The importance of scientific domains for technological diversification in European regions

Final report

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ABSTRACT

Smart Specialization policy prescribes regions to build on local capabilities to develop new activities. Studies have relied on data on patents, industries and occupations, but not yet on data on scientific domains. This report maps the scientific capabilities (publications) of 285 regions in Europe, and investigates the extent to which these scientific capabilities match their technological capabilities (patents) in 18 domains. In general, we find a positive relationship between a strong local scientific base in a domain and the ability of a region to develop new technologies in that domain for the period 2004-2018. We identified four types of regions in Europe. Strongholds combine a strong local scientific base with strong technological performance in the same domain. Scientific leaders show a strong scientific base but a weak performance in patenting in the same domain, while technology leaders show a strong local technological base in a domain, without having a strong underlying scientific base. Followers score low on both dimensions in a domain. Now and then, regions in Europe change over time, like scientific leaders that manage to transform into strongholds in a specific domain.

1. INTRODUCTION

Regional capabilities are regarded as a key pillar of Smart Specialization policy (McCann and Ortega-Argilés 2015). This policy prescribes that regions should build on existing capabilities to develop new activities. There is strong support in the literature that regions are indeed primarily developing new activities (occupations, industries, technologies) that draw on relevant (related) capabilities present in the region (Boschma 2017; Hidalgo et al. 2018).

This relatedness framework has been applied in studies to map diversification opportunities of regions using different data sets, such as product data (Hidalgo et al. 2007; Cicerone et al. 2020), patent data (Kogler et al. 2013; Rigby 2015), industry data (Neffke et al 2011) and occupational data (Muneepeerakul et al. 2013). Boschma et al. (2014) and Guevara et al. (2016) were the first to apply the relatedness framework to explain the evolution of science at the city level in biotech and physics respectively. Guevarra et al. (2016) showed that the probability of developing a new scientific field in a country increases when related to scientific fields in which a country has strong expertise. Studies have also investigated whether scientific capabilities impact the probability of countries developing technologies that are related to scientific fields in countries (Pugliese et al. 2019; Catalána et al. 2020). However, there exists no study using the relatedness framework that explores how scientific capabilities may affect the development of new technologies at the regional level. Increasing our understanding of the importance of scientific knowledge for opportunities of regions to develop new technologies in Europe would add another dimension to the Smart Specialization policy that is still unexplored.

It would also provide new insights into the role of scientific knowledge and universities for regional development. The relationship between science (publications) and technology (patents) has been extensively examined (Narin et al. 1997; Callaert et al. 2014; Patelli et al. 2017). Studies show that science can act as a source of knowledge for innovation (e.g. Acs et al. 1992; Audretsch and Feldman 1996; Anselin et al. 1997; Varga 2000; Fleming and Sorenson 2004; Laursen and Salter 2004; Moreno et al. 2005; Leten et al. 2014). However, studies have also shown that this relationship is far from straightforward. Local firms may lack the absorptive capacity to benefit from scientific excellence in a region (Bilbao-Osorio and Rodríguez-Pose 2004**;** Rodríguez-Pose and Crescenzi 2008; Bonaccorsi 2017), or institutional barriers may hamper university-industry collaborations in regions (Ponds et al. 2010; Bikard and Marx 2020). However, no studies have yet applied the relatedness framework to assess systematically how well scientific knowledge is transformed into technologies in regions.

This report aims to map the scientific and technological capabilities of regions in Europe for 18 domains (such as Chemistry or Clinical Medicine), based on scientific publication and patent data. We assess whether there is an overlap between the scientific and technological base of regions in Europe in each of the domains. We examine the extent to which a local scientific base is accompanied by a strong technological presence of a region in the same domain. Our study identifies 4 types of regions in Europe, depending on the degree of overlap between the scientific and technological bases of regions in the 18 domains. We also estimate a diversification model to assess the role of local scientific capabilities for the development of technologies in the 18 domains in 285 NUTS-2 regions in Europe. The study finds a positive relationship between a strong local scientific base in a domain and the ability of a region to develop technologies in that domain during the period 2004-2018.

The report is structured as follows. Section 2 provides a brief literature review. Section 3 explains how scientific domains are linked to technology fields, how relatedness between domains is calculated, and how we derive a measure of complexity for each domain. Section 4 presents the degree of overlap between the scientific and the technological bases of a region in each of the 18 domains, and identifies 4 types of regions. Section 5 presents the main findings of the regional diversification model. Section 6 concludes and discusses the implications for Smart Specialization policy and future research.

2. Brief literature review

There is an agreement that new scientific and technological knowledge do not start from scratch. Rather, it builds on existing pieces of knowledge that are combined in new ways (Dosi 1982). Scientific researchers are often trained in narrowly defined academic disciplines, they work in relatively homogenous departments, and they are embedded in social and professional networks (Guevarra et al. 2016). This makes that researchers are involved in search processes that tend to be highly localized (Nelson and Winter 1982). It limits the opportunities to acquire new knowledge they are not familiar with and to enter distant fields (Atkinson and Stiglitz 1969), like it will be hard for a sociologist to move into physics and excel in that academic field.

This makes that researchers develop new ideas mainly within their own scientific and technological domain. This is not to say that researchers are not engaged in interdisciplinary research and do not cross scientific and technological boundaries. But when they do, they interact and collaborate with fields that are close to their own domain. In academia, this is reflected in the composition of research consortia, publishing behavior in multiple academic fields, and citation behavior across domains. This behavior reveals information on how relevant academic fields are to each other: it reveals knowledge flows across scientific fields in which knowledge from other fields is used to create knowledge in an academic domain (Guevarra et al. 2016). Studies consider domains to be related when they cite each other, or when they cite similar literature (Boyack et al. 2005; Leydesdorff and Rafols 2009; Waltman et al. 2010).

These maps of knowledge flows across (related) scientific domains can be used to assess the potential of an organization (like a university or a firm), a region or a country to enter a new academic domain (Guevarra et al. 2016; Alshamsi et al. 2018). The probability that a region will enter a new scientific domain is then expected to depend on the local presence of related domains. This comes close to the diversification literature on regions (Neffke et al. 2011) and countries (Hidalgo et al. 2007) in which the same principle of relatedness (Hidalgo et al. 2018) is applied to explain the dynamics of technologies (Rigby 2015), industries (Neffke et al. 2011) and occupations (Muneepeerakul et al. 2013) in regions. Boschma et al. (2014) and Guevara et al. (2016) were the first to apply this relatedness framework to explain the emergence of new scientific specializations in cities. Boschma et al. (2014) did a study on the dynamics of scientific knowledge in biotech in 276 cities. They showed that new scientific topics in biotech (proxied by words in scientific publication headings) develop in cities where related scientific topics already exist. Guevarra et al. (2016) showed that the probability of developing a new scientific field (as proxied by publishing in a new research area in physics) in a country increases when related to scientific fields in which a country has already strong expertise.

When moving into new domains, regions also have a strong incentive to develop new domains that are complex. Complexity makes knowledge hard to codify and difficult to imitate (Kogut and Zander 1993). The more complex a knowledge domain is, the more it can act as a source of regional competitive advantage. Hidalgo and Hausmann (2009) defined products as complex when they combine many capabilities which makes them hard to copy. Scholars have demonstrated that increasing the complexity of an economy is beneficial for economic development (Hidalgo and Hausmann 2009; Davies and Mare 2019; Mewes and Broekel 2020). But despite this strong incentive to develop complex activities, regions often fail to do so (Balland et al. 2019). Only a few places like large urban regions can master complex knowledge because they provide access to a wide range of capabilities that need to be combined to develop complex activities (Balland and Rigby 2017). As a consequence, complex activities are produced by a few regions where they contribute to long-run competitive advantage (Mewes and Broekel 2020). This contrasts with simple knowledge domains that are easy to copy and therefore have little economic value (Davies and Mare 2019).

Balland et al. (2019) argue that regions should develop new knowledge that is not only related to existing knowledge in a region but is also more complex. The complexity of technologies, products and professions has been assessed in numerous studies. However, few studies (Heimeriks et al. 2019) have assessed the complexity of scientific knowledge, or the complexity of scientific domains. We attempt to unravel the complexity of scientific domains.

A critical question is whether the production of scientific knowledge actually leads to new technologies. The relationship between science (publications) and technology (patents) has been widely examined (Narin et al. 1997; Callaert et al. 2014; Patelli et al. 2017). Studies tend to report a positive impact of science on patenting and regional development (Acs et al. 1992; Audretsch and Feldman 1996; Jaffe and Trajtenberg 1996; Anselin et al. 1997; Varga 2000; Fleming and Sorenson 2004; Moreno et al. 2005; Leten et al. 2014).

However, studies also show this relationship is far from straightforward. Audretsch and Feldman (1996) have demonstrated that scientific research is not useful for every industrial sector, such as mechanical and chemical sectors (Leten et al 2014). There may also be a disconnect between the scientific knowledge and the absorptive capacity of firms in regions (Rodríguez-Pose 2001; Bilbao-Osorio and Rodríguez-Pose 2004; Bonaccorsi 2017). And many scholars have underlined the importance of institutional barriers that may hamper university-industry collaborations in regions (Ponds et al. 2010).

What has been underexplored is that relatedness might be an important factor that enables the diffusion of scientific knowledge and the development of new technologies. Tran (2020) found that relatedness between science and technology facilitates knowledge diffusion from science to invention in a region and increases the value of the invention. Other studies (Pugliese et al. 2019) examined whether scientific capabilities impact the probability of countries to diversify into technologies that are related to scientific fields. For instance, Catalána et al. (2020) found that the more a technology is related to the scientific portfolio of a country, the higher its entry probability. However, there exists no study yet that explores how scientific capabilities in specific domains provide opportunities to regions to develop new technologies in these domains. This will be done in this report for 285 European regions.

3. CHARACTERIZING SCIENTIFIC DOMAINS

This report will map the scientific and technological capabilities of regions in Europe, based on scientific publication and patent data. In particular, we assess whether there is an overlap between the scientific and technological base of regions in Europe in 18 domains. This section explains how we link scientific domains to technologies. Then, we characterize each scientific domain in terms of their level of relatedness with other domains and their level of complexity.

Linking scientific domains to technologies

There are several ways of determining a link between scientific fields and technologies. Scientific fields are often identified by linking scientific journals to specific scientific domains. Technological fields are identified by technology classes that are mentioned on patents. To connect scientific to technological domains, some studies use publication-patent citations, that is, data on citations on a patent by a local inventor in the region to scientific publications of researchers in the region. A relatedness measure for each pair of technology domain (patent class) and scientific field (linked to scientific journals) can then be derived from co-occurrences between a technology and a scientific field (Tran 2020).

We use patent documents to link scientific domains to technologies, based on the description of technology (CPC) classes at the sub-domain level. Science Metrix defines 20 scientific domains. Each scientific domain consists of sub-domains. For instance, the domain Agriculture, Fisheries & Forestry includes the sub-domains Agronomy & Agriculture, Dairy & Animal Science, Fisheries, Food Science, Forestry, Horticulture, and Veterinary Sciences. For some scientific sub-domains (like the ones in Agriculture, Fisheries & Forestry), it is straightforward to link them to technological classes, based on the description of the CPC classes in patent documents. For other scientific domains, this is less straightforward. For example, the domain of Enabling & Strategic Technologies consists of 7 sub-domains which do not always have a perfect match with CPC classes. In those cases, we employ text-mining techniques to link each sub-domain to CPC classes. In the end, we decided to exclude two domains from our analyses. The domain of Philosophy & Theology was removed because it could not be linked to any of the CPC classes. The domain Engineering was also removed because it was linked to almost every CPC class. In this way, we managed to link 18 scientific domains to specific technology classes, and thus, to link scientific and technological capabilities in each of these domains.

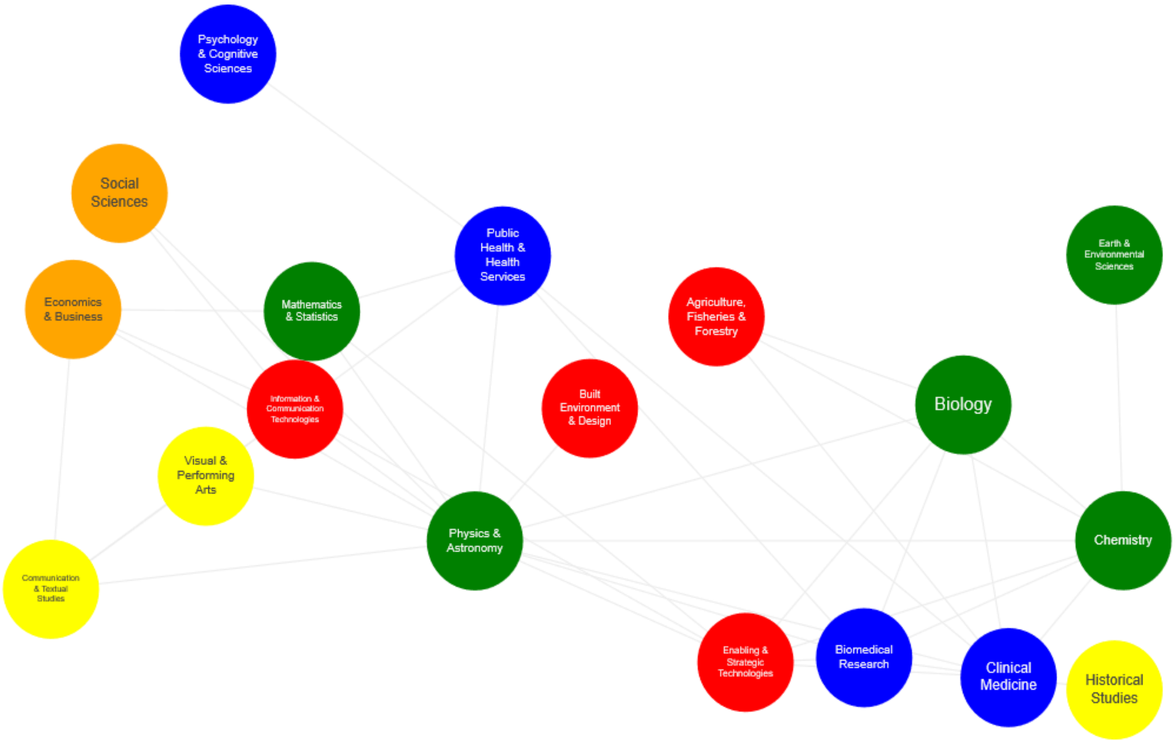
Measuring relatedness between scientific domains

As mentioned before, some scientific fields are relevant to each other for knowledge production because they share similar capabilities, while other scientific fields have nothing in common. But how to determine which scientific domains are related to each other? This can be done in various ways. One can identify knowledge flows between sciences through co-citation networks that are based on references to different papers associated with disciplines in the same reference list of a paper (Boyack et al. 2005). Direct citation networks link academic fields when a paper from one discipline cites a paper from another. Another way concerns bibliographic coupling in which pairs of disciplines are connected when papers from different fields cite the same other papers. One could also follow the product space methodology of Hidalgo et al. (2007), in which two scientific fields are considered related if they are simultaneously over-represented in the same regions.

We developed a new approach to assess relatedness between scientific domains. We use the information on the links between scientific domains and CPC classes to derive a measure of relatedness between scientific fields. Relatedness is based on normalized co-occurrences of the 18 scientific domains on patent documents. If CPC classes linked to scientific field *1* often show up in combination on the same patent document with CPC classes linked to scientific field *2*, we consider the two scientific fields related. We normalize the co-occurrences using the cosine method. The relatedness between scientific fields can be formalized as a network, the *Science Space*, a $n*n$ network where the individual nodes i (i =1, n) represent 18 scientific fields, and the links between them indicate their degree of relatedness.

Figure 1 shows the Science Space for the period 2014-2018. Colors indicate groups of sciences by Science Metrix: the red coloured represent Applied Sciences, the yellow coloured Arts and Humanities, the orange coloured Economic and Social Sciences, the blue coloured Health Sciences, and the green coloured Natural Sciences. The highest relatedness scores are between the scientific fields of Information & Communication Technologies, Mathematics & Statistics, and Physics & Astronomy. Some scientific fields like Physics & Astronomy and Information & Communication Technologies are positioned more central in this scientific network: they share similar capabilities with many other sciences. This stands in contrast to other sciences like Historical Studies, Earth & Environmental Sciences, Psychology & Cognitive Sciences, and Built Environment & Design that are related with one other scientific domain only.

Figure 1. Science Space in Europe



https://www.paballand.com/asg/dg-regio/scientific-relatedness/scientific-space.html

Figure 1 shows the science space only for the 5-year period 2014-2018. We have also calculated the relatedness between these scientific fields for other 5-year periods: 2000-2003, 2004-2008, and 2009-2013. The relatedness scores for all periods can be found in the following link:

https://www.paballand.com/asg/dg-regio/scientific-relatedness/rel-p1-p4.html

Measuring the complexity of scientific fields

As explained in Section 2, some scientific knowledge might be complex while other scientific knowledge is less so. The more complex knowledge is, the more it can act as a source of regional competitive advantage, because it will be harder to absorb by others. This contrasts with simple knowledge that is easier to copy. But how to determine the knowledge complexity of scientific fields? There exists no complexity measure for scientific fields. Hidalgo and Hausmann (2009) argued that economic complexity is about the division of labor in which individuals narrow down their expertise and specialize (Jones 2009). This idea can be applied to science where a division of labor between scientists can be observed at the level of a scientific paper (Wuchty et al. 2007). The complexity of a scientific field can then be proxied by the average size of a team involved in a publication in a scientific field (Balland et al. 2020), or by the share of publications in a field that involves international co-authorship.

We follow Hidalgo and Hausmann (2009) in which complexity reflects the difficulty of mastering capabilities that are required to excel in a domain which is shown by its rarity on the one hand, and the diversity of capabilities that need to be combined on the other hand. Complexity is measured by using the eigenvector reformulation of the method of reflection (Balland and Rigby 2017). The starting point is a binary-valued network that connects regions to scientific domains in which they have a Relative Scientific Advantage. This matrix M has dimension n = 285 regions (NUTS-2) by k = 18 scientific domains. This matrix M is row standardized along with its transpose. The resulting product matrix is a square matrix with dimension equal to the number of scientific domains. The complexity of each domain is given by the elements of the second eigenvector of the matrix.

Table 1 ranks the 18 scientific domains in terms of their complexity for the period 2014-2018. The most complex domain is Physics & Astronomy, followed by Chemistry, Mathematics & Statistics, Enabling & Strategic Technologies, and Information & Communication Technologies. The least complex scientific domains are in Public Health & Health Services, Social Sciences, and Psychology & Cognitive Sciences. This complexity ranking of sciences more or less corresponds to the complexity ranking of scientific fields when looking at the share of international publications in a scientific field.

Table 1. Complexity of scientific fields

Rank	Scientific field	Complexity
1	Physics & Astronomy	1,28
2	Chemistry	1,19
3	Mathematics & Statistics	1,03
4	Enabling & Strategic Technologies	1,03
5	Information & Communication Technologies	0,78
6	Earth & Environmental Sciences	0,15
7	Agriculture, Fisheries & Forestry	0,06
8	Biology	-0,06
9	Clinical Medicine	-0.26
10	Built Environment & Design	-0,3
11	Historical Studies	-0,32
12	Economics & Business	-0,41
13	Biomedical Research	-0,48
14	Communication & Textual Studies	-0,7
15	Visual & Performing Arts	-0,73
16	Psychology & Cognitive Sciences	-0,92
17	Social Sciences	-1,02
18	Public Health & Health Services	-1,49

4. Overlap between scientific and technology domains in regions

A key objective is to determine whether a region with a strong scientific base in a particular field also shows a strong technological base in the same field. This would signal that regions have a strong capacity to turn scientific knowledge into new technologies. Section 3 explained how scientific domains have been linked to technology fields. We use this to determine whether there is a (mis)match between the scientific and the technological base in a region.

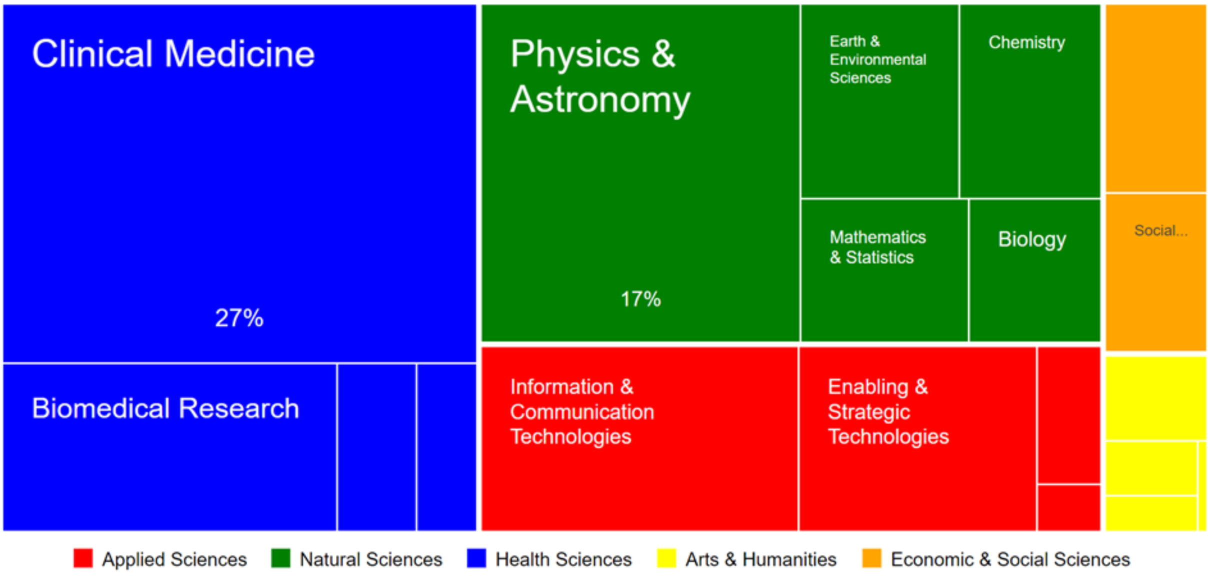
We measure the scientific knowledge base of a region by the number of scientific publications by local researchers in scientific journals that are linked to a scientific domain. We use the information provided by Science Metrix that links scientific journals to the 18 scientific domains. We measure the technological base of a region by the number of patents by local inventors in a particular domain (which is associated with specific technology classes). In Table 2, we outline the number of scientific publications and patents for each domain in 32 European countries (EU-27, the UK and the four EFTA countries) for the period 2014-2018.

Table 2. Number of scientific publications and patents in 18 domains in Europe 2014-2018

Domain	Scientific publications	Patents
Agriculture, Fisheries & Forestry	174,869	17,929
Biology	261,907	13,455
Biomedical Research	489,247	18,207
Built Environment & Design	56,962	16,668
Chemistry	325,519	59,559
Clinical Medicine	1,721,224	44,301
Communication and Textual Studies	52,583	1,609
Earth & Environmental Sciences	285,800	9,106
Economics & Business	185,927	4,254
Enabling & Strategic Technologies	485,100	42,118
Historical Studies	59,627	137
Information & Communication Technologies	478,046	57,334
Mathematics & Statistics	134,949	26,875
Physics & Astronomy	777,400	80,794
Psychology and Cognitive Sciences	152,768	389
Public Health & Health Services	167,250	2,655
Social Sciences	200,467	2,076
Visual & Performing Arts	6,747	2,335

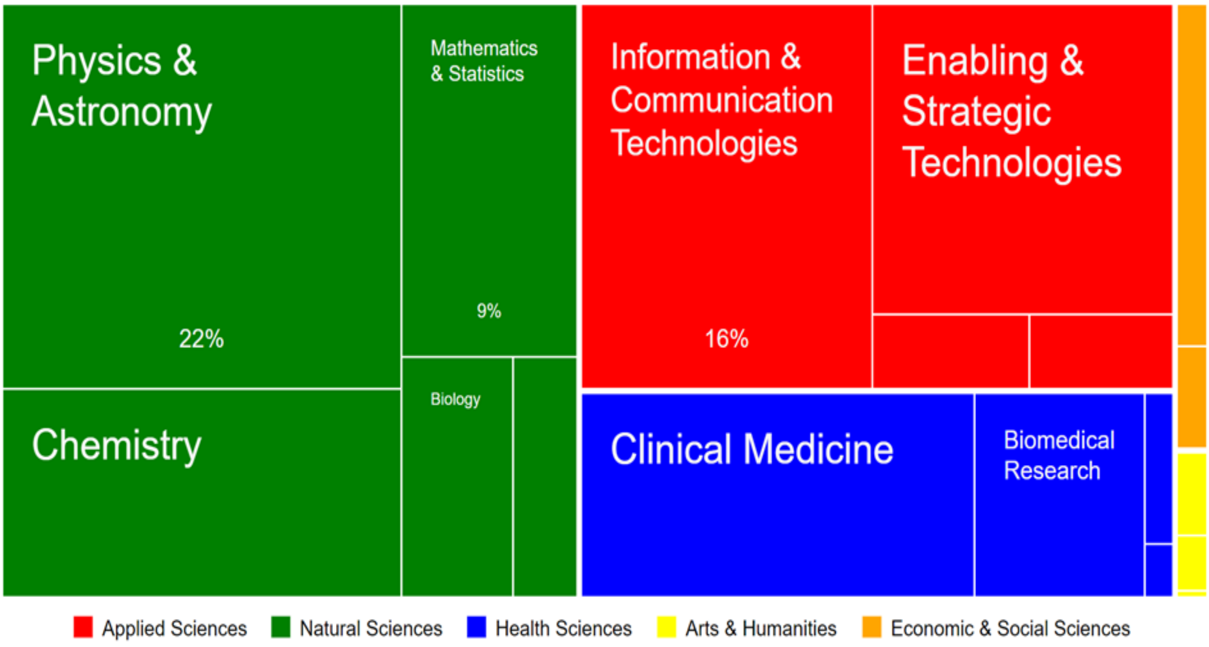
For illustrative purposes, we compare the scientific and technological profile of the Île-de-France region in the 18 domains in Figures 2 and 3 respectively. For example, Île-de-France shows a strong scientific base in Health (about half of its scientific publications is in that field), but its technological base in Health is less pronounced (only 17 percent of patents in that field).

Figure 2. Scientific profile of Île-de-France region in 18 domains (share of publications)



https://www.paballand.com/asg/dg-regio/scientific-relatedness/FR10-pub.html

Figure 3. Technological profile of Île-de-France region in 18 domains (share of patents)



https://www.paballand.com/asg/dg-regio/scientific-relatedness/FR10-pat.html

Four types of regions

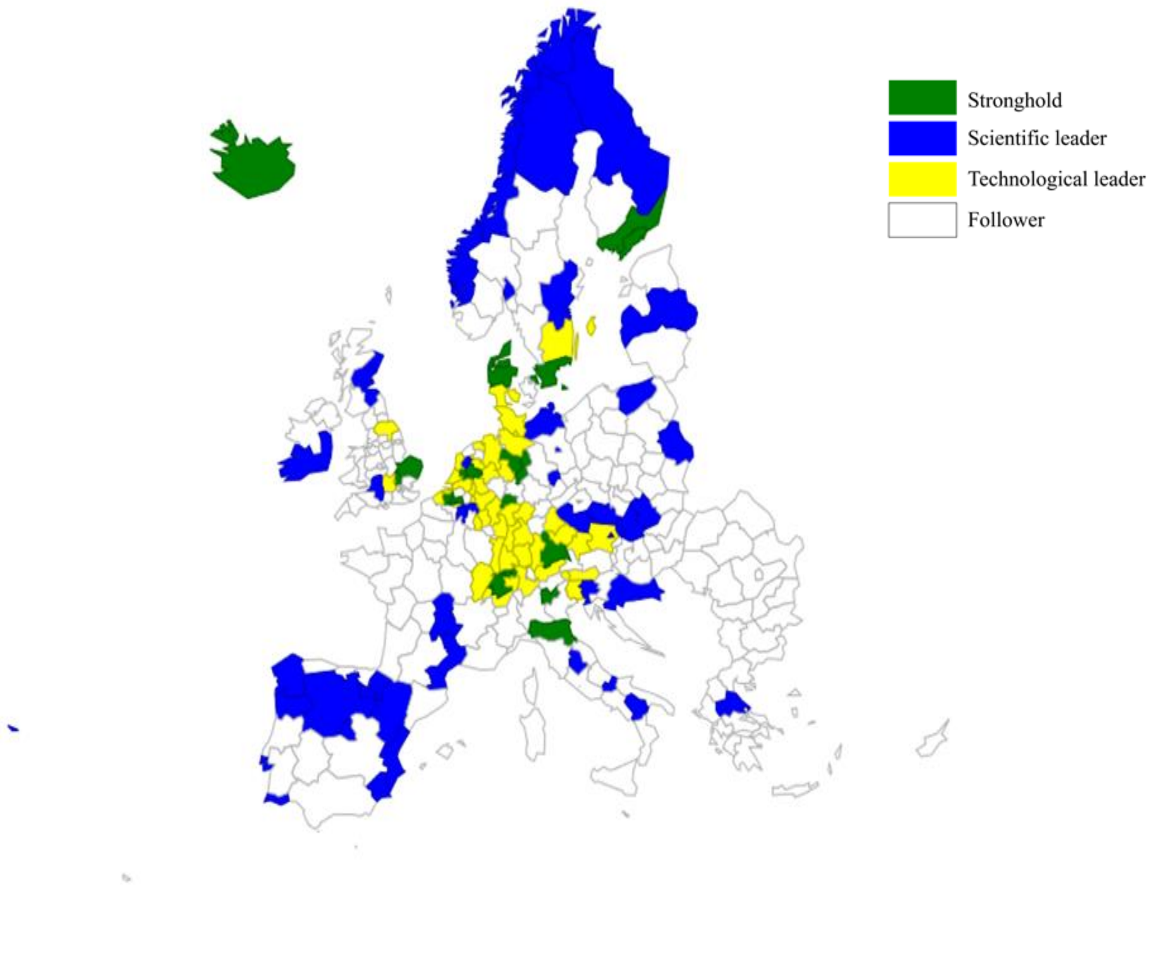
For each domain, we compare the spatial distributions of publications and patents per capita in Europe. Per domain, we distinguish four types of regions: (1) **strongholds** refer to regions that are successful in technologies in the same domain in which they have a strong scientific presence. Strongholds belong to the top 25% (in terms of ranking) for both the number of patents per capita and the number of publications per capita in a domain; (2) **scientific leaders** refer to regions that show a strong scientific base but a weak performance in patenting in a domain. This signals that local scientific knowledge has not resulted in a strong performance in patenting in the same domain. Scientific leaders belong to the top 25% (in terms of ranking) for the number of publications but not for the number of patents per capita; (3) **technology leaders** stand for regions that combine a relatively weak scientific base with a strong performance in patenting in a domain. Technology leaders belong to the top 25% (in terms of ranking) regarding the number of patents but not the number of publications per capita. Technology leaders show that a strong technological base in a region in a domain does not necessarily go together with a strong underlying local scientific knowledge base; (4) **followers** concern regions that do not belong to the previous 3 categories: they score relatively low on both science and technology indicators in a domain.

Below, we briefly present the four types of regions for each domain one by one. The four types of regions are determined by their performance in science and technology per capita in a domain for the period 2014-2018. Due to the low patenting activity in the domains of Communication and Textual Studies (1,609 patents), Historical Studies (137 patents), Psychology and Cognitive Sciences (389 patents), Social Sciences (2,076 patents) and Visual and Performing Arts (2,335 patents), we do not present these domains below. Appendix 1 provides details of the scores of all regions in each domain with respect to the relative number of scientific publications and patents per capita and the absolute numbers of scientific publications and patents in a region.

Agriculture, Fisheries and Forestry

As shown in Figure 4, we identified 23 European strongholds in the domain of Agriculture, Fisheries and Forestry. The top 5 of strongholds consists of the Capital Region of Denmark (DK), East Flanders (BE), Central Denmark (DK), Gelderland (NL) and Inner London-West (UK). Scientific leaders can be found in many countries in Europe: their strong scientific performance per capita is not matched by a similar performance in patenting. The strongest scientific leaders in this domain are Prague (CZ), Oslo and Akershus (NO), South East (CZ), Northern Norway (NO) and East Middle Sweden (SE). Technology leaders are more concentrated in Europe, especially in Germany: these regions patent a lot but they lack a strong scientific base in this domain. The top 5 technology leaders is: the Lake Geneva region (CH), Rheinhessen-Pfalz (DE), West Flanders (BE), Weser-Ems (DE) and Karlsruhe (DE).

Figure 4. A map of strongholds, followers, scientific and technology leaders in the domain of Agriculture, Fisheries and Forestry in Europe (per capita)

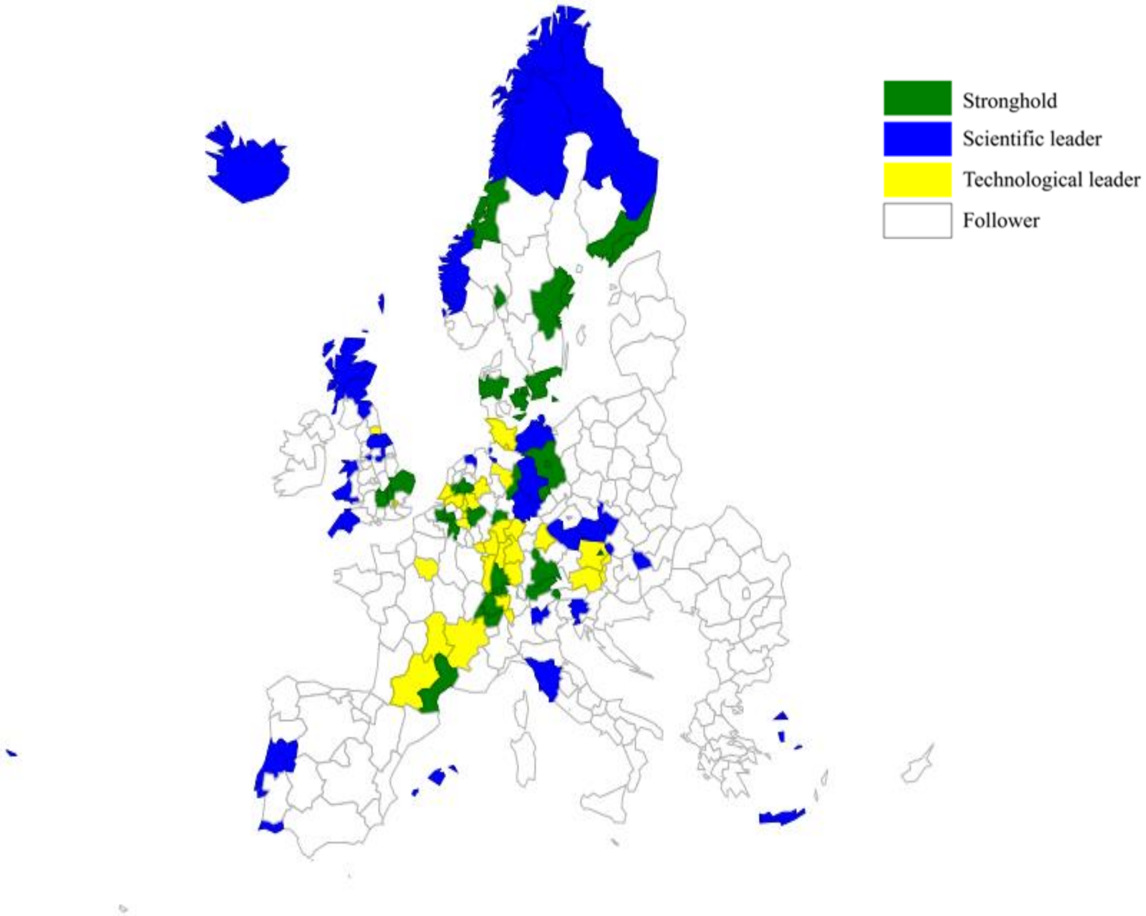


https://www.paballand.com/asg/dg-regio/scientific-relatedness/maps/stronghold-pc/agriculture-fisheries-&-forestry.html

Biology

Figure 5 shows the map of Europe for the Biology domain. We identified 36 strongholds that combine a strong scientific and technology base in this domain. The top 5 of these strongholds is made up of three UK regions: Inner London-West (UK), Zurich (CH), the Capital region of Denmark (DK), Berkshire, Buckinghamshire and Oxfordshire (UK), and East Anglia (UK). The top 5 of regions that excel in science but not in patenting in Biology (the so-called scientific leaders) consists of Upper Norrland (SE), Prague (CZ), Northern Norway (NO), Eastern Scotland (UK) and North Eastern Scotland (UK). Almost no regions in Southern and Eastern Europe belong to the group of technology leaders in Biology. The top 5 of technology leaders (showing high levels of patenting not matched by their scientific performance) is dominated by German regions: Karlsruhe (DE), Tubingen (DE), Darmstadt (DE), Rheinhessen-Pfalz (DE) and Ile de France (FR).

Figure 5. A map of strongholds, followers, scientific and technology leaders in the domain of Biology in Europe (per capita)

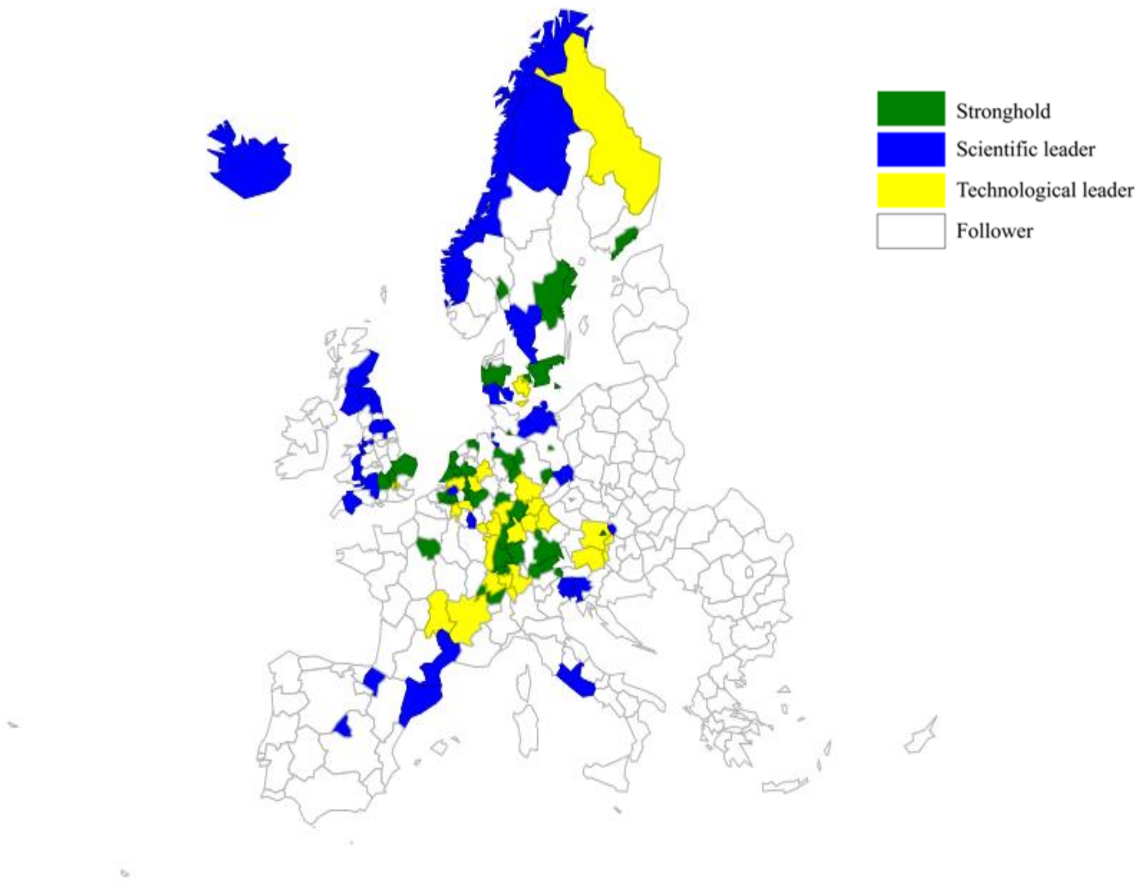


https://www.paballand.com/asg/dg-regio/scientific-relatedness/maps/stronghold-pc/biology.html

Biomedical Research

Figure 6 shows a high amount of strongholds (40 in total) that combine a strong scientific and technology base in the domain of Biomedical Research, but none of these is located in Eastern and Southern Europe. The top 5 of strongholds is dominated by Swiss regions: the Capital Region of Denmark (DK), Inner London-West (UK), Northwestern Switzerland (CH), the Lake Geneva region (CH) and Zurich (CH). Scientific leaders in Biomedical Research that combine high scientific performance with relatively low patenting activity per capita are slightly more spread across Europe. The top 5 of scientific leaders consists of Eastern Scotland (UK), Prague (CZ), Upper Norrland (SE), Merseyside (UK) and Bratislava (SK). The top 5 of technology leaders is again dominated by German regions but led by a Dutch region: North Brabant (NL), Mittelfranken (DE), Darmstadt (DE), Rheinhessen-Pfalz (DE) and Saarland (DE).

Figure 6. A map of strongholds, followers, scientific and technology leaders in the domain of Biomedical Research in Europe (per capita)

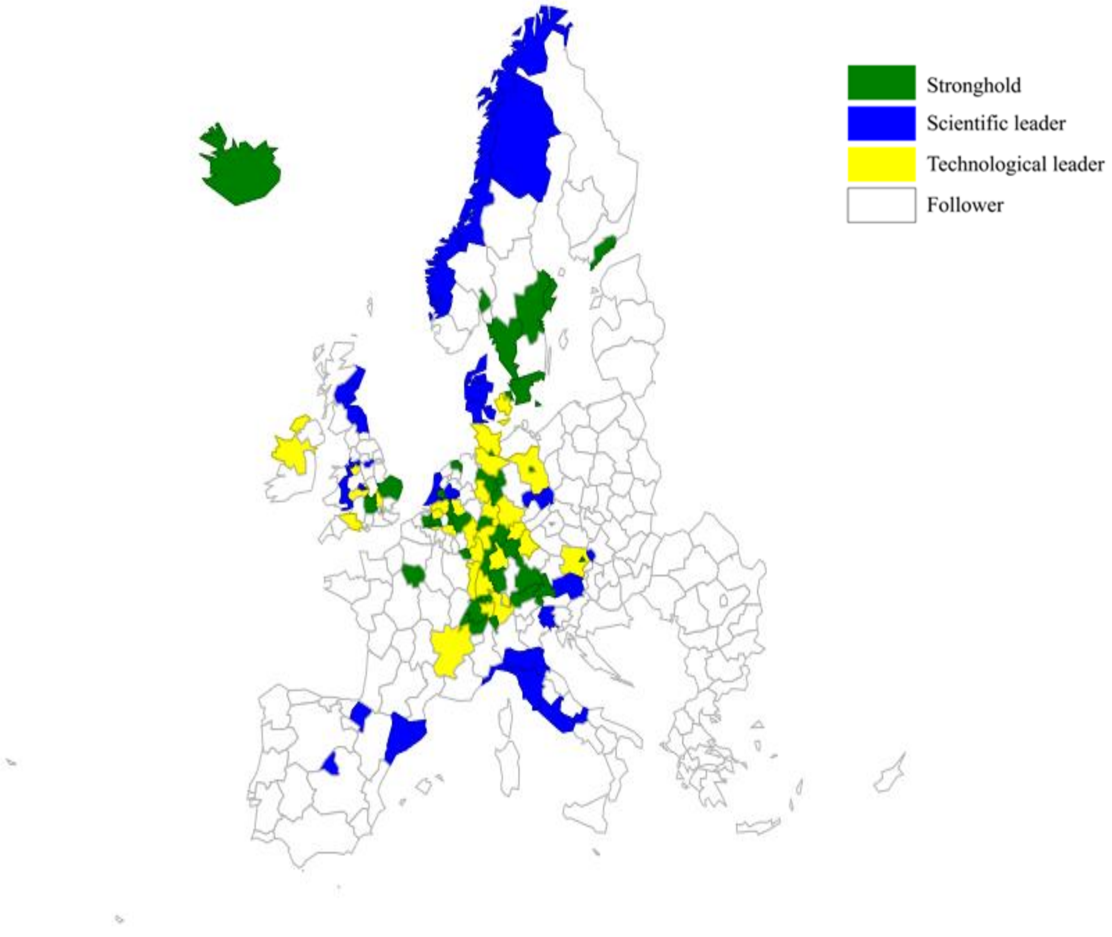


https://www.paballand.com/asg/dg-regio/scientific-relatedness/maps/stronghold-pc/biomedical-research.html

Clinical medicine

Figure 7 shows the map of Clinical Medicine in Europe. We could identify 39 strongholds, of which the top 5 looks the same as for Biomedical Research: Capital Region of Denmark (DK), Northwestern Switzerland (CH), the Lake Geneva region (CH), Inner London-West (UK) and Zurich (CH). The strongest scientific leaders, that is, regions that underperform in patenting despite their excellent scientific performance, are North Holland (NL), Central Denmark (DK), Trondelag (NO), Upper Norrland (SE) and Prague (CZ). There are 31 technology leaders that overperform in patenting but score relatively low on scientific performance in Clinical Medicine per capita. The top 5 technology leaders ranks as follows: North Brabant (NL), Freiburg (DE), Darmstadt (DE), Eastern Switzerland (CH) and Central Switzerland (CH).

Figure 7. A map of strongholds, followers, scientific and technology leaders in the domain of Clinical Medicine in Europe (per capita)

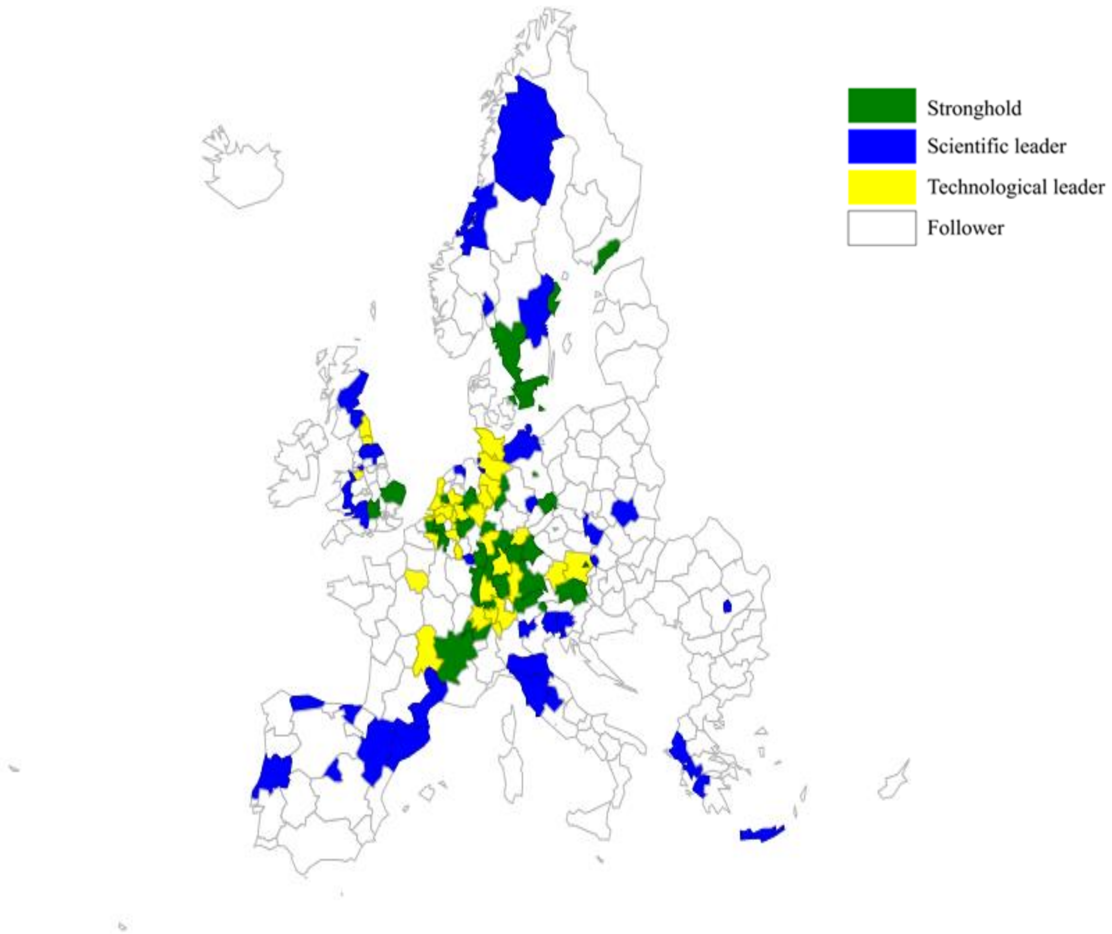


https://www.paballand.com/asg/dg-regio/scientific-relatedness/maps/stronghold-pc/clinical-medicine.html

Chemistry

Figure 8 shows the map with the four types of regions for Chemistry in Europe. We identified a total of 31 strongholds. The top 5 of strongholds in Chemistry consists of Northwestern Switzerland (CH), Zurich (CH), Flemish Brabant (BE), the Capital Region of Denmark (DK), Stockholm (SE) and Inner-London-West (UK). Scientific leaders are more evenly spread across Europe. Remarkable is that the top 5 of scientific leaders in this domain are found mainly in Eastern Europe: Prague (CZ), Bratislava (SK), Groningen (NL), Western Slovenia (SI) and Bucharest (RO). The top 5 of regions of technology leaders that give evidence of high performance in technology but low performance in science per capita are Darmstadt (DE), Dusseldorf (DE), Limburg (NL), Freiburg (DE) and Upper Austria (AT).

Figure 8. A map of strongholds, followers, scientific and technology leaders in the domain of Chemistry in Europe (per capita)

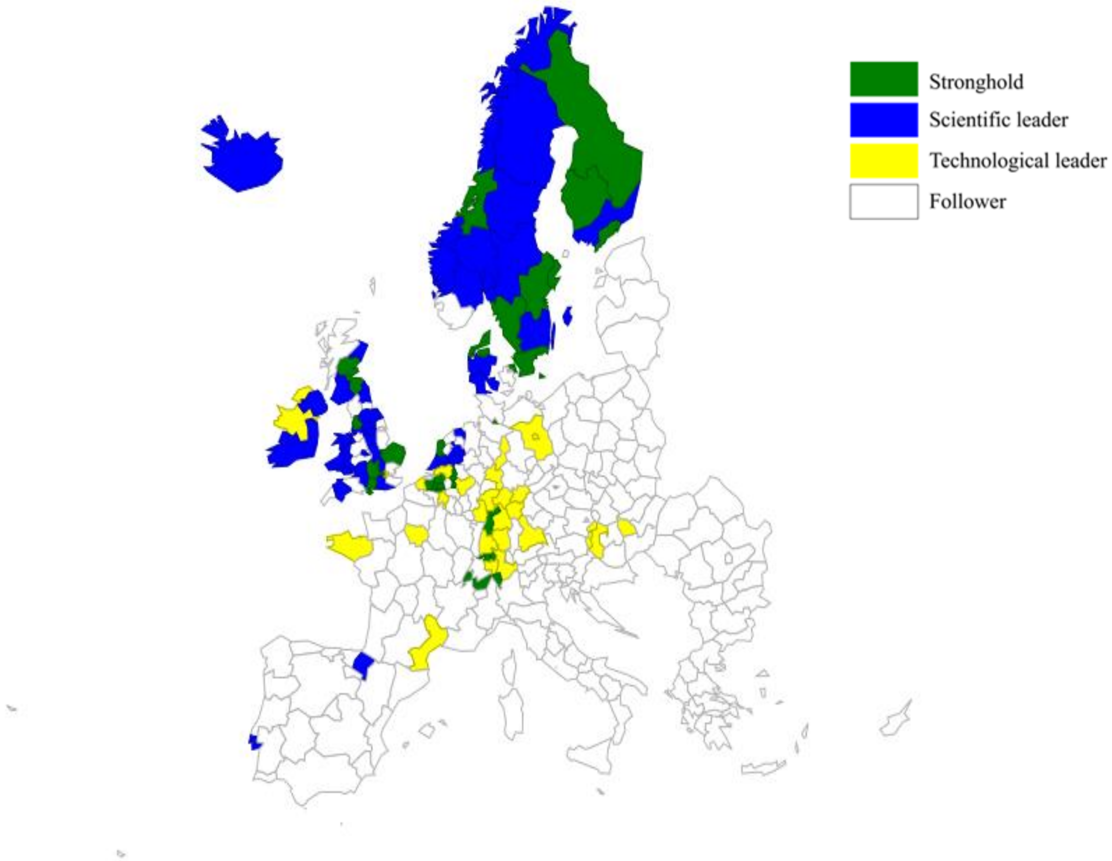


https://www.paballand.com/asg/dg-regio/scientific-relatedness/maps/stronghold-pc/chemistry.html

Public Health and Health Services

Figure 9 shows the map of Europe regarding Public Health and Health Services. Caution is needed when interpreting the findings because there is not much patenting going on in this domain (see also Table 2). 31 regions belong to the group of strongholds, of which the top 5 consists of Inner London-West (UK), the Lake Geneva region (CH), the Capital Region of Denmark (DK), Stockholm (SE) and Helsinki-Uusimaa (FI). Remarkable is that scientific leaders that score high on science per capita but do little patenting in this domain are located almost exclusively in Northern Europe. Groningen (NL), Utrecht (NL), Oslo and Akerhus (NO), Upper Norrland (SE) and North Yorkshire (UK) belong to the top 5 of these scientific leaders. The top 5 of regions of technology leaders that overperform in patenting but score relatively low on science per capita are North Brabant (NL), Mittelfranken (DE), Oberfranken (DE), Central Switzerland (CH) and Oberbayern (DE).

Figure 9. A map of strongholds, followers, scientific and technology leaders in the domain of Public Health and Health Services in Europe (per capita)

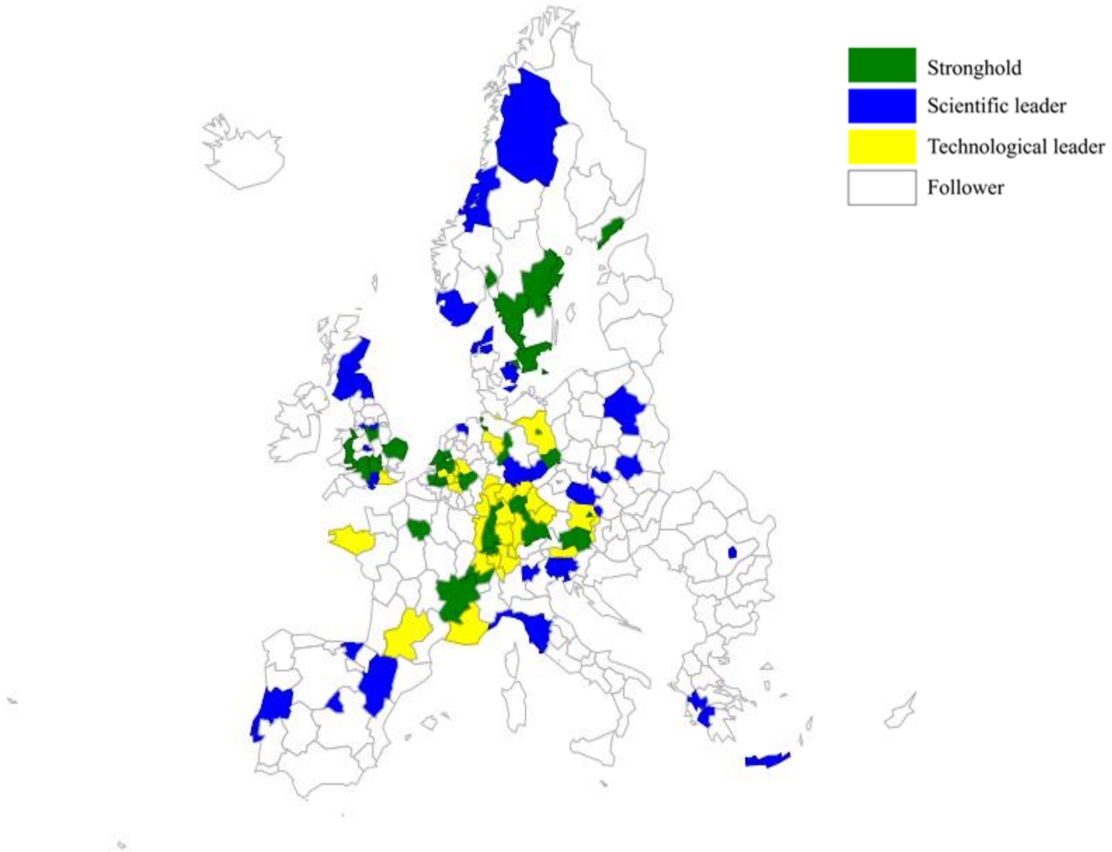


https://www.paballand.com/asg/dg-regio/scientific-relatedness/maps/stronghold-pc/public-health-&-health-services.html

Enabling and Strategic Technologies

Figure 10 shows the geography of the domain of Enabling and Strategic Technologies in Europe. There are 36 strongholds in Europe that show a combination of high science and technology performance. The top 5 of strongholds consists of Inner London-West (UK), Flemish Brabant (BE), the Capital Region of Denmark (DK), Zurich (CH) and North Western Switzerland (CH). Scientific leaders that patent less in this field can be found almost anywhere in Europe. The strongest scientific leaders are Trondelag (NO), Prague (CZ), Upper Norrland (SE), Trento (IT) and North Jutland (DK). The top 5 of technology leaders consists of Hamburg (DE), Tubingen (DE), Darmstadt (DE), Rheinhessen-Pfalz (DE) and Central Switzerland (CH). These regions, many of which are found in Germany, represent a high technological performance per capita in this domain which is not matched with an equally strong scientific knowledge base.

Figure 10. A map of strongholds, followers, scientific and technology leaders in the domain of Enabling and Strategic Technologies in Europe (per capita)

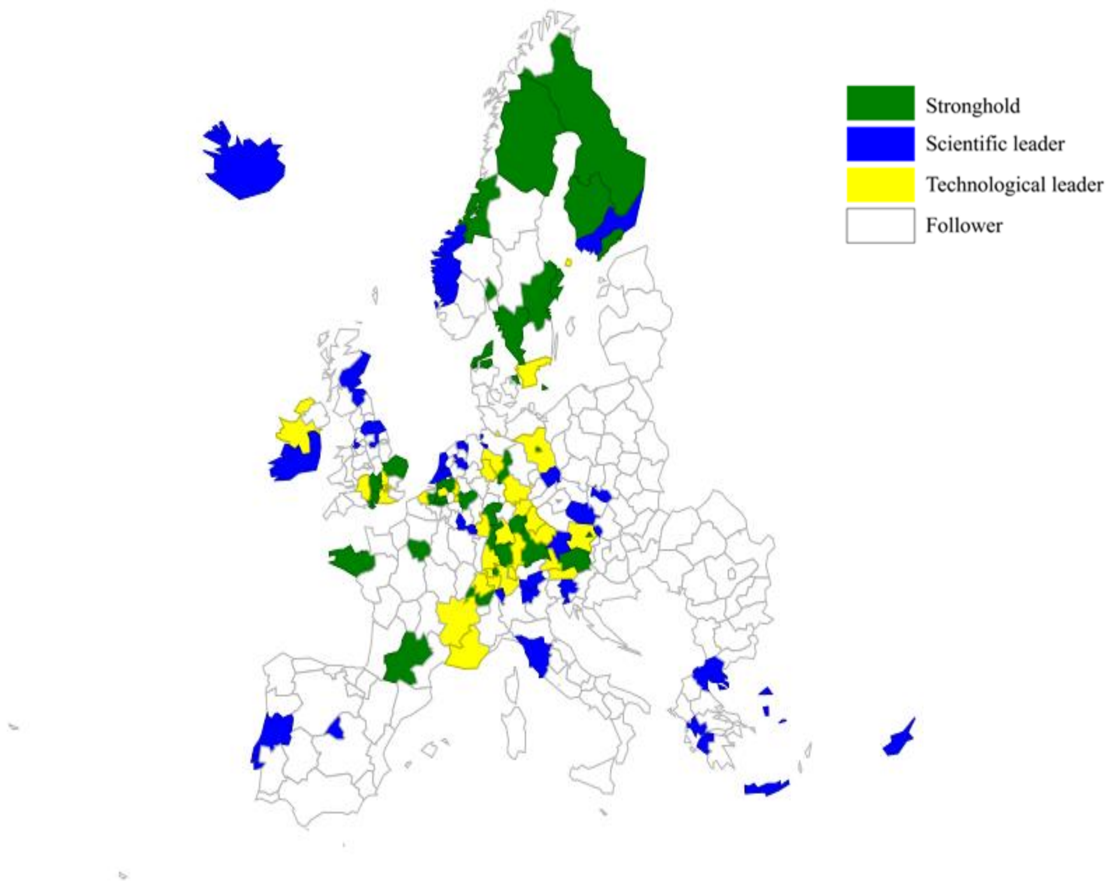


https://www.paballand.com/asg/dg-regio/scientific-relatedness/maps/stronghold-pc/enabling-&-strategic-technologies.html

Information and Communication Technologies

Figure 11 shows the map of regions in Information and Communication Technologies. 34 regions in Europe can be considered a stronghold: they match a strong scientific base with a strong technology base in this domain. The top 5 of strongholds includes Inner London-West (UK), Helsinki-Uusimaa (FI), Zurich (CH), Stockholm (SE) and the Lake Geneva region (CH). 37 regions in Europe have been defined as scientific leaders. They score high on scientific performance but do not match that level as far as patenting per capita. The top 5 of scientific leaders is as follows: Trento (IT), Luxembourg (LU), Ticino (CH), Prague (CZ) and Saarland (DE). We found 35 technology leaders showing a mismatch between their scientific capabilities (relatively weak) and technology capabilities (relatively strong) in this domain. The top 5 of technology leaders consists of South Sweden (SE), Inner London-East (UK), Stuttgart (DE), Hamburg (DE) and Oberpfalz (DE).

Figure 11. A map of strongholds, followers, scientific and technology leaders in the domain of Information and Communication Technologies in Europe (per capita)

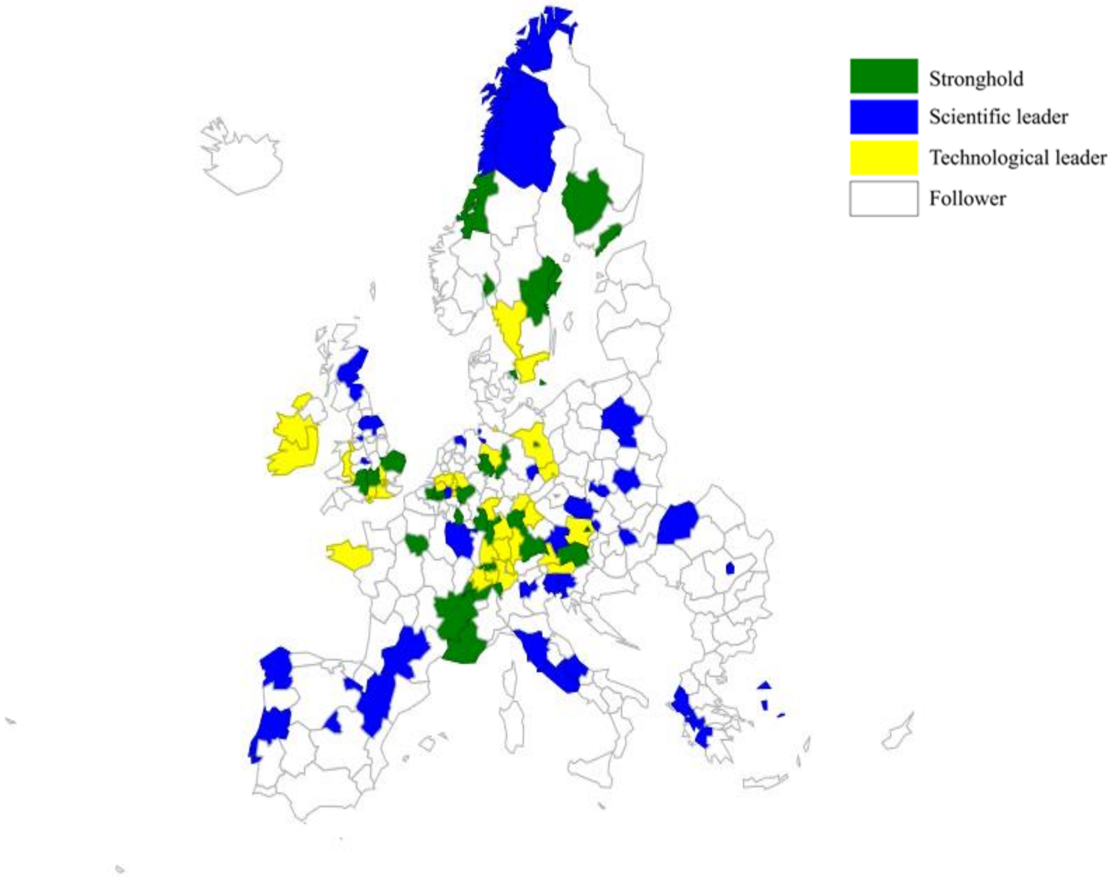


https://www.paballand.com/asg/dg-regio/scientific-relatedness/maps/stronghold-pc/information-&-communication-technologies.html

Mathematics and Statistics

Figure 12 shows that 33 regions in Europe match a strong scientific base with a strong technology base in the domain of Mathematics and Statistics. The top 5 of these strongholds consists of Inner London-West (UK), Lake Geneva region (CH), Zurich (CH), Ile de France (FR) and Flemish Brabant (BE). Scientific leaders are spread more evenly across European countries. The top 5 scientific leaders are as follows: Prague (CZ), Trento (IT), Epirus (EL), Bucharest (RO) and Bratislava (SK). We found 35 technology leaders: the top 5 consists of North Brabant (NL), Inner London-East (UK), South Sweden (SE), Brittany (FR) and Oberfranken (DE).

Figure 12. A map of strongholds, followers, scientific and technology leaders in the domain of Mathematics and Statistics in Europe (per capita)

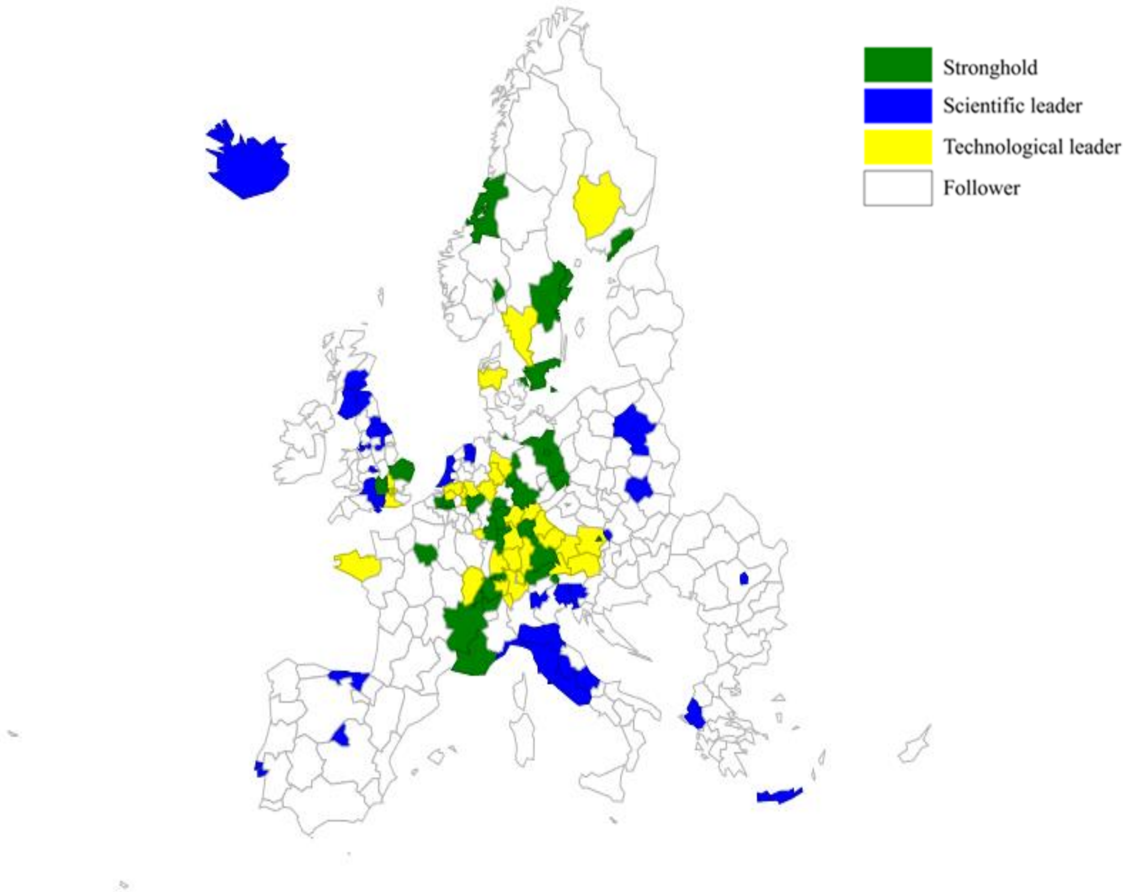


https://www.paballand.com/asg/dg-regio/scientific-relatedness/maps/stronghold-pc/mathematics-&-statistics.html

Physics and Astronomy

Figure 13 shows the map with the four types of regions for the domain of Physics and Astronomy. We identified 35 strongholds in Europe that combine a strong scientific and technology base in this domain. When we look at the top 5 strongholds, it includes three regions (Inner London-West, the Lake Geneva region and Zurich) that also belonged to the top 5 in the domains of Information and Communication Technologies and Mathematics and Statistics. The full top 5 strongholds in Physics and Astronomy is Inner London-West (UK), the Lake Geneva region (CH), Karlsruhe (DE), Zurich (CH) and Oberbayern (DE). The top 5 scientific leaders consists of Prague (CZ), Friuli-Venezia Giulia (IT), Groningen (NL), Bratislava (SK) and Trento (IT). The top 5 technology leaders, showing high levels of patenting not matched by their scientific performance per capita, is as follows: Brittany (FR), Stuttgart (DE), Freiburg (DE), Voralberg (AT) and Central Switzerland (CH).

Figure 13. A map of strongholds, followers, scientific and technology leaders in the domain of Physics and Astronomy in Europe (per capita)

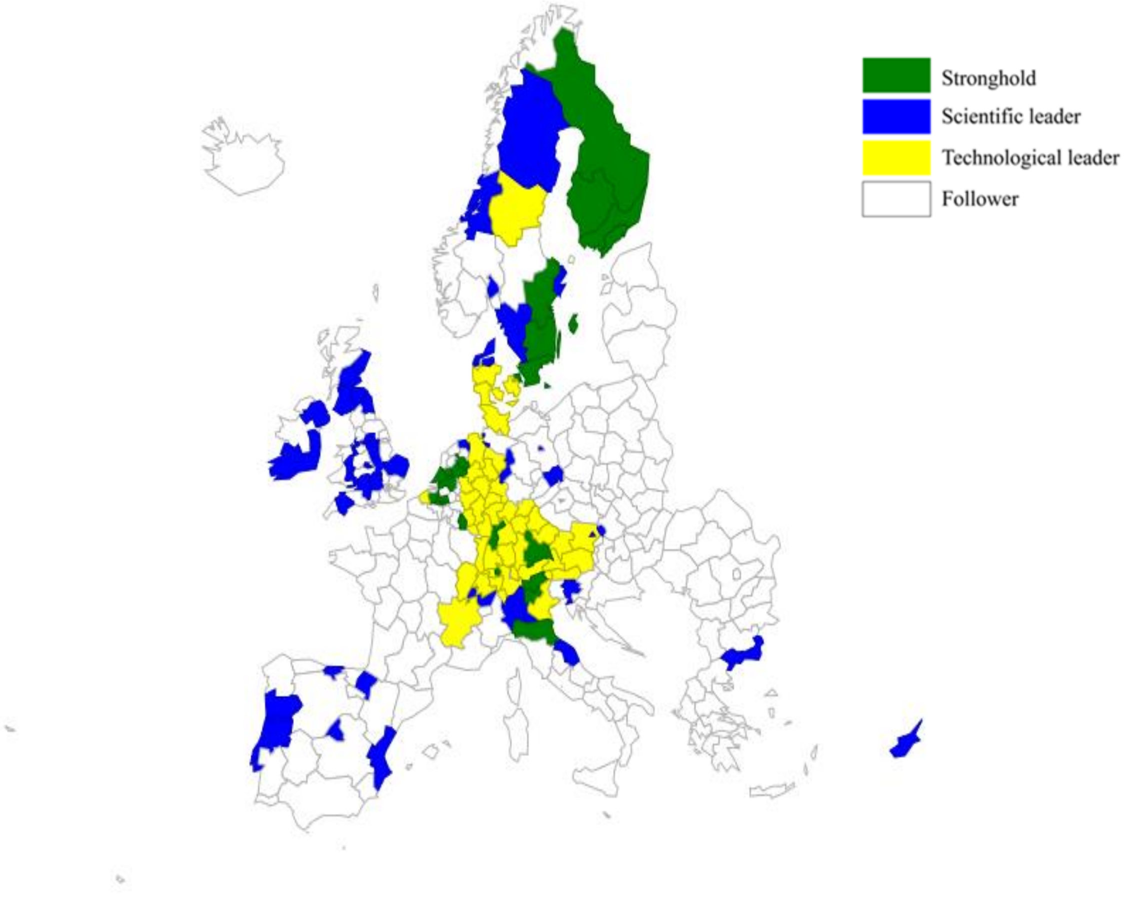


https://www.paballand.com/asg/dg-regio/scientific-relatedness/maps/stronghold-pc/physics-&-astronomy.html

Built Environment and Design

Figure 14 depicts the map for Built Environment and Design. We identified only 22 strongholds in Europe. Apparently, it is rarer to combine a strong scientific and technology base in this domain. The top 5 of strongholds consists of Zurich (CH), the Capital region of Denmark (DK), East Flanders (BE), Helsinki-Uusimaa (FI) and South Holland (NL). The top 5 of scientific leaders includes Inner London-West (UK), Trondelag (NO), Upper Norrland (NO), North Jutland (DK) and Prague (CZ). The top 5 of technology leaders, showing high levels of patenting that are not matched by their scientific performance, is the following: Voralberg (AT), Arnsberg (DE), Schwaben (DE), Detmold (DE), and Central Switzerland (CH).

Figure 14. A map of strongholds, followers, scientific and technology leaders in the domain of Built Environment and Design in Europe (per capita)

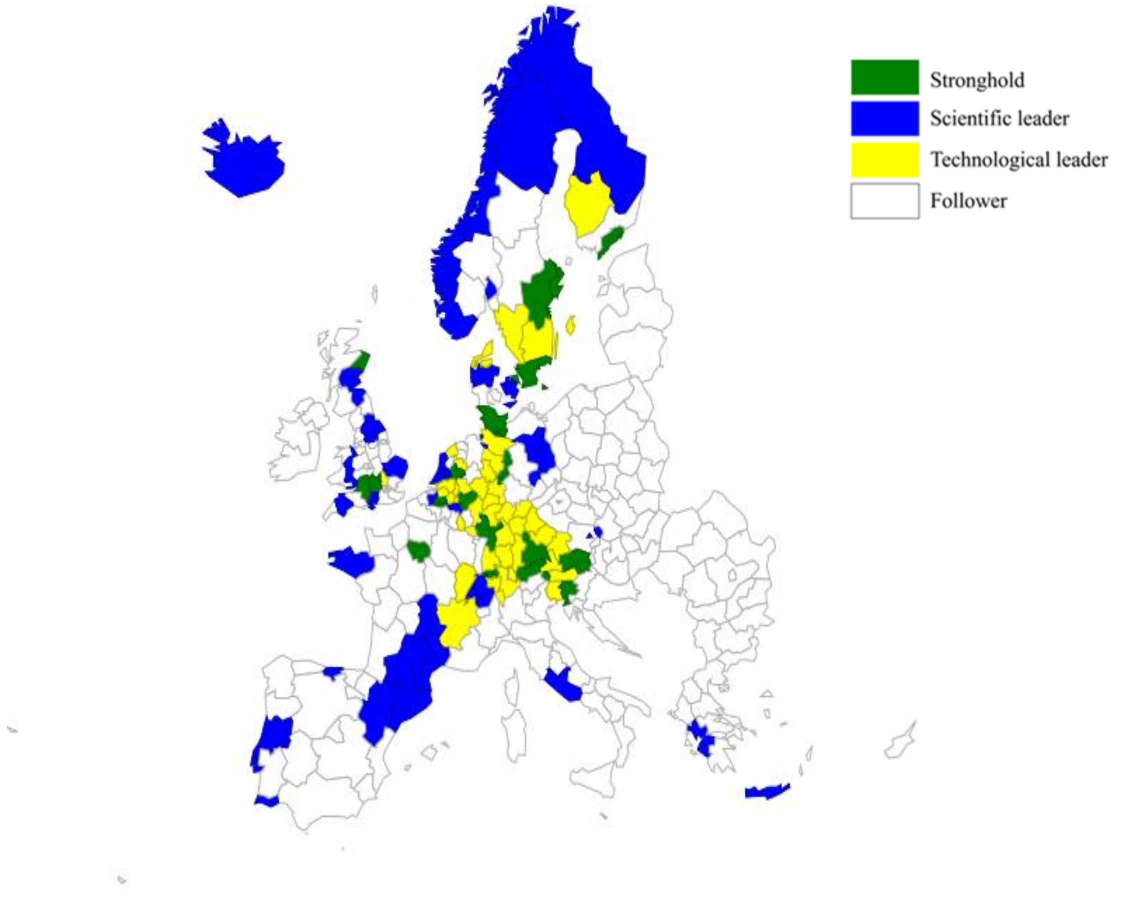


https://www.paballand.com/asg/dg-regio/scientific-relatedness/maps/stronghold-pc/built-environment-&-design.html

Earth and Environmental Sciences

Figure 15 shows the map for the domain of Earth and Environmental Sciences. We identified 25 strongholds in Europe, of which the top 5 consists of Zurich (CH), the Capital region of Denmark (DK), Helsinki-Uusimaa (FI), Berkshire, Buckinghamshire and Oxfordshire (UK) and Walloon Brabant (BE). The top 5 of scientific leaders concerns Bremen (DE), Inner London-West (UK), Trondelag (NO), Utrecht (NL) and Devon (UK), while the top 5 of technology leaders is as follows: Stuttgart (DE), Ticino (CH), Darmstadt (DE), Mittelfranken (DE) and Oberpfalz (DE).

Figure 15. A map of strongholds, followers, scientific and technology leaders in the domain of Earth and Environmental Sciences in Europe (per capita)

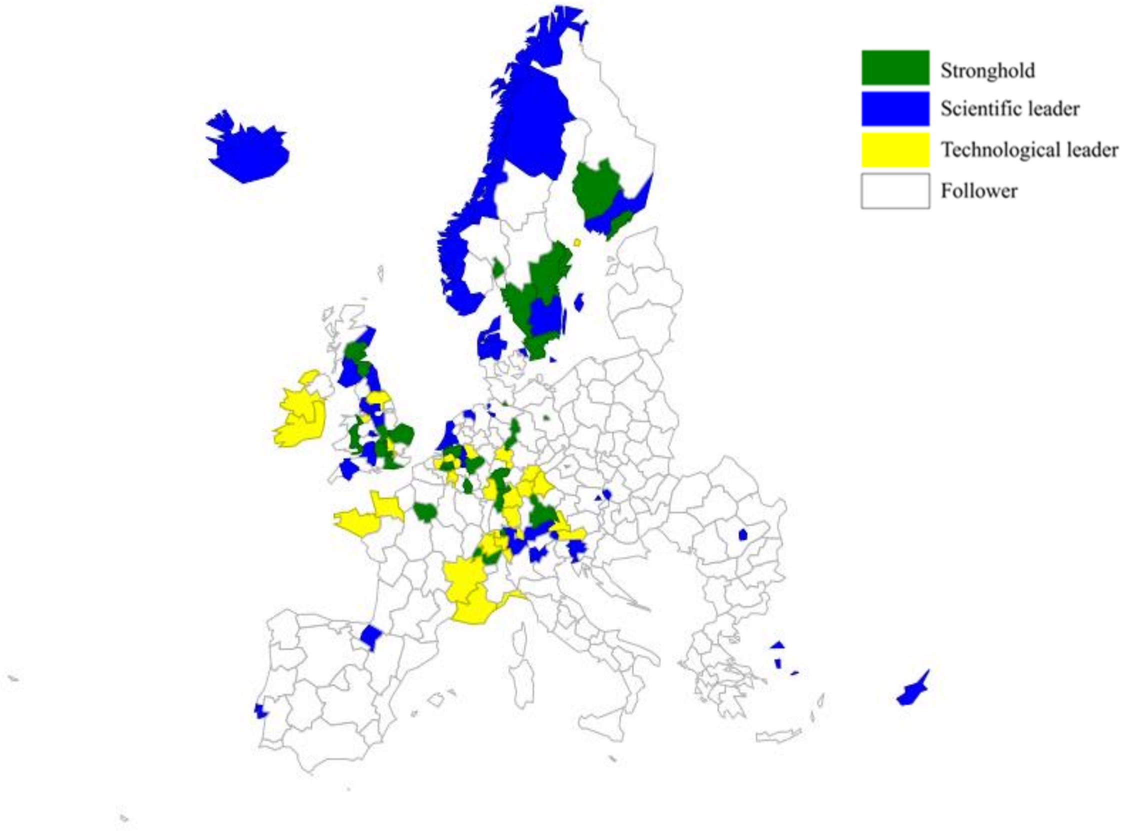


https://www.paballand.com/asg/dg-regio/scientific-relatedness/maps/stronghold-pc/earth-&-environmental-sciences.html

Economics and Business

Figure 16 shows the map of Europe for Economics and Business. 31 regions in Europe could be considered strongholds that combine high scientific and technological performance in this domain. The top 5 consists of Inner-London West (UK), Walloon Brabant (BE), Zurich (CH), Helsinki-Uusimaa (FI) and Luxembourg (LU). The top 5 of scientific leaders (having strong scientific but weak technological capabilities per capita) consists of Trondelag (NO), Prague (CZ), the Capital Region of Denmark (DK), Bratislava (SK) and Groningen (NL). The top 5 of technology leaders is dominated by UK regions: Outer London - East and North East (UK), Outer London – South (UK), Central Switzerland (CH), Mittelfranken (DE) and Cheshire (UK).

Figure 16. A map of strongholds, followers, scientific and technology leaders in the domain of Economics and Business in Europe (per capita)



https://www.paballand.com/asg/dg-regio/scientific-relatedness/maps/stronghold-pc/economics-&-business.html

In general

What general conclusions can be drawn so far? Strongholds tend to concentrate in Northern and Western regions in Europe, combining a strong scientific and technological presence in the same domain. Zurich (CH), Inner London-West (UK) and the Capital Region of Denmark (DK) are a stronghold in many domains, but also regions like the Lake Geneva region (CH) and Helsinki-Uusimaa (FI). Scientific leaders are often more spread across Europe, combining a strong scientific knowledge base with relatively weak technological capabilities in a domain. The region of Prague, followed by regions as Upper Norland (SE) and Bratislava (SK), are often mentioned in the top 5 of scientific leaders. Technology leaders are often found in Germany: they combine high levels of patenting with a relatively weak scientific knowledge base in domains. Regions like Darmstadt (DE), Central Switzerland (CH), Mittelfranken (DE) and Rheinhessen-Pfalz (DE) show up most frequently as top 5 technology leaders in Europe. Germany is a country that stands out, housing high numbers of strongholds and especially technology leaders in many domains, but it lacks scientific leaders (in which technological excellence is not matched by scientific performance) in any of the domains. Followers are found in many parts of Eastern Europe and Southern Europe in almost all domains. Regions in Southern Europe pop up as scientific leaders now and then, but rarely as strongholds and technology leaders: they tend to patent at relatively low levels, even when they have strong local scientific capabilities in a domain. Some regions in Eastern Europe sometimes score high as scientific leaders, especially in Chemistry, but regions in Eastern Europe seldomly belong to the categories of strongholds and technology leaders.

So far, we looked at the scientific and technological performance of regions per capita. When we take the absolute numbers of publications and patents (see maps in Appendix 1), we observe for almost all domains that the spatial distribution of patenting in Europe is more unevenly distributed than the spatial pattern of scientific publications. Now, the region of Ile de France (FR) stands out as a stronghold in almost any domain, followed by Oberbayern (DE). Spanish regions like Catalonia and Madrid, and to a lesser extent Andalusia, score high as scientific leaders in absolute terms, showing that Spanish regions (like Italian regions) fail without exception to build a strong presence in technologies in domains in which they own a strong scientific base. In absolute terms, Inner London-West is often a scientific leader rather than a stronghold in many domains: strong in science, but less so in technology. German regions are also often technological leaders in absolute terms: they patent more than could be expected from their (weak) scientific base in a domain. Oberbayern (DE), Noord-Brabant (NL), Mittelfranken (DE) and Darmstadt (DE) are key technology leaders in many domains.

Dynamics of regions in Europe, 2009-2018

We also investigated whether regions shifted from one category to another in all 18 domains from the period 2009-2013 to 2014-2018. How many regions have managed to become a stronghold in a domain during this period, and were these regions more likely to be a technology or a scientific leader before? What we are especially interested in is whether scientific leaders can transform themselves into strongholds in a domain, and thus showing an ability to improve their patenting activity to match their strong scientific capabilities. And to what extent have followers been able to upgrade their technological and scientific capabilities over time?

Table 3 presents the main findings. First, what can be observed is that most regions stayed within the same category. This is true for all categories, but especially for followers. Second, as expected, what are very rare events is that followers turn into strongholds (total of 8 cases) or the other way around (5 cases), and that scientific leaders move into technology leaders (10 cases) or *vice versa* (5 cases). North Jutland (DK) and West Sweden (SE) managed to transform themselves twice from being a follower to a stronghold. Third, in 54 cases, scientific leaders were able to transform themselves into strongholds in a domain, which amounts to a transition probability of almost 8%. This shows that a strong scientific knowledge base of a region can lead to the local development of strong technological capabilities in the same domain. This happened in many European countries, like in Trento (IT) (3 domains), Brussels (BE) (3 domains), Hannover (DE) (2 domains), South Finland (FI) (2 domains) and Luxembourg (LU) (2 domains). However, scientific leaders can also become followers, with a transition probability of 12%. Examples where that happened in 3 domains are Lancashire (UK), Epirus (EL), Estonia (EE) and North Holland (NL).

Table 3. Evolution of types of regions 2009-2018

		2014-2018			
		Follower	Scientific leader	Technology leader	Stronghold
2009-2013	Follower	2,965	102	139	8
	Scientific leader	87	555	10	54
	Technology leader	120	5	438	34
	Stronghold	5	79	33	424

What is remarkable in Table 3 is that technology leaders are quite often downgraded to the category of followers (120 cases, with a transition probability of 20%), but seldomly to the ranks of strongholds in a domain. The list of 34 technology leaders that made it to stronghold is dominated by German and Swiss regions, like Oberbayern (3 domains), Hamburg (3 domains), Northwestern Switzerland (3 domains), Koln (2 domains), Mittelfranken (2 domains) and Espace Mittelland (2 domains). Furthermore, strongholds look resilient over time, but if they change, they are more likely to become scientific leaders than technology leaders. Examples of the former transition are regions like Oslo and Akershus (NO) (6 domains), Upper Norrland (SE) (4 domains), Groningen (NL) (4 domains), Utrecht (NL) (3 domains), Brussels (BE) (3 domains), Eastern Scotland (UK) (3 domains), East Anglia (UK) (3 domains), Hampshire and Isle Of Wight (UK) (3 domains) and Central Denmark (DK) (3 domains). Examples of strongholds that downgraded to technology leaders are Freiburg (DE)

(3 domains), Espace Mittelland (CH) (3 domains), Oberfranken (DE) (2 domains), Tubingen (DE) (2 domains), Ile de France (FR) (2 domains) and Rhone-Alpes (FR) (2 domains). Finally, it seems slightly easier for followers to become a technology leader than a scientific leader in a domain, but the transition probabilities are low (3.2% and 4.3% respectively).

5. RELATIONSHIP BETWEEN SCIENTIFIC BASE AND NEW TECHNOLOGY DOMAINS IN REGIONS

So far, we showed for each domain whether there is a match or not between the scientific and the technological base of regions. The next step is to determine to what extent a region has the potential to develop technologies in a domain, given their specific scientific base. We make use of the relatedness framework proposed by Balland et al. (2019) to make that assessment.

Balland et al. (2019) argue that regions should develop new technologies that are not only related to existing capabilities in a region but also make the regional economy more complex. Relatedness provides an indicator of the cost of diversifying from existing activities to a new activity in a region. Activities are considered related when they share similar capabilities and rely on similar knowledge and skills. The more related a potential new activity is to existing activities in a region, the lower the costs to develop this new activity. Complexity provides a way of assessing the potential economic benefits of diversifying into a new activity. As discussed, complexity refers to complex activities that are almost impossible to copy and are therefore of high economic value (Hidalgo and Hausmann 2009): the higher the economic complexity of this activity, the higher the potential economic benefits.

To assess the potential of a region to develop technologies in each domain, we use a relatedness indicator that captures the idea that a region is more likely to develop technological domains that are related to existing technologies in the region. This requires two steps. First, we calculate a Tech Space to determine relatedness between pairs of technologies. We use the same normalized co-occurrences approach as for the Science Space (using the Cosine). Second, we use the Tech Space to calculate for a region *r* the density of technologies in the vicinity of a technological domain *i*. To increase the level of precision, we triangulate the computation of Relatedness Density with all CPC classes rather than with only the 18 domains. Assume that 'Clinical Medicine' is related to 100 technologies (we use a binary example here, but the relatedness variable is continuous in reality). If the region has a Relative Technological Advantage (RTA) in 10 of these technologies, Relatedness Density around Clinical Medicine is 10/100 = 10%. The density of technologies around technological domain *i* in region *r* is derived from the sum of relatedness $\varphi_{i,j,t}$ of technological domain *i* to all other technologies *j* in which the region has a RTA, divided by the sum of relatedness of technological domain *i* to all other technologies *j* in the reference region (Europe):

$$\text{RELATEDNESS\_DENSITY}_{i,r} = \frac{\sum_{j \in r, j \neq i} \phi_{ij}}{\sum_{j \neq i} \phi_{ij}} * 100$$

Besides relatedness, we account for the complexity of domains and the scientific knowledge base of a region to assess the potential of a region to develop technology domains. How we measured the complexity of domains has been explained before. To capture the effect of the local scientific knowledge base, we calculate the degree of specialization in a scientific domain in a region. It is a continuous variable, measured as the Relative Scientific Advantage (RSA) in a scientific domain. The RSA in a scientific domain *i* in time *t* is given as the share of publications in domain *i* in the region's scientific portfolio, divided by the share of scientific domain *i* in the scientific portfolio of Europe as a whole:

$$RSA_{r,i} = \frac{publications_{r,i} / \sum_i publications_{r,i}}{\sum_r publications_{r,i} / \sum_r \sum_i publications_{r,i}} > 1$$

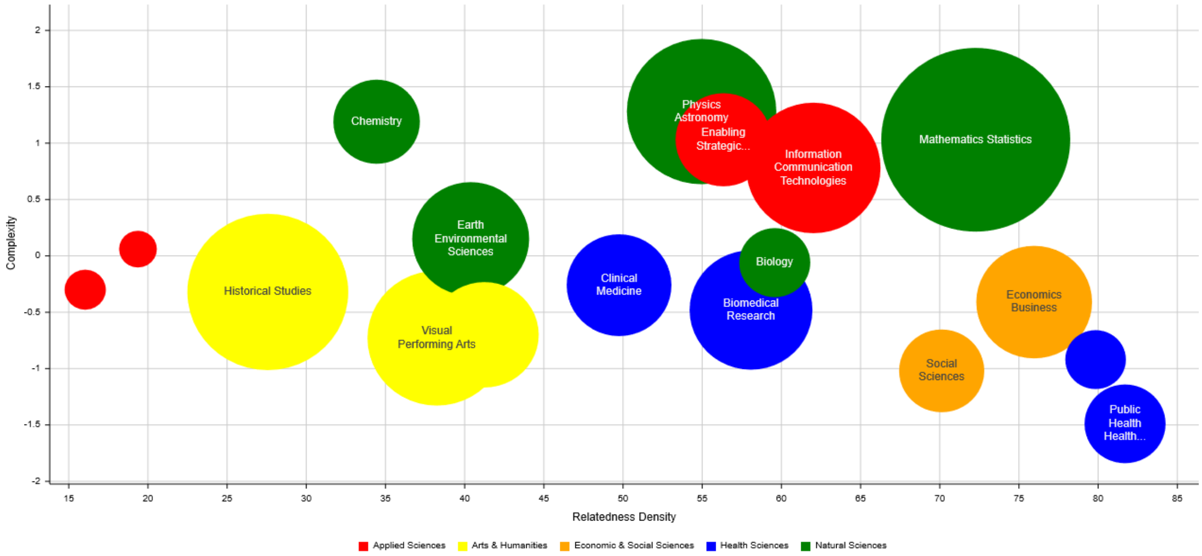
Some descriptives

The previous measures allow us to assess the potential of a region to develop new technologies in the 18 technology domains. We illustrate this by comparing these potentials for three types of regions. Figure 17 shows the example of a major urban region, the Île-de-France region in France. Figure 18 presents the example of Silesia, an old industrial region in Poland, and Figure 19 shows the example of Extremadura, a peripheral region in the South of Spain.

In the three figures, each domain is represented by a bullet. The size of the bullet indicates how specialized the region is in a scientific domain (based on publications): the larger the size of the bullet, the more the region is specialized in that domain. It captures the idea that a region is more likely to develop a technological domain the more the region is specialized in the same scientific domain. A Relative Scientific Advantage (RSA) higher than 1 means that the region is specialized in that scientific domain. The X-axis shows the Relatedness Density. This indicator captures the idea that a region has a higher potential to develop a technology domain the more technologies are present in the region that are related to this domain. The Y-axis shows the level of complexity of each domain. This captures the idea that a region will accrue higher economic benefits the higher the complexity of a domain.

Figure 17 shows that Île-de-France has the highest potential to develop new technologies in Mathematics & Statistics, Information & Communication Technologies and Psychics & Astronomy because the region scores high on all three indicators (scientific excellence, technological relatedness and complexity) in these domains. Île-de-France also seems to have potential in domains like Public Health & Health Services and Economics & Business because of its high score on relatedness. However, these domains are not that complex, and the region also does not have very strong scientific capabilities in these domains (RSA<1). The region shows some potential in Biomedical Research due to the local presence of a strong scientific knowledge base (RSA>1) and related technologies, but this domain is less complex. Île-de-France also shows some potential in Enabling & Strategic Technologies because this domain is highly complex and the degree of relatedness with local technologies is high, but the region shows less scientific excellence in this domain. In contrast, Île-de-France shows a relatively low potential to develop technologies in the two domains colored red on the left, which represent Agriculture, Fisheries & Forestry and Built Environment & Design, because these score low on all three indicators. There is no scientific excellence in the region in this domain, local technologies that might have supported their development are almost completely missing in the region, and the two domains are not very complex either.

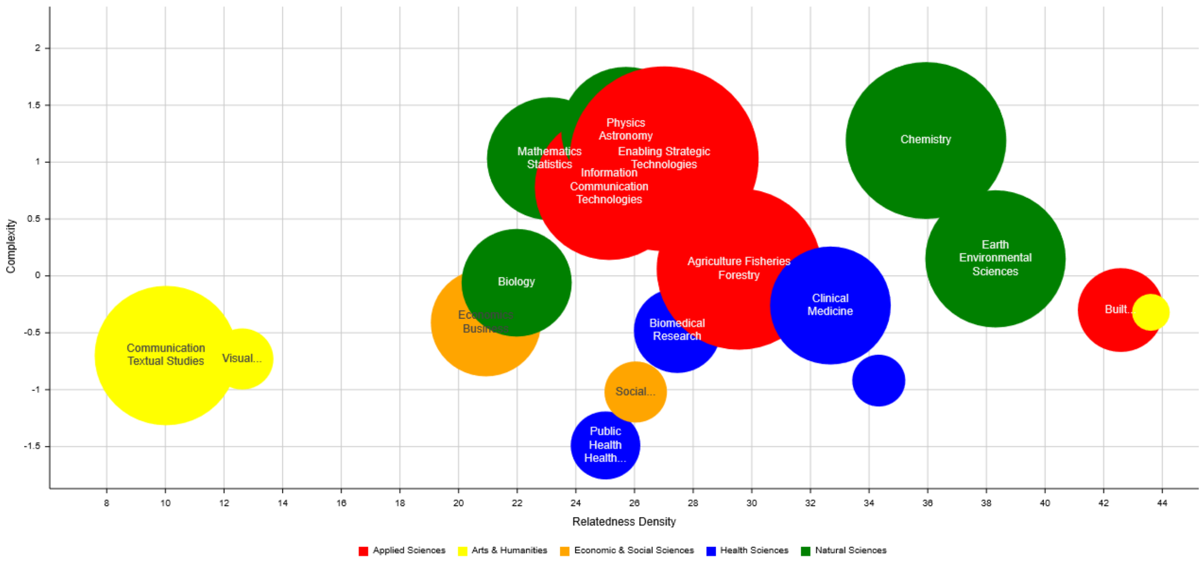
Figure 17. The potential of Île-de-France (FR10) to develop 18 technological domains



https://www.paballand.com/asg/dg-regio/scientific-relatedness/s3-graphs/FR10.html

Figure 18 represents the case of the old industrial region of Silesia. This tells a very different story compared to the Île-de-France region. Silesia has the highest potential to develop new technologies in Chemistry and Earth & Environmental Sciences because the region scores relatively high on all three indicators: it shows scientific excellence (RSA>1) in these domains, the local presence of related technologies is relatively high, and the two domains are complex. Silesia tends to show some potential also in complex domains like Enabling & Strategic Technologies, Information & Communication Technologies and Agriculture, Fisheries & Forestry due to a strong scientific knowledge base, but the local presence of related technologies is relatively weak. However, Silesia tends to show a low potential to develop new technologies in domains like Visual & Performing Arts, Public Health & Health Services, Economics & Business and Biology, as it shows low scores on all three indicators.

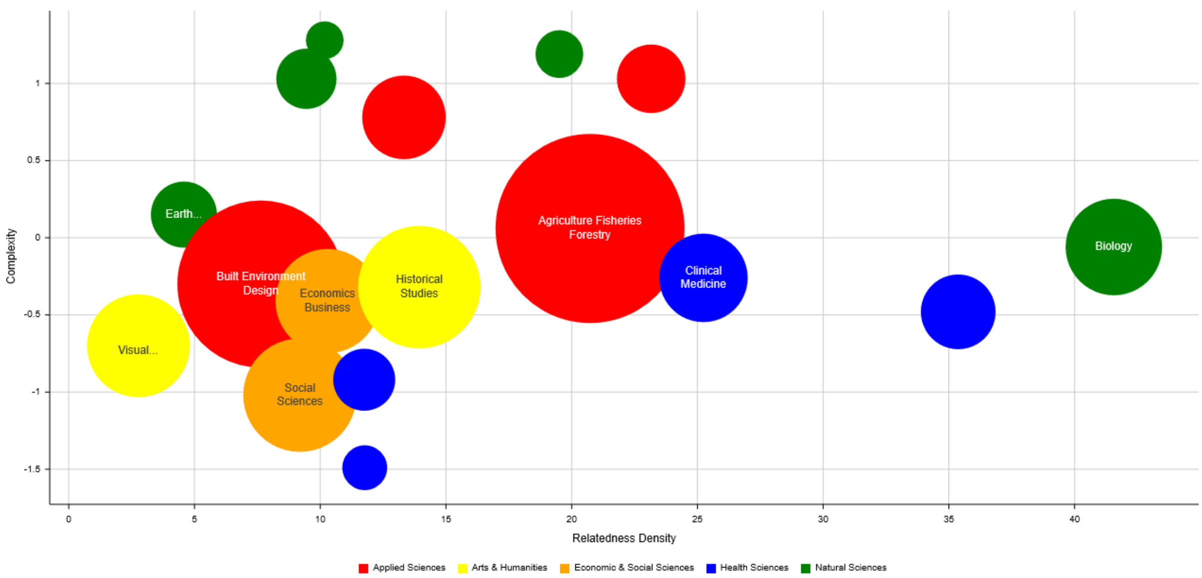
Figure 18. The potential of Silesia (PL22) to develop 18 technological domains



https://www.paballand.com/asg/dg-regio/scientific-relatedness/s3-graphs/PL22.html

Figure 19 presents the Spanish region of Extremadura, again a very different case. This peripheral region shows potential to develop new technologies in domains like Biology, Clinical Medicine and Agriculture, Fisheries & Forestry, because these domains show some complexity, and Extremadura shows a strong scientific knowledge base in these domains (RSA>1) and some presence of related technologies that can provide relevant resources. Other domains like Built Environment & Design and Economic & Business tend to show some potential because the region has some scientific capabilities in these domains, but it basically lacks related technologies on which these technological domains could build, and the complexity of the domains is not that high.

Figure 19. The potential of Extremadura (ES43) to develop 18 technological domains



https://www.paballand.com/asg/dg-regio/scientific-relatedness/s3-graphs/ES43.html

Regional diversification model

The descriptive analyses so far have shown that the overlap between scientific and technological capabilities varies across regions and domains. To dynamically test how prior scientific knowledge leads to technological diversification, we assess quantitatively the extent to which a local scientific knowledge base in a domain contributes to the ability of a region to develop technologies in that same domain in a region.

Following Boschma, Balland, and Kogler (2015), we assess the probability of 285 NUTS-2 regions in Europe (EU-27, UK, the four EFTA countries) to enter a new technological domain in the period 2004-2018. Patent data are used and derived from the OECD REGPAT dataset (2020 version) that makes a distinction between 654 patent classes (CPC) at the 4-digit level.

The dependent variable is the entry (1), or not (0), of a new specialization in 1 of the 18 technological domains in a region. A linear probability model is used to assess the probability that a region develops a Relative Technological Advantage (i.e. RTA>1) in a new technological domain in the period 2004-2018. Following other studies, we assess the entry probability of a new technological domain in a time window of 5 years, for 3 subsequent periods (2004-2008; 2009-2013; 2014-2018). The maximum number of observations is 285 (regions)*18 (domains)*3 (periods) = 15,390. By construction, we exclude the regions in each next period that are already specialized in a domain. We have a total of 9,995 potential entries.

All independent variables are measured in the period before the time window of 5 years. So, for the first entry period 2004-2008, we construct the independent variables for the period 2000-2003. The main variable of interest is Scientific Specialization, captured by the Relative Scientific Advantage (RSA) measure, as explained earlier. It assesses the effect of the degree of specialization in a scientific domain in a region on the entry probability of new technologies in that same domain in a region. The other variable of interest is Relatedness, which is measured by the Relatedness Density measure explained before. It assesses the effect of related technologies on the entry probability of a new technological domain in a region.

We ran a linear probability model with time-fixed effects to estimate the impacts of Scientific Specialization and Relatedness Density on technological diversification in regions in Europe. The first model in Figure 20 shows a positive and significant coefficient of Scientific Specialization: the higher the Scientific Specialization of a region in a specific domain, the higher the likelihood that this region will develop new technologies in that same domain. The second model shows that Relatedness Density is also positive and significant. This confirms earlier studies that a new technological domain is more likely to enter a region when related to existing technologies in a region. Model 3 shows that the positive effect of Scientific Specialization remains when Relatedness Density is included. So, in general, science does translate well into new technological domains at the regional scale in Europe. In Models 4-6, we included region and industry fixed effects. Results remain qualitatively similar for the two variables of interest, while the overall fit of the models increases.

Figure 20. Diversification model

	(1)	(2)	(3)	(4)	(5)	(6)
Scientific specialization	0.014***		0.013***	0.014***	0.013***	0.014***
	(0.004)		(0.004)	(0.004)	(0.004)	(0.004)
Relatedness density		0.002***	0.002***	0.002***	0.004***	0.004***
		(0.0003)	(0.0003)	(0.0003)	(0.0005)	(0.001)
Period FE	yes	yes	yes	yes	yes	yes
Region FE	no	no	no	yes	no	yes
Industry FE	no	no	no	no	yes	yes
Constant	0.162***	0.151***	0.139***	0.076	0.092***	0.023
	(0.007)	(0.007)	(0.008)	(0.060)	(0.020)	(0.062)
Observations	9,995	9,995	9,995	9,995	9,995	9,995
R^2	0.001	0.005	0.006	0.074	0.021	0.091
Adjusted R^2	0.001	0.004	0.006	0.047	0.019	0.062
Residual Std. Error	0.383 (df = 9991)	0.382 (df = 9991)	0.382 (df = 9990)	0.374 (df = 9706)	0.379 (df = 9973)	0.371 (df = 9689)
F Statistic	4.964*** (df = 3; 9991)	15.697*** (df = 3; 9991)	15.096*** (df = 4; 9990)	2.701*** (df = 288; 9706)	10.390*** (df = 21; 9973)	3.163*** (df = 305; 9689)
Note:	*p**p***p<0.01					

6. Conclusions and implications

This report compared the scientific and technological capabilities of 285 European regions in 18 domains. First, we explored which of the 18 domains share similar capabilities. It turned out that the 3 domains of Information & Communication Technologies, Mathematics & Statistics and Physics & Astronomy are the most related ones, sharing capabilities with many other domains. We also developed a new measure to determine the level of complexity of the 18 domains. Our findings suggest that the most complex domain is Physics & Astronomy, followed by Chemistry, Mathematics & Statistics, Enabling & Strategic Technologies and Information & Communication Technologies.

When exploring the degree of overlap between the scientific and technological base of regions in Europe in the 18 domains, we identified 4 types of regions. The first type consists of regions that combine a strong scientific and technological base in the same domain. Strongholds tend to concentrate in Northern and Western regions in Europe, like Zurich (CH), Inner London-West (UK) and the Capital Region of Denmark (DK). The second type concerns a group of regions that have a strong scientific base but a poor technological performance in a domain. These so-called scientific leaders are often more spread across Europe, showing a strong scientific base but failing to build a strong local presence in technologies in the same domain. The Prague region (CZ) and regions as Upper Norland (SE) and Bratislava (SK) often belong to the top 5 scientific leaders in domains. The third group of regions consists of technology leaders that have a strong technological base in a domain without having a strong scientific base in that domain. German regions like Darmstadt, Mittelfranken and Rheinhessen-Pfalz but also the Swiss regions of Central Switzerland belong to this group in many domains. These regions demonstrate that strong technological capabilities in a domain do not necessarily require a strong underlying local scientific base. The fourth type of regions concerns so-called followers and includes the highest number of regions. They score relatively poorly both in science and technology in almost all 18 domains. Followers are found in most East European regions, as well as in many peripheral regions in Southern Europe.

We also investigated whether regions shifted from one category to another in a domain in the period 2009-2018. We found that most regions did not change position. This is especially true for followers that often seem to be trapped, although some followers managed to upgrade their technological capabilities. Most interesting was the finding that scientific leaders turn into strongholds in a domain now and then, suggesting that a strong scientific knowledge base in a region may provide a base for the development of technological capabilities in the same domain. Another finding was that technology leaders were quite often downgraded to the category of followers but seldomly managed to move up to the ranks of strongholds in a domain.

Besides looking at the degree of overlap between scientific and technological domains in regions, we investigated whether a scientific knowledge base of a region enhanced the probability of a region to develop technologies in the 18 domains. We estimated a technological diversification model including 285 NUTS regions. We found a positive relationship between a strong local scientific base in a domain and the ability of a region to develop new technologies in that specific domain during the period 2004-2018.

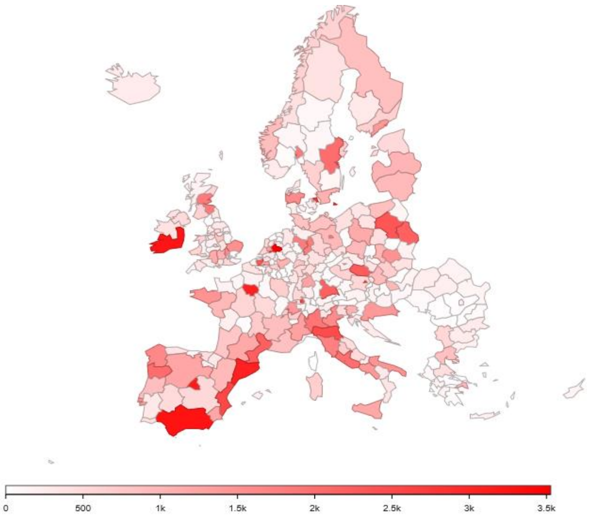
Possible policy implications are the following. First, our study shows that local scientific capabilities provide opportunities to regions to develop new technologies in specific domains. This finding is relevant for Smart Specialization policy that argues that regions should build on local capabilities to develop new and revive existing activities. The study makes clear that local scientific knowledge in specific domains, rather than local scientific knowledge *per se*, matters in this respect. This aligns with the idea that Smart Specialization policy should target very specific capabilities and develop a tailor-made policy that accounts for the specific assets and needs in regions. Exploiting local scientific capabilities in specific domains would add another dimension to the Smart Specialization policy that is still relatively unexplored. Second, the study also made clear that a strong scientific knowledge base (including the presence of universities) does not necessarily result in new technologies and regional development. This has high policy relevance, as policy could aim to tackle barriers and bottlenecks that prevent regions to exploit fully their scientific potential. Third, we identified 4 types of regions when looking at the overlap between their scientific and technological base. For each of these types, one should formulate region-specific policy recommendations. In strongholds, it seems a matter of maintaining scientific excellence and staying at the scientific frontier. Scientific leaders are the most interesting case because in these regions policy should take away barriers that prevent the exploitation of local scientific capabilities and their diffusion into the regional economy. In the case of technological leaders, our findings suggest they have a hard time to become a stronghold. On top of that, there might be a risk of lock-in when these regions do not build a solid science base that connects to their technological base. As Pezzoni et al. (2019) have shown, combining technological components with a science-based nature results in new technologies that are more disruptive and have more of an impact. While for followers, it is important that new scientific knowledge (or a new center of excellence) is created not in isolation from but closely related to existing activities in the region. This would avoid the classic policy mistake to build scientific cathedrals in the desert.

These findings also call for further research. First, there is a need to study how EU regions compare to regions in the US and China when it comes to the matching of scientific and technological output. Second, there is a need to replicate this study using an alternative relatedness measure that captures relatedness between scientific fields and technologies. This measure could be used to test whether regions in Europe are more likely to develop technologies that are related to scientific fields. Third, we identified a match or mismatch between scientific and technological output in specific domains in regions, but we did not investigate why this is the case. A follow-up study should examine whether this is due to a weak absorptive capacity of local firms, poor science-industry linkages, national institutions, among other factors. Fourth, we should check how public funding in some domains translates into technological output for different domains, using Horizon Europe data or ERDF data. Fifth, we did not account for the fact that scientific knowledge available in other regions may be relevant for a region, the more so when the region is short of that knowledge. Regions have access to scientific knowledge in other regions through research collaborations, for instance (Moodysson 2008). This could be included as an additional variable, assessing the effect of inter-regional scientific ties on the ability of regions to develop technologies (Balland and Boschma 2020). Sixth, we used patent data to assess whether local scientific knowledge results in new technologies in regions. This is one way of measuring the local impact of science, but there are also other effects that have not been included in this study, like the education of high-skilled people, knowledge spillovers to local firms, academic spinoffs, and innovations by firms. Seventh, it would be interesting to explore in detail the dynamics of specific regions over time. For instance, we found cases of scientific leaders transforming into strongholds in a domain, but the question is why and how. Finally, there is a need to replicate this study with publication data with a finer classification.

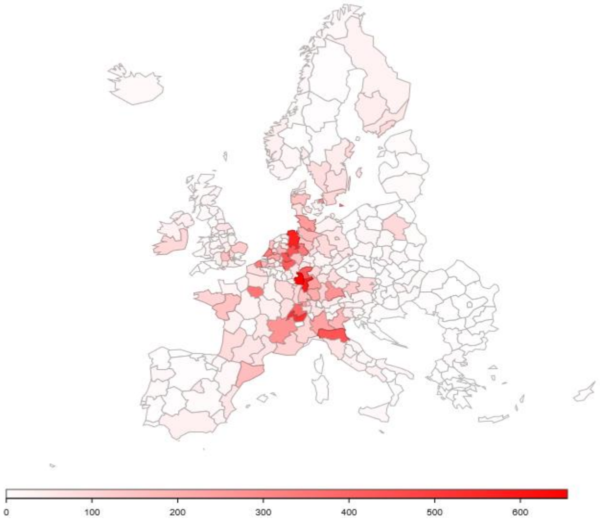
Appendix 1. Maps of Europe in all 18 domains, in absolute and relative terms

Agriculture, Fisheries and Forestry

Map of Europe: (a) number of scientific publications and (b) number of patents in Agriculture, Fisheries and Forestry 2014-2018



(a)

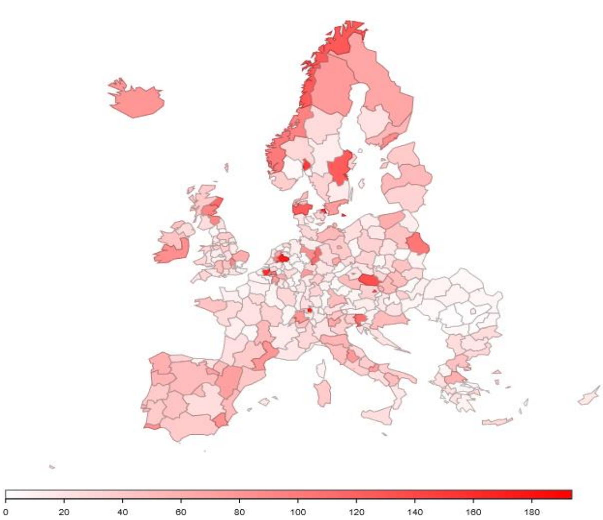


(b)

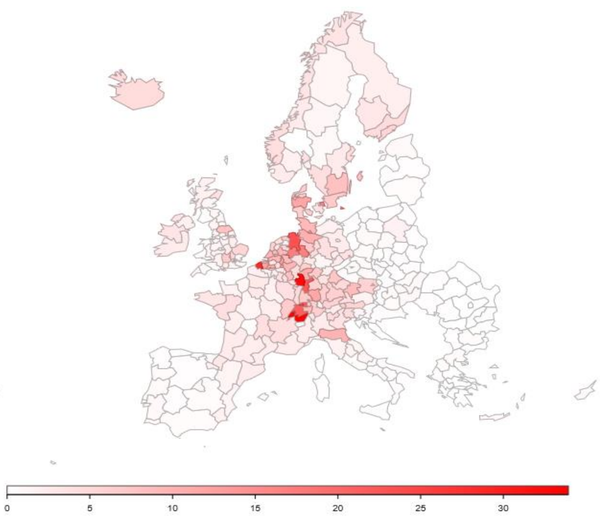
https://www.paballand.com/asg/dg-regio/scientific-relatedness/maps/count-pub/agriculture-fisheries-&-forestry.html

https://www.paballand.com/asg/dg-regio/scientific-relatedness/maps/count-pat/agriculture-fisheries-&-forestry.html

Map of Europe: (a) number of scientific publications per inhabitant and (b) number of patents per inhabitant in Agriculture, Fisheries and Forestry 2014-2018



(a)



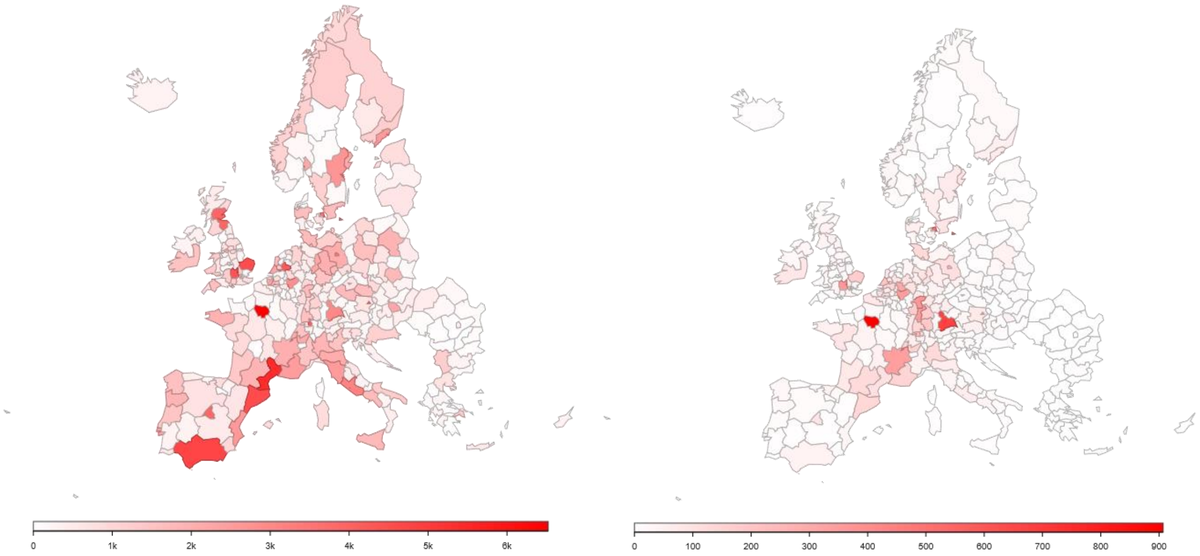
(b)

https://www.paballand.com/asg/dg-regio/scientific-relatedness/maps/pub-pc/agriculture-fisheries-&-forestry.html

https://www.paballand.com/asg/dg-regio/scientific-relatedness/maps/pat-pc/agriculture-fisheries-&-forestry.html

Biology

Map of Europe: (a) number of scientific publications and (b) number of patents in Biology 2014-2018



(a) (b)

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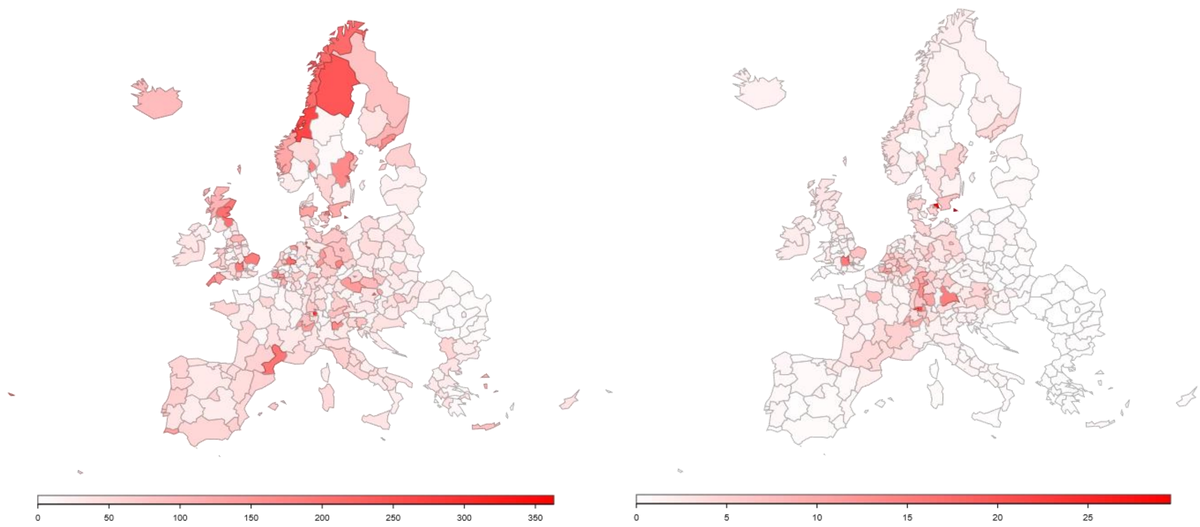
https://www.paballand.com/asg/dg-regio/scientific-relatedness/maps/count-pat/biology.html

Map of Europe: (a) number of scientific publications per inhabitant and (b) number of patents per inhabitant in Biology 2014-2018



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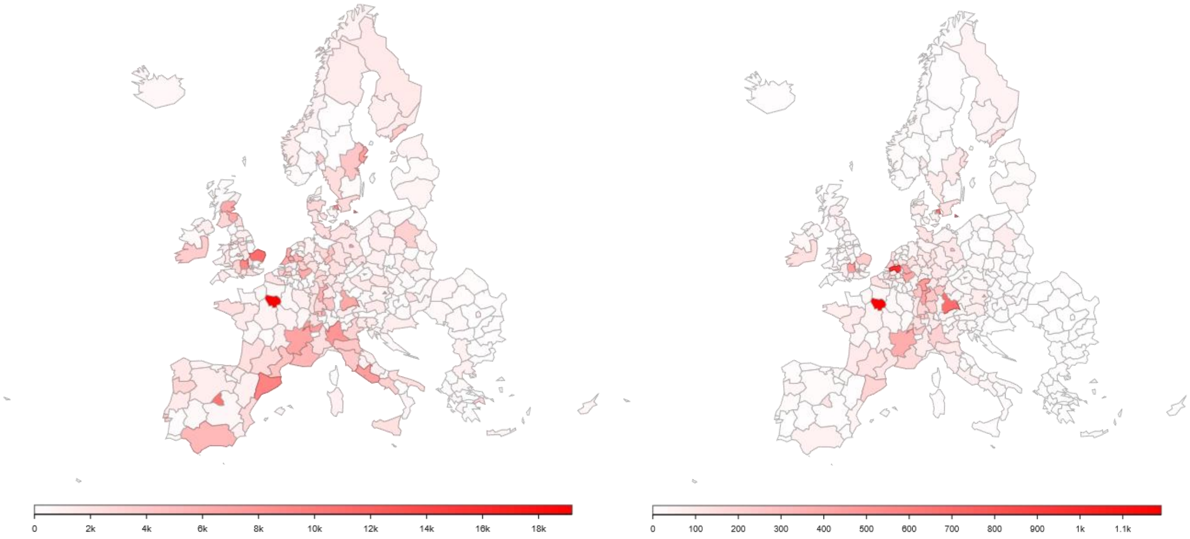
https://www.paballand.com/asg/dg-regio/scientific-relatedness/maps/pat-pc/biology.html

Biomedical Research

Map of Europe: (a) number of scientific publications and (b) number of patents in Biomedical Research 2014-2018



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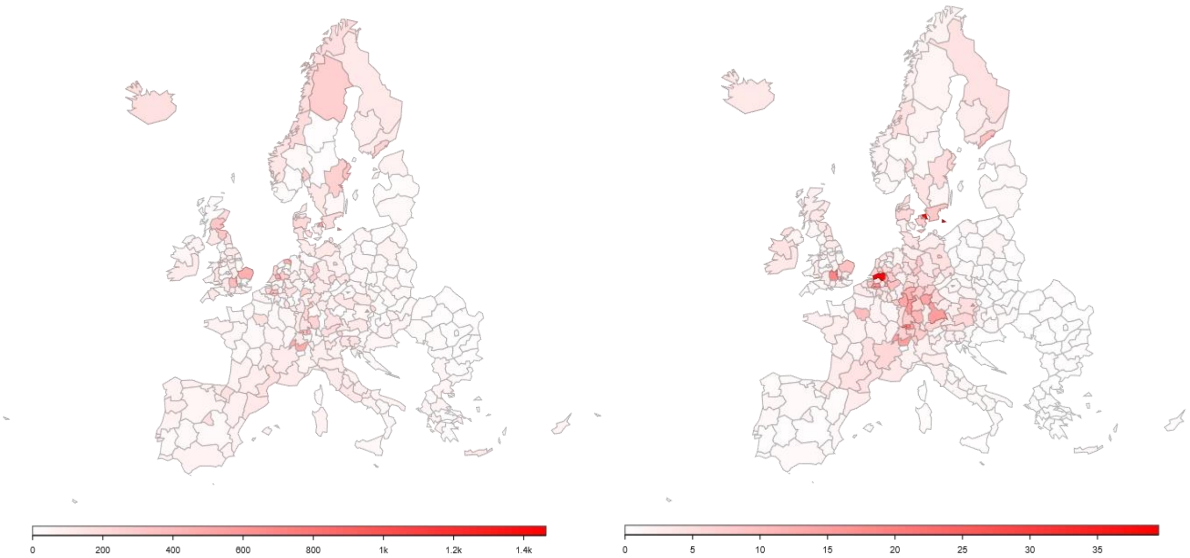
Map of Europe: (a) number of scientific publications per inhabitant and (b) number of patents per inhabitant in Biomedical Research 2014-2018



(a) (b)

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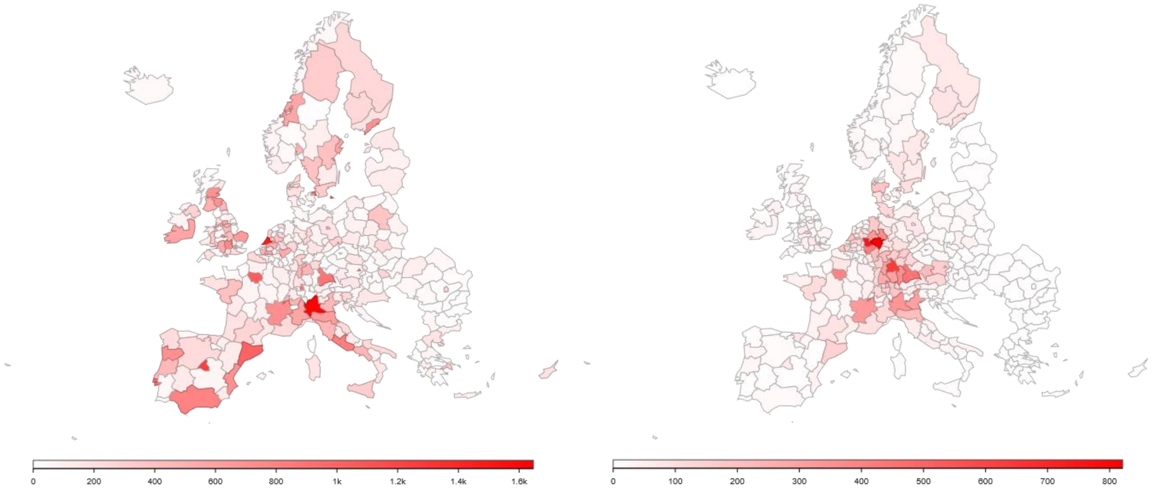
https://www.paballand.com/asg/dg-regio/scientific-relatedness/maps/pat-pc/biomedical-research.html

Built Environment and Design

Map of Europe: (a) number of scientific publications and (b) number of patents in Built Environment and Design 2014-2018



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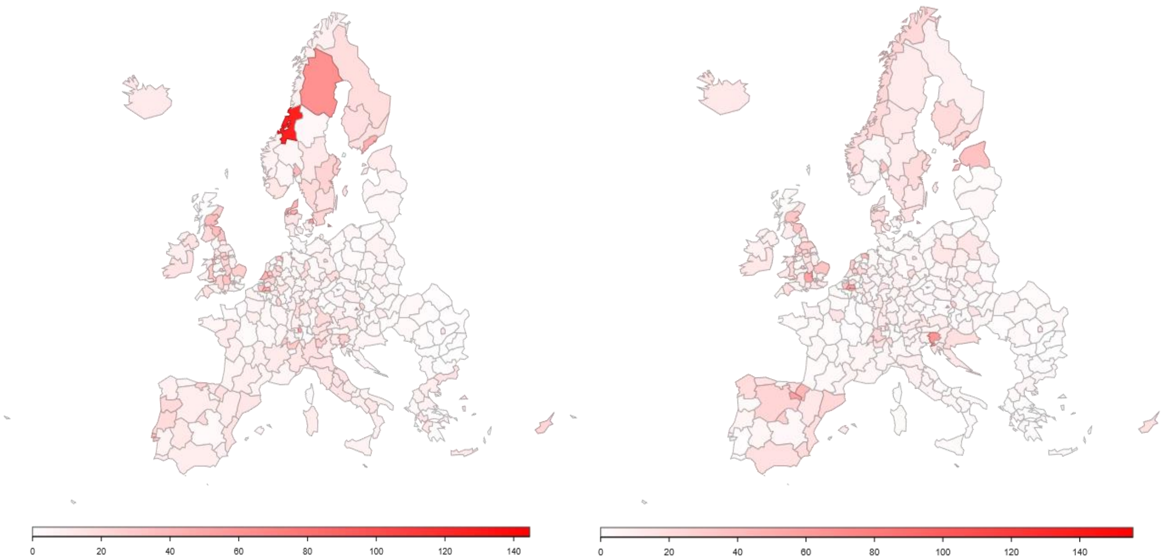
https://www.paballand.com/asg/dg-regio/scientific-relatedness/maps/count-pat/built-environment-&-design.html

Map of Europe: (a) number of scientific publications per inhabitant and (b) number of patents per inhabitant in Built Environment and Design 2014-2018



(a) (b)

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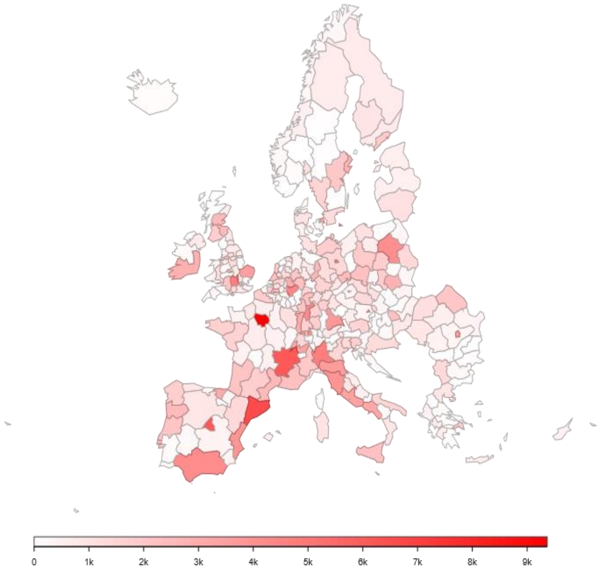
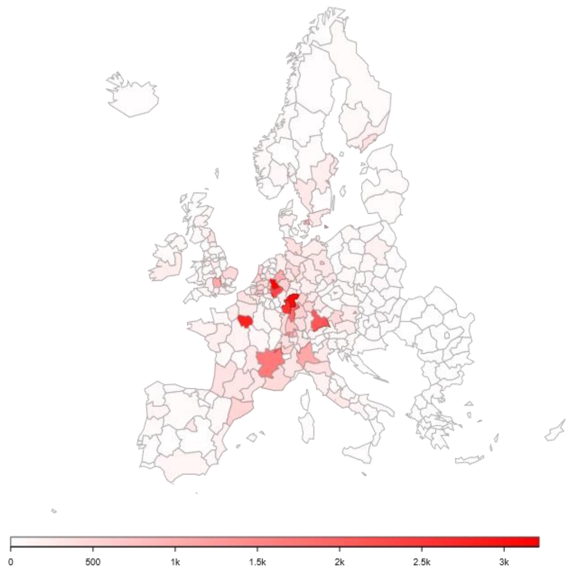
https://www.paballand.com/asg/dg-regio/scientific-relatedness/maps/pat-pc/built-environment-&-design.html

Chemistry

Map of Europe: (a) number of scientific publications and (b) number of patents in Chemistry 2014-2018





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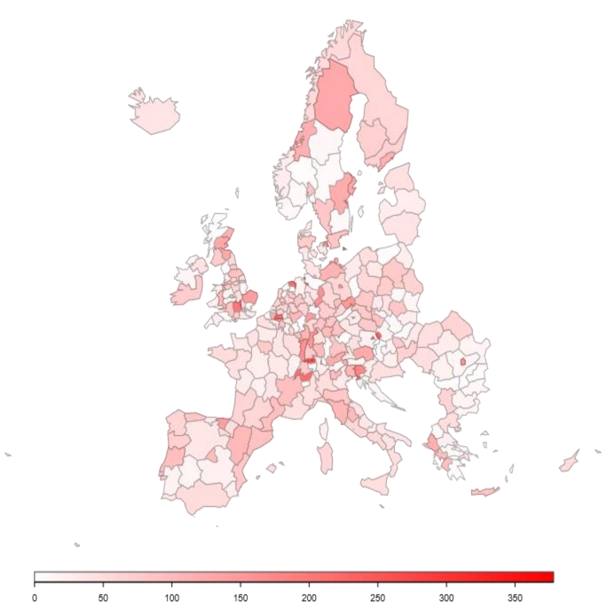
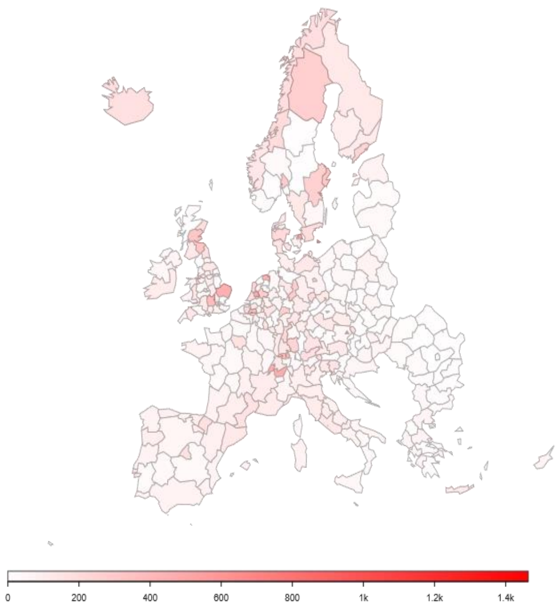
https://www.paballand.com/asg/dg-regio/scientific-relatedness/maps/count-pat/chemistry.html

Map of Europe: (a) number of scientific publications per inhabitant and (b) number of patents per inhabitant in Chemistry 2014-2018





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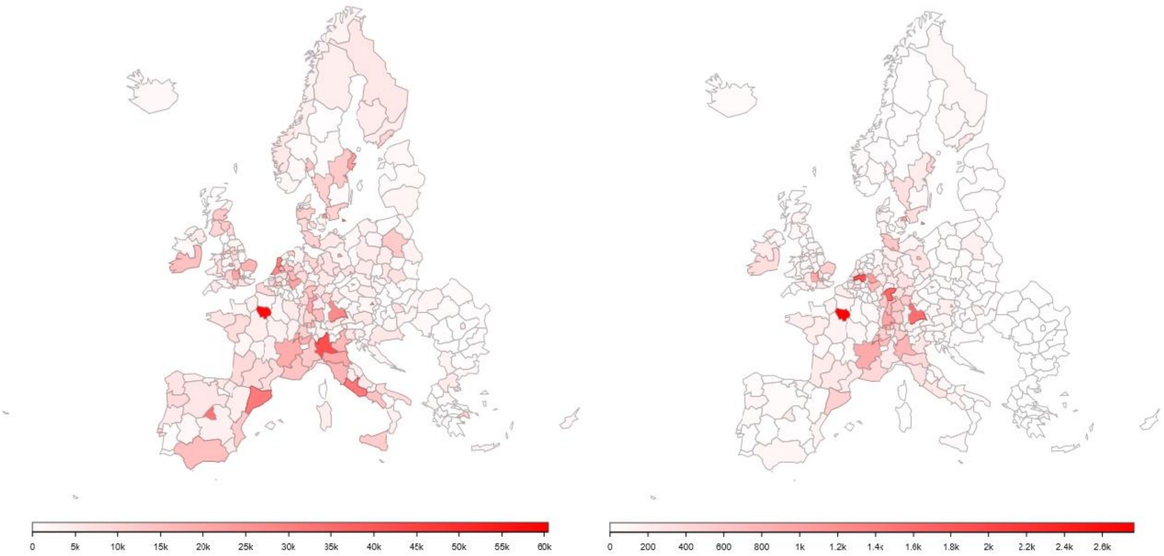
https://www.paballand.com/asg/dg-regio/scientific-relatedness/maps/pat-pc/chemistry.html

Clinical Medicine 2014-2018

Map of Europe: (a) number of scientific publications and (b) number of patents in Clinical Medicine 2014-2018



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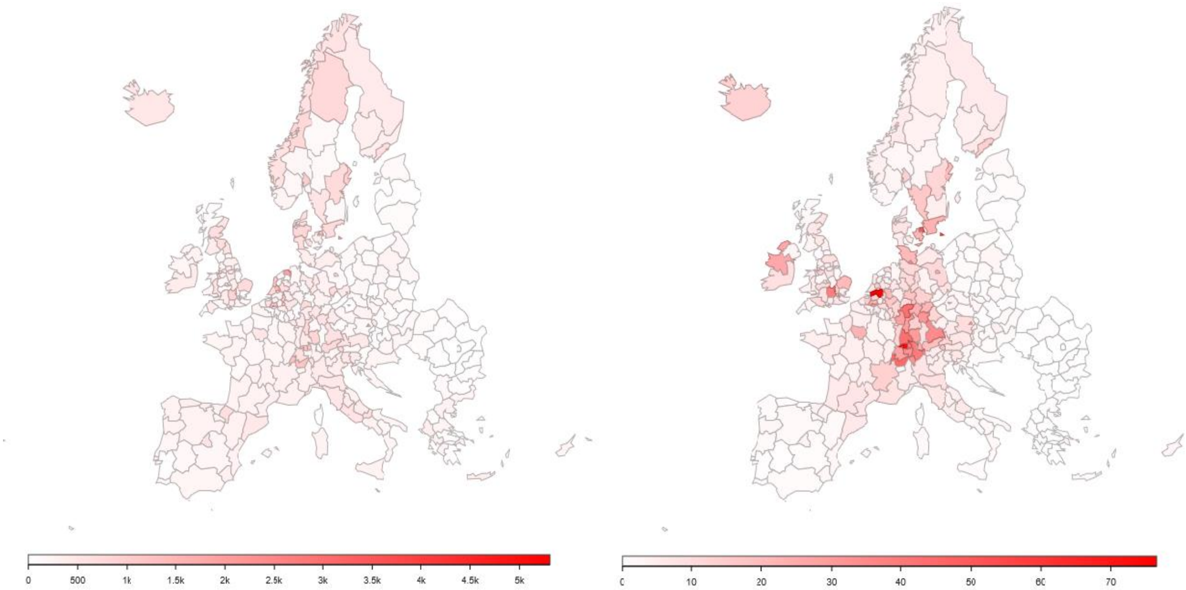
Map of Europe: (a) number of scientific publications per inhabitant and (b) number of patents per inhabitant in Clinical Medicine 2014-2018



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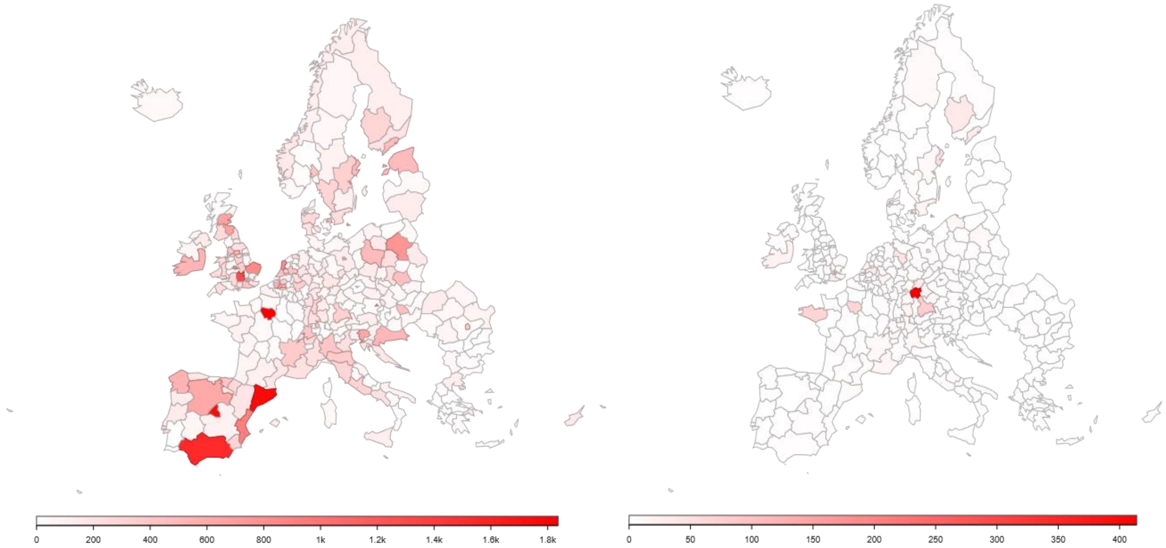
https://www.paballand.com/asg/dg-regio/scientific-relatedness/maps/pat-pc/clinical-medicine.html

Communication and Textual Studies

Map of Europe: (a) number of scientific publications and (b) number of patents in Communication and Textual Studies 2014-2018



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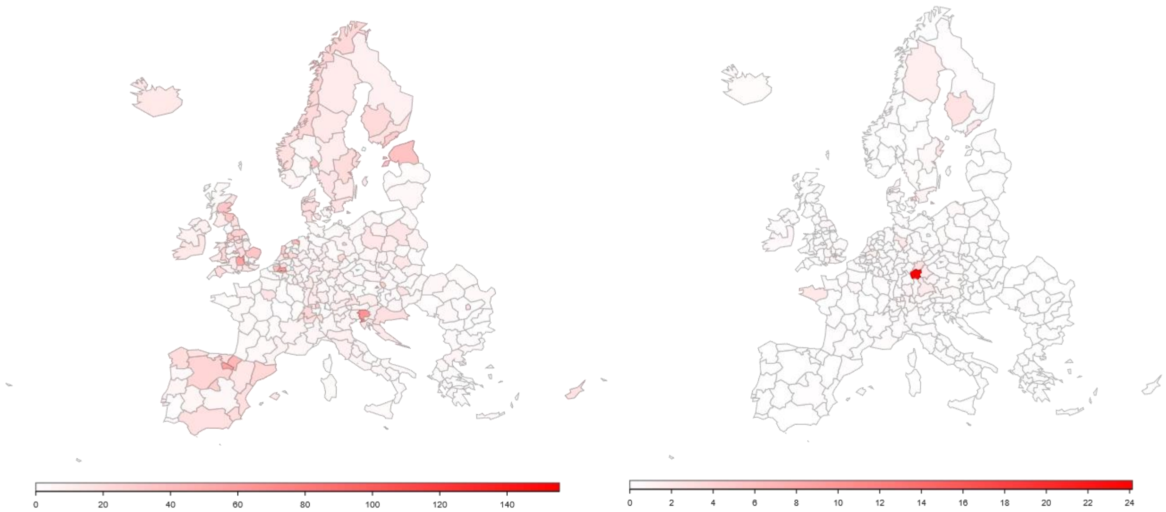
Map of Europe: (a) number of scientific publications per inhabitant and (b) number of patents per inhabitant in Communication and Textual Studies 2014-2018



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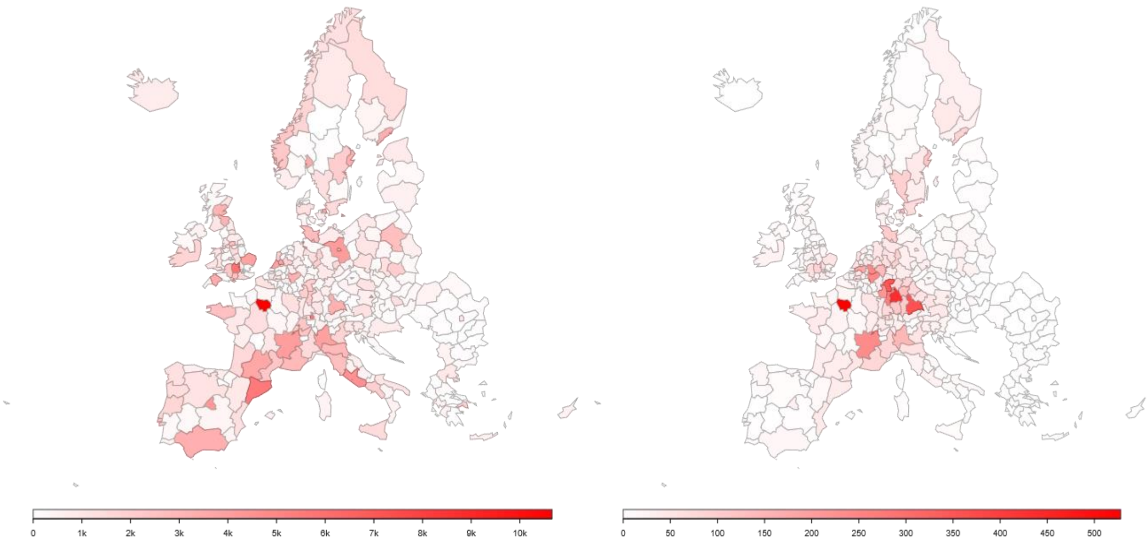
Earth and Environmental Sciences

Map of Europe: (a) number of scientific publications and (b) number of patents in Earth and Environmental Sciences 2014-2018



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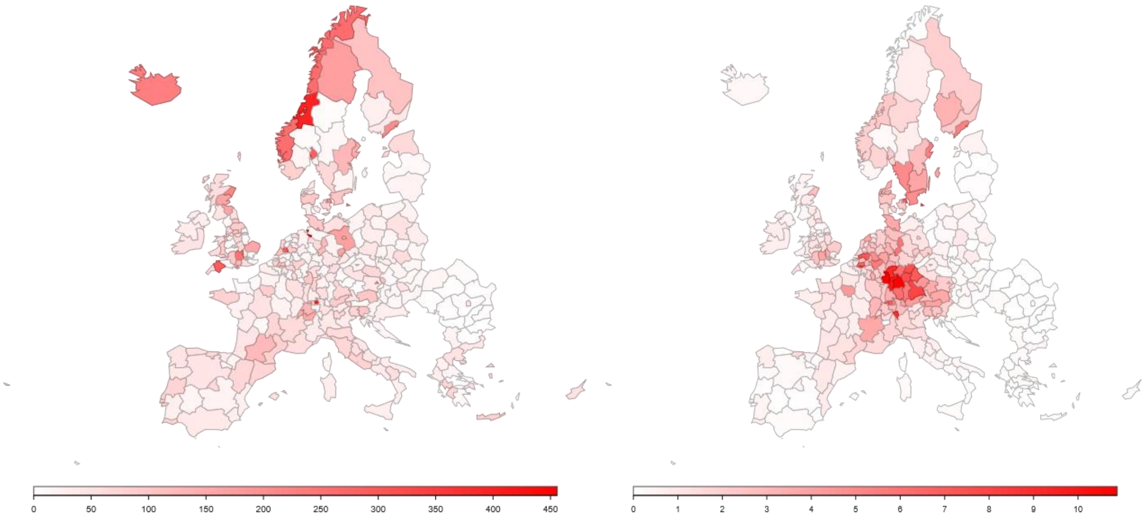
Map of Europe: (a) number of scientific publications per inhabitant and (b) number of patents per inhabitant in Earth and Environmental Sciences 2014-2018



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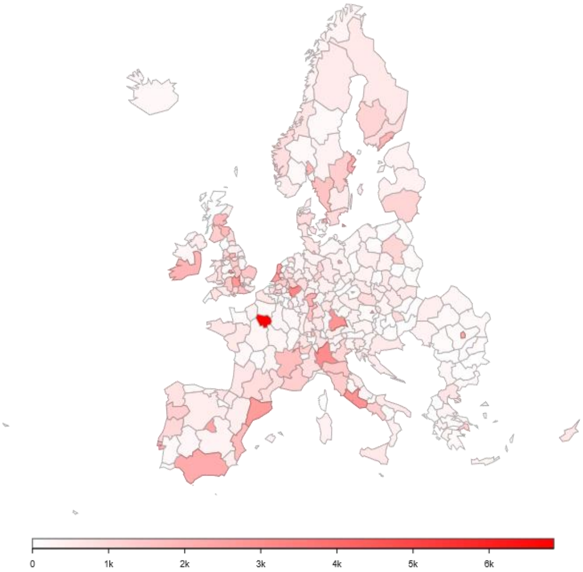
https://www.paballand.com/asg/dg-regio/scientific-relatedness/maps/pat-pc/earth-&-environmental-sciences.html

Economics and Business

Map of Europe: (a) number of scientific publications and (b) number of patents in Economics and Business 2014-2018



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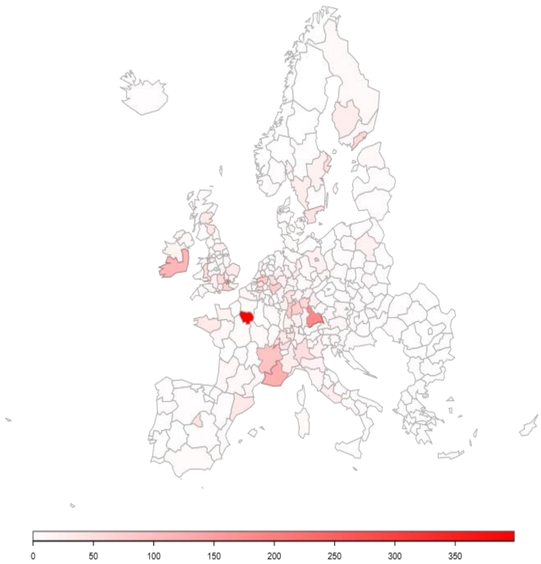

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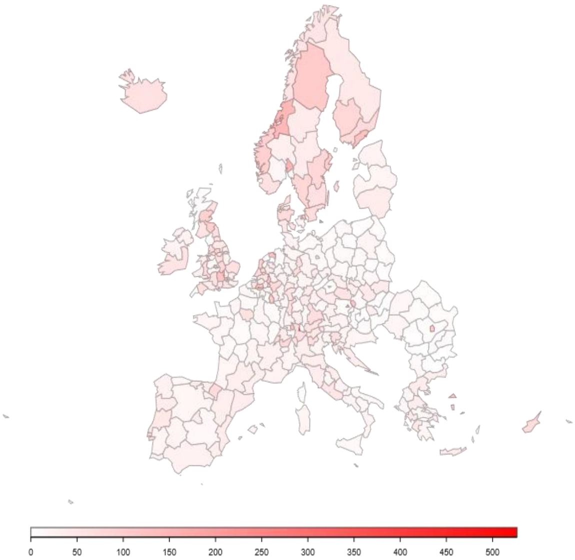
https://www.paballand.com/asg/dg-regio/scientific-relatedness/maps/count-pat/economics-&-business.html

Map of Europe: (a) number of scientific publications per inhabitant and (b) number of patents per inhabitant in Economics and Business 2014-2018



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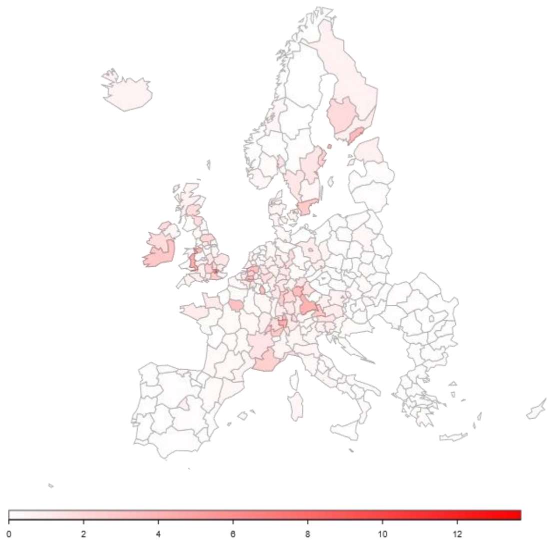

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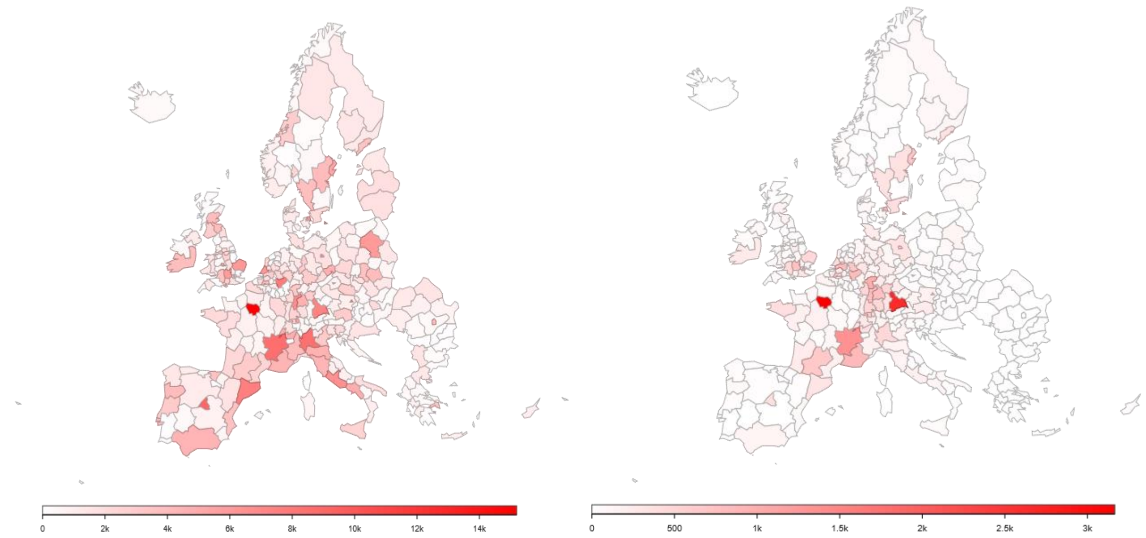
https://www.paballand.com/asg/dg-regio/scientific-relatedness/maps/pat-pc/economics-&-business.html

Enabling and Strategic Technologies

Map of Europe: (a) number of scientific publications and (b) number of patents in Enabling and Strategic Technologies 2014-2018



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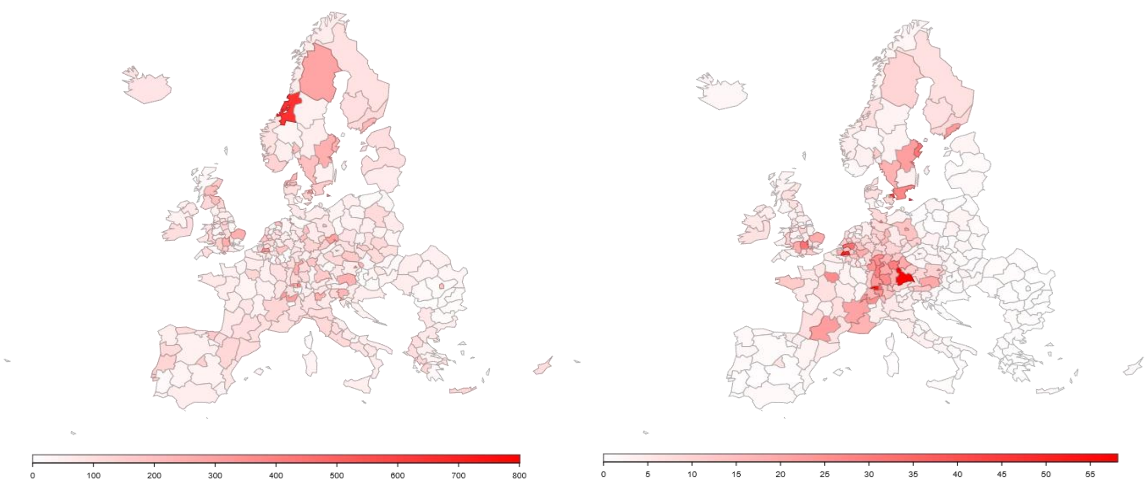
https://www.paballand.com/asg/dg-regio/scientific-relatedness/maps/count-pat/enabling-&-strategic-technologies.html

Map of Europe: (a) number of scientific publications per inhabitant and (b) number of patents per inhabitant in Enabling and Strategic Technologies 2014-2018



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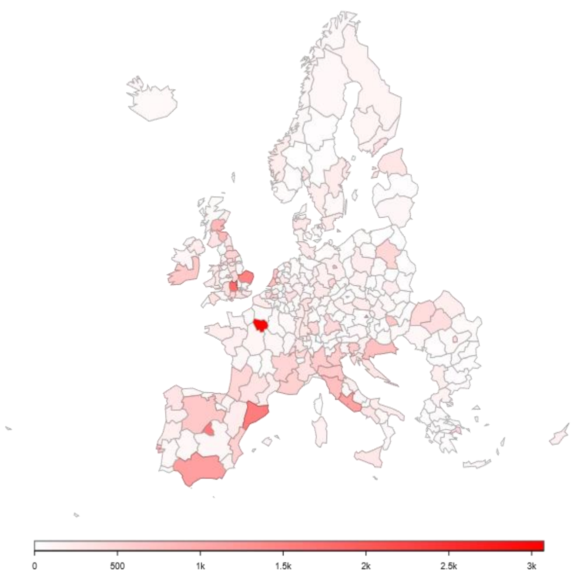
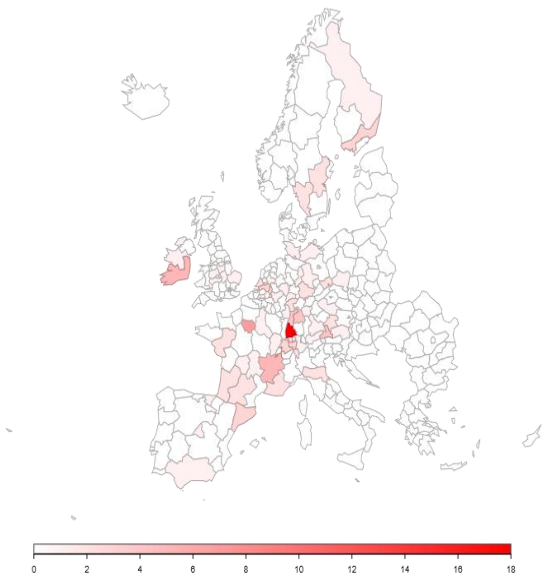
https://www.paballand.com/asg/dg-regio/scientific-relatedness/maps/pat-pc/enabling-&-strategic-technologies.html

Historical Studies

Map of Europe: (a) number of scientific publications and (b) number of patents in Historical Studies 2014-2018





(a) (b)

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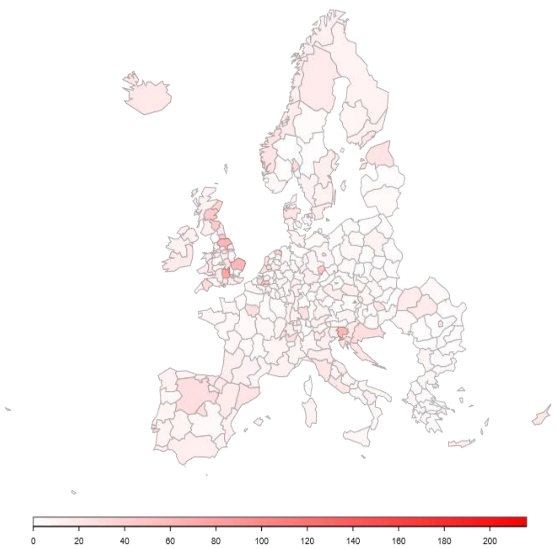
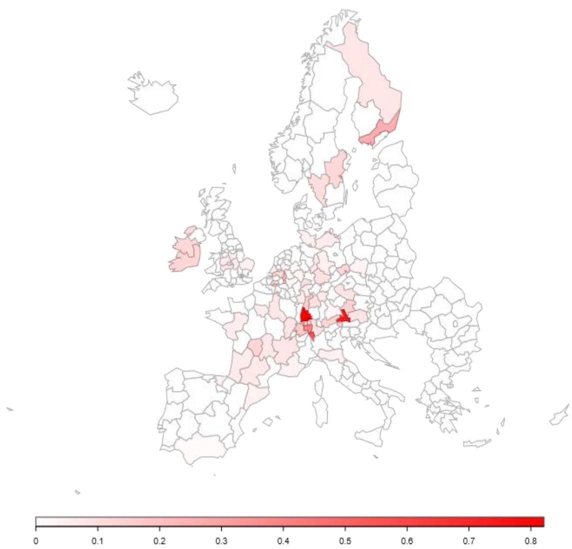
Map of Europe: (a) number of scientific publications per inhabitant and (b) number of patents per inhabitant in Historical Studies 2014-2018





(a) (b)

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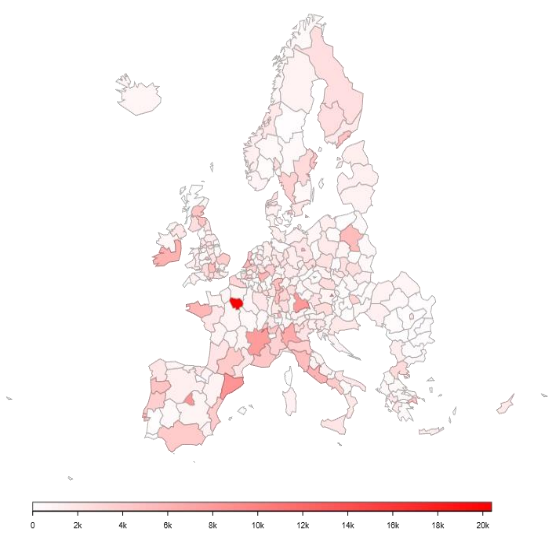
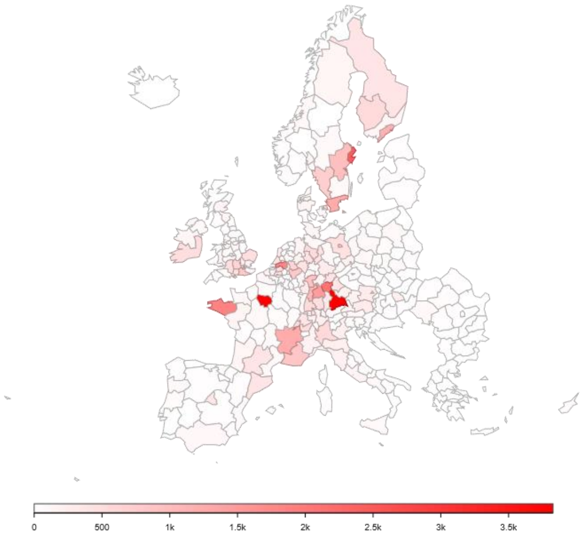
https://www.paballand.com/asg/dg-regio/scientific-relatedness/maps/pat-pc/historical-studies.html

Information and Communication Technologies

Map of Europe: (a) number of scientific publications and (b) number of patents in Information and Communication Technologies 2014-2018



(a)

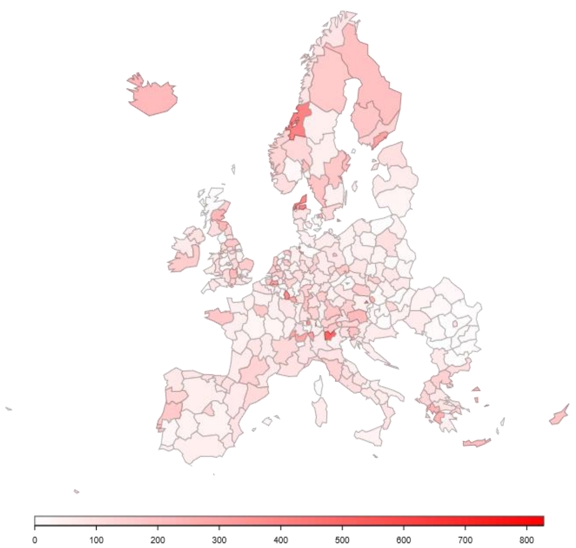


(b)

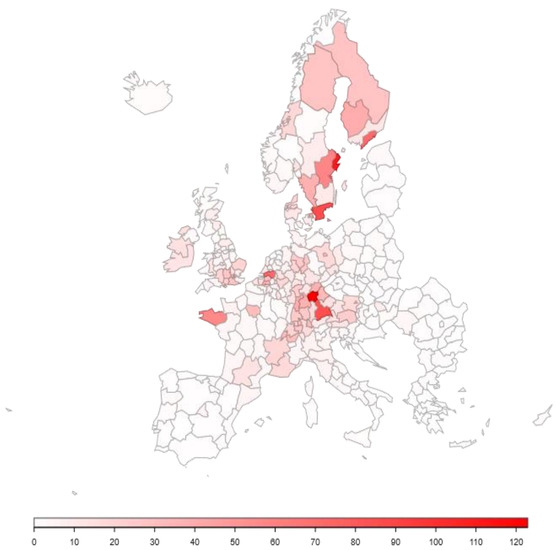
https://www.paballand.com/asg/dg-regio/scientific-relatedness/maps/count-pub/information-&-communication-technologies.html

https://www.paballand.com/asg/dg-regio/scientific-relatedness/maps/count-pat/information-&-communication-technologies.html

Map of Europe: (a) number of scientific publications per inhabitant and (b) number of patents per inhabitant in Information and Communication Technologies 2014-2018



(a)



(b)

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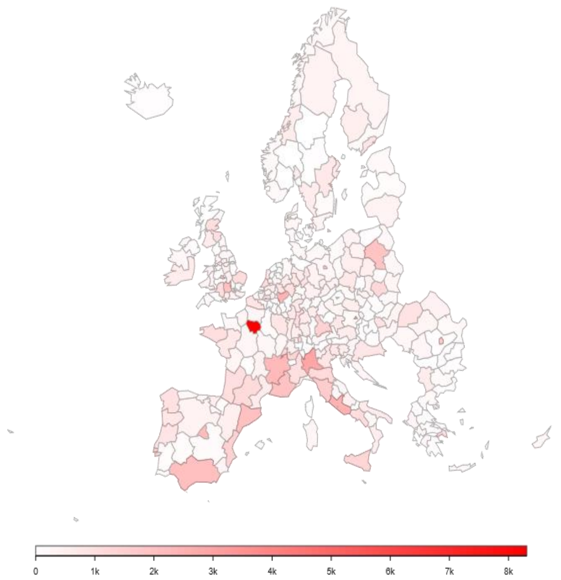
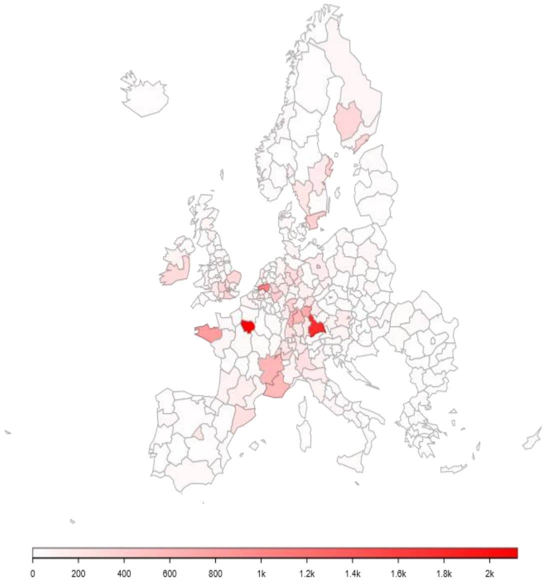
https://www.paballand.com/asg/dg-regio/scientific-relatedness/maps/pat-pc/information-&-communication-technologies.html

Mathematics and Statistics

Map of Europe: (a) number of scientific publications and (b) number of patents in Mathematics and Statistics 2014-2018



(a)



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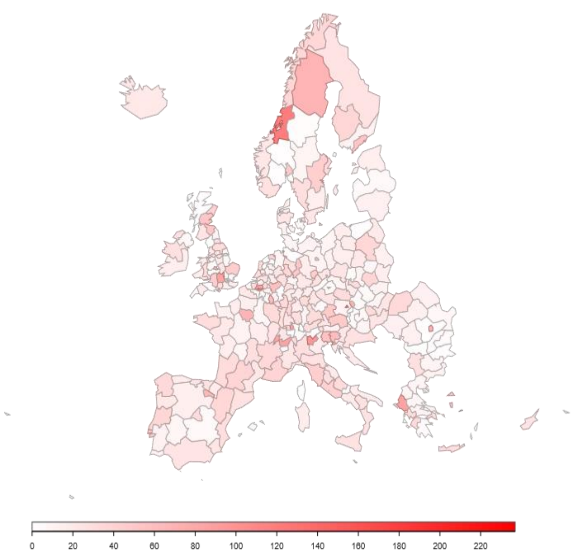
Map of Europe: (a) number of scientific publications per inhabitant and (b) number of patents per inhabitant in Mathematics and Statistics 2014-2018



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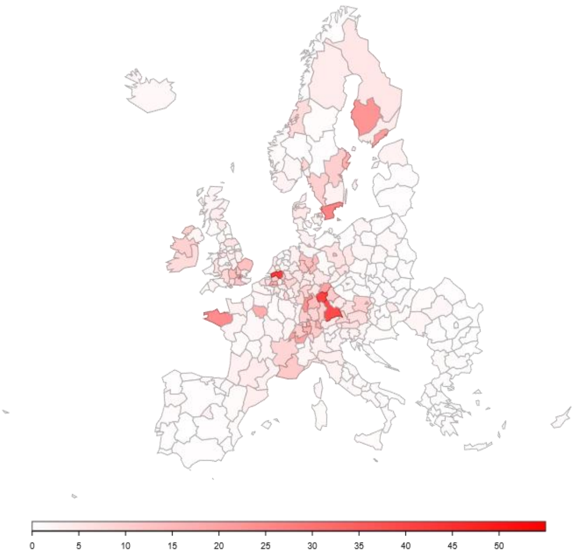

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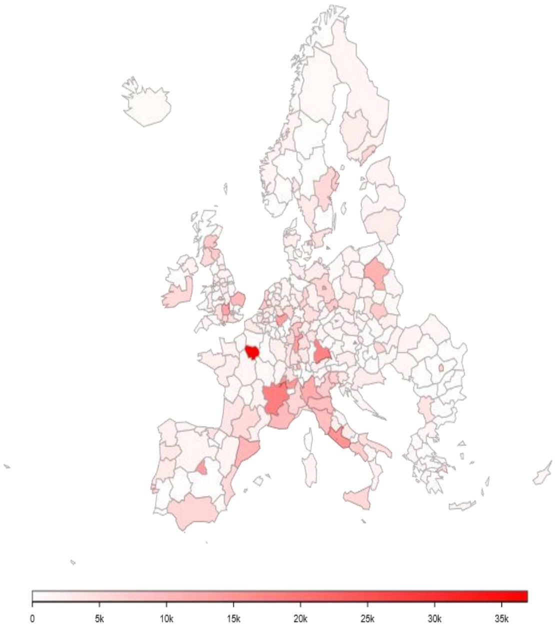
Physics and Astronomy

Map of Europe: (a) number of scientific publications and (b) number of patents in Physics and Astronomy 2014-2018



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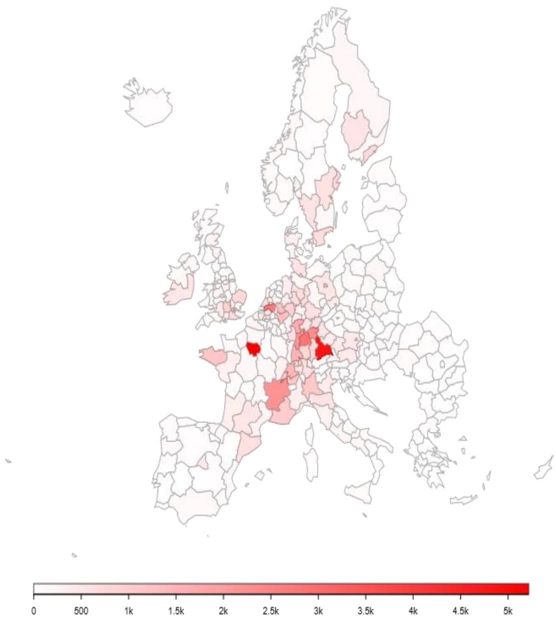

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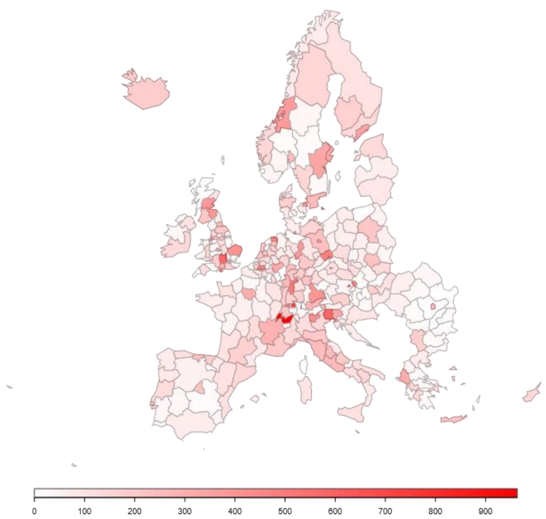
Map of Europe: (a) number of scientific publications per inhabitant and (b) number of patents per inhabitant in Physics and Astronomy 2014-2018



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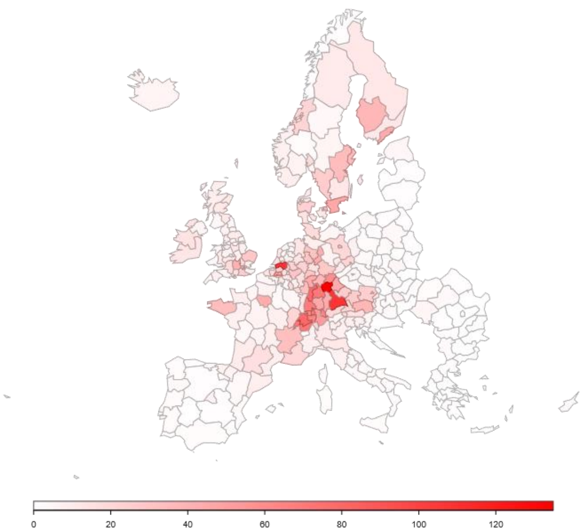

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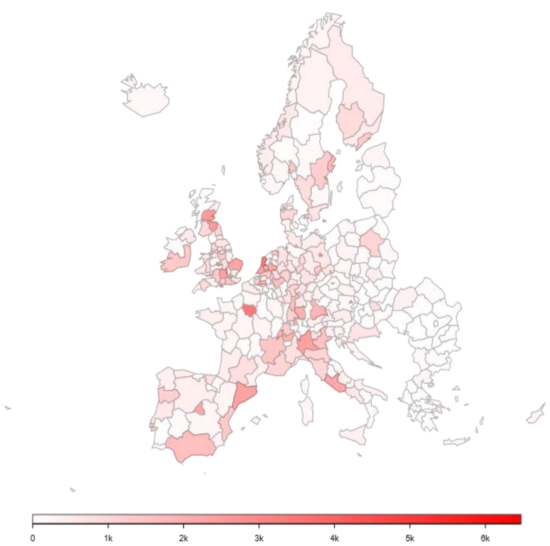
Psychology and Cognitive Sciences

Map of Europe: (a) number of scientific publications and (b) number of patents in Psychology and Cognitive Sciences 2014-2018



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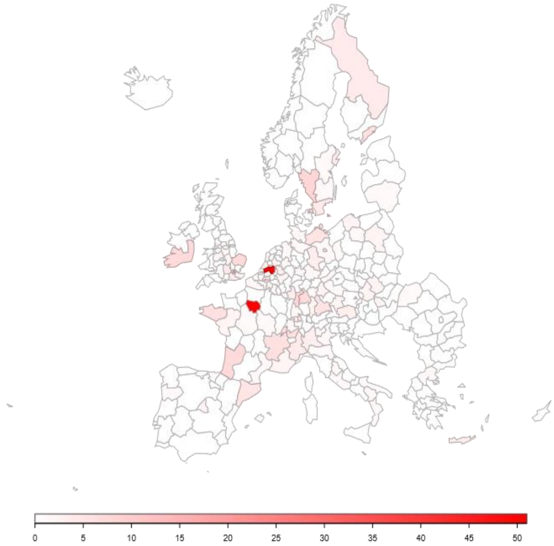

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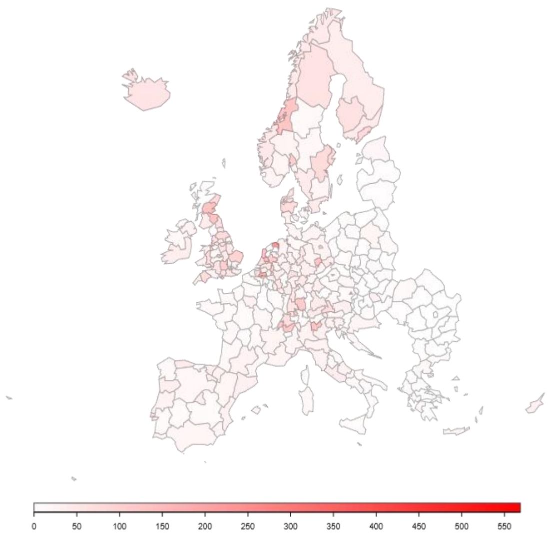
https://www.paballand.com/asg/dg-regio/scientific-relatedness/maps/count-pat/psychology-&-cognitive-sciences.html

Map of Europe: (a) number of scientific publications per inhabitant and (b) number of patents per inhabitant in Psychology and Cognitive Sciences 2014-2018



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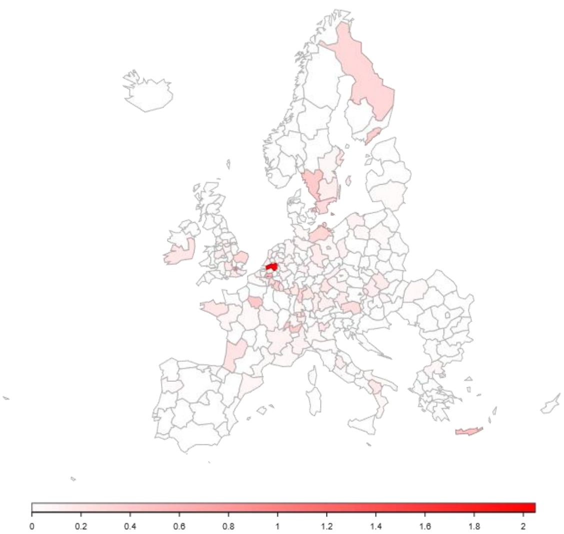

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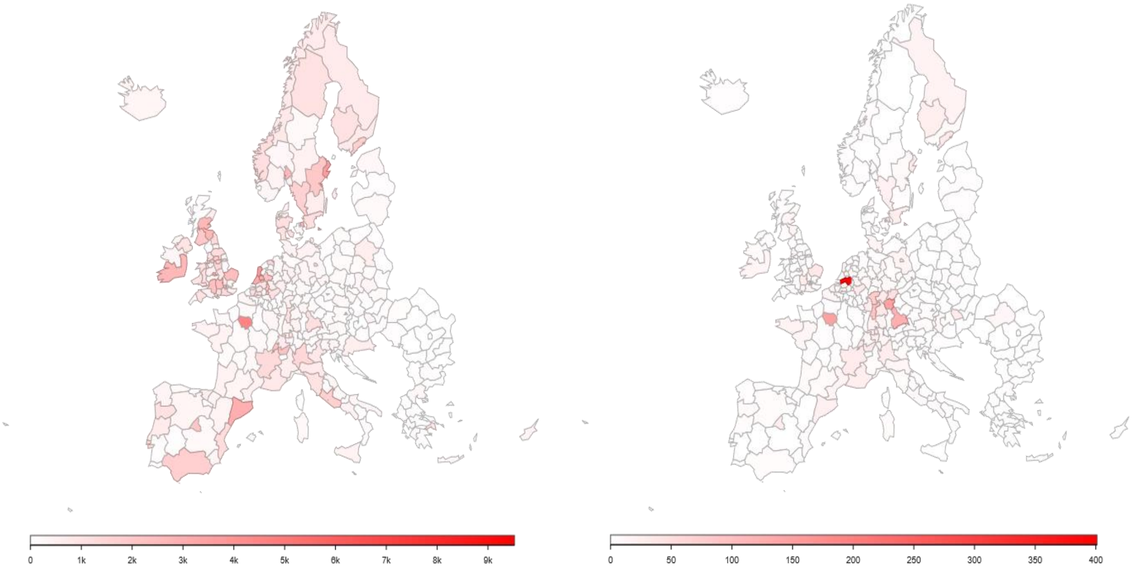
Public Health and Health Services

Map of Europe: (a) number of scientific publications and (b) number of patents in Public Health and Health Services 2014-2018



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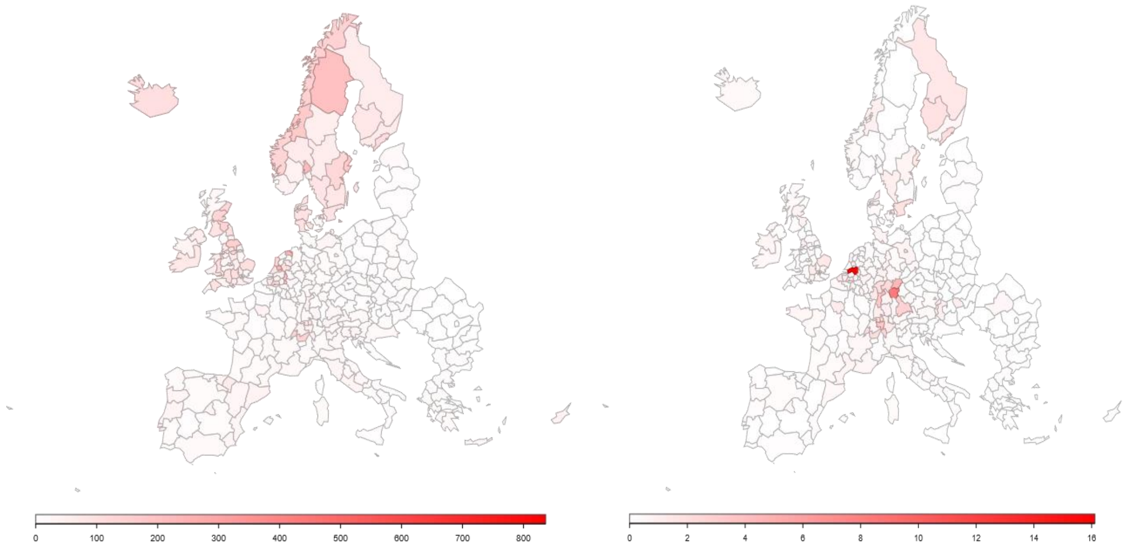
Map of Europe: (a) number of scientific publications per inhabitant and (b) number of patents per inhabitant in Public Health and Health Services 2014-2018



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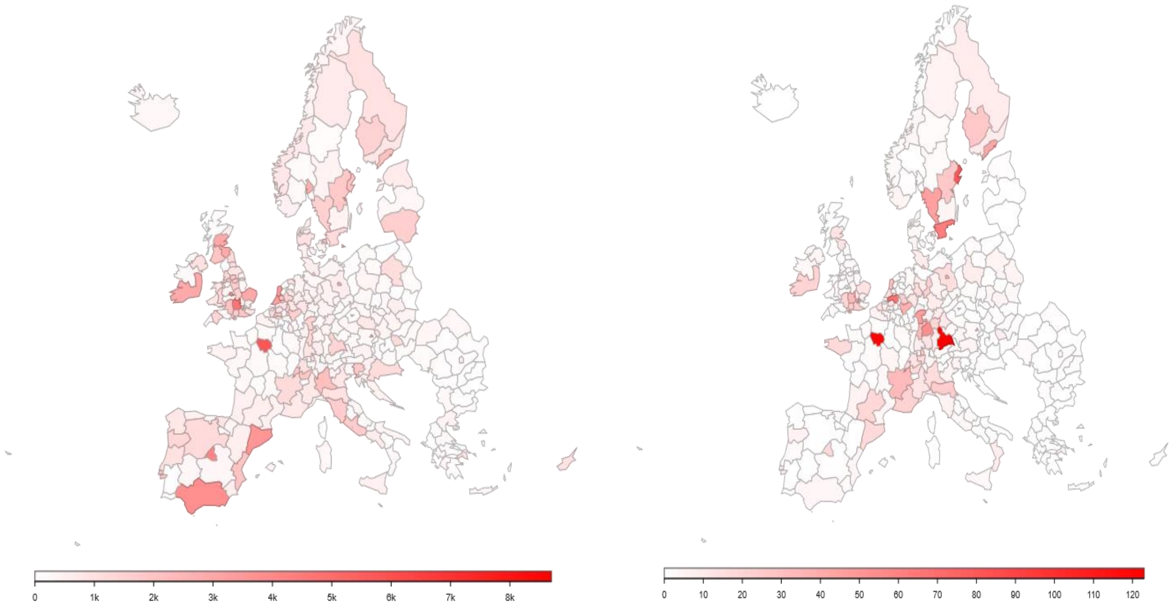
Social Sciences

Map of Europe: (a) number of scientific publications and (b) number of patents in Social Sciences 2014-2018



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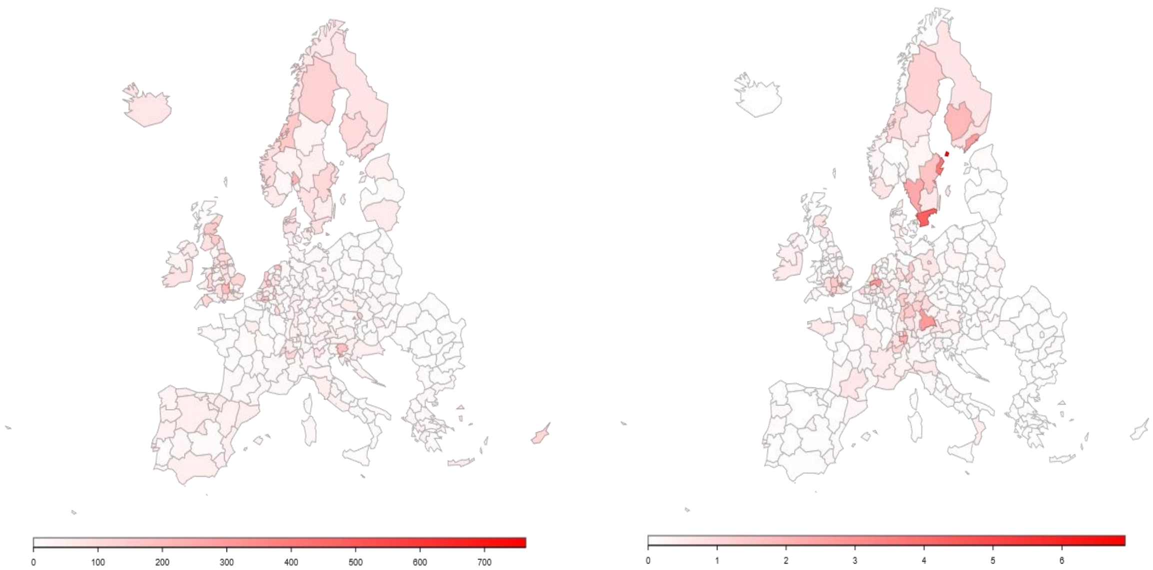
Map of Europe: (a) number of scientific publications per inhabitant and (b) number of patents per inhabitant in Social Sciences 2014-2018



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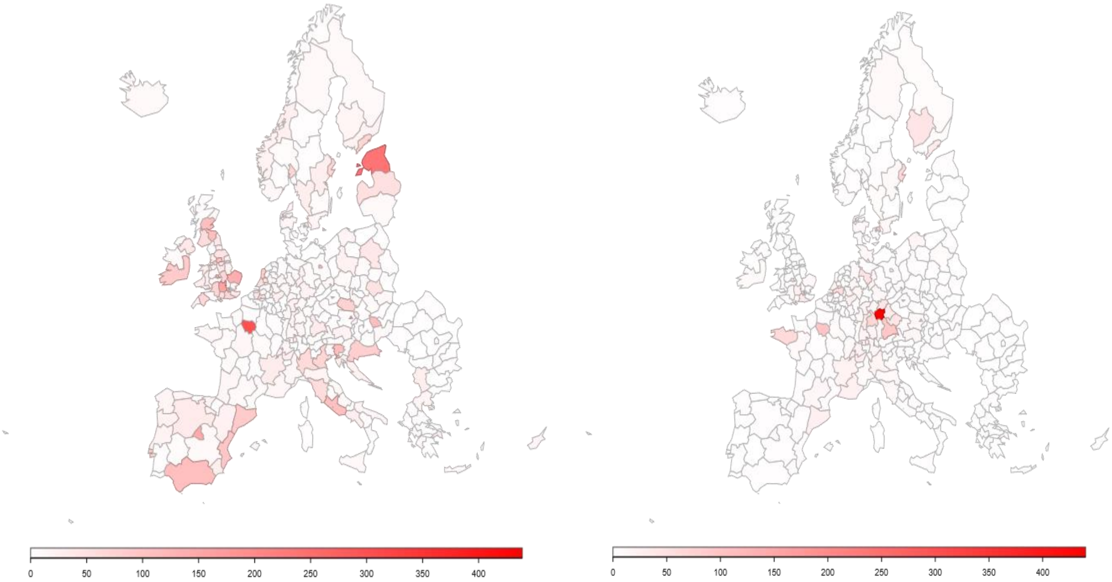
Visual and Performing Arts

Map of Europe: (a) number of scientific publications and (b) number of patents in Visual and Performing Arts 2014-2018



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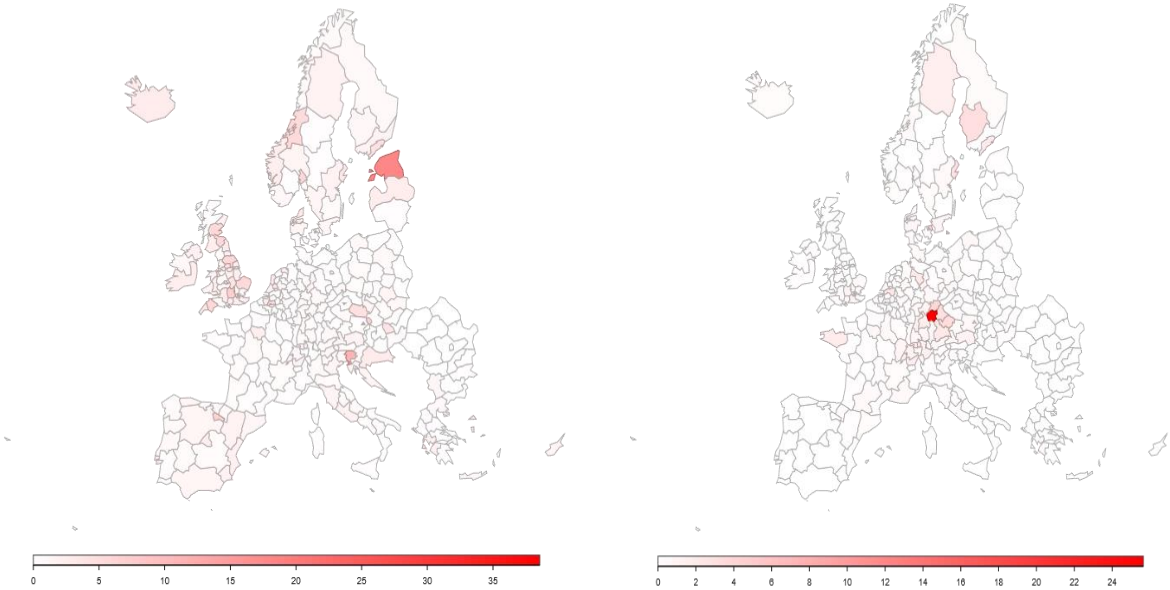
Map of Europe: (a) number of scientific publications per inhabitant and (b) number of patents per inhabitant in Visual and Performing Arts 2014-2018



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