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Scientific network centrality of European regions: the role of territorial resources

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***Abstract* -** This article provides an original framework for analyzing networks of scientific collaborations in Europe at regional level. Which are the determinants of the observed clustering phenomenon? Which is the role of the territories? The aim of this article is to provide empirical evidence in order to answer to these questions. For this, we base our analysis on scientific collaborations between European regions in eight different disciplines (e.g. Medicine, Chemistry…) over the period 2001-2011. A normalized centrality measurement is proposed. We test the impact of territorial resources and field scientific characteristics on regions centrality in each of the analyzed discipline. Firstly, the analysis highlights a strong heterogeneity between disciplines, showing the need of carrying out specific investigation for each of them. Second, the results show the different roles played by local resources, according to the disciplines. Finally, the article discusses the implications of these results in terms of science and innovation policies.

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INTRODUCTION

Actors able to reach more central network position will more likely benefit from network (Burt 1992; Borgatti 2005), in terms of knowledge access and diffusion, of performance and influence on the others actors (Gilsing et al., 2008; Maggioni et al., 2007; Ponds et al., 2010). That is why stimulating the network participation of scientific institutions localized in a specific region is important from a regional policy perspective.

To investigate the characteristics and the centrality of scientific networks, regions are often considered as a relevant unit of analysis (Autant-Bernard et al., 2007), even if they encompass several universities and public research organizations that develop specific collaborations depending on their specialization, size and strategy.

The determinants of scientific networks centrality have been investigating in the literature in several ways (Wanzenbock et al., 2015; Sebestyén and Varga, 2013). The geographic perspective analysis is developed around two main approaches: the internal capacity and the territorial one.

First, centrality depends on the resources of the actor itself. In the case of regions, it means the R&D and scientific resources of the institutions localized in the region represent a driver for network centrality (Autant Bernard et al, 2007; Barber et al., 2011). Internal capacity is required not only to engage in collaborations, but also to benefit from knowledge transmitted via network inter-linkages. Some scholars pointed out that the region's strength in knowledge production is one of the most crucial factors for developing central position in knowledge networks (Broekel and Brenner, 2011; Grossman and Helpman, 1991).

Second, spatial dimension is associated to the impact of geographical proximity on the development of actors' collaboration (Boschma and Frenken, 2010). Scientific institutions are embedded in economic and technological environment. This territorial embeddedness gives the opportunity to access to nearby resources localized in the regions and the surrounding territories (Wanzenock et al., 2015; Berge et al., 2015). Spatial embeddedness could affect a region's network position due to spillover mechanisms resulting from economic dependencies, agglomeration dynamics or core-periphery structures in nearby regions (see Feldmann and Kogler, 2010; Breschi and Lissoni, 2009).

In this sense, scientific network centrality of regions depends not only on internal resources of the universities and research organizations, but also on the various regional resources nearly accessible (Wanzenbock et al., 2014). The focus of this study is to investigate how the combination of these resources affects the region's scientific centrality in Europe.

In line with Hoekman et al. (2010), we explore how the scientific centrality of a region depends on economic and scientific regional attributes and how this could vary depending on the scientific field under analysis. As disciplines are based on different production and knowledge diffusion patterns (e.g. Bonaccorsi, 2008), we assume that driving factors determining the centrality of a region can vary according to discipline. Our analysis attempts contribute to this literature in two main ways. First, it contributes to the debate around the regional policy supporting local scientific activities. We underline some major challenges for regional policymakers wanting to bring regional scientific communities closer to the center of the European network. Boosting collaboration can be effective if the actual driving factors are activated Second, we simultaneously take into account both the general characteristics of the territory and the specific scientific characteristics of each discipline (i.e. intra-discipline variables), as well as potential inter-discipline effects. So we contribute to identify the specificities of scientific disciplines in the regional policy perspective.

For our study, we use data from Web of Sciences (henceforth WoS) from 2000 to 2011 covering eight broad scientific disciplines. For each discipline, we calculated the valued degree centrality for each European region. In order to make meaningful comparisons between disciplines, we propose an original normalization method. Based on the rich-club phenomenon approach, a threshold value for each distribution is identified, and the degree of centrality for each region is normalized accordingly. To control for spatial effect, we follow the empirical strategy adopted by Wanzenbock et al. (2014) and a panel version of Spatial Durbin Model (henceforth SDM) is applied to our degree of centrality data.

The paper is organized as follows: the second section briefly presents the literature that should be taken into account together to analyze the determinants of regional network centrality. Here, we present the literature covering the determinants of regional resources and we make some assumptions about their impact on scientific network centrality. The third section presents the data and methods, namely the network construction and the econometric model adopted. The fourth section presents the empirical exercise and main results for each of the eight scientific disciplines analyzed. The last section offers a conclusion, discussing the main results and implications for policymakers.

1. THE DIFFERENT SCALES OF TERRITORIAL RESOURCES AS DRIVING FACTORS OF SCIENTIFIC NETWORK CENTRALITY

Economic and geographic literature shows that territorial resources can play an important role to understand how economic actors develop (Asheim et al., 2005). Based on this literature, we identify some questions concerning the impact of local resources on the centrality of regions within the European scientific network that deserve more research than what actually done. We organize the analyses around three main dimensions: the internal resources of the region (2.1) and the spillovers within a region (2.2) and between a region and the surrounding ones (2.3).

1.1. The scientific/internal resources as driving factors of scientific centrality

Academic literature focusses on regional innovation system diversity and trajectories in terms of their R&D and innovation capabilities (Asheim, 2006; Pinto, 2009). This diversity is frequently presented as a dichotomy between core/leader vs. periphery/follower in regional innovation systems (Doloreux et al., 2008; OECD, 2011). Regions with low capabilities and performance are often not well integrated into the European research area. For (regional or European) policymakers, the challenge is therefore to support peripheral regions in moving out of their isolation (Doloreux et al., 2008; Hewitt-Dundas et al., 2011). Based on this literature, we wonder which factors could influence centrality.

The scientific centrality of an actor depends first on the resources of the actor itself. In the case of regions, it means that the R&D and scientific resources of the institutions localized in the region can be a driver for network centrality (Autant Bernard et al., 2007; Barber et al., 2011). Internal capacity is required not only to engage in collaborations, but also to benefit from knowledge transmitted via network inter-linkages. Some scholars pointed out that the region's strength in knowledge production is one of the most crucial factors for developing central position in knowledge networks (Broekel and Brenner, 2011; Grossman and Helpman, 1991). According to this literature, scientific resources can be analyzed in terms of financial resources dedicated to research institutions, which represent the critical mass, i.e. scientific production, and in terms of scientific excellence, i.e. impact or visibility (Zitt et al., 2000; Tjissen et al., 2007). In order to reduce disparities, regional policy actions are designed to increase the scientific capacity of research institutions on the one hand and push the pursuit of scientific excellence on the other

(Benneworth et al., 2007). For R&D policy, one of the main challenges is about the equilibrium between scientific production and scientific excellence. In other words, is the scientific production which makes a region more central or/and the quality of its production? Answering to this question could help to orientate the R&D policy.

This question must be analyzed at the disciplines level. Indeed, the impact of scientific regional resources on centrality may vary between disciplines because knowledge production dynamics differ between scientific regimes. Bonaccorsi (2008) shows that some key differences between disciplines exist because the resources required for their development are different. The author identifies what he calls technical complementary that includes physical infrastructures. Disciplines like physics and astrophysics require significant infrastructures while such an investment plays a relative minor role in biology or chemistry (Bonaccorsi, 2008; Genuth et al., 2010). We assume that while regional policymakers have an increasing role in scientific policy (Perry, 2007; Crespy et al., 2007), bolstering scientific resources does not have the same impact among the disciplines.

1.2. The local spillovers effects on scientific centrality

Beyond internal resources, the literature shows the impact of various types of spillovers (such as knowledge spillovers or industry spillovers, cf. for instance Capello, 2009 for a review) on the development of the local actors.

Thus, from the Regional Innovation System (RIS) perspective, regional scientific development depends on the proximity and interactions between public and private research (Kratke et al., 2009). Scientific capabilities are more concentrated in regions characterized by high levels of private R&D and economic growth (Asheim et al., 2006). We therefore assume that regional economic and innovative capacities contribute indirectly to strength the development of regional scientific institutions and, a fortiori, of the centrality of the regional scientific institutions.

However, the impact of this support may vary between disciplines. Bonaccorsi (2008) states that one of the key differences between disciplines is based on institutional complementarities: public and private interactions vary between disciplines and these interactions do not have the same impact on all disciplines. For instance, for applied scientific activities, the private sector may play a more important role than for fundamental research activities: in medicine as in engineering science, collaborations between public and private research are essential for producing new scientific results, while for mathematics or fundamental physics this is definitely less the case (Todt et al., 2007; Merito et al., 2007).

Moreover, the analysis at the discipline level, allows us to test the effects of some possible "inter-discipline spillovers" in an adaptation of inter-industry spillovers. Indeed, as shown at the industry level, what is it done in one sector can positively influence the development of other sectors. We make the assumption that the more the region is central in different scientific disciplines, the higher the probability to be central in one specific discipline is.

1.3. Surrounding territorial resources as spillovers and their impact on network centrality

A large literature shows the influence of surrounding regions on a region's own outcome such as economic growth, gas emission or knowledge production (Jaffe, 1989; Feldman, 1994; Autant-Bernard, 2001). In the literature, local knowledge spillovers influence the development of surrounding regions. Because of growth spillovers (for instance Arora and Vamvakidis, 2005), a region growth depends also on outcome and behavior of neighboring regions. In both cases, the main idea is that the proximity between regions creates opportunities for interactions that influence the development of the regions. However, if knowledge spillovers are rather considered as having positive effects, in some cases, surrounding territorial R&D has a negative impact on regional knowledge production (Autant-Bernard, 2012), negative effects which may result from core-periphery relations between neighboring regions. In other cases, the presence of large infrastructure such as an airport (Percoco, 2010) could contribute to generate spillover over the surrounding regions. Thus a large panel of activities can have a spillover effect on other regions. From the policymaker perspective, the variety of positive and negative spillovers associated with the surrounding regions introduces some challenges for implementing horizontal multi-governance (Koschatzky et al., 2007): when is it possible for regions to cooperate? When are they competing?

In this context, as for knowledge production or economic growth, we suppose that spatial spillovers could have an impact on the capacity of scientific communities to become more central in the European network. Such spatially lagged characteristics are referred to as accessibility or connectivity measures (Ponds et al., 2010). High accessibility between two regions implies a high level of opportunities for interaction, and therefore a high level of potential (negative or positive) spillovers between two regions. In this context, we consider that spillovers from surrounding regions can also impact the way regions collaborate. Following Wanzenbock et al. (2014), we assume that "spatial connectivity affects a region's network position due to spillover mechanisms resulting from the spatial concentration of industries, knowledge-intensive sectors and organizations and the resulting economic dependencies and core-periphery structures between nearby regions" (p.343) (see, e.g. Feldman and Kogler, 2010).

Results regarding territorial spillovers may vary significantly between disciplines. If it is true that technical and institutional complementarities affect the development of disciplines (Bonaccorsi, 2008; Mora Valentine et al., 2002), we assume that they are very likely to work differently depending on the geographical scale. More specifically, technical complementarities seem to depend on huge investments more related at a "macro-region" level, if not related at a country policy level. The administrative borders of regions could therefore be too narrow. We expect positive or negative externalities from neighbouring regions.

The identification of scale has clear implications in terms of policy, namely with regard to the appropriate policymaker intervention level. When local resources are rolled up with regional ones, regional policymakers can play a key role in supporting economic development (Tödling et al., 2005). Conversely when surrounding regions influence local development, regional policymakers have to develop various forms of collaboration with others levels of public administration in order to support economic development (Medeiros, 2013). According to this perspective, therefore, policymakers have to address horizontal and vertical multi-governance challenges (Koschatzky et al., 2007). Our empirical analysis would propose different level of intervention according to the discipline considered.

2. REGIONAL NETWORKS: DATA AND METHODS

2.1. Data

In order to investigate the European scientific system, we focus on the existing collaboration between regions (NUTS2) in 8 broad scientific disciplines (see Table 1) defined by OST (2010) as an aggregation of Thomson Reuters Scientific Categories[1]. Data of co-publications among regions (EU27) used and citations associated

[1] The articles published in multidisciplinary journals are reallocated to these disciplines using the Thomson Reuters re-assignation procedure to subject categories.

come from the Web of Science (WoS) database, which contains information from most journals covering all scientific fields. We retrieve all scientific articles, letters, notes and reviews published between 2000 and 2011 and related to research collaborations between EU regions. A publication is considered as research collaboration between regions if it contains at least two different institutional addresses corresponding to two different NUTS2 regions. The publications co-authored by intra-regional institutions are therefore excluded and our study is limited to bilateral and multilateral inter-regional co-authorship. Our sample is based on four sets of smoothed data corresponding to 3-year periods: 2000-2002, 2003-2005, 2006-2008, and 2009-2011. Our empirical study covers 265 regions across 27 European countries. As publications are mainly written by public researchers, the network studied can be considered as the public scientific network.

Table 1: The Scientific Disciplines

Fundamental biology	Physics
Medicine	Science of the universe
Applied biology / ecology	Engineering sciences
Chemistry	Mathematics

2.2. Methods

We use the data on scientific publications co-authored by inter-regional institutions to build a network, by discipline and by period, where the actors /nodes are the regions and the links between them are co-publications. The value of the link between two regions is given by the number of collaborations in common in a given discipline over the period under analysis. We are therefore considering a weighted network.

The centrality of each region is captured by its degree of centrality. However, since we are considering a weighted network, referring to the degree of centrality can pose problems, as shown by Opsahl et al. (2010). In a weighted network, the degree of centrality is given by the sum of the weight of actor's links: in our case it would correspond to the number of inter-regions collaborations carried on by the focal region. However, this approach means that we completely lose the information about the number of partners: the same value of centrality (e.g. ten) can correspond to very different scenarios (e.g. one partner with which you have collaborated ten times or ten collaborations with ten different partners). Opsahl et al. (2010) propose a definition of the degree in a weighted network that is able to grasp both aspects of collaboration: quantity (i.e. degree) and strength. The weighted degree of centrality for actor i is therefore defined as the following:

$$C_D^{w\alpha}(i) = k_i \times \left(\frac{s_i}{k_i}\right)^{\alpha} = k_i^{(1-\alpha)} \times s_i^{\alpha} \tag{1}$$

where ki is the number of partners and si the sum of the strength of links between players, and α is the weighting parameter for each of the two aspects. We decide to set α as equal to 0.5 because we have no specific reasons to assign more importance to one aspect over another.

For meaningful comparison between degrees of centrality across eight different disciplines and across time, we propose a methodology to normalize the degree of centrality based on the rich-club phenomenon. Following the approach developed by Zhou and Mondargon (2004) and generalized by Serrano (2008), it is possible to check whether there is a breakpoint over the degree of centrality distribution of a discipline and so establish if regions are structured around a core (i.e. rich club) and a periphery[2].

Table 2: Weighted Links

Discipline		# Pairs of regions	Mean	Median	Max
	2000-2002				
Fundamental biology		12106	3.041	1.000	236.333
Medicine		13728	5.031	1.000	390.333
Applied biology/eco		7670	1.463	0.667	61.667
Chemistry		9897	2.167	0.667	183.000
Physics		10006	6.191	1.333	358.333
Science of the univ		8858	2.150	0.667	118.667
Engineering science		8739	1.726	0.667	127.667
Mathematics		3820	0.839	0.333	22.000
	2003-2005				
Fundamental biology		13270	3.342	1.000	243.000
Medicine		16197	6.072	1.333	534.667
Applied biology/eco		9233	1.579	0.667	77.000
Chemistry		10757	2.307	1.000	211.667
Physics		11063	7.202	1.333	429.667
Science of the univ		10775	3.272	1.000	198.333
Engineering science		10336	2.041	0.667	165.667
Mathematics		4504	0.941	0.333	38.333
	2006-2008				
Fundamental biology		15286	4.040	1.000	297.333
Medicine		18161	7.851	1.333	699.000
Applied biology/eco		11863	1.881	0.667	94.333
Chemistry		12053	2.527	1.000	265.333
Physics		12638	7.836	1.667	517.667
Science of the univ		13243	4.906	1.000	303.333
Engineering science		11558	2.157	0.667	218.000
Mathematics		5301	1.054	0.667	50.000
	2009-2011				
Fundamental biology		17745	5.341	1.333	393.333
Medicine		20729	10.145	2.000	1009.667
Applied biology/eco		14881	2.418	1.000	136.667
Chemistry		13007	2.789	1.000	322.333
Physics		13507	13.216	2.000	585.333
Science of the univ		16211	6.782	1.667	419.000
Engineering science		12428	2.418	1.000	259.667
Mathematics		6060	1.152	0.667	70.667

Once the degree of centrality has been calculated for each region, $CDw\alpha(i)$, we look at the characteristics of its distribution in order to identify the existence of a core-periphery structure (Serrano, 2008). To say that a network is characterized by

[2] This is only a necessary condition. The most central regions only constitute a core if the links between them are particularly intensive, i.e. the number of links between core members is greater than "the corresponding value in a randomized version of the graph that preserves the degree distribution" (Serrano, 2008, p. 4). Once this second condition is satisfied, it is possible to claim that the network analysed displays a core-periphery structure.

such a structure, a necessary condition is the presence of a break-point in the complementary cumulative distribution of actors' degrees of centrality.[3] Once the break-point is identified, the degree of centrality of each region in a specific discipline in a given period is divided by the corresponding value. This methodology allows us to take into account on the one hand the difference between disciplines in terms of number of collaborations, and on the other hand, the difference over time of number of collaborations that could impact on the value of centrality.

Table 3: Core Characteristics

Discipline	Min degree	Core size	Core share
2000-2002			
Fundamental biology	191.053	87.000	0.328
Medicine	279.564	89.000	0.336
Applied biology/eco	79.297	93.000	0.351
Chemistry	141.539	89.000	0.336
Physics	306.844	61.000	0.230
Science of the univ	116.565	85.000	0.321
Engineering science	113.287	79.000	0.298
Mathematics	28.337	90.000	0.340
2003-2005			
Fundamental biology	207.958	92.000	0.347
Medicine	351.994	92.000	0.347
Applied biology/eco	98.919	89.000	0.336
Chemistry	152.116	92.000	0.347
Physics	387.457	55.000	0.208
Science of the univ	194.048	77.000	0.291
Engineering science	138.444	83.000	0.313
Mathematics	32.660	96.000	0.362
2006-2008			
Fundamental biology	260.898	93.000	0.351
Medicine	433.188	92.000	0.347
Applied biology/eco	134.005	100.000	0.377
Chemistry	178.863	90.000	0.340
Physics	400.932	60.000	0.226
Science of the univ	271.980	74.000	0.279
Engineering science	163.310	80.000	0.302
Mathematics	46.733	83.000	0.313
2009-2011			
Fundamental biology	339.274	97.000	0.366
Medicine	529.426	99.000	0.374
Applied biology/eco	177.837	107.000	0.404
Chemistry	206.753	86.000	0.325
Physics	578.575	66.000	0.249
Science of the univ	366.999	83.000	0.313
Engineering science	180.849	86.000	0.325
Mathematics	48.819	97.000	0.366

[3] More technically, it is necessary to (i) compute the log-CCDF (complementary cumulative distribution function) of log-degree; (ii) "use a piece-wise linear regression of log-degree and log-CCDF using a moving threshold to get best fit for power law coefficients" (Zelnio, 2012, p. 604).

2.3. Network and core identification

We build 32 networks: eight disciplines/networks for each of the four periods. Table 2 shows the main distribution links values, i.e. s_i of equation 1.

We applied the methodology described in this section to the 32 networks in order to detect if there is a breakpoint, and, if so, its value. All of them show this structural breakpoint. Table 3 shows the minimum value and the number of regions that are on the right tail of the distribution (i.e. core).

The critical threshold of the core represented by the minimum degree increases over time for each domain. Both these factors reflect the network dynamics in the different fields studied. The differences between disciplines are striking. For instance, the minimum degree for Physics is ten times that for Mathematics, with the other six disciplines report values between the two extremes. Another difference concerns the relative size of the core. The main differences are among disciplines, where for instance Applied Biology is between 50 or more per cent greater than Physics. Less important are differences within the same discipline over time. This can be interpreted as sign of a certain inertia of the status of core member. In any case, the descriptive statistics show that these differences should be taken into account and raise questions over analysis that covers all disciplines together.

2.4. The determinants of centrality

The aim of our empirical exercise is to identify driving factors of regional position in the inter-regional scientific co-publications network. In order to compare results over different disciplines, we consider the degree centrality of the region normalized relative to the minimum degree necessary to belong to the core to be the dependent variables. This normalization allows us to compare the results in terms of magnitude of the coefficients. Otherwise they would be meaningless.

Moreover, we intend to control for spatial effect, in particular to check if the regions close to region i affect its potential to be central. To do so, we use an analytical framework that accounts for spatial knowledge spillover effects in our co-publications network analysis of EU regions (Autant-Bernard, 2012). A panel version of SDM (Elhorst, 2003 and 2012; Wanzenbock et al., 2014) is applied to our degree of centrality data. This model turns out to be more appropriate in empirical analysis for calculating the magnitude of direct impacts and indirect or spatial spillover effects (Autant-Bernard and LeSage, 2011; Elhorst, 2012). It makes it possible to distinguish between direct, indirect and total effects.

The panel SDM is written as follows:

$$y_t = \rho W y_t + X_t \beta_1 + W X_t \beta_2 + u_t$$

$$u_t = \mu + \tau_t + \epsilon_t$$

where y_t is an Nx1 vector containing degree of centrality in a discipline normalized relative to the minimum degree for belonging to the core, for each region (i=1,..., N) (Table 3) at time t where t=1, 2, 3, 4. Each of these four periods corresponds to 3-year of observations, namely 2000-2002, 2003-2005, 2006-2008, and 2009-2011. X_t is an NxK matrix of exogenous explanatory variables including a constant term. W is an NxN non-negative matrix of known constants describing the connections between regions. W, generically labelled spatial weight matrix (see, e.g., Anselin 1988) is constant over time, with the element of W in row i and column j denoted by w{ij}. The components of W are given by: w{ij}=0 for all i=j by assumption since no spatial unit can be considered its own neighbour, and w{ij}=1 if region i and region j are contiguous (i.e. they have a border in common) and w{ij}=0 otherwise. W is row-standardised, meaning that the row elements sum up to 1. Wy_t corresponds to Nx1 vector of the spatially-lagged dependent variable and WX_t is an NxK spatial lag matrix of K independent variables. The centrality of each region is then assumed to rely on weighted average centrality of its neighbouring regions and a weighted average of its neighbours' exogenous explanatory variables. The rho parameter associated with spatial lag of y_t is the spatial autoregressive coefficient and reflects the strength of the spatial interaction; β_1, β_2 denote Nx1 vectors of response parameters of predictors X and their spatial lag respectively. u_t denotes a Nx1 vector of error terms, with μ region specific fixed effects, τ_t period specific fixed effects and ε_t an Nx1 vector of normally distributed, homoscedastic and uncorrelated errors. The Maximum Likelihood procedure is applied to the spatial Durbin model (Elhorst, 2003) for estimating regression parameters based on fixed effects.

The explanatory variables, i.e. X_t, selected can be classified in two different groups: regional economic resources and scientific activities. With regard to the first, we considered some economic data for the period 1995-2011 retrieved from the Eurostat website in June 2013. In particular, for each region, we downloaded: the GDP per capita relative to the EU27 average, normalized to 100; the R&D expenditure level (% of GDP), broken down by Public and Private sector[4]. We opted to capture the relative degree of development of a region by a normalized measure of GDP per capita because this is the main criterion for identifying the target regions for the European Cohesion policy (i.e. a region with less than 75% of average GNP per capita). Finally, we selected an input variable such as human resources in Science and Technology (thousands of people) that is supposed to capture the research effort in each region and therefore its size.

The second set of variables measures scientific activities. Over all periods under observation, data on publications of regions in each discipline are taken into account. Two measures are defined: (i) the share of the discipline out of the total scientific production of the regions and (ii) the relative impact of each region's output in each discipline This is measured by the average number of citations received by the region in a given discipline benchmarked against the average number of citations received by the EU in the same domain. These two measures should capture respectively the quantity and quality of the results of the scientific efforts of each region in a specific field. They should make it possible to define the objective of a regional scientific activities policy. Is it reaching a sufficient critical mass? Or is the quest for excellence the silver bullet? Are they two sides of the same coin? Finally, we have defined a variable which counts how many other disciplines the region is already in the core in order to capture some inter-disciplinary spillovers, if there are any. This variable is calculated on the base of the network analysis explained previously.

3. RESULTS

Tables 4 and 6 presents the estimated coefficients for the eight disciplines, while, following Wanzenböck et al. (2014), Tables 5 and 7 present the average impact estimates for each discipline on the magnitude and significance of direct, indirect and total impacts on a region network position that would arise from a change in one unit of our regional characteristics, averaged over space and time. More specifically, the direct impacts measure the effects of region-internal characteristics on a region's network centrality, while the indirect impacts estimate the sum of spatial spillover effects, i.e. influences of changes in region-external characteristics. The overall influence of distinct characteristics on regional network centrality at the regional level is given by the total impact. LeSage (2009) shows that there are two

[4] To overcome a minor problem of missing data for some regions in Eurostat data, we use the median ratio procedure as suggested by Hollanders et al. (2012).

possible (equivalent) interpretations of the total effects. One interpretation (the one that we adopt in our discussion) reflects how changing an explanatory variable of all regions by some constant amount would affect the centrality of an average region. LeSage and Pace (2009) label this as the average total impact on an observation. The total effect includes both the average direct impact plus the average indirect impact. The second interpretation measures the total cumulative impact of a change in each explanatory variable in region i on the centrality of all neighboring regions, which Lesage and Pace (2009) label the average total impact from an observation.

Before looking at each of the eight regressions, it is worth noting that geographical space has a role in explaining core membership in six out of the eight disciplines analyzed. The estimates for the spatial autoregressive parameter (i.e. rho) are highly significant and positive for Fundamental Biology, Medicine, Applied Biology, Chemistry, the Science of the Universe and Engineering Sciences but not for Physics and Mathematics.

Table 4: Estimation results of fixed effects panel SDM (first set of disciplines)

	Fundamental biology		Medicine		Applied biology/ecology		Chemistry	
	coef.	t	coef.	t	coef.	t	coef.	t
GNP per capita	0.0008	0.8340	0.0023*	2.4710	0.0034***	3.5710	0.0007	0.7540
Number Fields Core Membership	0.0243***	4.8640	0.0158***	4.2500	0.0507***	4.6820	0.0324***	4.9990
Human resources in S&T	-0.0002	-1.0670	0.0001	0.4880	-0.0001	-0.3480	-0.0003**	-2.6490
Public R&D expenditures	0.1750**	3.1890	0.0992*	2.2450	0.1010	1.4000	0.1210*	2.2320
Private R&D expenditures	0.0118	0.6050	0.0530**	2.7640	0.0339	1.0060	0.0228	0.9290
Relative Impact	0.0927***	3.9990	0.0421***	3.8260	0.0767***	3.9780	0.0263	1.7880
Publication Share by field	0.5880**	3.0700	0.3040***	4.2630	0.9040***	4.3590	0.4770***	3.7130
W x GNP per capita	0.0019	1.6150	0.0014	1.4720	0.0030*	2.1450	0.0008	0.6620
W x Number Fields Core Membership	0.0150	1.4220	0.0014	0.1360	-0.0046	-0.3290	0.0262**	2.6420
W x Human resources in S&T	0.0002	1.1920	0.00004	0.3690	0.0003*	2.1750	0.0001	1.0840
W x Public R&D expenditures	0.0775	0.9750	-0.0268	-0.4620	-0.0313	-0.3170	-0.0188	-0.2280
W x Private R&D expenditures	0.0376	0.9480	0.0429	1.1190	0.0516	0.7830	0.0571	1.4920
W x Relative Impact	0.0493	1.2230	0.0014	0.0630	-0.0330	-0.8070	-0.0015	-0.0490
W x Publication Share by field	0.1080	0.3740	-0.0491	-0.3610	-0.1020	-0.3020	-0.7040***	-3.777
ρ	0.1030*	2.2370	0.3480***	6.3250	0.2790***	7.5200	0.1950***	4.9480
Observations	1060		1060		1060		1060	
Log Likelihood	1451.6000		1668.2000		1010.2000		1436.9000	

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

The first column of Table 5 presents impact measures for Fundamental Biology. With regard to direct impact, we observe that a region's capacity for scientific knowledge production is decisive for its centrality. It is unsurprising that the quantity (number of publications) and quality (relative impact) of scientific production in the discipline have a positive impact on centrality in fundamental biology. Moreover, the public R&D expenditure and being core in other disciplines also play an important role. With regard to indirect effects, we observe no spatial spillover impacts on a region's network centrality. This result differs from findings in previous literature on the spatial dimension of knowledge production which consider the existence of spatial spillovers from surrounding regions. In fundamental biology, surrounding resources would not directly impact centrality. The total impact estimation confirms direct impact results. Moreover, being in a rich region or surrounding by rich regions, also positively influence the centrality of a region. Total impact estimates suggest that activities in the field and the level of public R&D expenditure particularly influence network positioning in this discipline. These results suggest that in Fundamental Biology, in order to be central, regions need a large amount of regional scientific resources.

The second column of Table 5 presents impact measures for Medicine. Every variable except Human Resources in Science and Technology has a significant positive impact. Direct impact estimates suggest that regional production in the field is significantly an important capacity factor for being central in Medicine.

Being surrounding by rich regions (i.e. regions with higher GDP per capita) contributes to being a central region. This result confirms the significance of economically based spillover effects for centrality in scientific networks (Wanzenböck et al., 2014). Such spatial dependencies may for example arise due to the location of universities, which often tend to be located in regions surrounding urban centres, with further consequences on cross-regional commuting flows between regions.

Table 5: Marginal effects estimates of changes in SDM regressors (first set of disciplines)

	Fundamental biology Mean	Medicine Mean	Applied biology/ecology Mean	Chemistry Mean
Direct effects				
GDP per capita	0.0009	0.0025**	0.0037***	0.0008
Number Fields Core Membership	0.0244***	0.0162***	0.0507***	0.0335***
Human resources in S&T	-0.0002	0.0001	-0.00004	-0.0003**
Public R&D expenditures	0.1750**	0.0985*	0.0989	0.1200*
Private R&D expenditures	0.0126	0.0587**	0.0384	0.0260
Relative Impact	0.0933***	0.0432***	0.0755***	0.0261
Publication Share by field	0.5820**	0.3050***	0.9030***	0.4430***
Indirect effects				
GDP per capita	0.0021	0.0032*	0.0052**	0.0010
Number Fields Core Membership	0.0194	0.0100	0.0129	0.0391**
Human resources in S&T	0.0002	0.0001	0.0004*	0.0001
Public R&D expenditures	0.1060	0.0117	-0.0014	0.0065
Private R&D expenditures	0.0419	0.0902	0.0811	0.0734
Relative Impact	0.0656	0.0236	-0.0141	0.0052
Publication Share by field	0.1700	0.0781	0.1850	-0.7440***
Total effects				
GDP per capita	0.0030***	0.0057***	0.0089***	0.0017
Number Fields Core Membership	0.0438***	0.0262	0.0636**	0.0727***
Human resources in S&T	-0.00002	0.0001	0.0004	-0.0002
Public R&D expenditures	0.2820**	0.1100	0.0975	0.1260
Private R&D expenditures	0.0545	0.1490*	0.1190	0.0994
Relative Impact	0.1590***	0.0668	0.0614	0.0313
Publication Share by field	0.7520*	0.3830	1.0890*	-0.3010

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Given the total impact estimates for our regional characteristics in Medicine, the pattern observed for direct effects has been partly reversed. Total impact estimates for Medicine show only significant positive effects for a region's GDP and private R&D expenditure. Positive capacities based on effects due to the level of public R&D expenditure, being core in other fields and activities and visibility in Medicine are removed when region-internal and external impacts are considered together in our regional arrangement. These results suggest the importance of being in a rich region or surrounded by rich regions where firms do R&D.

In Applied Biology (third column Table 5), the economic level of the region, the effect of being core in other fields and activities and visibility positively influence the centrality of the region. Direct impact estimates suggest that regional production in the field is one of the most important factors. Positive spatial spillover impacts on a region's network centrality can be observed for the estimates for GDP and Human Resources in Science and Technology. Thus network centrality seems to be related to the economic strength of neighboring regions. Total effects confirm the importance of the economic level of the region and surrounding regions. Moreover, the number of disciplines in which the region is core is an important factor. However, the most important impact is the production of publications in Applied Biology. Quantity of scientific output matters. Regional quality is not any more significant, which suggests that it is important to be surrounded by dynamic regions but not ones which are too good.

Table 6: Estimation results of fixed effects panel SDM (second set of disciplines)

	Physics		Science of the Universe		Engineering science		Mathematics	
	coef.	t	coef.	t	coef.	t	coef.	t
GDP per capita	0.0018*	2.2480	0.0013	0.8540	0.0017	1.7740	-0.0004	-0.2610
Number Fields Core Membership	0.0455***	4.4370	0.0810***	4.8210	0.0363***	4.6780	0.0573***	4.4870
Human resources in S&T	0.0001	0.6160	-0.0003	-1.3330	-0.0002	-1.1440	-0.0001	-0.6130
Public R&D expenditures	0.0617	0.9390	0.0027	0.0290	0.1710**	2.8140	0.2540*	2.3230
Private R& D expenditures	-0.0018	-0.0630	-0.0366	-0.7910	0.0121	0.5010	-0.0182	-0.3690
Relative Impact	0.129***	5.2520	0.1780***	5.0340	0.0399**	3.1100	0.0269**	2.7540
Publication Share by field	0.8150***	4.1380	0.6520	1.6280	0.6040***	4.3700	1.8330***	3.6260
W x GDP per capita	0.0008	0.6320	0.0050*	2.3380	0.0021	1.5520	0.0022	1.1420
W x Number Fields Core Membership	0.0145	0.9360	-0.0046	-0.1690	0.0184	1.6370	-0.0137	-0.5470
W x Human resources in S&T	-0.00002	-0.1530	0.0002	0.7840	0.0003*	2.0670	0.0003	1.6550
W x Public R&D expenditures	-0.1700	-1.8400	-0.1920	-1.3740	-0.1340	-1.4100	-0.1210	-0.7710
W x Private R&D expenditures	0.0255	0.622	0.0929	1.092	0.0414	0.857	0.147*	2.171
W x Relative Impact	-0.0762*	-2.4060	-0.0896	-1.6820	0.0513	1.8430	0.0082	0.3840
W x Publication Share by field	-0.4760	-1.7030	0.7680*	2.0810	0.0254	0.1070	0.7170	0.6590
ρ	0.0535	1.5320	0.1270**	3.0560	0.1930***	4.5700	0.0480	1.2550
Observations	1060		1060		1060		1060	
Log Likelihood	1043.6000		657.2000		1256.5000		667.1000	

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

For network centrality in Chemistry (last column of Table 5), the regional level of publications has a positive impact. More surprisingly, the relative impact of the region is not significant. This means that the quality of publications does not contribute to increasing a region's degree of centrality. It is the only field with such a result. The number of fields in which the region is already core and the level of public R&D expenditure positively affect centrality. Finally, although it is low, the level of Human Resources in Science and Technology has a negative impact, which is puzzling. In the Chemistry network, a positive spatial spillover impact can be observed for estimates of the number of core fields in surrounding regions. By contrast, the level of publications in Chemistry has a strong negative impact. This suggests that surrounding regions need to be leaders in other fields but not too productive in chemistry. Negative effects may, for instance, result from core-periphery relations between neighboring regions (Wanzenböck et al., 2014). The total impact reduces this negative spillover effect since only the number of core fields is significant. In

Chemistry, the production of publications and their visibility would not be so important from a pan-European perspective. By contrast, being core in different fields and surrounded by regions in different fields makes a significant contribution to increasing a region's centrality.

For network centrality in Physics (first column Table 7), at the regional level, the field's quantity of production and quality largely contribute to the centrality of the region. Being core in other fields and the level of GDP influence centrality as well. The only significant spillover effect has a negative impact and it is the relative impact of the surrounding regions. At the total effect, only being core in other disciplines and the GDP per capita are still significant. Direct and indirect effects for both quantity and quality in physics cancel each other out. This suggests a core-periphery structure of the location of the activities in physics. To be central, a region needs to be surrounded by dynamic regions in economic activities and sciences (other than in physics).

Table 7: Marginal effects estimates of changes in SDM regressors (second set of disciplines)

	Physics	Science of the Universe	Engineering science	Mathematics
	Mean	Mean	Mean	Mean
Direct effects				
GNP per capita	0.0018*	0.0015	0.0018*	-0.0003
Number Fields Core Membership	0.0451***	0.0802***	0.0369***	0.0564***
Human resources in S&T	0.0001	-0.0003	-0.0002	-0.0001
Public R&D expenditures	0.0580	-0.0039	0.1660**	0.2480*
Private R&D expenditures	-0.0013	-0.0334	0.0142	-0.0159
Relative Impact	0.1270***	0.1750***	0.0421**	0.0266**
Publication Share by field	0.8000***	0.6590	0.6020***	1.8150***
Indirect effects				
GNP per capita	0.0009	0.0055*	0.0028	0.0021
Number Fields Core Membership	0.0181	0.0070	0.0306*	-0.0109
Human resources in S&T	-0.00001	0.00015	0.0003	0.0003
Public R&D expenditures	-0.1740	-0.2110	-0.1210	-0.1110
Private R&D expenditures	0.0272	0.0995	0.0533	0.1520*
Relative Impact	-0.0721*	-0.0753	0.0703*	0.0104
Publication Share by field	-0.4650	0.9430*	0.1690	0.7990
Total effects				
GNP per capita	0.0027*	0.0070***	0.0046***	0.0018
Number Fields Core Membership	0.0632**	0.0872*	0.0675***	0.0456
Human resources in S&T	0.00008	-0.00015	0.00012	0.00021
Public R&D expenditures	-0.1160	-0.2150	0.0448	0.1370
Private R&D expenditures	0.0260	0.0661	0.0675	0.1370
Relative Impact	0.0550	0.0994	0.1120**	0.0370
Publication Share by field	0.3360	1.6020**	0.7700**	2.6140*

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

In the Science of the Universe (second column Table 7), the experience of being core in other disciplines and above all the relative impact of the region positively influence the centrality of the region. A positive spatial spillover impact can be observed for estimates of the GDP and scientific production in the field. Being surrounded by rich regions which produce many publications in Science of the Universe contributes to centrality. The total impact confirms the importance of the economic and scientific level of surrounding regions. Moreover, the number of disciplines in which the region is core is important. However, the positive effect of relative impact is removed. This means that to be central in the Science of the Universe a region needs to be surrounded by regions with a high level of scientific production but low relative impact (that means not too good).

For the Engineering Sciences network (third column Table 7), almost all the estimates are significant. This means that financial (GDP and Public R&D expenditures) and scientific resources (being core, production and quality of the research in engineering sciences) are the region-internal drivers. In particular, scientific production and public R&D expenditure have a strong impact. These impacts are reinforced by scientific production and the experience in being core in the surrounding regions. By contrast, public R&D expenditure has negative spillover effects even if it is not significant. This one is strong enough to cancel out the direct impact of public R&D expenditure in the total impacts.

For the Mathematics network, (last column Table 7), the resources dedicated to public R&D influence the centrality of regions. The main impact is largely due to the level of scientific production in the discipline. It is a surprise to note a positive spillover impact of surrounding private R&D expenditures. The total impact, only and largely accounts the level of scientific production. The relative impact is no more significant as both direct and indirect impacts seem to balance each other out.

4. DISCUSSION

This research brings several results according to the impacts of scientific and territorial resources on European regions network centrality. It highlights the differences between disciplines and stresses the importance to take into account territorial resources at various geographical scale.

The observed heterogeneity across disciplines shows how important it is to carry out disaggregated analysis. For instance, Wanzenbock et al. (2014), which adopted the same econometric methods but analyzed the scientific network at an aggregated level, found different results in terms of the effects of surrounding regions. Analyzing scientific networks without regard to disciplinary specificities could erase and hide important differences.

Thus, our results show that according to the disciplines, the role of internal resources differs and does not automatically improve the scientific network centrality. For instance, in fundamental biology, it is worthwhile to invest in both production and excellence to increase centrality. In mathematics, it is better to focus on excellence; the effort for scientific production would be useless at the global level. Finally, in physics, none investment on scientific internal resources gives some positive effects on centrality.

In more general terms, the observed heterogeneity raises the issue of the different roles that regional resources can play and consequently the different implications for policymaking. First of all, let us return to the interpretation of the results in the SDM method used. On the one hand, it is possible to use the direct effects and the indirect effects. This analysis can determine what influence each independent variable, i.e. the normalized degree of centrality. However, on the other hand, it is necessary to check if the results are still significant overall and, then to look at the sign and magnitude of the overall effect. Indeed only the analysis of the total effects makes it possible to identify which (direct or indirect) effect dominates.

The results can be organized around the various possible combinations between positive, zero or negative direct and indirect effects. In our opinion, each combination can be interpreted in terms of the role a territory could play. Three cases have been observed:

- The parameters of the direct and the indirect effects for a factor have the same sign. A strengthening territorial effect is in play. For example, if the parameter is positive, increasing the scientific production of the region and its neighbors increases the centrality of the focal region.

- The parameters of the direct and indirect effects for a factor are a different sign: there is a competitive effect between territories. For instance, the increase of its own scientific production would increase the centrality of the region but an increase by surrounding regions would have a negative effect on it centrality.

- The parameter of the direct effect is significant but, that of the indirect effect is not (or vice-versa): we assume that there is independence between regions. For instance, increasing regional scientific production would increase centrality but growth of scientific production among nearby regions would no impact on centrality.

These three possible combinations should be compared with the total effects results in order to verify if overall, territorial effects are still in operation or not.

In fundamental biology, territory seems generally independent, the indirect effect parameters are not significant and the total effects parameters, which are significant, are more or less the same as those of the direct effects. However, in engineering science, territory has a reinforcing role – the parameters of the direct and indirect effects, as well as those of total effects are positive. The surrounding regions have a reinforcing role and support local effects. This is particularly true for the quality of the science. This result shows that in this discipline, administrative territory boundaries should not be applied consistently in order to develop collaboration on scientific activities.

For the other disciplines, we have no overall result but different cases according to the variable taken into account. In mathematics, territories are more competitive than complementary. Indeed, the surrounding regions have a negative impact and, when we look at the total effect, only scientific production has a significant effect. In many cases (such as quality, private R&D, public R&D), the direct and indirect effects cancel each other.

In medicine, territories are in competition (even if we do not observe significant spillover effects), except in terms of economic development. Indeed, only economic factors (private R&D and GDP) are significant at the total effect level. This could mean that regions can become more central if they are surrounded by rich regions with private R&D activities but no science activities. The economic territory would be larger than the administrative region and play a reinforcing role. With regard to scientific activities, the regions would compete with each other.

In Science of the Universe, territory plays a particularly important role because the factors of the surrounding regions contribute the most (GDP and scientific production) to the centrality of the region, it is already core in other disciplines.

For the remaining four other disciplines, there are several similarities. We therefore propose to discuss them by the factors driving centrality rather than by the disciplines. One of the most interesting results is the impact of scientific activities (quantity or number of publications and quality or relative impact) in the field performed by surrounding regions. The territories are in competition for excellence in research. Indeed, for Physics, Science of the Universe, Applied Biology (and also in Mathematics and Medicine), the quality of the surrounding regions have a negative impact on centrality. That means that for these disciplines, there is a core-periphery structure with regard to the location of disciplines: if one region is central, the surrounding ones would do less good science. This has a clear implication in terms of research organization at a country level: it is unlikely that two regions that are good in sciences would be close to each other. Surprisingly the results are not the same for chemistry: the quality of science does not have any impact (direct or indirect).

In terms of scientific production, we observe a competition between territories in two disciplines. Indeed, scientific production has the same negative effect for physics and chemistry. If a region is surrounded by large producers in their fields, it is less central.

Being central in other disciplines (and/or complementarity between disciplines) increases centrality for almost all disciplines. Except in Mathematics and Applied Biology, there is a reinforcing effect from surrounding regions.

The diversity of the cases observed shows how important it is to carefully choose the relevant territorial scale for the development of research activities collaborations. Indeed, depending on the disciplines and factors taken into account, the territory does not play the same role. In general, our results can be summarized as follows; to explain the scientific centrality of a region, economic variables show a more strengthening complementarity between regions while scientific factors tend to be neutral or show competition between regions.

The various impacts of territories on centrality have some effects on public policy in the horizontal and vertical forms of governance approaches. Governance type should be selected according to the role played by the territory. We can therefore identify four potential cases by level of public intervention.

Table 8: Case of policy intervention

Case	Effect			Role of territories	Regional policy	Level of intervention
	total	direct	Indirect			
1	+	+	+	Reinforcing	Active	**Horizontal Multi-governance** – Incentive for coordination
2	+	+	Insignificant	Not relevant	Active	**Regional governance** – no interest in coordination
3	+	Insignificant	+	Larger scale	Not useful	**Vertical Multi-governance** – macro region level
4	+	+	-	Competition	Active, only if direct effect overcame indirect effect (less effective than case 1)	**Regional governance or nothing**

According to our results, two previously identified typical cases lead to "traditional" public policies. For fundamental biology, an independently-led regional policy will have the most chance of effectively increasing the region's centrality in the discipline.

For engineering sciences, policymakers wishing to optimize the effects of their policies need to coordinate their actions with surrounding regions. In such cases, regional policymakers have to foster horizontal multi-governance.

For other disciplines, policymakers need to carefully adapt their strategy; they have to shift from a cooperative to competitive paradigm depending on the driving factors. Table 9 summarizes when, according to the significant factors, regional policymakers should act alone and when they should cooperate. It should be noted that in our study, in the case of competition between territories direct and indirect effects cancel each other out for total effects.

For instance, to be more central in Mathematics, a region only needs to invest in the production of scientific publications. In Medicine and Applied Biology, policymakers should develop horizontal multi-governance policies for economic factors and act at a regional level for private R&D in the case of Medicine and scientific production for Applied Biology.

Table 9: Policy intervention by scientific disciplines

Scale of the territory	Regions only	Collaboration between regions	Competition between regions	Changing scale of the territory
Policy intervention	**Regional**	**Horizontal governance**	**Regional**	**Vertical multi-governance**
Fundamental Bio	All			
Engineering sc.		All		
Physics	GDP Core			
Science of the Universe	Core			Scientific production GDP
Mathematics	Scientific production			
Chemistry		Core		
Medicine	Private R&D	GDP		
Applied Biology	Scientific production Core	GDP		

The complex picture that our analysis allows us to draw shows that policymakers should adapt their interventions according to disciplinary specificities. This is true for two main reasons: (1) not all variables play the same role for each discipline, and (2) the territorial scale of intervention can differ significantly according to the discipline and variable taken into account.

Our analysis does, however, suffer some limitations. The first concerns the data on scientific activities. Scientific co-publications only capture a part of actual scientific collaborations. Moreover, coverage of different disciplines is heterogeneous. In particular, Humanities and Social science coverage is very low in WoS and it has not been possible to analyze these disciplines too. Second, the explanatory variables are relatively few and standard. Taking into account other variables would imply reducing the number of regions analyzed, and therefore, most likely, covering the most peripheral regions less. Moreover, our research identifies that there are positive or negative spillovers on centrality according the disciplines. Further research is needed to explain these different results. Finally, the relationship between network centrality and excellence deserves further investigation.

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La centralité des régions européennes dans les réseaux scientifiques : le rôle des ressources territoriales

Résumé - Cet article fournit un cadre original pour examiner les réseaux de collaborations scientifiques au niveau des régions européennes. Quels sont les facteurs qui conduisent au phénomène de clusterisation observé ? Quel est le rôle des territoires ? L'objectif de cet article est d'apporter des résultats empiriques permettant de fournir des éléments de réponse à ces questions. Pour cela, nous nous appuyons sur l'analyse des collaborations scientifiques entre les régions européennes dans huit disciplines différentes (Médecine, Chimie...) sur la période 2001-2011. Une mesure de la centralité normalisée est proposée. Nous testons l'impact des ressources territoriales et des spécificités scientifiques sur la centralité des régions dans chacune des disciplines. L'analyse met en avant une forte hétérogénéité entre les disciplines, montrant l'importance de réaliser des analyses spécifiques pour chacune d'elles. Les résultats montrent également les différents rôles que jouent les ressources locales, selon les disciplines. Enfin, l'article discute de l'implication de ces résultats en termes de politiques de la science et de l'innovation.

Mots-clés

Réseaux scientifiques
Régions européennes
Centralité
Ressources territoriales
Politiques de la science et de l'innovation