Bricks or people? Investing more and better in Science, a dilemma for South American countries.

Running head: How should South America invest better in science?

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Bricks or people? Investing more and better in Science, a dilemma for South American countries.

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Highlights:

- South American countries need to increase their Science & Technology investment
- Uruguay urgently needs a plan of scientific development not to lag behind its neighbors
- Investment in people should be prioritized against infrastructure for a vigorous scientific system

ABSTRACT

Productivity of the Science and Technology (S&T) sector of Latin American countries would require more public and private investment to increase. Despite significant progress in the first 15 years of this century, South American investment in Science as percentage of GDP has been 10-fold lower than that of Europe. Though the need to increase S&T investment is clear, less obvious is whether money should go to infrastructure or human capital. Using global databases we assessed scientific productivity, number of researchers and resources devoted to S&T. We evaluated production for Europe, the Americas and China. We then focused on three Mercosur countries: Argentina, Brazil and Uruguay. Scientific production was related to S&T expenditure and to the number of researchers. We found that countries investing ~2% of their GDP may have a 5-fold variation in their productivity. Our results suggest that human capital explains a higher proportion of the S&T productivity than the total amount of resources devoted to science. Thus, people would matter more than infrastructure in determining the scientific output. The positive trends in the resources devoted to Science in Argentina, Brazil and Uruguay do not allow, though, to reach in a decade the levels of productivity of European countries.

1. INTRODUCTION

Latin American countries face the challenge and need to strengthen their science and technology (S&T) system. This urgency is based on cultural, economic, social,

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geopolitical and economic reasons. Science is a human right and makes a fundamental contribution to the cultural heritage of peoples (en.unesco.org/themes/science-society) but it is also critical in economic terms (Watson, Crawford, and Farley 2003; Mazzucato 2015). This has consequences not only at the economic level through the diversification of export products or import substitution, but also at the geopolitical level. A mature system of S&T guarantees economic and cultural sovereignty and independence(Varsavsky 1974; Dvorkin 2017). On the other hand, science is key to understanding the dynamics of social processes and designing strategies that promote both human and social development (Elguea 1985). Empirical evidence shows a strong association between a country's scientific and technological development and its performance in terms of economic and human development (Ranis 2011; Noroozi Chakoli and Madadi 2014; Pelinescu 2015).

Assessing the maturity and impact of a country's S&T system requires to consider multiple dimensions. Such assessment must document products, their quality and the effects on society and the rest of the scientific community. Not devoid of criticism (reviewed in (Cesaroni and Gambardella, n.d.; Invernizzi and Davyt 2019)), comparisons are often based on proxies associated with the number of documents and, more recently, their impact through the number of citations received (King 2004). The SCImago Journal and Country Rank (SJR), provides a record of scientific articles published by scientists from each country (Butler 2008).

A country's scientific productivity is related to its scientific tradition and legacy, the level of preparation of its human capital and, to a large extent, the resources that the society makes available to scientists (Staudt 2010). The S&T system shows a significant inertia, since the development of capacities – human, organizational and infrastructural – takes years (May 1997). The maturation process of a researcher, from the completion of their undergraduate studies, involves postgraduate studies and postdoctoral experiences that typically take between 6 and 10 years. However, almost 40 years ago, it was already clear that even with large-scale training programs, low wages and unfavorable working conditions for researchers in many countries represent a constraint and often contribute to a brain drain in trained human resources (Ardila, Trigo, and Pineiro 1982).

It is a truism that increasing S&T productivity requires more public and private investment in the system. Several countries in South America have made significant progress in this regard in the first 15 years of this century (Van Noorden 2014). Nonetheless, there have recently been serious setbacks (Paruelo, Acosta, and Pillar 2016). The structure of scientific expenditure has long been analysed and discussed (Ashanina 1971; Weiss and Passman 1991; Huidan, Dejin, and Sifeng 2009), and funding policies have evolved as delegation modes that coerce scientists into politically relevant topics(Braun 2003; Potì and Reale 2007) in a top-down approach. In the context of a scientific development strategy, it is not obvious, however, where money should be directed to as a priority, whether to infrastructure or human capital.

In this article, we evaluated general trends in S&T production and potential controls in a group of countries (Europe, Americas and China). We focused on the scientific production trends in three Mercosur countries (Argentina, Brazil and Uruguay), and provide evidence supporting the need to prioritize human capital over infrastructure.

2. Materials and Methods

2.1. Data and analysis

We used global databases to characterize scientific productivity, number of researchers and the resources devoted to Science and Technology. We assessed scientific productivity from the data compiled in the SCImago Journal Rank database (https://www.scimagojr.com/countryrank.php). Data on number of researchers and GDP invested in R&D were obtained from World bank database (https://data.worldbank.org/indicator/GB.XPD.RSDV.GD.ZS). Analyses were restricted to western hemisphere countries, but we included China given its qualitative and quantitative importance. The complete database analyzed is provided in the Supplementary Material as Supplemental Table 1.

To gain insight into the efficiency of a scientific system we normalized the corpus of scientific papers of each country and the number of researchers to the size of its population. Thus, we borrowed a concept from epidemiology and used the number of papers per 100.000 inhabitants (paper incidence) as a reporter of research output. For Argentina, Brazil and Uruguay we constructed time series of researchers per 100.000 inhabitants and percentage of GDP invested in science using data from 1996-2016 obtained from UNESCO Institute for Statistics (http://data.uis.unesco.org/).

2.2. Reproducibility

All data were processed in R/Bioconductor and the scripts are annotated and publicly available at http://github.com/danielprieto/people. Our analysis is strictly descriptive (based on linear regression models) and do not prove causality. The “explanatory” variables considered have an important level of co-variation. Clearly, the %GDP devoted to R&D is linked to the number of Researchers/100k inhabitants. Our analyses provide, however, indirect evidence to postulate hypotheses to guide scientific policy.

3. Results

3.1. Scientific production is related to budget

Scientific production is related to the investment effort in S&T. As expected, our analysis shows a significant correlation between the percentage of country GDP invested in S&T (S&T-GDP%) and the scientific knowledge production measured as the number of scholarly papers per inhabitant (SP/100K) (R^2=0.62, Figure 1). Considering the ratio of SP/100K and S&T-GDP% as a measure of efficiency of the S&T system, the Mercosur countries do not deviate much from the linear trend. Uruguay maps within the 95% CI of the linear regression, despite its lower relative investment in S&T compared to its neighbors Argentina and Brazil. It is followed in terms of economic scientific efficiency by Argentina. All 3 Mercosur countries analyzed display a better performance (per resource invested) when compared to China, the leading country in terms of scientific growth. The slope of the linear regression allows us to infer that a sustained and well-planned increase in S&T investment would increase scientific production at an approximate rate of 150 SP/100K for every 0.1% of the GDP invested in S&T.

3.2. Scientific production is highly dependent on the size of the research workforce of a country

Scientific production is related to the size of the research workforce. Again, it is not surprising that the production of scholarly papers correlated to the number of researchers (Figure 2). However, the proportion of the variability of SP/100K explained by the RW/100K is 20% higher that the proportion explained by S&T-GDP% (R^2=0.8, Figure 2). Uruguay proves efficient enough to map onto the regression line. Nonetheless, the size of its research output is limited by the number of researchers. Argentina has more researchers and fewer papers per 100K inhabitants – a situation comparable to that of China. Brazil lies in the same range of efficiency as Uruguay. Interestingly, we could identify a gap between two groups of countries in terms of relative scientific production and research workforce. One group with less than 150 RW/100K and a production lower than 1500 SP/100K and another with more than 200 RW/100K and a production higher than 1500 SP/100K (indicated with ellipses in Figure 2).

3.3. The size of research workforce depends majorly on its S&T expenditure

Research workforce size is related to S&T investment effort. S&T investment effort explains almost 80% the size of the research workforce (R^2=0.79, Figure 3). Every 1% step increase in S&T investment would bring 188 new researchers per 100.000 inhabitants. This effect also seems independent of GDP size (not shown). Within Mercosur, Uruguay and Argentina closely follow these figures. Interestingly, despite their notable increase in their S&T investment during the last years, Brazil and China have a lower number of researchers than expected.

3.4. Evolution of the scientific expenditure and workforce of Uruguay, Argentina and Brazil over 20 years. Current trend.

Argentina, Uruguay and Brazil showed between 1996 and 2016 a positive trend on the two potential determinants of scientific production, SP/100K and RW/100K (Figure 4). Nevertheless, the rate of increase was quite different among countries. Brazil almost doubled the growth rate of the Argentinian S&T-GDP% (0.021 vs 0.011). Moreover, the increase of S&T-GDP% was more consistent over time in the case of Brazil (Figure 4A and B), as the coefficient of determination of the linear fit indicated (0.83 vs 0.71). Uruguay showed not only the lowest S&T-GDP% among the three Mercosur countries, but also the least consistent increase (R^2=0.43) and at the lowest rate (0.007). Even spending a lower GDP percentage in S&T, Argentina showed not only more RW/100K but also a higher rate of increase than Brazil (Figure 4C and D) (3.63 vs 3.32). Uruguay's situation is far weaker in terms of RW/100K. The total number is about half the values of Argentina and the rate of increase of the number of researchers (2.13) is a 61% of the average rate of Brazil and Argentina(Figure 4E and F).

4. Discussion

The scientific production of a country (measured as peer reviewed articles registered by the Scimago database) is tightly correlated to the amount of money invested in Science and Technology and to the number of researchers, as expected. Aside from the general trend, the actual productivity of individual countries varied widely. Countries investing around 2% of their GDP may have a 5-fold variation in their productivity. However, the variability in production for a given research workforce is less variable as reflected by the highest R^2 of the relationship of SP/100k with RW/100k (0.80) than with S&T %GDP (0.62). This pattern suggests that human capital explains a higher proportion of the S&T productivity variability than the total amount of resources devoted to science. It follows that people would matter more than infrastructure in determining the scientific output.

The pattern observed reflects the variability among countries for a given year in such a way that it corresponds to a "spatial model" that incorporates inertial effects and legacies. How much do factors explaining differences among countries account for changes in time in a given country? This is a key question if the patterns described by the "spatial model" are to be used to devise policies. Clearly, there will be lags. Capacity building, both in terms of infrastructure and human capital will take time. Increasing the number of PhD's seems to be a critical step. The growth rate of the number of researchers may be limited by the number of local advisors. Investing money in the recruitment and generation of potential PhD advisors is also critical. As the regressions showed, enlarging the researcher workforce would have a more certain impact on productivity than investing in infrastructure. Moreover, increasing the number of scientists would accelerate the growth rate of the system. Of course, such increase may generate infrastructure bottlenecks. An interesting question in planning science is whether infrastructure should be an "offer" to researchers or if they should generate their own demand.

A gap can be observed between Latin American and European countries in terms of research workforce and money allocated to S&T, hence in scientific productivity. In Latin American countries RW/100K is well below 200 and the S&T %GDP under 1.3%. To fill up this gap is a major challenge to improve social, cultural, health and economic indicators. How possible is it for Mercosur countries to achieve levels of investment comparable to those of more developed countries? Which would be the best strategy to do so? Several alternatives may be considered (Weiss and Passman 1991).

Defining the target of S&T investment and research workforce is clearly a political issue. In Argentina a National Plan of the Science Ministry (Argentina Innovadora 2020) defined, in 2011, a goal of 1.65% of the GDP and to double the RW/100K in 2020 (circa 240 RW/100k). Such numbers correspond roughly to a 75% and a 50% of the current values of western European countries, for the S&T%GDP and the RW/100k respectively. If the trends observed until 2016 persist, for 2030 only Brazil would reach a S&T%GDP close to 1.65 (1.62). Argentina would reach a 0.74% and Uruguay just a 0.45%. Regarding RW/100k, none of these countries would reach those values (Argentina: 179, Brazil: 130 and Uruguay: 83). At least in the case of Argentina and Brazil the neo-liberal policies implemented in the last 4 years determined a growth rate even lower than the values used in the projection (Paruelo, Acosta, and Pillar 2016).

From these trends, it follows that an immediate injection of money into S&T is needed to substantially increase scientific productivity in Mercosur countries. The indirect evidence we provide here suggests that the main effort should be directed to increase the number or researchers. This would involve strengthening the opportunities for graduate level studies, but also the recruitment of scientists from abroad. The experience, prior to 2015, of the program RAICES in Argentina (https://www.argentina.gob.ar/ciencia/raices) allowed the re-instalation of more than 1000 Argentinian scientists that were working all over the world. To stop and reverse the so called "brain exodus" is a critical goal in the processes of capacity building in the scientific sector of the Mercosur countries. Such an approach might also help preventing the emergence of a Matthew effect such as that observed when China increased its scientific expenditure, by the end of 1990s to early 2010s (Zhi and Meng 2016). Recently, innovative approaches such as collective allocation of funds (Lancaster, Thessen, and Virapongse 2018) have been proposed to foster equity, diversity, reduce administrative costs and ultimately boost productivity of the ecosystem.

Our findings are consistent with several sources which have stressed that qualified human capital generates growth and structural change (Lichtenberg 1992; Temple and Voth 1998; Teixeira and Fortuna 2010). Research human capital fosters economy, as skilled and trained people contribute to enhancement of cultural and living standards (Bayarçelik and Taşel 2012; Kucharčíková 2014), but also as skilled researches will perform research more economically (Ashanina 1971). Investment in technology and equipment should follow, under a carefully planned Scientific Development Strategy deeply integrated into countries' Development Policies, or becoming the Development Policy itself. Policy can be conceived as an integral component of several determinants of development of an innovation system, together with Research and Development, Education and Training, among others (Borrás and Edquist 2019). The demands and connection of Research, its human capabilities and results with public and private sectors are relevant and must be payed attention. Otherwise, the scientific community connects to global research and publishing networks unaware of the challenges and problems that our countries face to sustainably achieve human capability- and freedom-centered Development.

4.1. Conclusions

Human-centered investment allows the consolidation of workgroups with critical sizes to tackle strategic issues and to better use infrastructure and equipment. Moreover, having consolidated teams would allow to better define infrastructure and equipment priorities. To increase the number people working in science and to invest in infrastructure are urgent needs in developing countries, but in that order of priority.

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CRediT author statement

Jose Paruelo: Conceptualization, Resources, Methodology, Writing – Original Draft, Supervision, Visualization. **Miguel Sierra**: Resources, writing – review & editing, validation, project administration. **Daniel Prieto**: Conceptualization, Investigation, Formal Analysis, Methodology, Data Curation, Software, Writing – Review & Editing, Visualization.

Figures

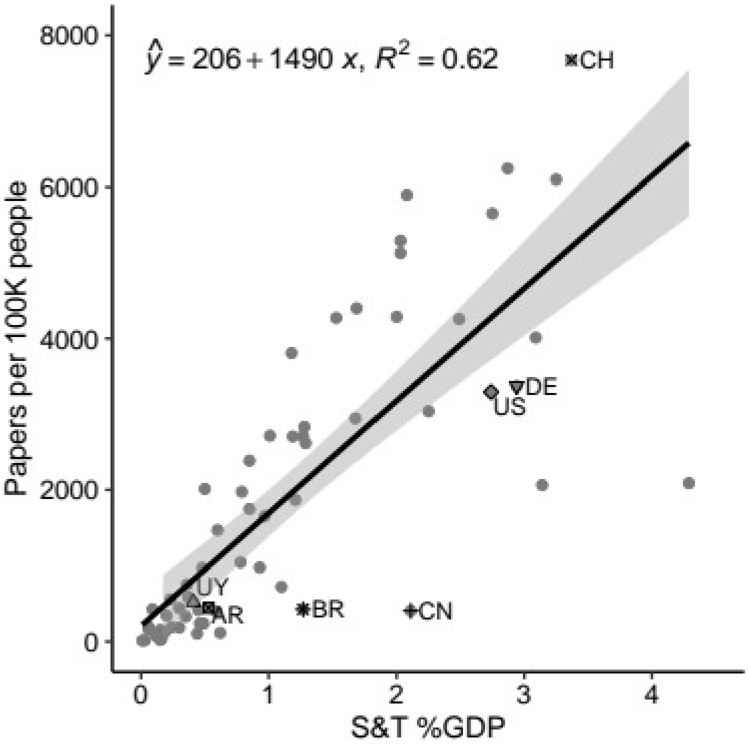

Figure 1. Relative scientific output normalized to population (SP/100K) relation to relative investment (S&T-GDP%). Each country is mapped as a dot. Highlighted countries are shown with a different dot shape and its 2-letter code. Solid line represents the best fit (R^2=0.62) linear regression corresponding to the equation y=1490x + 206, shaded region represents 95% confidence interval of the linear fit. AR: Argentina, BR: Brazil, CH: Switzerland, CN: China, DE: Germany, US: United States, UY: Uruguay.

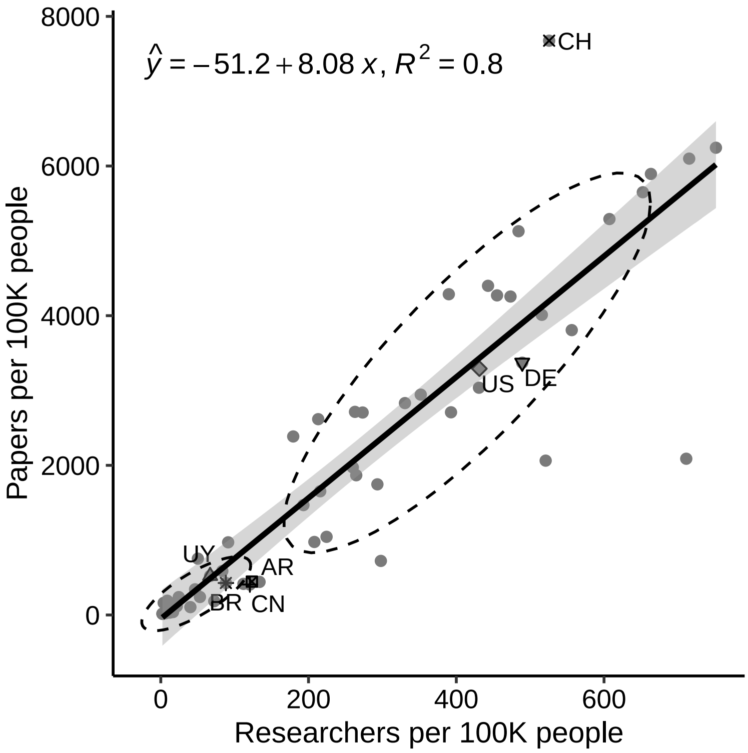

Figure 2. Relative scientific output normalized to population (SP/100K) dependence relative research workforce size (RW/100K). Each country is mapped as a dot. Highlighted countries are shown with a different dot shape and its 2-letter code. Solid line represents the best fit (R^2=0.80) linear regression corresponding to the equation y=8.08x – 51.2, shaded region represents 95% confidence interval of the linear fit. 75% confidence ellipses (dashed lines) were calculated for RW/100K under/over a cut-off value of 200. AR: Argentina, BR: Brazil, CH: Switzerland, CN: China, DE: Germany, US: United States, UY: Uruguay.

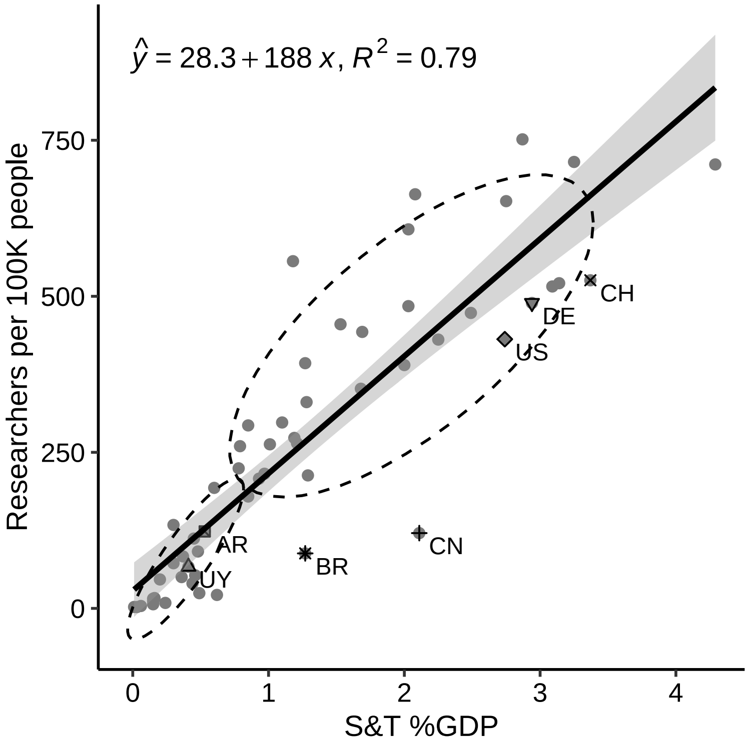

Figure 3. Relative research workforce size (RW/100K) dependence on relative investment (S&T-GDP%). Each country is mapped as a dot. Highlighted countries are shown with a different dot shape and its 2-letter code. Solid line represents the best fit (R^2=0.79) linear regression corresponding to the equation y=188x + 28.3, shaded region represents 95% confidence interval of the linear fit. 75% confidence ellipses (dashed lines) were calculated for S&T-GDP% under/over a cut-off value of 1. AR: Argentina, BR: Brazil, CH: Switzerland, CN: China, DE: Germany, US: United States, UY: Uruguay.

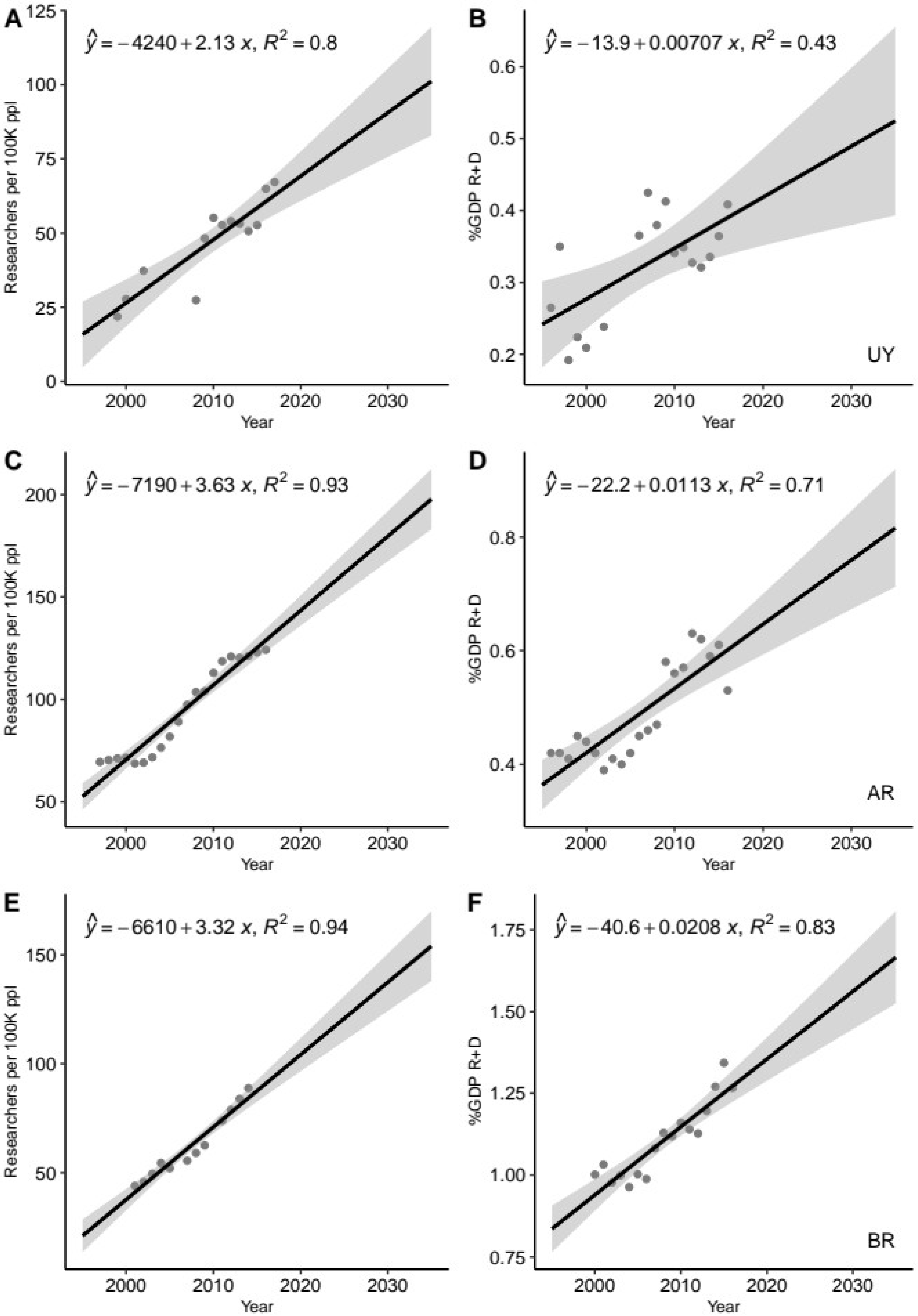

Figure 4. 20-year evolution of relative research workforce size (RW/100K) and relative expenditure in science and technology of 3 Mercosur countries. Argentina (A and B), Brazil (C and D) and Uruguay (E and F). The series corresponds to data from 1996-2016. Each timepoint (year) is mapped onto a dot. Timepoints beyond 2016 correspond to our linear projection. Solid line represents the best fit linear regression. Corresponding equations and R^2 values are indicated

in each panel, shaded regions represents 95% confidence interval of the corresponding linear fit. AR: Argentina, BR: Brazil, UY: Uruguay.