# Investigating the interplay between fundamentals of national research systems: performance, investments and international collaborations

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We discuss, at the macro-level of nations, the contribution of research funding and rate of international collaboration to research performance, with important implications for the "science of science policy". In particular, we cross-correlate suitable measures of these quantities with a scientometric-based assessment of scientific success, studying both the average performance of nations and their temporal dynamics in the space defined by these variables during the last decade. We find significant differences among nations in terms of efficiency in turning (financial) input into bibliometrically measurable output, and we confirm that growth of international collaboration positively correlate with scientific success, with significant benefits brought by EU integration policies. Various geo-cultural clusters of nations naturally emerge from our analysis. We critically discuss the possible factors that potentially determine the observed patterns.

## I. INTRODUCTION

The science of science policy (SoSP) [1] is emerging as an interdisciplinary field that aims at developing theoretical models and studying empirical evidence for the performance of scientific communities and individual researchers. This scientific activity can then help to develop policies for improving allocation of Research and Development (R&D) funding and strategical decision making. Within the field, a major issue has been that of identifying suitable quantities to characterize the research systems at the level of nations, in terms of scientific impact, development and competitiveness.

In this respect, many studies pointed out that the last years have witnessed a remarkable increase of the number of international collaborations in scientific research [2, 3]. This phenomenon has been studied and analyzed especially in the context of the European Union, where it appears to be a particularly strong clue of successful EU integration policies (see [4, 5], and [6] for a contrary view). However, also developing nations have increased their rates of collaboration with foreign, already developed nations, and empirical evidence suggests that this strategy is at the core of their successful entrance in the scientific community [7]. As noted by Persson [8], it is necessary to point out that the presence of a possible cause-effect relationship between scientific success and international collaborations is still an open issue. Furthermore, a common agreement on how to measure national success in a scientific field is still lacking. Two possible and commonly adopted measures of scientific performance are citation counts and journal placement, which are known to be positively correlated with the rate of internationalization of the scientific community of a nation [9–12]. In particular, it has been shown that the most successful teams are characterized by a moderate level of cultural diversity [13].

Of course, any study of national scientific production cannot neglect the role played by the availability of financial resources—namely, R&D funding. In a recent paper, Pan *et al.* [14] have shown that the research impact of a nation grows linearly with the amount of national R&D funding, pointing out also the presence of a peculiar effect: in order to be effective, public investments should exceed a certain threshold. As pointed out by Leydesdorff and Wagner [15], there is a great difference in national ability to transform financial input into bibliometric output. This is a highly controversial point. For instance, according to the analyses performed by Sandstrom *et al.* [16], there is no evidence that the amount of institutional funding correlates with competitiveness, overall performance, and top performance of a given nation, whereas, according to Fortin and Currie [17] impact is generally a decelerating function of funding. Once more, these mixed conclusions stress the need of a systematic approach to this kind of studies and the adoption of a shared definition of scientific success, which is one of the main purposes of the present work.

Notably, as we show at the end of this paper, a complex structure of geo-cultural clusters naturally emerges from this kind of studies. As originally pointed out by Frame *et al.* [18], international co-authorships are clearly biased by extra-scientific factors such as geography, politics and language. Also Luukkonen *et al.* [19] reached similar conclusions,

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suggesting the presence of cultural *centers* on which other nations hinge. In summary, three fundamental aspects naturally emerge as prominent features for a systematic analysis of nations scientific production: internationalization, funding, success, and, as a further resulting output, the presence of geographic and cultural communities. In this work we precisely address the issue of how the complex interaction between these fundamentals shape the scientific production of nations and their possible success.

Our paper is organized as follows. In Section II we describe our datasets and define the variables we are going to use in our analysis. In Section III we present our main results, namely, a static and dynamic analysis for the scientific performance of nations as a function of both level of internationalization and fundings to various types of research institutions. The concluding section summarizes our findings and discusses future perspectives.

## II. DATA & METHODS

In principle, one can consider different metrics to characterize national research systems, related both to financial input and bibliometric output. Here we focus on measures extracted from the databases that we describe below.

We collected data on national expenditure in scientific research and development from the Organization for Economic Cooperation and Development (OECD, www.oecd.org). Data refer to $N = 40$ developed nations and to years 2000-2012. All expenditures are expressed in terms of current purchasing power parity (in millions of US dollars). The overall expenditure indicator, known as GERD (Gross Expenditure on R&D), is divided into three main components: BERD (Business Expenditure on R&D), namely R&D expenditure performed in the business sector [20], including both public and private fundings, HERD (Higher Education Expenditure on R&D), expenditures for basic research performed in the higher education sector [21], again including both public and private fundings, and GOVERD (Government Intramural Expenditure on R&D), expenditures in the government sector [22] (we refer to [23] for a more detailed definition of these quantities). BERD is arguably important for innovation and economic growth, being closely linked to the creation of new products and production techniques (patents), and at the end to the innovation efforts of a country. Thus, in the context of studies focused on bibliometric scientific outputs (namely, papers), usually only HERD and GOVERD are considered to be relevant. In particular, Leydesdorff and Wagner [15] pointed out that HERD cannot be considered as a sufficient indicator of input to academic research, because in some nations (like China and Russia) GOVERD becomes larger than HERD. However, they also noted that the public research sector is often mission-oriented and therefore less driven by the institutional and scientific need to publish [23]. Since a shared consensus on what kind of input should be considered (to relate scientific success with) is still missing, here we take into account all three indicators for R&D funding (BERD, HERD and GOVERD) separately. Note that since we are interested in assessing the quality of the scientific output of a nation, we consider intensive metrics, that is, size-independent quantities obtained by normalization with the respective nation GDP. We denote as $\mathcal{B}_i(t)$, $\mathcal{H}_i(t)$ and $\mathcal{G}_i(t)$, respectively, such normalized BERD, HERD and GOVERD values for nation $i$ during year $t$ [24].

In order to measure scientific output, we use bibliometric data over years 1996-2013 collected from the SCImago website (www.scimagojr.com)—based on the Scopus database (www.scopus.com). Data refer to $N' = 239$ nations, $D = 28$ scientific domains and $d = 311$ scientific sub-domains (each belonging to one domain), and allow to obtain two simple indicators to build a measure of scientific success on: $d_{i\alpha}(t)$, *i.e.*, the number of scientific documents a nation $i$ published on domain $\alpha$ during year $t$, and $c_{i\alpha}(t)$, *i.e.*, the number of citations accrued by those papers up to now. Note that the large number of papers produced by a nation (*i.e.*, the law of large numbers) guarantees for the reliability of these quantities: we can safely assume that distortions that may affect a single paper are smoothed out [25]. However, we do not want to rely here on the traditional approach based on publication impact (*i.e.*, number of citations or documents) to measure scientific success [26, 27], because it suffers from a twofold drawback. First, citation statistics are highly biased for recent papers that had not enough time to attract citations [28], and thus need to be normalized properly for a time dynamical analysis—whereas, the number of published documents grows steadily in time. Second, the number of citations is an extensive measure that naturally correlates with nations size and number of published documents, thus requiring another normalization in order to compare the various national research systems. Other approaches [12] measure scientific performance of individual papers by comparing the total number of citations that paper has accrued to those of other publications of the same journal volume. Still, methods based on the journal where a paper is published suffer from all the exogenous and endogenous factors that enter in the effective publication mechanism and that are not linked to the real quality of the scientific work [12]. In order to avoid problems related to publication venues, and to properly normalize bibliometric data, we use citation and publication shares. The reason is that whenever a nation receives a larger share of citations compared to the fraction of papers it publishes, it is producing better-than-average science or science that has a greater impact. Formally, we define the scientific success of nation $i$ during year $t$ as:

$$\mathcal{S}_i(t) = \left( \frac{\sum_\beta c_{i\beta}(t)}{\sum_\beta \sum_j c_{j\beta}(t)} \right) \Bigg/ \left( \frac{\sum_\beta d_{i\beta}(t)}{\sum_\beta \sum_j d_{j\beta}(t)} \right), \tag{1}$$

meaning that we normalize a nation share of world citations (that is not time-biased) with its share of world documents, obtaining in this way an intensive measure for scientific performance. Of course, success can be also measured within a given domain $\alpha$ as

$$\sigma_{i\alpha}(t) = \left( \frac{c_{i\alpha}(t)}{\sum_j c_{j\alpha}(t)} \right) \Bigg/ \left( \frac{d_{i\alpha}(t)}{\sum_j d_{j\alpha}(t)} \right), \tag{2}$$

a definition that suggests an alternative approach to measure overall success:

$$\mathcal{S}'_i(t) = \frac{1}{D} \sum_\beta \left( \frac{c_{i\beta}(t)}{\sum_j c_{j\beta}(t)} \right) \Bigg/ \left( \frac{d_{i\beta}(t)}{\sum_j d_{j\beta}(t)} \right) \equiv \frac{1}{D} \sum_\beta \sigma_{i\beta}(t).$$

The difference between $\mathcal{S}$ and $\mathcal{S}'$ resides in how the different scientific domains are weighted in the averaging procedure. In particular, $\mathcal{S}$ does not distinguish between documents belonging to different scientific areas, whereas, $\mathcal{S}'$ weights the shares of scientific areas equally—as the sum over the different domains is performed only after the domain-specific successes are evaluated. Note also that $S$ is independent on the specific classification used for scientific sectors, and is less subject to noisy fluctuations affecting domains with overall few documents and citations. For these reasons, in what follows we use $\mathcal{S}$ to measure scientific success; yet, we have checked that using $\mathcal{S}'$ leads to almost identical quantitative results and thus, to our purpose, these metrics are interchangeable.

Finally, in order to assess the level of internationalization of the research system of a nation, we use the rate of international collaborations, defined as follows. Denoting as $d^*_{i\alpha}(t)$ the number of documents published by nation $i$ in domain $\alpha$ during year $t$ whose affiliations include more than one nation address, the level of internationalization of that nation at $t$ is defined as $\mathcal{I}_i(t) = [\sum_\beta d^*_{i\beta}(t)]/[\sum_\beta d_{i\beta}(t)]$. As for success, internationalization can be also measured within a given domain $\alpha$ as $\iota_{i\alpha}(t) = d^*_{i\alpha}(t)/d_{i\alpha}(t)$, which then brings to an alternative metric for overall internationalization: $\mathcal{I}'_i(t) = \sum_\alpha \iota_{i\alpha}(t)/D$. The two approaches lead to very similar quantitative results; according to the same reasoning used for scientific success, in the following we use the first definition of $\mathcal{I}$.

## III. RESULTS AND DISCUSSION

We now present and discuss the results of our analysis on the complex relationships between the three fundamental features of national research systems defined above (funding, success and internationalization). We focus over years 2004-2012, for which we have the maximum data coverage [29], and present two kinds of analysis: the study of interdependences between the time average values of these quantities, and the temporal evolution of nations in the space of the fundamentals. Note that time averages are denoted with a bar over the respective symbol; we thus have, for a given nation $i$, $\bar{\mathcal{S}}_i = \frac{1}{T}\sum_t \mathcal{S}_i(t)$, $\bar{\mathcal{I}}_i = \frac{1}{T}\sum_t \mathcal{I}_i(t)$, $\bar{\mathcal{B}}_i = \frac{1}{T}\sum_t \mathcal{B}_i(t)$, $\bar{\mathcal{H}}_i = \frac{1}{T}\sum_t \mathcal{H}_i(t)$ and $\bar{\mathcal{G}}_i = \frac{1}{T}\sum_t \mathcal{G}_i(t)$ as its average success, internationalization, BERD, HERD and GOVERD over the considered time span of $T = 9$ years, respectively. For the sake of graph readability, we use different colors to plot averages and trajectories of nations according to the following classification based on geographical, historical and cultural factors [30]:

- **Black**: United States;
- **Blue**: Commonwealth (Australia, Canada, Hong Kong, India, Malaysia, New Zealand, Singapore, South Africa, United Kingdom);
- **Green**: Western and Southern Europe (Austria, France, Germany, Greece, Ireland, Italy, Portugal, Spain);
- **Cyan**: Switzerland and Northern Europe (Belgium, Denmark, Finland, Netherlands, Norway, Sweden);
- **Red**: Eastern Europe (Czech Republic, Hungary, Poland, Romania, Russian Federation, Slovakia, Slovenia, Ukraine);
- **Brown**: Middle East (Egypt, Israel, Iran, Turkey);
- **Orange**: Asian region (China, Japan, South Korea, Thailand, Taiwan);
- **Magenta**: Latin America (Argentina, Brazil, Chile, Mexico).

### A. The internationalization of scientific research

Figures 1 and 2 report results of our analysis for the relation between internationalization and scientific success. Looking at the average values of these quantities (figure 1), we notice that they are significantly correlated, with a main trend that starts from Eastern European nations (lowest $\bar{\mathcal{I}}$ and $\bar{\mathcal{S}}$) and ends with Northern European nations and Switzerland (highest $\bar{\mathcal{I}}$ and $\bar{\mathcal{S}}$), with Western Europe and Commonwealth members in between. Significant outliers are represented by the United States that, because of their large self-consistency with respect to any other nation, rely much less on international collaboration to achieve the same level of scientific performance of the other western countries, and by Asiatic countries whose research systems are the least internationalized (supposedly for linguistic and cultural reasons).

An even more interesting picture emerges from the time dynamics analysis of nations in the $\mathcal{I} - \mathcal{S}$ plane (figure 2). For low values of $\mathcal{I}$ and $\mathcal{S}$ (mostly Asian and Middle East countries) we observe a chaotic-like dynamics, which however becomes more laminar as soon as the amount of international collaboration increases slightly. There we observe the Eastern European countries trying to catch up with the group of developed nations in scientific success, without relying much on increasing the rate of internationalization. Then, once scientific success approaches values close to 1, basically every nation enters into a stream that allows to increase success even more by increasing the amount of international collaborations. Notably, such a region comprises mostly Western and Northern European countries, where internationalization is stronger supposedly because of EU research integration policies. These policies thus seem to be rather beneficial in improving national research performances. Finally, United States are located away from the main stream (but are directed towards it), meaning that the increasing internationalization of their research system is not leading to immediate performance improvements—which will perhaps occur once they reach values of both $\mathcal{I}$ and $\mathcal{S}$ similar to those of the other developed nations. Note also that the slightly decreasing success of United States is also caused by the increasing success of almost all other nations, because our measure of success is based on citation and document shares (whose sum over all countries are separately conserved).

We can conclude this section with the following key message: Internationalization emerges as a fundamental parameter for the scientific development of nations. In this respect, the European Union mission of promoting integration among its constituent nations appears to be well-founded—yet, more for old members than for Eastern European countries.

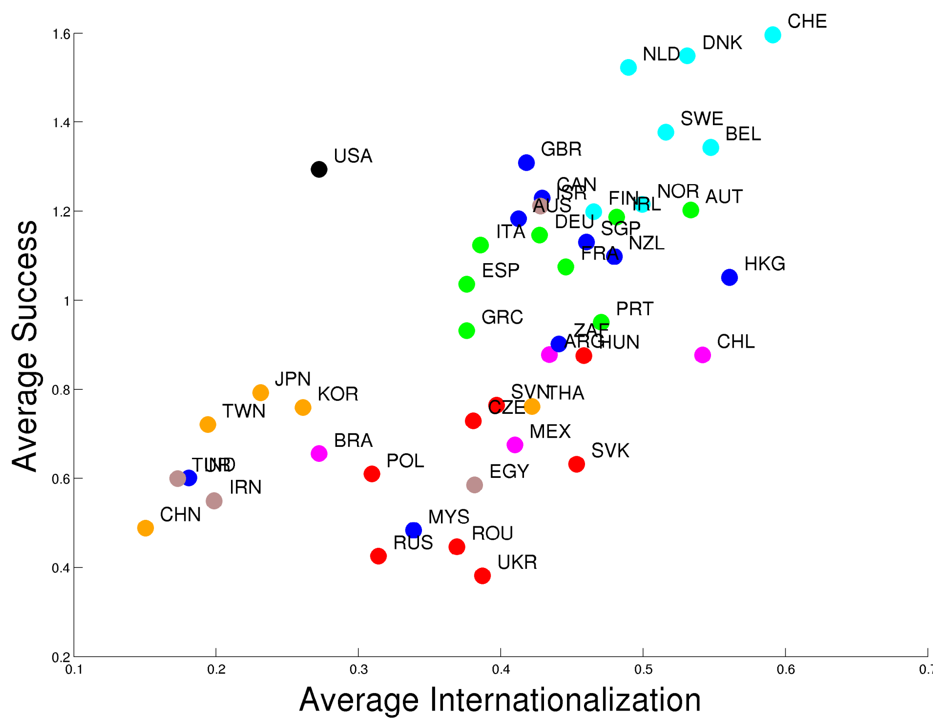


FIG. 1. Relation between average internationalization $\bar{\mathcal{I}}$ and average scientific success $\bar{\mathcal{S}}$ of nations.

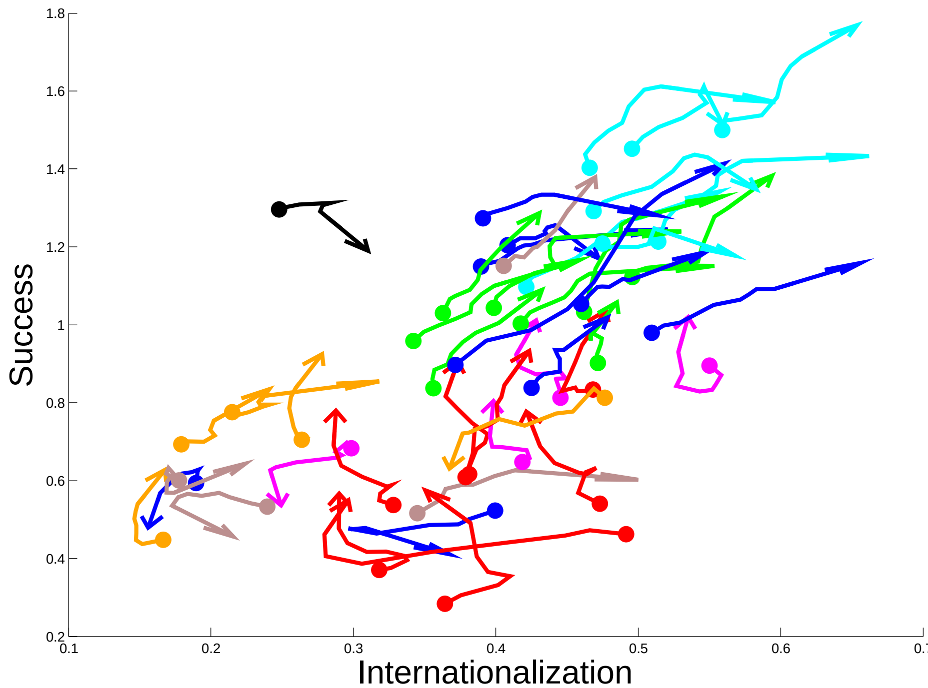


FIG. 2. Temporal evolution of nations in the plane of international collaboration $\mathcal{I}(t)$ and scientific success $\mathcal{S}(t)$.

### B. Outcome of R&D investments

We now turn our attention to the relation between "input" (represented by R&D funding) and "output" (bibliometric-based success) of national research systems. For the reasons explained in section Methods, we consider all three indicators (BERD, HERD and GOVERD) as measures for national research expenditures. Among them, BERD is arguably more related to an output in patents than in publications, yet the correlation between these kinds of output is likely to be high: the most competitive nations in science are also the most competitive in technology, and several causal and feedback relations exist between the creation of knowledge and the development of complex products [31]. Indeed, figure 3 shows that the scientific performance of nations is moderately correlated with BERD, and several patterns emerge. The main group, consisting of (most) Western and Northern Europe, Commonwealth members, United States and Israel, is characterized by high values of both success and BERD, with Italy, Spain and Portugal slightly falling behind in terms of BERD. Asian countries have similar BERD values to those of the western countries, but much lower scientific success. Eastern European countries are instead split into two groups, depending on their BERD. Finally, nations with the lowest BERD values are Argentina, Mexico and Greece, countries that underwent (or are currently undergoing) a sovereign debt crisis—that supposedly affected investors' trust and thus private fundings.

On the other hand, as figure 4 clearly shows, GOVERD is not related at all to the scientific performance of nations. This happens for two main reasons: i) research institutions that are internal to the government are generally less compelled to publish papers than research centers related to higher education, and therefore their output is aimed more at practical applications than at knowledge dissemination; as a consequence, bibliometric indicators cannot be suitable measures of their success; ii) GOVERD is a highly varying small percentage of GERD for most nations and thus more prone to noisy fluctuations than HERD: excluding peculiar countries like Russia and China, GOVERD amounts on average to 67% of HERD—a percentage that decreases to 43% when only western countries are considered.

Finally, and not surprisingly, HERD has the highest correlation with success, as shown by figures 5 and 6. In particular, the average values reported in figure 5 follow a definite trend that starts from Eastern European nations (lowest $\bar{\mathcal{H}}$ and $\bar{\mathcal{S}}$), continues with Asiatic and Latin American countries and then with Western Europe and Commonwealth members, and ends with Northern Europe and Switzerland (highest $\bar{\mathcal{H}}$ and $\bar{\mathcal{S}}$). Note that while a country placed above/below the mean trend features a more/less efficient research system, there are no significant outliers.

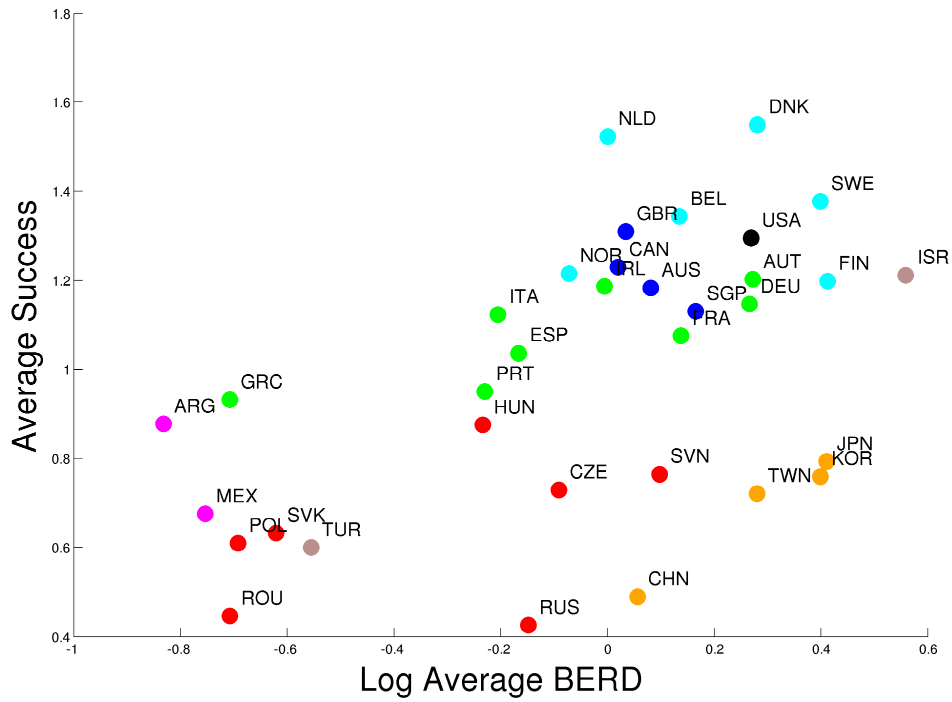


FIG. 3. Relation between average BERD $\bar{\mathcal{B}}$ and average scientific success $\bar{\mathcal{S}}$ of nations.

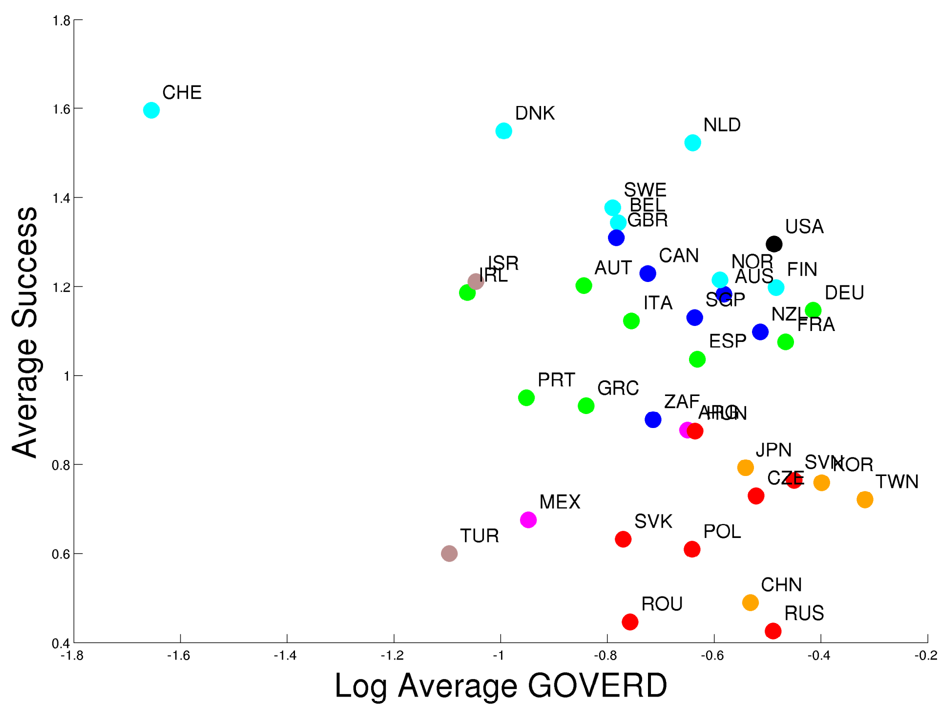


FIG. 4. Relation between average GOVERD $\bar{\mathcal{G}}$ and average scientific success $\bar{\mathcal{S}}$ of nations.

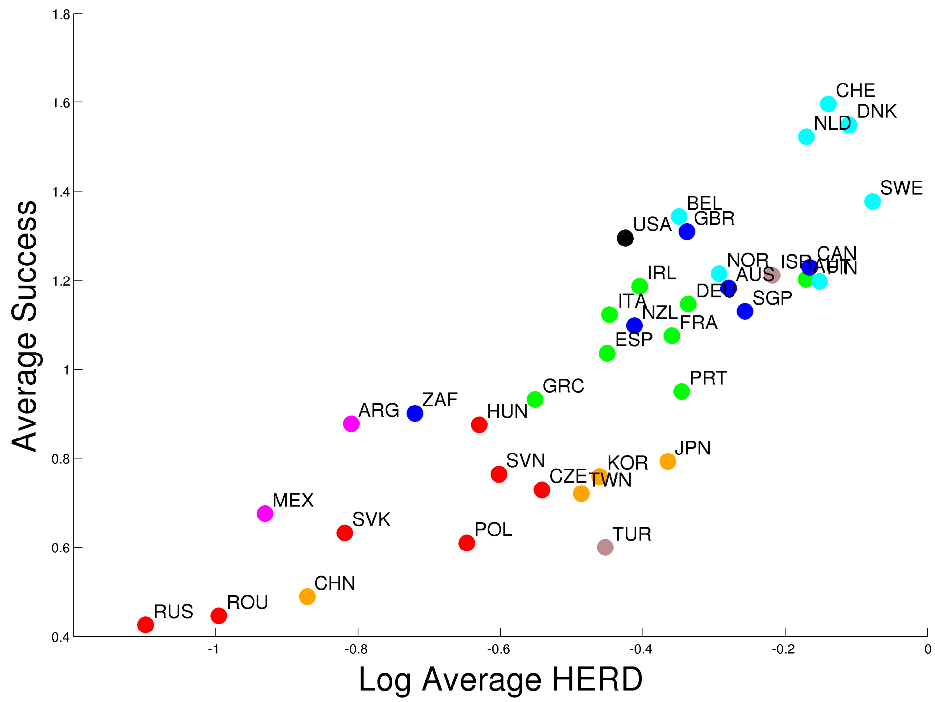


FIG. 5. Relation between average HERD $\bar{\mathcal{H}}$ and average scientific success $\bar{\mathcal{S}}$ of nations.

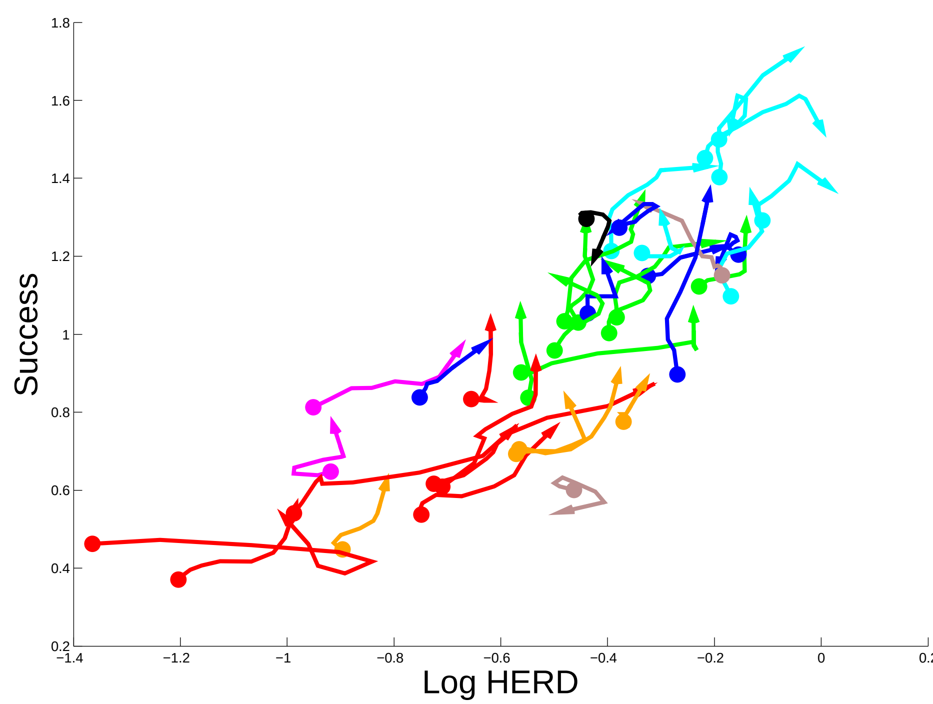


FIG. 6. Temporal evolution of nations in the plane of HERD $\mathcal{H}(t)$ and scientific success $\mathcal{S}(t)$.

The dynamical analysis of the time evolution of nations in the $\mathcal{H}-\mathcal{S}$ plane shown in figure 6 reveals that countries trajectories are generally smooth. Overall, most of the developed countries are increasing their R&D investments in time (even in periods of financial instability represented by the 2007-2009 financial crisis), a fact that brings to the increase of scientific performance—with some exceptions. The steepest growth of $\mathcal{S}(t)$ with respect to $\mathcal{H}(t)$ is observed for nations like Singapore, Italy, Greece and Hungary. For the latter European countries, the increasing success at constant investment can be at least partially explained by the drive of EU funding instruments. Instead, significant outliers are represented by United States and Turkey, for which both investments and success are decreasing (at least during the latest time window), and Israel, whose scientific performance is increasing in spite of a decrease in funding. We recall again that decreasing of success for some countries is due to the separate conservation of shares in the measure of success.

Because of the highest correlation between "inputs" and "outputs" of research observed in this latter case, in the following we focus solely on HERD as a metric for R&D funding. Differently form other works [32], we prefer HERD to HERD+GOVERD as the highest correlation with success is observed for the former case (because of the different focus of GOVERD we discussed above).

### C. Emergence of geo-cultural clusters

We now put together the three fundamental features of national research system, meaning that we analyse the position of individual nations in the three dimensional space defined by $\mathcal{I}$, $\mathcal{H}$ and $\mathcal{S}$. Figure 7 shows that geo-cultural structure naturally emerges in this space. The group of Asian nations is clustered together around medium-low values of HERD and very low internationalization, with China still behind the other countries in terms of scientific success. United States have similar values of $\mathcal{I}$ and $\mathcal{H}$, but they are disconnected from the group of Asian countries because of their much higher performance. East European nations are instead located (together with Latin America and South Africa) in the region of very low HERD, low internationalization and— as expected from the previous analysis—low success. Concerning in particular the East European countries, a gradual detaching pattern from Russia emerges: while Russia seems not to be recovering from the radical drop of investments since the break-up of the Soviet Union, the other nations are gaining scientific success by increasing R&D investments. However, while in some cases (Poland,

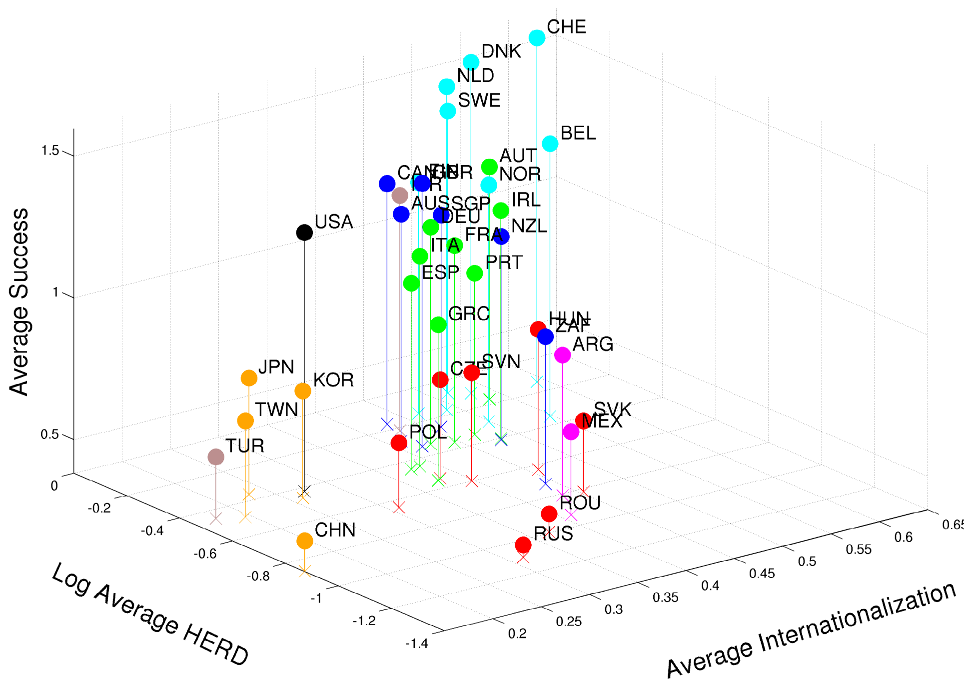


FIG. 7. Relation between average HERD $\bar{\mathcal{H}}$, average internationalization $\bar{\mathcal{I}}$ and average scientific success $\bar{\mathcal{S}}$ of nations.

Czech Republic, Slovenia) HERD values are now comparable to those of western countries, the scientific performance of ex-soviet countries is still low—a fact that questions the effectiveness of EU fundings in the East Europe area up to now. Moving further, the central dense cluster is composed of Western European countries and Commonwealth members (the latter having slightly higher HERD and success). Finally, Northern Europe and Switzerland are located in the region where all the fundamentals assume their highest values. Notably, these clusters are coherent with those found by Frame *et al.* in the late '70 [18], and by Luukkonen *et al.* in the early '90 [19]: they are inherited from the past, and seems indeed to endure in spite of the increasing internationalization of science and the integration policy of the EU in particular. Yet, these past works focused mainly on international co-authorships. By adding research investments and success as fundamental characterizing features, our analysis strengthen the importance of extra-scientific factors (history, geography, politics and language) in shaping the structure of national research systems.

## IV. CONCLUSIONS

The ability to assess the impact of the scientific system of a nation is crucial for both public and private stakeholders to determine scientific priorities and investments [27]. In this work, we have characterized national research systems through three fundamentals features: R&D investments, internationalization and bibliometric performance. We have systematically studied the evolution of nations in the space of these variables, and discussed the emerging patterns of geo-cultural affinities between countries.

Note that many ways to evaluate the quality of scientific research have been proposed in the literature, but few have proved satisfactory. In fact, the traditional approach based on shares of citations or documents [26, 27] is biased by definition towards large nations—thus not allowing for a fair comparison of the different national research systems. Moreover, the number of published papers gives no clear information about the quality of the research they contain, whereas, a temporal analysis based only on citation statistics suffers from the time delays paper needs to attract citations. Other approaches based on publication venues [12] instead are affected by all the factors entering in the effective publication dynamics that can follow different criteria than the scientific quality of papers themselves. We thus proposed here an alternative approach of measuring scientific performance as the ratio of citation shares to publication shares, which avoids all the problems mentioned above. The idea behind is that whenever a nation receives a larger share of citations compared to the proportion of papers it publishes, it is producing science that has a greater impact than the world average. We remark that our metric for success is intensive and rewards nations with high number of citations per paper. This is the reason why countries (like China) having a rapid growth in publication outputs, but only a gradual improvement of impact, perform poorly in our study. Note finally that Scopus and other bibliometric databases collect only documents written in English and published in international peer-reviewed journals, while a significant part of the scholarly production in the areas of social sciences and humanities is not published in international journals, but in national journals, in book chapters or in monographs, and not necessarily in English [33]. For the sake of completeness, we decided to include these domains in our analysis, keeping in mind that while they are few and their weight is thus small, this could result in a slight bias towards anglophone nations—that may be the reason for the slightly better performance of Commonwealth members with respect to Western Europe.

Concerning research investments, we have focused on HERD (basically, the expenditure to form and fund highly qualified research personnel at universities), showing that government intramural fundings provide little information on the quality of scientific output, whereas, R&D expenses in the business sector do provide some information but mainly because of the correlation between scientific and technological performance. We then confirmed that the scientific impact of a nation grows with the amount of HERD [14], pointing to the ambiguity of the R&D funding scheme and the lack of an appropriate measure for scientific success as the cause of contradicting views on this issue [16]. Yet, it is important to remark that there are lags between changes in research funding and publication outputs (as for outputs and their impact) of the order of two-three years, so that multivariate models may be necessary to deeply understand the productive dynamics of science and innovation [27].

We also confirm that the amount of international collaboration in science is steadily growing in time [11, 18] and that almost all nations are nowadays involved in international collaborations [2]—which generally lead to research of higher impact [12]. Internationalization is stronger in Western and Northern Europe, supposedly as an effect of EU Commission to stimulate collaboration within European countries [4, 5]. The fact that EU countries are also increasing scientific success to top levels and at fast peace testifies the rate of progress towards the European Research Area (ERA) vision. Note that international collaborations are especially important for fostering frontier research, needed to address global challenges that requires input from a wide range of expertises. However, according to *Science Europe* [34], with the European Research Council (ERC) grant scheme being dedicated to investigator-driven research, the current absence of ERC Synergy Grants from the funding schemes, and the Horizon 2020 Societal Challenges primarily focused on near-market applied research, funding opportunities for collaborative basic and frontier research at the EU level are at the moment quite limited. This may put future scientific progress at a stake. Nevertheless, internationalization emerges from our analysis as an additional fundamental parameter for the scientific development of nations, and in this sense the EU has been rather successful (up to now).

Putting together all three fundamentals, we observe clearly discernible patterns [18], caused by various factors as different as history, geography, politics, language [14]. For instance, the Asian nations are not increasing the level of internationalization of their research systems, possibly because countries like Japan and China are more scientifically isolated than other developed countries. Additionally, large research systems rely less on international co-authorship [18]—the same happens for the United States, that evolve similarly to western counties in internationalization but with a negative offset due to their larger self-consistency. Eastern Europe on the other hand is slowly detaching from the Russian attractor, trying to catch up with the rest of EU nations that have a remarkable performance. In particular, Northern European countries and Switzerland are the top players according to our intensive metric, that defines the mean quality of single papers rather than the overall national scientific impact: their research system is both the most efficient and successful.

Finally, note that our assessment of the scientific success of nations based on publication impact is in line with the quantification of the level of scientific diversification and competitiveness, pursued through appropriate algorithm that leverage on the detailed structure of national research systems [31]. Remarkably, this latter approach was originally developed for economics, and used to successfully measure the economic potential and competitiveness of countries, together with the complexity of produced goods [35, 36]. Scientific and economic production of nations thus seems to follow similar structural patterns. Moreover, the heterogeneous dynamics of nations we find here reflect those found for economic development (laminar for developed countries, chaotic for underdeveloped countries) [37]. An interesting perspective thus could be the study of scientific development in the context of diffusive dynamics of countries in the space of scientific domains, as it was done for economic development in the space of products [38]. Overall, the parallelism found between scientific and economic production can be seen as a natural consequence of the coupling and co-evolution of the different compartments of the innovation ecosystem. We believe future research will be bound to face the challenge of identifying the micro-determinants and their complex interactions that are responsible for the observed emergent macro-properties of the innovation ecosystem, allowing to unfold the complex interplay between scientific advancement, technological progress, economic development and societal changes.

## ACKNOWLEDGMENTS

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[22] The government sector includes departments, offices and other bodies which furnish (but normally do not sell) to the community common services other than higher education, as well as those that administer the state and the economic and social policy of the community, and the non-profit institutions controlled and mainly financed by government but not administered by the higher education sector.

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