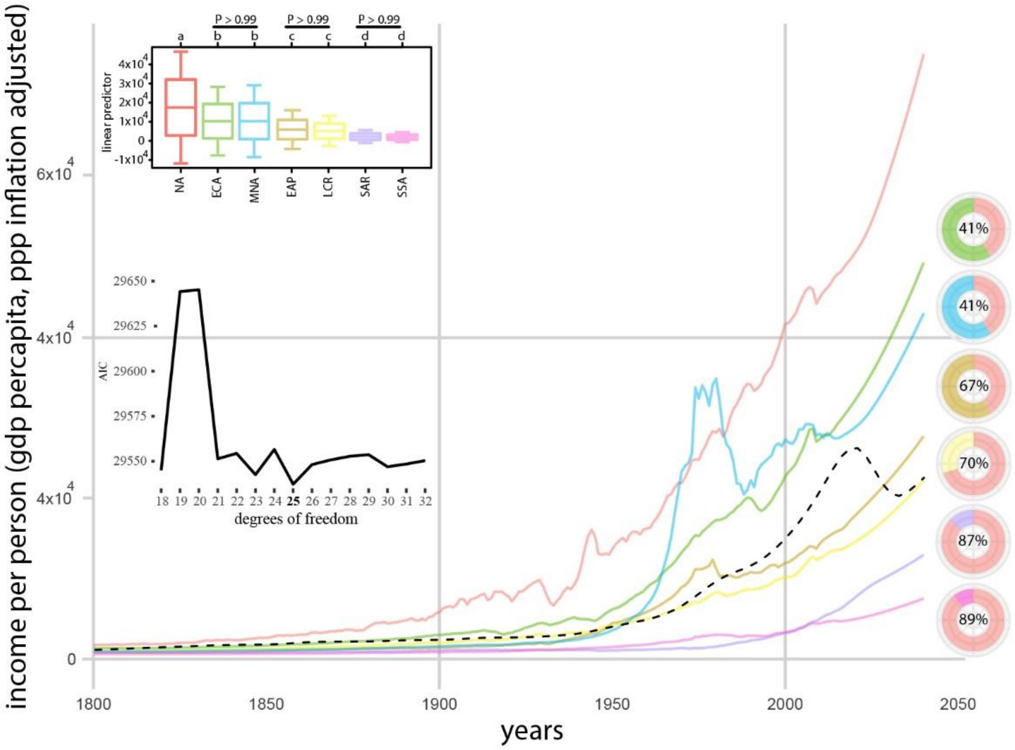

Figure 1. Two centuries of income per person growth and a comparison of the gaps between World Bank regions. Three pairs of regions, that did not show significant differences, can be grouped according to the results of a Tukey-multiple-comparisons of means test. The donuts show the percentage of the gap maintained with NA, after integrating the areas under each curve. The estimated mean growth is represented by the dashed black line. The inserted line chart shows a subset of degrees of freedom that were considered for the cubic regression spline model (i.e., mean growth – dashed line) and their corresponding AIC values.

In terms of size and tempo of income per person, SSA and SAR share noticeable small size and late tempo (Fig. 2a, quadrant IV), both have a marked late peak growth rate of economic development. Small economies are also LCR, EAP, and MNA, but share a history of early tempo, all having an early peak growth rate of economic development (Fig. 2a, quadrant III). The two remaining regions, NA and ECA, are the largest in size and have an early tempo (Fig. 2a, quadrant II). A contrast of size and intensity shows a strong correlation, where the largest economies are also the largest in growth rate, and with NA and ECA occurring in quadrant I (Fig. 2b) and LCR, SSA, and EAP in quadrant III as the regions with the lowest growth rate and size (Fig. 2b). Tempo and intensity separate regions into three groups. LCR and EAP are low intensity-yearly tempo regions (Fig. 3c, quadrant III). MNA, NA, and ECA are large intensity-early tempo regions (Fig. 2c, quadrant IV). SSA and SAR are low intensity-late tempo regions

(Fig. 2c, quadrant II). There are no World Bank regions for the categories of large size-late tempo (Fig. 2a, quadrant I), large size-low intensity (Fig. 2b, quadrant II), and large intensity-late tempo (Fig. 2c, quadrant I). A strong correlation is present between size and intensity of growth (i.e., the largest the economy, the faster it grows); however, a weak negative correlation is present between size and tempo or between tempo and intensity (i.e., the largest the economy, the earlier or more intense it grows).

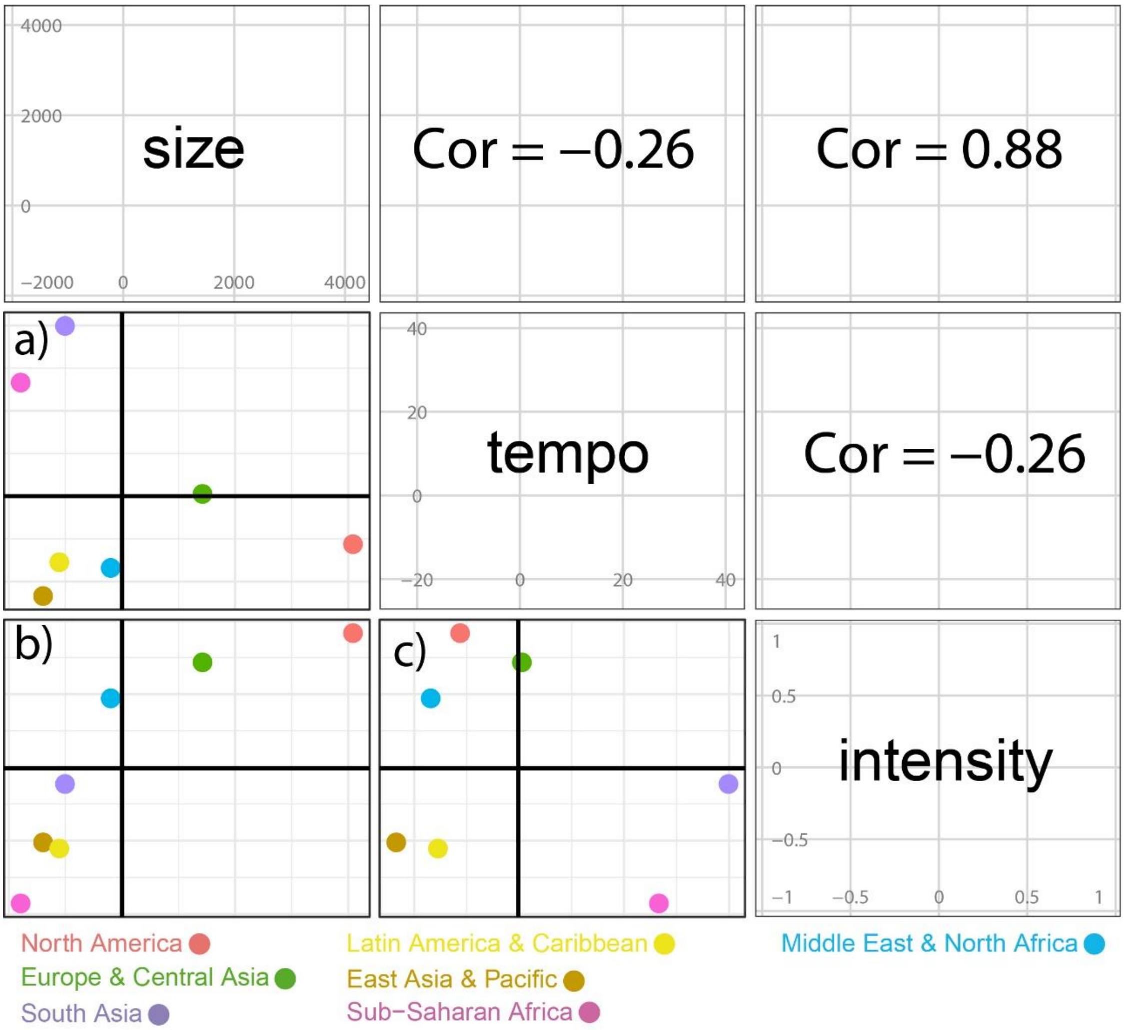

Figure 2. Scatter plot matrix and Pearson correlations of the size, tempo, and intensity that were extracted from income per person growth curves in Figure 1. Letters a), b), and c) have been used to identify scatterplots between components of growth.

A pattern in which one or two regions (i. e. NA and EAP) dominate the space of growth is also evident for the indicators of knowledge, where regions such as LCR, SSA, and SA are essentially flat lines (Fig. 3). The gap for LCR, as measured by the areas under each curve is large, over 90% for all indicators, except for high-tech exports where it is 62%. There is a scarcity of data for expenditure on education and expenditure on R&D. Particularly, within the available time frame, data for expenditure on education is grainy and discontinuous, which precludes confidence for growth curve analysis. The post-hoc analysis allows for groupings and additional contrasts (Fig. 4). Three groups of regions for patent applications are possible to define, with NA and EAP as the first two leading groups, and ECA, LCR, MNA, and SAR as the lowest group. For high tech exports, EAP is the leading region with NA in a second position, ECA and LCR occur near the mean trend line (Fig. 3), and MNA, SAR, and SSA with minimum contributions. Essentially, no differences occur for expenditure on education among regions, except for NA and ECA, which dominate this indicator. However, we should highlight that the scarcity of data for this latter indicator precludes finer or reliable contrasts. The trends for expenditure on scientific publications reflect the trends for expenditure on R&D, where both have NA and ECA as the dominant regions. Except for expenditure on education, where LCR is in the third place (Fig. 3), the region occupies the fourth or a lower position in the group of seven regions for all other indicators. LCR remains always below the third quartile for any of the indicators of knowledge, except for R&D expenditure in which it is closer to the median.

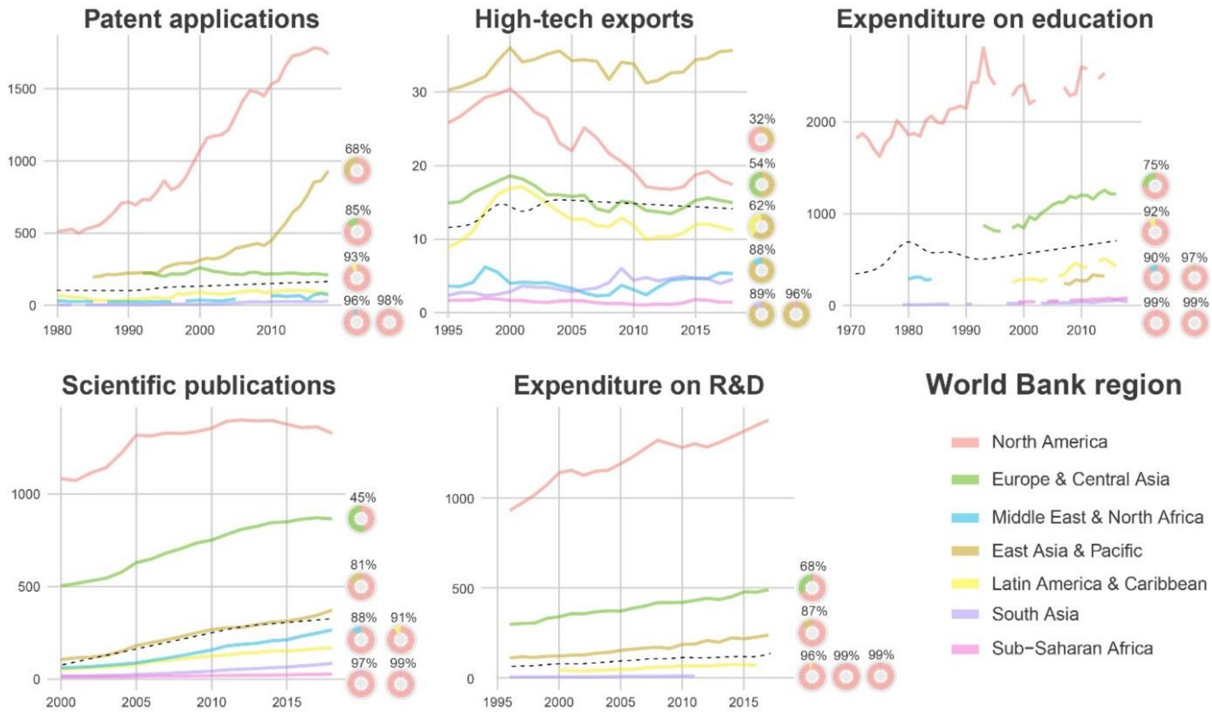

Figure 3. Growth trends for the indicators of knowledge. The donuts show the percentage of the gap maintained with the leading region, after integrating the areas under each curve. The punctuated black line represents the fitted model (the mean trend line).

The lattice that resulted from the combination of size, tempo, and intensity growth curves provided several insights into how LCR remains as part of those regions with a large gap (Fig. 4). For patent applications, LCR remains in the quadrants of low size, late tempo, and low intensity. In terms of high-tech exports, LCR remains very close to the mean in terms of size and has an early tempo and high intensity. This is the only indicator of knowledge in which LCR remains close to ECA. Low size, early tempo, and large intensity are observed for the production of scientific publications in LCR, although tempo and intensity were not significant ($P > 0.05$). It is a remarkable contrast that for the latter indicator, NA is the lowest region in terms of intensity, but the largest in size and with the earliest tempo. For expenditure on education and expenditure on R&D, either the paucity of data or the lack of structure in the growth curves (i.e., the curves were close to straight lines), precludes a detailed growth curve analysis, particularly for the components of tempo and intensity which were not significant ($P > 0.05$); it is, however, noticeable, the presence of LAC as part of the lowest regions in the size component of growth (Fig. 4).

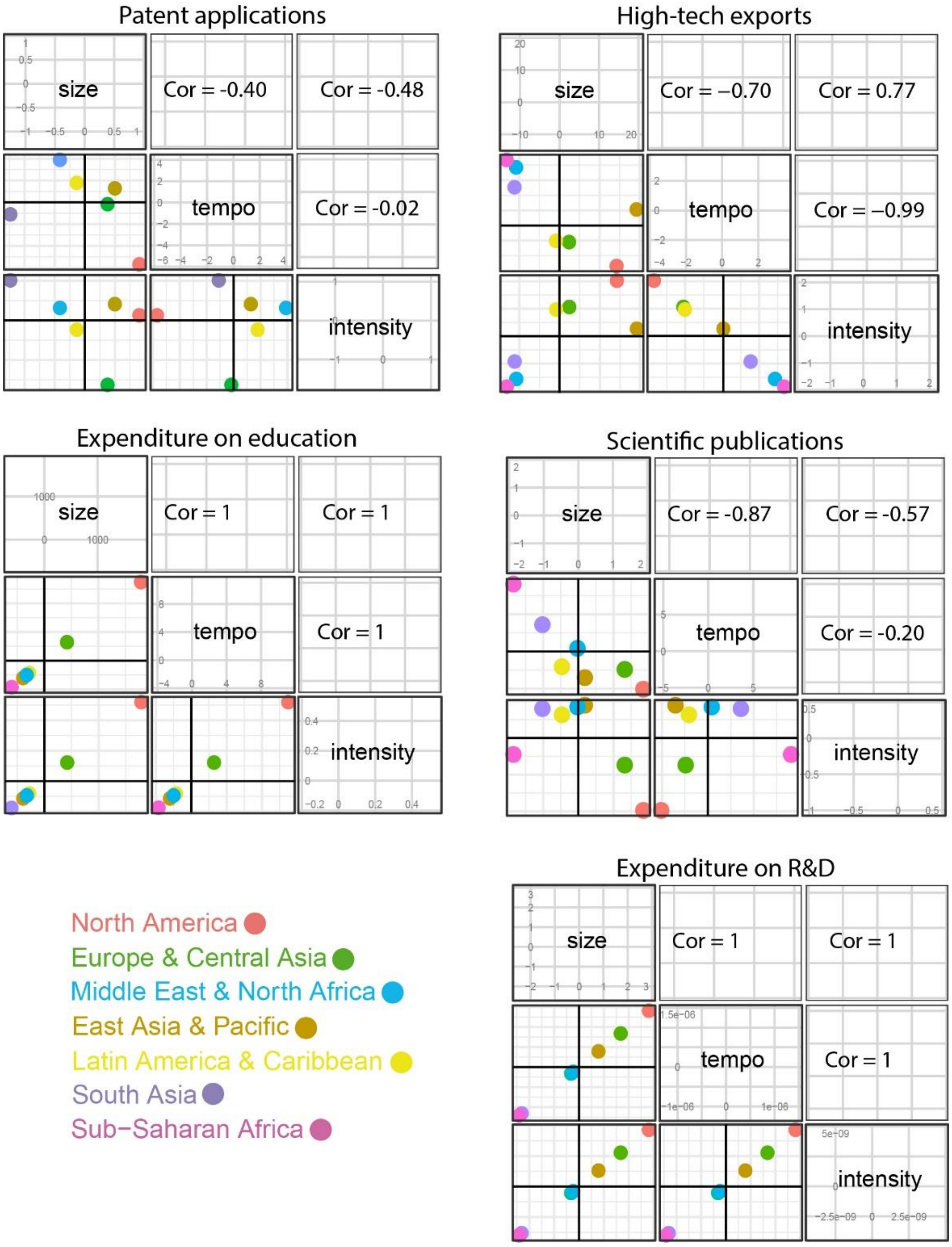

Figure 4. A lattice of the components of growth for the indicators of knowledge. The paucity of data or the lack of resolution for expenditure on education and expenditure on R&D precluded detailed analysis of tempo and intensity for these indicators.

Correlations provided a sense of how all three indicators for growth interact over all of the World Bank regions. The correlation between tempo and intensity for high-tech exports is noticeably strong but inverse and this had to do with a marked trend by NA of an early large growth curve and a later marked decline, which is slightly like the trend for LCR and ECA. For the latter indicator, size and tempo show a relatively strong negative correlation, which suggests that World Bank regions with a small production of high-tech exports appeared lately. A negligible correlation is found between tempo and intensity for patent applications and suggests no discernable process between the time in which world regions acquired more intense growth to produce patents. Size and tempo are also strongly but negatively related to scientific publications, which points to a process in which certain World Bank regions acquire early dominance over the production of knowledge, and the late appearance of other regions represented minor contributions to the established bulk of production. Tempo and intensity do not seem to have a strong interaction, which implies that a high rate of production of scientific and technical literature may not have depended on time. Because of the lack of consistent time series or structure, correlations for expenditure on education and expenditure on R&D are not fully reliable and should be interpreted with caution.

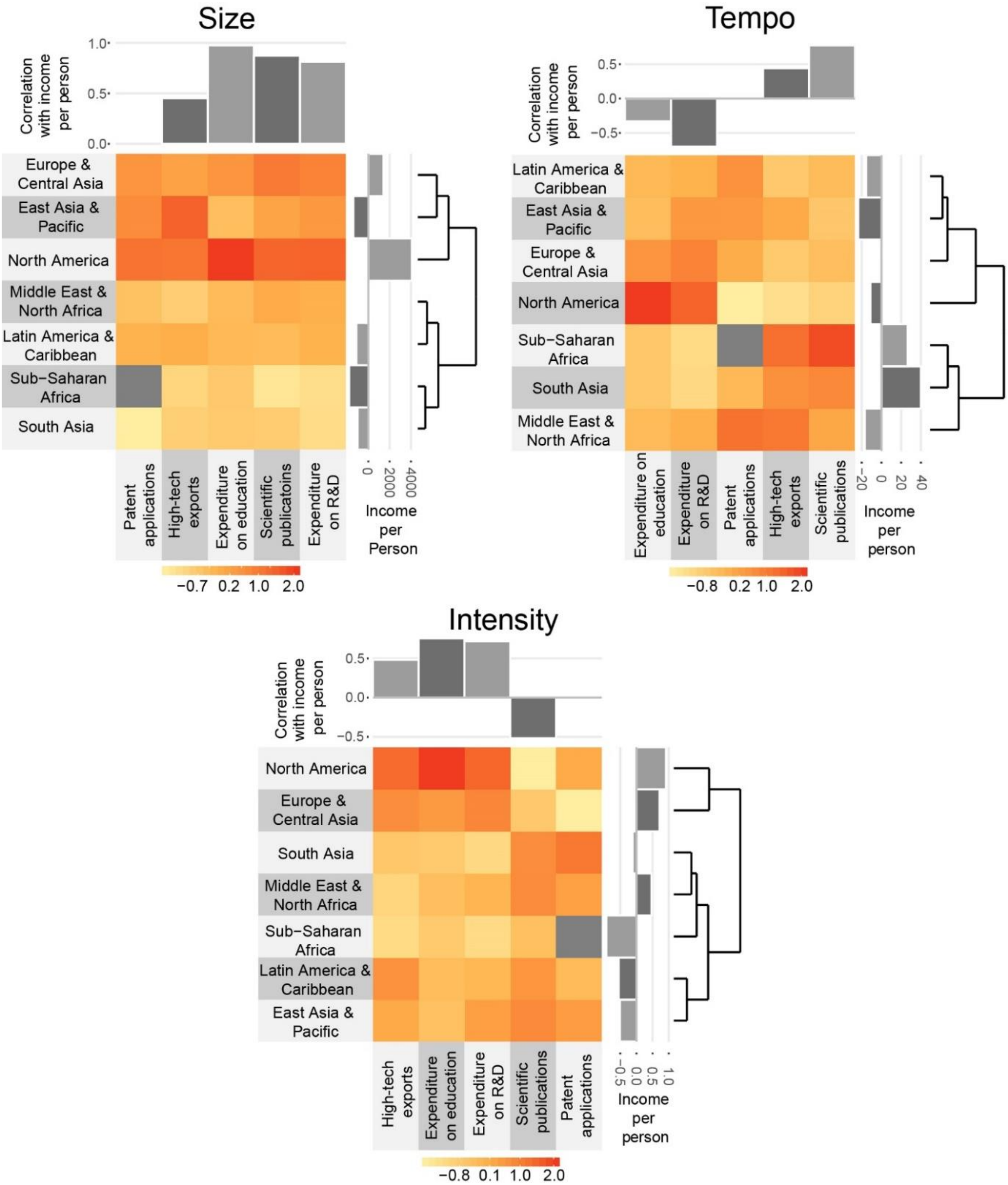

Figure. 5. Heatmaps of the three components of growth for the indicators of knowledge across the World Bank regions, correlations of each component to income per person, and a classification based on the latter variable. The

negative income per person is relative to the normalization of this variable. Normalization of each component of growth indicates a trend towards the left or right of a mean centered on zero in terms of standard deviations, and specific to each component of growth.

Classification on the heatmaps (Fig. 5) show for the component of size in growth, across all indicators of knowledge, that NA, EAP, and ECA form one group with the highest values overall. The rest of the regions, including LCR, form the second group with low values in size. Strongly correlated with income per person on the size component of growth are expenditure on education, scientific publications, and expenditure on R&D. However, high-tech exports are not as strongly correlated as the former. Correlation with patent applications was not possible because of missing data for SSA.

For the tempo component of growth, two groups are also possible to define, one with late tempo (i.e., higher values) for patent applications, high-tech exports, and scientific publications, and formed by SSA, SAR, and MNA; and one with a more or less homogenous tempo across the indicators of knowledge and formed by LCR, EAP, ECA, and NA. Of interest is the late tempo exhibited by NA for expenditure on education, a region which shows late bursts of allocation of resources for this latter category. In terms of correlations with the tempo component of income per person, scientific publications are strongly and positively correlated, while expenditure on R&D shows a strong negative correlation. In other words, the later there is a larger income per person, the earlier the expenditure on R&D, and the earlier there is a large income per person, the earlier there is a large production of scientific publications.

The intensity component of growth shows that NA and EAP form one group with the highest values overall, while the rest of the regions form a second group. The stronger the intensity of income per person, the lower the intensity for the number of scientific publications. This trend may have to do with the marked decline in the number of publications, as can be noticed in the curve for NA and EAP during the last years (Fig. 3.). Intensity for income per person is strongly correlated with the intensity of expenditure on education and expenditure on R&D. On the heatmap (Fig. 5), it is noticeable that the region with the highest intensity for expenditure on education is NA, while for patent applications is EAP. Intensity is also large for NA in the indicators of high/tech exports and expenditure on R&D (Fig. 5).

In general, for all cases of size, tempo, and intensity of growth in the components of knowledge, LCR remains an unremarkable region, as part of other regions that often show a negative trend for size and intensity in income per person, when this variable has been normalized.

4. Discussion: drivers of knowledge gaps

The results provided in the present assessment of regional gaps showed that the contrasting extremes in development, which are NA and SSA, define the expanse of the gap in the size and intensity of economic growth; along this gap, LCR remains the second lowest. LCR shows stagnation in its participation in the global economy (CAF et al., 2018). The region represented 7.1% of the global economy in 1960, while its participation in 2019 was only 7.3% (constant US $ 2010, World Bank, 2020). The economic gap (GDP per capita in constant terms) between NA and LCR increased in the last 57 years; a period in which the difference in GDP per capita between the two regions rose from 4.8 to 5.8 times (World Bank, 2020).

A key indicator for explaining economic growth is labor productivity. Population growth exceeding labor force growth results in stagnant productivity for LCR (Pandian, 2016; Sheehey, 1996). The limited stock of human capital in poor countries makes them less efficient at adding to that stock; which, in a vicious cycle. facilitates the reproduction of further lack of human capital accumulation; however, as labor force growth rates get larger with population growth, a reduction in the gap of per capita income levels is expected across world regions or countries (Nell, 2020; Sheehey, 1996). The GDP per person employed in the region shows a decline when compared to other countries and regions. In 1991, world productivity was 23.2% lower than that of LCR. In 2019, world productivity was 8.5% higher than that of LCR (World Bank, 2020).

Knowledge increases rapidly in the world, and this growth should favor larger economic, social, and technological development throughout the world regions. However, the potential benefits offered by globalization and liberal trade regimens for the international diffusion of technology can only be effectively delivered with a complementary effort for indigenous innovation and the presence of modern institutional and government structures that are devoted to promoting innovation systems (Fu et al., 2011; Gao, 2015). Yet, the historical insertion of LCR economies—which are based mostly on primary export products—in the international markets, intellectual property asymmetries, and the weakening of the integration project in the LCR region are all factors that preclude proper assimilation of international knowledge and technology (Cango, Ramos-Martin, & Falconí, 2018) and results in knowledge being unevenly distributed worldwide (UNDP, 2019).

4.1 Internal drivers of knowledge gaps

In the absence of indigenous innovation efforts, the income gap between developed and developing countries will never be closed (Fu et al., 2011; Nell, 2020). However, there is a cost and there are conditions for technology diffusion and its adoption, where local requirements are absorptive capacity and complementary assets (Howell, 2016); in the absence of such conditions, the greater use of external knowledge is often accompanied by an equivalent decrease in the internal capacity of indigenous science and technology development (Fu et al., 2011).

Given an adequate allocation of human talent in the productive sectors (Yao, 2019), education and technical skills contribute to explain the evolution of labor productivity (Chansarn, 2010; Manuelli & Seshadri, 2014). LCR increased public spending on education from 3.4% to 4.9% of GDP between 1998 and 2015 (World Bank, 2020); this ameliorated the growth in the gap in public spending on education with most regions of the world. In 1998 per capita public spending on education in LCR was 10.6 times lower than that of the United States, 8.9 times lower than that of Canada, and 5.2 times lower than that of the European Union. By the year 2015, LCR had narrowed the gap, nearly halving it with the United States (5.4 times) and Canada (5.5 times) (World Bank, 2020). However, significant gaps remain, as the historical accumulated gap in the growth trajectory estimated in our study was 92%. Education remains a considerable challenge for the region since large fractions of its population remain without access to education of quality (Fischman & Ott, 2018), and the population is still growing faster than in NA or ECA (World Bank, 2020).

Investment in research and development (as a percentage of GDP) has been steady in the world, at 2.1% of GDP between 2000 and 2017 (World Bank, 2020). In the case of LCR, it increased meagerly, from 0.6% of GDP in the year 2000 to 0.7% in 2017 (World Bank, 2020). When compared to the rest of the world, per capita spending on research and development in LCR is considerably low. By the year 2000, this indicator of knowledge for LCR was 27.7 times lower than that of the United States, 19.1 times lower than that of Canada, and 12.2 times lower than that of the European Union. Investment per person is still insufficient in LCR, which for 2015 was 18.8 times lower than that of the United States (World Bank, 2020).

The lesser levels that LCR maintains with the rest of the world in terms of income per capita, public expenditure in education and R&D per capita result in a reduced generation of knowledge. Replicating knowledge requires low marginal costs; however, generating knowledge requires significant investments in infrastructure and human capital. Both conditions are capable of articulating education and training from the initial levels to advanced stages that result in applied research and technological developments (Ciocca & Delgado, 2017).

Structural change towards the modern productive sector and technological catch-up (i.e., absorption of technology) are two essential conditions on which the development of countries depends (Lavopa & Szirmai, 2018). Even if there is an expanding modern sector, there may be insufficient technological catch-up. A region such as LCR, with a notably expanding modern sector in the 1990s, remained caught in a development trap and in contrast to a growing Asia where technological improvement was possible (Lavopa & Szirmai, 2018). Thus, technological catch-up requires a properly educated and capable population, without which this necessary component for development will not be possible.

The number of patent applications of LCR is markedly low (World Bank, 2020). In 1995, the share of patents from residents in the region barely reached 0.7% of the world total. By the year 2018, patent applications by residents had reduced to 0.4% of the world total. This reduction in the world share of patents has widened the knowledge gap. Measured by the number of patents per million inhabitants, the gap between the United States and LCR went from 51.2 times the number of patents filed by LCR in 1995 to 68.6 times in the year 2018 (World Bank, 2020). To ameliorate this increasing gap in technological capability, assimilation and mastering of new technologies through investment in education would allow the modern sector to increase capital and labor output (Lavopa & Szirmai, 2018).

A similar gap to that obtained for patents is also present for scientific publications. Technical and scientific publications in LCR accounted for 2.9% of the world publications in 2003, a number that increased to 4.2% by 2018. In general, LCR has reduced the gaps in publications (per million inhabitants) by 2020, halving them with NA and ECA; however, the gap widened with EAP, which is mostly due to the impressive growth of South Korea and China (World Bank, 2020). The number of scientific publications has a close relationship with the number of researchers dedicated to R&D (Rosenbloom et al., 2015). In 2014, South Korea had 1.9 times the number of researchers per million inhabitants than LCR. China had 11.4 times as many researchers as LCR per million inhabitants (World Bank, 2020). The larger population allocated to the scientific and research sector may explain the widening gap in scientific publications. Countries trapped in middle-income ranges require moving human resources from low-wage activities and routinized tasks to knowledge-based production and the use of cutting-edge technological innovations (Lavopa & Szirmai, 2018).

Given the assessment of growth trajectories presented in this study, any observed reduction of the present gaps between LCR and more developed regions of the world has been meager and insignificant. Overall, the trends for LCR are essentially flat lines with unremarkable size (as the specific growth component measured in the present study); intensity, however, is relatively large for patent applications, high-tech exports, and scientific publications. The former mirrors the slight reduction in the proportions of gaps that we have mentioned earlier and an intensive rate of R&D investment that has been previously reported by other authors (Gonzalez-Brambila et al., 2016). Caution is however necessary at interpreting these results, as our analysis is unable to discriminate on the differential quality of the measured indicators of knowledge. As we have mentioned in the results section, high-tech exports was the only indicator of knowledge in which the component of size remained close to the mean of the world regions. Yet, our measurement is coarse as it does not distinguish between maquila-type industries—that maintain low intellectual value or absorption of technological knowledge— and high-tech native industries in which knowledge and technology have been properly assimilated (Lavopa & Szirmai, 2018).

Internal factors that preclude catch-up derive from the lack of investment dedicated to research and development, limited productive diversification, the weak articulation between education and the job market, and lack of innovation. A weak State, lack of affordable funding, and a large proportion of the population with unfulfilled basic needs (e.g., access to drinkable water, sanitation, electricity, transport infrastructure) pose countries in the region with a dilemma on how to properly use the available budget. The political cycle, however, tends to favor short-term policies with an eye on the next elections, instead of implementing long-term plans for the development of science and industrialization. The investment dedicated to R&D and its distribution with a focus on expenditure efficiency and quality may reduce knowledge gaps. However, to be successful, R&D processes need to be sustained over time, considered as a state policy, and not just as a transitory measure.

4.2. External drivers of knowledge gaps and the international trade insertion

Another driver of knowledge gaps is the international trade insertion of the region. LCR has asymmetrical trade relations that undervalue (in monetary terms) the exported goods. The latter are usually without added value and result in expensive imported goods and services, especially those with a high degree of added technology. The dependence on natural resources is the most vulnerable form that an economy can assume; given that, due to the existence of unequal exchange, maintaining or increasing domestic consumption and investment levels implies having to export increasing amounts of natural resources, with associated environmental impacts that are not reflected in the prices of such exported goods (Hornborg, 1998; Hornborg & Martinez-Alier, 2016).

Indeed, this sort of unequal exchange (Ciplet & Roberts, 2017; Prebisch, 1950, 1959; Ricci, 2019; Singer, 1950) is complemented by the existence of ecologically unequal exchange. As there are more exports than imports, measured in physical units, there are also more local environmental impacts and socio-environmental conflicts (Bunker, 1984, 1985; Samaniego et al., 2017). Besides, there is also a calorically unequal exchange (Falconí, RamosMartin, & Cango, 2017; Ramos-Martin, Falconí, & Cango, 2017); that is, food exports, as measured in calories, with lower unit prices than imported calories.

LCR exports raw materials and food and imports technology. In both cases, the region is unable to set prices on international markets. Regardless of the changes in international prices, the export structure shows little diversification over time (Fig. 6). During the entire analyzed period in this study, more than half of the region's exports have been raw materials, low-tech products based on natural resources, or low technology, without perceiving significant changes that may indicate a shift in the current trend for exports, technological capability, and modern sector. This dependency on commodities has been the result of the lack of investment in education and research, which, as we have discussed, are necessary engines for labor productivity and economic growth.

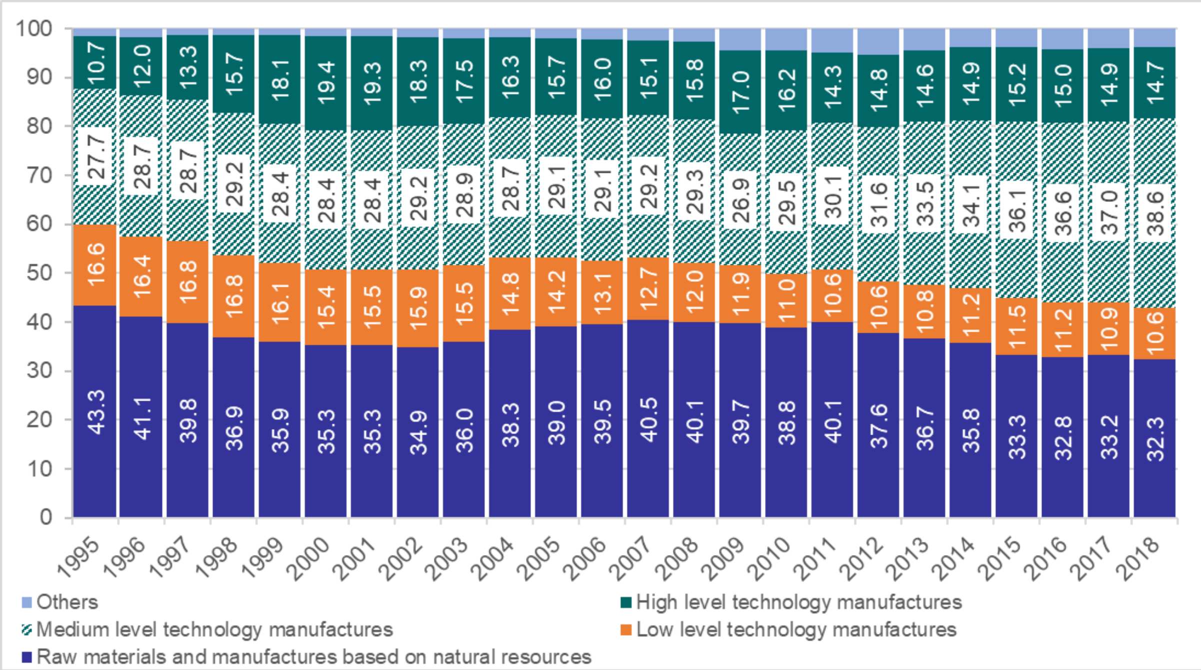

Figure. 6. Latin America and the Caribbean: Structure of exports by technological intensity between 1995–2018 (Unctad, 2019).

4.3. Intellectual property asymmetries

Current knowledge gaps are also aggravated by the international system of patents and intellectual property, which hinders the acquisition of knowledge and technology by poor countries (Cango, Ramos-Martin, & Falconí, 2018). It is a vicious cycle in which poor countries cannot devote the same resources in terms of research, innovation, and technological development, which in turn results in a lower number of patents that compel these countries to continue depending on technological developments that occur in other parts of the world. The problem is further aggravated by the impossibility of the population to properly access and use those patents, either due to the absence of absorptive capacity or the lack of complementary assets that are capable of assimilating and mastering these patents (Howell, 2016).

4.4. The weakening of the process of regional integration

LCR is a region that includes low and middle-income countries that share shortcomings in their scientific and technological policies (Gonzalez-Brambila et al., 2016). In this context, the actions of individual countries may have a marginal impact, so in recent years, initiatives to improve regional integration were looked forward to (e.g., CELAC). Multilateral forums were created in which a certain harmonization of educational, research, and industrial policies was sought. LCR countries looked at European integration and the leap that it meant not only for its already developed scientific and technological sectors but for its articulation with the processes of industrialization and public policies (Hayward, 1995).

In recent years, the change in the political cycle in the region, from leftist-progressive to right-wing neoliberal governments has implied a weakening of the regional integration process (Reid, 2017). There is no longer the political will in many countries to seek collective solutions to common problems; thus, returning to the weakness of individual action in each country. This weakening implies an obstacle to coordinate science and technology policies, the generation of research networks, as well as the common use of resources toward development (Albornoz, 2020). The worrying outcome is that the region offers no alternatives to the current reprimarization observed in international trade (Cooney, 2016). As reiterated in the recent study by the United Nations International Resource Panel, the region maintains the historical role of being a supplier of raw materials for industrialized economies (IRP, 2019).

Conclusions and policy recommendations

Our analysis is unique in the sense that we assessed gaps of development in knowledge by decomposing growth in its three essential parameters, which are size, tempo, and intensity. According to our analysis, LCR maintains a historical gap of 70% with NA in income per person growth over the last two centuries. SAR and SSA are close to a 90% gap, which will require special conditions and considerable efforts for a catch-up. Four regions remain on or below the mean trend in economic growth (i. e. SSA, SAR, LCR, and EAP), and three regions above (NA, ECA, and MNA). Catch-up processes should necessarily consist of policies and mechanisms that secure sustainability and equitable development but also achieve economic growth, and that incorporate the complexities and peculiarities of native cultures, geographies, and natural endowments (Demeterova et al., 2020; Li & Lin, 2019).

A contrast of size and intensity shows a strong correlation, where the largest economies, NA and ECA, are also the largest in growth rate. This pattern is also evident for the indicators of knowledge, with regions such as LCR, SSA, and SA having a small size component of growth. Labor productivity helps to explain the result of economic growth. Labor productivity in LCR in 1991 was above the world average, whereas in the year 2018, LCR had a value 12.6% lower than the world average, showing a decline over time and an incapability to keep up with the development in other regions, particularly with EAP. Concerning NA, despite the widening gap in income per capita for LCR, the region has slightly reduced the gap in education expenditure per capita, which reflects both the low starting point of the region, but also efforts deployed in the last decades (i.e., measured as intensity in our study).

In relation to NA, our study showed that the gap for LCR is over 90% for all indicators of knowledge. In terms of the number of patents, LCR remains in the quadrants of low size, late tempo, and low intensity. Despite the growth in patent filing in the region, LCR represented only 4.2% of world-filed patents in 2018. The United States had 68.6 times more patent applications per million inhabitants than LCR in 2018, making it difficult for the region to close the gap. For high-tech exports, LCR remains close to the mean in terms of size and has an early tempo and high intensity. This is the only indicator of knowledge in which LCR remains close to ECA.

For the number of publications, LCR has been classified by our study as a region with low size, early tempo, and large intensity; however, these values were not significant. The slight reduction in the gap for this indicator seems related to NA as being the lowest region in terms of intensity, but the largest in size and with the earliest tempo. In 2018, LCR represented 4.2% of the world's scientific publications, and has slightly reduced the gap with all regions, except for EAP; the latter is heavily pulled up by China's performance. We observed a decline in growth for scientific publications, in the curves for NA and EAP during the last years, which could be associated with the inverse correlation found between intensity for the number of scientific publications and intensity for income per person. The latter relationship opens room for future research at investigating the causes of the plateau reached by NA in terms of publications and to analyze why growth in income per capita seems to be slowing the rate of growth in publications.

Saturation is a concept that we propose for explaining how historical gaps, as the integration of accumulated differences in growth curves through time, will eventually reach a value close to 100% (they will approach the limit as an asymptote) with NA as the reference. Large gaps, above 90%, are present for regions such as LCR, SSA, and SAR in indicators of knowledge, such as expenditure on R&D or scientific publications. The latter represents a trend towards saturation, in which added intensity and size—as components of growth—by more developed regions will no longer represent significant increases in the magnitude of the historical gap, as this will remain a fraction close to 100%. This is a concept that integrates the historical trajectory of World Bank regions and which meaning can be applied to the study of long-term trends, and long-term strategies of development. Avoiding the state of long-term saturation by regions such as LCR should include sound strategies for development.

Access to knowledge, as an essential component for economic development, is not only about strengthening basic and applied research; but also, about down-to-earth knowledge and research, that enhances adaptability to cope with changing future scenarios. This implies turning knowledge into useful realities to solve the problems demanded by today's society. Income, productivity, and knowledge gaps between LCR and several countries, regions, and the world average are widening. Investment in education, research, and development (as a share of GDP) is necessary, but not sufficient, to reduce knowledge gaps.

With this in mind, we propose several measures for debate (Kesidou & Romijn, 2008): 1) a new productive specialization focused on knowledge and not only on resources endowment, particularly on viable and affordable sectors such as software development; 2) prioritization of innovation activities focused on unsatisfied basic needs, with the intervention of strong developmental states that can negotiate with international capitalists, capture investment and drive such investment towards promissory technology-intensive sectors; 3) sustained investment in education quality, which requires reversing the structural weakness of the State. This third measure is based on the fact that local knowledge spillovers in developed economies are possible due to government subsidies toward universities and firms that conduct substantial R&D; 4) strengthening professional education, for the formation of highly-skilled employees, that should be linked to local industry; 5) deepening processes of regional integration and South-South cooperation, with long-term multilateral agreements between countries from the region, to foster mobility, informal interaction and knowledge transmission by relaxing labor laws, and that avoid parallel efforts in a region that is characterized by budget constraints, with synergies and economies of scale.

LCR and the countries in the region must learn from past experiences of success and development. China's achievements in economic and technological development were accomplished by a national ideology centered on technocratic rationality and technology-driven modernization. Leaders of this nation emphasized science and technology as the key factors for reaching economic productivity. China's empowerment in the global economy was based on state-backed science, technology, and innovation to enhance its production systems and stimulate economic growth (Xu et al., 2016).

Resource constraints and high investment costs for establishing sound R&D processes are real and present challenges facing the development of LCR (Fu et al., 2011). However, cultural traditions and practices that are corrosive to the installation of national R&D also challenge development (e.g., corruption) (Goldstein & Drybread, 2018; Rotberg, 2019). National and regional proposals are needed to lay the foundations of a proactive and innovative region, solidly based on science and technology. But above all, strong and sustained policies over time are urged in support of the generation of knowledge and to create long-sought innovation ecosystems. The future is not about emulating the path set by rich countries; but rather, about learning from countries that managed to shorten those gaps in the shortest time possible.

Conflict/declaration of interest statement

The authors declare no conflict of interest or personal relationships with other people or organizations that could inappropriately influence (bias) their work.

CRediT authorship contribution statement

Pablo Jarrín-V: Formal analysis, Methodology, Validation, Visualization, Writing - review & editing. **Fander Falconí**: Conceptualization, Writing - review & editing. **Pedro Cango**: Data curation, Formal analysis, Methodology. **Jesus Ramos-Martin**: Investigation, Writing - review & editing, Supervision.

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Appendix A. Supplementary data

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