

Regional technological diversification and the global network of embodied R&D: Evidence from the exposure of European regions

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Abstract

We investigate the role of the Global Network of embodied R&D (GNRD) in the regions' capacity to diversify their technologies. We maintain that inventive efforts of regions in hub-industries of the GNRD increase their "exposure" to global R&D knowledge and foster their capacity of technological diversification, attenuating the role of relatedness in that. Using new raw data of the GNRD, we test these hypotheses on a panel of NUTS2 regions for 13EU countries over the period 2004-2019. Results confirm our hypothesis with interesting nuances and suggest that the regional positioning in the GNRD represents a crucial leverage of technological diversification.

Keywords: relatedness, global innovation networks, diversification, revealed technological advantage

JEL codes: R11, R15, O31, O33

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1. Introduction

The gain of new technological specializations over time is a fundamental mechanism through which regions can increase their growth opportunities, escape lock-in knowledge traps, and react to external shocks (Davies & Marè; 2021; Hane-Weijman et al., 2021). However, technological diversification is not an easy process and rather depends on the regional endowment of a proper mix of scientific, techno-economic, and socio-institutional factors (Boschma, 2017).

A large body of research has shown that regions tend to diversify in new technologies relying on similar capabilities of the existing ones and, in this sense, cognitively “related” to them (Balland, 2016). “Relatedness” makes regional diversification unfolds as the “branching” of existing technologies (Tanner, 2014). However, a broad set of regional factors affect this branching process by either complementing or substituting the role of relatedness (for a review, see Santoalha, 2019). Among these factors, an important one is represented by the linkages that regional actors entertain with players outside their local boundaries. Indeed, these extra-regional linkages can allow regions to access external knowledge and capabilities that could be internally missing or scarce, and feed new recombinations of their knowledge base and escape the risk of getting locked in existing technologies (Ascani et al., 2020; Hesse & Fornahl, 2020; Miguelez & Moreno, 2018).

As Balland and Boschma (2021, p. 1059) have recently recognised, “[...] *studies on regional diversification have primarily focused on regional capabilities, but neglected the role of interregional linkages [...].*” In particular, as recently recognised by Boschma (2021), limited attention has so far been dedicated to the relationship between regional technological diversification and Global Value Chains and Networks, representing pivotal circuits of economic transactions and knowledge diffusion across spaces around the World (Cooke, 2017).

In this paper, we contribute to filling this gap by proposing an original focus on the “Global Network of embodied R&D” (henceforth GNRD): the network of industries through which R&D is generated and exchanged across the World via the intersectoral flows of commodities in which R&D gets embodied (Fusillo et al., 2021).

We argue that the GNRD is a pervasive network and a crucial source of innovative knowledge, and regions can increase their access to it by putting inventive efforts in the (national) industries that constitute “hubs” in the same network. Following an “augmented” relatedness approach, we expect that being exposed to the GNRD increases the regional capacity to diversify in technological terms. We also expect that the same exposure makes this diversification more explorative by attenuating the role of relatedness in favouring its unfolding.

Using raw data from a recent analysis of the GNRD (Fusillo et al., 2021), we propose a new network-based indicator of the regional exposure to the GNRD and find confirming evidence of our expectations with respect to the EU13 (NUTS2) regions, observed over the period 2004-2019.

The rest of the paper is structured as follows. In Section 2, we review the background literature and illustrate the role of the GNRD and the relative regional exposure. Section 3 presents our dataset and the empirical application, and Section 4 illustrates the main results. Section 5 concludes with a discussion, policy implications, and future research avenues.

2. Background literature

2.1. Regional technological branching, extra-regional linkages, and global innovation networks

One of the key tenets of the economic geography literature on regional technological diversification is that new technologies typically “branch” out of existing ones (Tanner, 2014), drawing on “related” capabilities (Boschma, 2017; Balland et al., 2019). Following this stream of literature, a wide set of local factors have been proved to account for technological branching in a relatedness framework, and evidence has also been obtained about their role in moderating the effect of relatedness: either by reinforcing or attenuating it (for a review see Santoalha, 2019). Among these factors, the linkages that regional actors entertain with players outside of their local boundaries have not yet received comprehensive attention.

In a very schematic way, these linkages have been classified into: (i) *regional inflows of non-local actors* and (ii) *non-regional linkages of local actors*. As for the former, attention has been chiefly posed on inward Foreign Direct Investments (Zhu et al., 2017; He et al., 2018; Crescenzi et al., 2015; Castellani et al., 2022), the interregional mobility of key individuals, like managers, skilled employees, scientists and engineers, and migrant inventors (Miguelez and Morrison, 2021; Binz et al., 2016; Hartog, 2015; Bahar & Rapoport, 2014; Trippel, 2013), and the entry of foreign entrepreneurs and firms (Neffke et al., 2018; Elekes et al., 2019). As far as *non-regional linkages* of local actors are concerned, the focus has been nearly exclusively placed on trade relationships, showing the role of export specialisation of neighbour regions (Boschma et al., 2016) and of the imports on which new export products can rely (Andersson et al., 2013).

Notwithstanding their importance, these extra-regional relationships are far from exhausting the array of channels through which new knowledge can be pumped in and absorbed by regions and, in turn, increase their capacity to diversify their technologies. Among these, an important understudied channel is represented by the regional participation to the international networks of commodities, labour and knowledge through which the value of industries is created and appropriated across the

globe: that is, Global Value Chains (GVC) and other global networks, like Global Production Networks (GPN) and Global Innovation Networks (GIN), into which the analysis of the former has evolved (Cooke, 2017).

As recently acknowledged by Boschma (2021), regional diversification analysis has drawn only limitedly on the vast and varied literature about Global Value Chains (GVC) (Kano et al., 2020). Among the heterogeneous streams of this research body, a particularly relevant one is that on Global Innovation Networks (GIN).¹ In brief, these are networks of actors – both firm and non-firm based – collectively involved, not only in producing and exchanging commodities and goods (Ambos et al., 2021), as in GVC, but also and above all in creating and diffusing innovative knowledge across the spatial contexts in which they are located and embedded (Wagner and Leydesdorff 2005; Ernst 2009; Cooke 2013; Chaminade et al. 2016).

Drawing on and extending this latter body of studies, in the following we look at the relationship between GIN and technological diversification in a threefold novel way. First, we exploit new data availability to identify and investigate a specific kind of GIN, representing the “Global Network of embodied R&D” (GNRD) (Fusillo et al., 2021). Second, we propose a novel way to investigate the extent to which regions participate to such a network by proxying this participation with their “exposure” to the GNRD hub-nodes. Third, we argue that such exposure enriches the region with innovative knowledge of a global kind, which enhances its technological diversification abilities and moderates the role of relatedness for that to happen.

2.2. The Global Network of embodied R&D (GNRD)

R&D is notably one of the most important innovation inputs, as it represents the primary source of new knowledge creation for firms and organisations that invest in it (Cohen and Levinthal, 1990; Lau and Lo, 2015). R&D efforts are highly risky, costly, and often of such a scale to require the involvement of multiple individual partners (e.g., firms and inventors), who interact among them on joint projects from different locations by giving rise to R&D networks (Tomasello et al., 2017). These networks are made up of *purposeful* R&D interactions among actors (nodes) that are increasingly dispersed in geographical terms, among which innovative knowledge is transferred and circulated in a disembodied way, without the need of getting encapsulated in any material support (physical or

¹ In addition to GIN studies, important insights for the understanding of regional diversification also come from other three connected research streams about: i) GVC and “competence upgrading” of local clusters; ii) GVC and Geography of Functions; iii) Global Production Networks (GPN). While these are all sources of important conceptual and empirical inputs (for which see Boschma, 2021), the GIN approach appears to us more cogent for the understanding of regional technological diversification.

human capital) (Scherngell, 2021). The international geographical scale to which the networks at stake may lead can provide the regional nodes that are part of them with the opportunity of accessing novel (e.g., foreign) knowledge feeding technological diversification processes.

An as much widespread source of external knowledge for regions is represented by R&D networks constituted by flows of innovative knowledge occurring among the economic units that invest in R&D through their underlying techno-economic relationships. An important case of them is represented by flows of R&D expenditure (edges), which circulate among sectors (nodes), getting “embodied” in intersectoral flows of intermediate commodities and goods (Leoncini and Montresor, 2003). The extant literature has so far analysed these intersectoral networks of embodied R&D at the country or, at most, cross-country level (in a comparative fashion) by resorting to national input-output tables (see, among others, Leoncini, Maggioni, & Montresor, 1996; Montresor and Vittucci Marzetti, 2008; Guan and Chen, 2009; Soo and Ghazinoory, 2011; Taalbi, 2020). Conversely, the lack of extensive data about worldwide input-output tables and sectoral disaggregated R&D expenditures has delayed the construction and investigation of what can be called the Global Network of Embodied R&D (GNRD): the network that maps industries of different countries in their supplying and acquiring R&D, in an embodied way, across the globe.

Taking stock of newly available data, Fusillo et al. (2021) have recently proceeded to the construction and analysis of such a network, whose generic link “reports the R&D expenditure performed over time by each industry, within each country, that diffuses to the other industries, of the same country and other world countries, via the correspondent flows of intermediate goods, domestic and foreign, respectively” (Fusillo et al., 2021, pag. 7).² Based on this structure, the GNRD can be seen as a particular case of GIN, made up of the circulation of innovative knowledge with a high global stance. On the one hand, this knowledge is generated by the R&D efforts undertaken by different (in principle, all) countries across the World. On the other hand, such globally produced knowledge is exchanged across countries through pervasive national and international transactions of intermediate commodities. In light of that, the GNRD can represent the source of truly global innovative knowledge for regions from which their technological diversification capacity could greatly benefit (see Section 2.3).

Nevertheless, linking regions to the GNRD and evaluating its role for regional technological diversification is a difficult task. In the absence of regional input-output tables that extend beyond Europe (Ivanova et al., 2019; Thissen et al., 2018) and, above all, without industry-disaggregated

² The nodes of the GNRD are thus country-industry nodes, like the German “manufacture of motor vehicles, trailers and semi-trailers” or the Japanese “manufacture of computer, electronic and optical products”.

R&D expenditure data at the regional level, it is not possible to have a direct measurement of the regional participation to the GNRD, similar to that obtained about the regional participation to standard GVC (Colozza and Pietrobelli, 2021).³ However, as we will argue in the following section, in order to bypass these difficulties, the local capacity to take stock of the external knowledge at stake can be investigated by looking at how “exposed” regions are to the “central” industry-country nodes of the GNRD.

2.3. The regional exposure to GNRD central nodes and technological diversification

Like in every other kind of network, GNRD (country-industry) nodes have different importance. In network analysis, this importance is often operationalised with the concept of “centrality” in various respects. Some country-industries of the GNRD are more widely innervated (in-degree centrality) by the R&D knowledge generated at the global level. In contrast, some others can contaminate, in terms of R&D knowledge, the other nodes to a comparatively more significant extent (out-degree centrality). The centrality role of GNRD nodes can also be ascertained by combining these two inward and outward dimensions and singling out the country-industries that are more active in releasing R&D to key-absorber nodes at the global level than in absorbing R&D from global key-diffuser ones. By exploiting this net diffusing property, which we measure with the network idea of “net hubs” as discussed in Section 3.2, we are able to identify the poles of the GNRD with the greater potential of diffusing globally exchanged R&D knowledge.

As previously mentioned, these hubs are country-industry and not region-industry nodes. However, regions can be, at least indirectly, linked to them on the basis of two considerations. First, as the embodied R&D exchanges observed at the national level for a certain industry are the aggregate outcome of those made by the same industry across its constituting regions, we can reasonably argue that regions contribute to, as well as benefit from, the GNRD centrality eventually played by the corresponding industry of their own country. To clarify, let us suppose the German “electronics” sector is identified as a GNRD hub. This implies that the sector is a net conveyer of (embodied) global R&D-based knowledge, not only to the whole German country but also to its constitutive regions, whose global relationships are the main responsible for the net hubness role of the German electronic sector.

³ Because of the discussed shortage of sufficiently fine-grained data, the construction of an interregional version of the GNRD, whose nodes are region-industries, is to date technically unfeasible. This is due to a lack of required data at the regional level, which regional modellers have already faced in the literature, and for whose solution different approaches have been proposed: like the development of compensation methods to estimate inter-industry and inter-regional trade effects and of methodologies to regionalize national input-output coefficients (see, among others, Flegg et al., 1995; McCann and Dewhurst, 1998; Spoerri et al., 2007; Bonfiglio, 2009; Kowalewski, 2015).

The second and more salient consideration is that the opportunity of contributing to and benefiting from the hubness of a given sector of their own country in the GNRD can be exploited by regions to a variable extent. Depending on the weight the industry at stake is given in the regional innovation systems that have contributed to its hubness in the country, each region could be thought to have a heterogeneous “exposure” to the GNRD hubs. In other words, the higher the innovative relevance a certain industry finds in a region, the higher the contribution and, in turn, the exposure of the same region to the GNRD hub eventually identified by the same industry within their country. As discussed in Section 3, such an innovative relevance can be ascertained in different ways that are crucially affected by data availability issues.

In the light of their characteristics, GNRD hubs can represent a potential element of “structural change” for regions, similar to that identified by the literature in foreign firms and foreign direct investments (Neffke et al., 2018; Castellani et al., 2022). Hence, regions can exploit their exposure to GNRD hubs in order to i) increase their technological diversification capacity and ii) make it more explorative (i.e., less reliant on relatedness).

As far as point i) is concerned, by increasing its inventive involvement in an industry that constitutes a hub for its country in the GNRD, a region gets more and better exposed to the innovative knowledge that is created at the global level, through the inter-country-industry exchanges that constitute the network. Such a gain of exposure can be expected to increase the regional capacity to absorb global R&D-based knowledge and use it for novel recombinations of locally available ones, which are at the basis of the entry of new technologies (Boschma, 2017). In brief, we maintain that a higher exposure to the hubs of the GNRD increases the local-global mix of regional knowledge, the regional capabilities of Schumpeterian recombinant innovations that this entails, and its capacity of technological diversification. Accordingly, we put forward the following hypothesis:

Hp1: *The higher the GNRD regional exposure, the higher the regional capacity of technological diversification.*

As far as point ii) is concerned, having access to more global innovative knowledge (through higher exposure to the GNRD hubs) not only enriches the opportunities of recombinant innovations but also increases their novelty with respect to pre-existing technologies. As discussed in Section 2.1, the regional branching literature has shown that some of its drivers might mitigate the role of relatedness to pre-existing specialisations in making new ones more likely to enter the region. In other words, these factors can attenuate the cognitive constraints that the existing knowledge base and the advantages of being closer to it pose to the development of unrelated technologies (e.g., Montresor & Quatraro, 2017, 2020). Although conditionally on the level of relatedness, this has especially

emerged with respect to the external global knowledge brought to the region by FDI and multinational activities (Zhu et al., 2017; Neffke et al., 2018; Elekes et al., 2019; Castellani et al., 2022). As the R&D-based knowledge generated in the GNRD and conveyed by its hub industries is also of a global nature, we expect that it could also enable regions to overcome the stickiness of local capabilities and jump further into less related new technologies. We thus put forward the following second hypothesis:

Hp2: *The higher the GNRD regional exposure, the more explorative (i.e., less cognitively related) the regional capacity of technological diversification.*

3. Empirical application

We test our research hypotheses on a sample of 197 European NUTS-2 regions for the EU13 (i.e., the EU15 excluding Greece and Luxembourg) over the period 2004-2019. This sample results from the merge of three datasets: the OECD REGPAT database (October 2021 version), from which we get regional patent data; the European Regional Database maintained by Cambridge Econometrics, accessed to collect information on regional controls; and the raw data of the GNRD over the period 2009-2013 made available by Fusillo et al. (2021), to construct our focal regressor.

3.1. Dependent variables

Following Montresor & Quatraro (2017), we look at the technological diversification of regions in aggregated terms without focusing on the specific technologies that enter the regional knowledge base. Furthermore, we propose to disentangle the effects of higher exposure to GNRD on technological diversification at its extensive and intensive margin. At the extensive margin, the focus is on the regional capacity to extend its existing set of technological specialisations through the “simple” entry of any new technology into the local knowledge base. This is captured by a dummy, $Div EM_{rt}$, taking value 1 if, at time t , region r acquires at least one new technological specialisation - that is, a specialisation the region did not have at $t-k$ (with $k = 1$ as a benchmark) – and such specialisation is kept for (at least) one year (at $t+1$). This is done to attenuate the potential distortion introduced by inherent patent volatility. Formally, $Div EM_{rt}$, equals 1 if:

$$\sum_s NewRTA_{rst} \geq 1 \quad (1)$$

and:

$$RTA_{rst+1} \geq 1 \text{ for at least one } NewRTA_{rst} \quad (2)$$

In the previous equations, $NewRTA_{rst} = 1$ if $RTA_{rst} \geq 1$ and $0 \leq RTA_{rst-1} < 1$, and RTA_{rst} is a dummy, which is equal to 1 if region r has a Revealed Technological Advantage in technology s , and 0 otherwise. Following the extant literature, this is the Balassa indicator, or Location Quotient, built up on the basis of technology-specific (at the 4-digits CPC level) regional and World patent data (see Montresor & Quatraro, 2017).

At the intensive margin, we instead look at region r 's capacity to intensify the gain of new technologies by getting a higher number of acquired technological specialisations. Thus, we construct the variable $Div IM_{rt}$, which simply counts the number of new specialisations that region r acquires in t , which were not present at time $t-1$. Formally:

$$Div IM_{rt} = \sum_s NewRTA_{rst} \quad (3)$$

where $NewRTA_{rst}$ is defined as above.

3.2. Main regressors

Our new main regressor is represented by the exposure of region r to the GNRD, $ExposGNRD_{rt}$, and is constructed in two steps. In the first step, we make use of the inter-country / inter-sectoral network of embodied R&D flows of the GNRD built up by Fusillo et al. (2021) - for which construction details are provided in Appendix A - and identify its country-industry "net hubs". As anticipated in Section 2.2., the net hubness property identifies those country-industry nodes whose centrality in diffusing large amounts of embodied R&D toward highly attracting industries (hubs) is more relevant than their ability to acquire large amounts of embodied R&D flows from highly diffusing industries (authorities). Formally, the net hub indicator, H_{ic} , of industry i in country c is defined as a dummy variable taking value 1 if the ratio between its network hub score, Hub_{ict} , and its authority score, $Authority_{ict}$, is greater or equal to 1:

$$H_{ic} = 1, \text{ if } Hub_{ict}/Authority_{ict} \geq 1 \quad (4)$$

In Eq.(4), Hub_{ict} measures the amount of embodied R&D diffusion towards the most attracting industries of industry i in country c at time t ; $Authority_{ict}$ measures, instead, the amount embodied R&D acquisitions from the most diffusing industries.⁴

As we noticed, the GNRD is only observable from 2009 to 2013. Moreover, the rank of centralities tends to be relatively stable across time, as changes in the structure of GNRD, made up of R&D expenditure embodied in the international and intersectoral flows of intermediate goods, are smooth. These considerations induced us to focus on a static identification of the net hubs indicator, H_{ic} , where the hub to authority ratio for each industry in each country is uniquely set equal to 1, if it amounts to 1 in at least 3 out of 5 available years (the 2009-2013 GNRD available time-span).

In the second step, we measure the different exposure of regions to the country-industry GNRD hubs. We do that by proxying the weight the relevant industry is given in a regional innovation system by the intensity of regional inventions in that industry. To begin with, we match CPC technology classes with the classification of economic activities at the ISIC rev.4 four-digit level, using the concordance tables proposed in Lybbert and Zolas (2014). We then simply assign regional patents to the corresponding economic sector and count the number of unique inventors residing in a given region, active in each industry. This inventors' intensity weight is then used to capture the extent to which regions participate and benefit from the GNRD hubs of their country. Formally, region r 's exposure to the GNRD is defined as:

$$ExposGNRD_{rt} = \frac{(\sum_{i=1}^I Inventors_{i,r,t} * 1[H_{i,r \text{ in } c}])}{\sum_{i=1}^I Inventors_{i,r,t}} \quad (5)$$

where $Inventors_{i,r,t}$ is the number of active inventors in industry i of region r at time t ; $H_{i,r \text{ in } c}$ is the net hub indicator of industry i in the country c to which region r belongs and $1[H_{i,r \text{ in } c}]$ is the indicator function, taking value 1 if the industry i of region r (in country c) is identified as net hub according to equation 4. In brief, the regional exposure variable measures the share of regional active inventors in country-hub industries (as derived from the inter-country inter-sectoral GNRD) over the total number of inventors in the region.

Figure 1 offers a graphical visualization of the geographical distribution of our GNRD exposure variable at the beginning (2004-2008, panel a) and the end (2014-2018, panel b) of our reference period. Boundaries are outlined in black, while regions are coloured according to the quintile rank of the distribution, where darker colors indicate higher quintiles. Regions highly involved in hub

⁴ Appendix B reports the analytical definition of the hub and authority score indicators of a network node.

industries are concentrated in Western European countries, like France, Austria and Germany. High levels of exposure can also be found in Northern European countries, like Swedish regions, and in Portugal. Furthermore, the geographical distribution of the indicator is also relatively stable over time.

[INSERT FIGURE 1 ABOUT HERE]

The identified picture apparently reveals a sort of atypical geography. Quite interestingly, this does not resemble the distribution of other regional indicators of global linkages, which could be deemed related to the exposure at stake, like, for example, those based on the multinational activities of regional firms. With respect to the same periods of Figure 1, Figure 2 reports the regional stock of FDIs, inward and outward.⁵ This distribution is more homogeneous and only slightly overlapping with that of GNRD exposure, exhibiting concentration in regions around capital and the mostly advanced cities. This reveals that our proposed indicator looks beyond FDIs and multinationals activity and thus requires closer inspection.

[INSERT FIGURE 2 ABOUT HERE]

The second independent variable in our diversification analysis is represented by the relatedness of the existing regional technological specialisation to the newly acquired ones. Given the regional level of our technological diversification variable, we still follow Montresor and Quatraro (2017) and construct, for each time period t , the average relatedness density, $AvRD_{rt}$, that the new technologies of region r reveals with respect to its pre-existing ones at $t-1$. For the construction steps of this variable, see Appendix C.

3.3. *Econometric strategy*

Our econometric strategy consists of two sets of two-way panel fixed-effects models estimated through OLS.⁶ In the first set, we test for $Hp1$ by estimating the following model:

⁵ The stock of FDI is calculated by applying the Perpetual Inventory Method (PIM) to the yearly sum of inward and outward FDIs located in a given region, using a depreciation rate of 15%. Data on the greenfield cross-border investment projects are extracted from the fDI Markets database.

⁶ Given the dichotomic nature of the extensive margin diversification variable, in the specification with $DivEM_{rt}$ as dependent variable this implies that a linear probability model (LPM) is employed.

$$y_{rt} = \alpha + \beta_1 AvRD_{rt} + \beta_2 ExposGNRD_{rt-1} + \beta_3 \log(GDP_{rt-1}) + \theta_r + \varphi_t + \varepsilon_{rt}$$

where y_{rt} represents, in turn, the dichotomic (extensive margin) and the continuous (intensive margin) version of the regional diversification variable, $Div EM_{rt}$ and $\log(Div IM_{rt})$, respectively; $AvRD_{rt}$ is the average relatedness density, and $ExposGRDN_{rt}$ the regional exposure to the GNRD.

In addition to our focal regressors, we control for regional growth by including the logarithm of Gross Domestic Product in the previous year ($\log(GDP_{rt})$), for regional (NUTS2) fixed effects θ_r , to account for region-specific time-invariant unobservables, and for year fixed effects φ_t , to adjust for common shocks in the period of analysis. ε_{rt} is an idiosyncratic error term.

In the second set of estimates, for both model versions (with extensive and intensive diversification), we augment the previous model by adding an interaction term between $ExposGNRD_{rt-1}$ and $AvRD_{rt}$, through which we test for our Hp2. In all specifications, we cluster the standard errors on NUTS2 regions to account for heteroskedasticity.

In concluding our analysis, in order to better address the extent to which the regional exposure to the GNRD affects regional technological diversification at the intensive margin, we run quantile regression estimates of the model with respect to $Div IM_{rt}$. More precisely, we use panel quantile regression with regional and year fixed-effects following Canay (2011), and we weight each model by the population density to have more balanced interquantile estimates.

Tables 1 and 2 report the main descriptive statistics of our variables and their pairwise correlations, respectively.

[INSERT TABLE 1 ABOUT HERE]

[INSERT TABLE 2 ABOUT HERE]

4. Results

Table 3 reports the results of our baseline model. Columns 1 and 3 show the estimated coefficients when the regional technological diversification is computed at the extensive margin ($Div EM$), while Columns 2 and 4 refer to the same variable at the intensive margin ($Div IM$).

[INSERT TABLE 3 ABOUT HERE]

The regional exposure to the GNRD appears, *per se*, positive and statistically significant, but only at the 10% level with respect to *Div EM* (column 1) and at a higher level (5%) with respect to *Div IM* (column 2). This provides only partial support to our Hp1, suggesting that the knowledge that arguably enters the region through the exposure to the GNRD is positively associated with regional technological diversification. Yet, it is more functional to the intensity of regional technological diversification rather than to the simple acquisition of the relative capacity to do so.

The region's capacity to diversify its technologies over time correlates positively with the relatedness between those entering its knowledge space and its pre-existing ones (the AvRD coefficient is positive and significant). Furthermore, technological diversification is apparently easier for larger regions (the GDP coefficient is positive and significant).

Moving to Hp2, Columns 3 and 4 reveal that, when conditioning the effect of GNRD on relatedness, our focal regressor turns out highly statistically significant (1% level). Furthermore, confirming Hp2, the estimated interaction term is negative and highly significant. This signals that the exposure to GNRD in fact provides regions with an access to global innovative knowledge that increases the novelty of the knowledge recombinations underlying diversification, by mitigating the cognitive constraints of the pre-existing knowledge base on the development of new specialisation. This occurs both with respect to *Div EM* and *Div IM*, and suggests that a higher exposure to the global R&D network might also be a crucial leverage for regions to overcome the stickiness of their local capabilities and specialise in newer and less (more) related (unrelated) technologies.

In order to shed further light on the role of our focal regressor, we investigate whether threshold effects are in place when looking at the role of *ExposGNRD* in regional technological diversification at the intensive margin. To address this point, in Tables 4 and 5, we report the results of quantile regressions in the absence and presence of the interaction term, respectively. Table 4 shows that, while average relatedness is still positive and strongly significant for all the four reported quantiles (and the same holds for GDP), the exposure to the GNRD is only significant for the higher quantiles of the distribution (i.e., q75 and q95). This suggests that the exposure to international knowledge operates more effectively when relevant diversification processes are already set and ongoing (with respect to *Div EM*), thus relying on the experience conveyed to regions by a strong intensity of already acquired new technologies (i.e., q75 and q95 of the distribution of *Div IM*).⁷

[INSERT TABLE 4 ABOUT HERE]

⁷ Further graphical evidence is provided in Figure D1 in Appendix.

When the quantile estimates are repeated by adding the interaction term between *ExposGNRD* and *AvRD*, the results in Table 5 appear consistent with those reported in Table 3 (Column 4), both in signs and statistical significance. The increase in the magnitude of the *ExposGNRD* coefficient is confirmed, showing a significant estimate already near the median of the distribution. As Figure D2 in Appendix reveals, the magnitude of the estimated coefficient for the interaction term shows an overall decreasing pattern, though this drop is not monotonic.

[INSERT TABLE 5 ABOUT HERE]

In order to check for the robustness of our main findings, we finally perform a sensitivity analysis by developing an alternative indicator of the regional exposure to GNRD, which refines the way in which industry “centrality” is defined in the relative indicator (see Section 3.2). More precisely, the centrality of a given industry i in country c is calculated as the sum of the GNRD flows out-going from all countries in industry i . Each of them is, then, respectively weighted by the share of in-flows the focal country c receives from the other countries in industry i , out of country c total in-flows in the focal industry. The rest of the construction is then repeated with respect to the new centrality score (see Appendix D for details). Table D1 in the Appendix shows that the estimation results using the alternative regional GNRD exposure variable are robust across the board.

5. Conclusions

The regions’ capacity to renew their knowledge base by diversifying the technological specialisation portfolio represents a crucial leverage of local development, through which escaping lock-in traps in pre-existing knowledge domains and triggering resilient reactions to shocks that make them obsolete. This capacity has been shown to rely on a wide set of factors, the majority of which refer to and interoperate with the regional capabilities of branching existing technological competencies into new related ones. Regional external drivers of technological diversification have instead found only limited attention in the literature, which has remained so far nearly silent about the role played by the regional participation to Global Value Chains and Global Networks of different nature. Given the extensive evidence on the role plaid by the latter in innovation and “competence upgrading” of regions, this represents an unfortunate gap.

Building on the relevance of R&D for technological development and on its global geography, the present paper contributes to filling this gap by focusing on the network that emerges by mapping the flows of R&D knowledge embodied in inter-industry exchanges of commodities across world countries: in brief, the Global Network of embodied R&D (GNRD). Using new raw data for the

GNRD construction (Fusillo et al., 2021), we propose a novel methodology to connect regional industries to the hub (country-industry) nodes of the GNRD. Our empirical analysis is carried out on EU13 NUTS2 regions over the period 2004-2019 and aims at investigating whether the regional exposure to the GNRD significantly accounts for their technological diversification.

Results suggest a positive relationship between regional technological diversification and the exposure to the GNRD with a number of nuances and related policy implications. First, we find that the positive association between regional exposure to GNRD and technological diversification is stronger with respect to the region's capacity to intensify its diversification process (in terms of new technological entries) than with respect to engaging in new diversification paths (through a new technological entry). Accordingly, directing regional inventive activities toward industries that can give better access to the GNRD serves more to widen the spectrum of new technological specialisation than to simply penetrate the domain of the still unmastered ones. Second, the estimated moderating role on relatedness suggests that a higher exposure to the GNRD enables regions to diversify in a more unrelated way. Thus, strengthening regional exposure to innovative knowledge that is created at the global level, through policy actions that prioritise regional contribution/benefit of central nodes in the GNRD, could be a leverage to escape the lock-in that excessive path-dependence may engender. Third, the contribution of the GNRD to the intensity of technological diversification mainly accrues to regions with the highest level of such intensity. This suggests that pushing unconditionally on the GNRD exposure is not ubiquitously efficient. Prioritising inventive activities in central GNRD industries works more effectively in reinforcing existing virtuous diversification patterns than in enabling still incipient ones.

The results of our empirical exercise are not free from limitations. The main one is represented by the indirect connection we established between regions' diversification and the GNRD, being the latter represented by country-industry nodes. Future research may overcome such limitation by calling for greater efforts toward the provision of extensive regionalised worldwide input-output tables and sectoral disaggregated R&D expenditures. A second limitation is represented by the focus that GNRD implicitly poses on formal (i.e., R&D-based) inventive efforts and embodied channels of knowledge diffusion. In this respect, enlarging the scope of the retained innovative flows would require more systematic data than those currently available. Nevertheless, by focusing on the role of international linkages, this work represents a novel and relevant contribution to positioning the analysis of regional technological branching in a more global setting of determinants.

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TABLES

Table 1. Descriptive statistics

	N	Mean	St. Dev.	Min	Max
$(\log)Div\ IM_{rt}$	3,100	3.849	0.742	0	4.727
$Div\ EM_{rt}$	2,892	0.957	0.202	0	1
$AvRD_{rt}$	3,100	0.112	0.042	0	0.214
$ExposeGNRD_{rt-1}$	3,085	0.108	0.148	0	0.873
$ExposeGNRD_{rt-1} * AvRD_{rt-1}$	3,085	0.013	0.019	0	0.150
$(\log)\ GDP_{rt-1}$	3,085	10.657	0.846	6.924	13.494
$(\log)\ popDens_{rt-1}$	3,085	5.190	1.213	1.194	9.322

Table 2. Pairwise correlation matrix

	1	2	3	4	5	6	7
1 $(\log)\ Div\ IM_{rt}$	1						
2 $Div\ EM_{rt}$	0.556	1					
3 $AvRD_{rt}$	0.934	0.436	1				
4 $ExposeGNRD_{rt-1}$	0.073	0.023	0.097	1			
5 $ExposeGNRD_{rt-1} * AvRD_{rt-1}$	0.259	0.107	0.293	0.933	1		
6 $(\log)\ GDP_{rt-1}$	0.635	0.275	0.593	-0.110	0.014	1	
7 $(\log)\ popDens_{rt-1}$	0.290	0.123	0.269	-0.163	-0.119	0.472	1

Table 3. Technological diversification – extensive (*Div EM*) and intensive (*Div IM*) – and regional exposure to the GNRD

	(1) Div EM	(2) Div IM	(3) Div EM	(4) Div IM
ExposGNRD (t-1)	0.202* [0.112]	0.427** [0.184]	0.587*** [0.223]	0.913*** [0.301]
AvRD	0.915*** [0.181]	10.802*** [0.347]	1.286*** [0.267]	11.345*** [0.485]
ExposGNRD (t-1) * AvRD			-4.199*** [1.550]	-6.008** [2.601]
GDP (t-1)	0.077** [0.036]	0.289*** [0.077]	0.069** [0.034]	0.257*** [0.073]
Constant	0.006 [0.406]	-0.516 [0.855]	0.058 [0.392]	-0.199 [0.812]
Observations	2,892	3,085	2,892	3,085
R-squared	0.156	0.867	0.163	0.868
Number of NUTS-2	196	197	196	197
Year FEs	YES	YES	YES	YES
NUTS-2 FEs	YES	YES	YES	YES

Notes. Dep. Vars: Likelihood of regional technological diversification, in model (1) and (3), it equals 1 if a region r at time $t+1$ maintains the RTA in at least one of the new RTA developed by the region at time t (with respect to time $t-1$); Extent of regional diversification in model (2) and (4), the (log) number of new RTA of region r at time t with respect to time $t-1$. Columns (1)-(4) are estimated with a two-way fixed effects model (Linear Probability Model in Columns (1) and (3)). All regressions are weighted by population density. Regional exposure to GNRD (ExposGNRD) and (log) GDP are lagged by one year. Heteroskedastic robust standard errors reported in brackets are clustered at the regional level.

Table 4. Intensive technological diversification and regional exposure to the GNRD: quantile regression with no interaction with AvRD

	(1) q25	(2) q55	(3) q75	(4) q95
ExposGNRD (t-1)	-0.0964 [0.0592]	0.0354 [0.0255]	0.0654*** [0.0221]	0.0905*** [0.0282]
AvRD	14.4781*** [0.3260]	11.8739*** [0.3022]	11.0684*** [0.2678]	10.1126*** [0.2580]
GDP (t-1)	0.0409*** [0.0144]	0.0476*** [0.0071]	0.0541*** [0.0050]	0.0617*** [0.0050]
Constant	1.7365*** [0.1572]	2.1113*** [0.0661]	2.1808*** [0.0470]	2.2668*** [0.0523]
Observations	3,085	3,085	3,085	3,085
Year FEs	YES	YES	YES	YES
NUTS-2 FEs	YES	YES	YES	YES

Notes. Dep. Var: Extent of regional diversification, the (log) number of new RTA of region r at time t with respect to time $t-1$. All models are estimated using a two-way fixed effects quantile regression, weighted by population density. Models report the estimates for selected quantiles: the 25th (column 1), the 55th (column 2), the 75th (column 3) and the 95th (column 4). Regional exposure to GNRD (ExposGNRD) and (log) GDP are lagged by one year. Bootstrapped standard errors are reported in brackets.

Table 5. Intensive technological diversification and regional exposure to the GNRD: quantile regression including interaction with AvRD

	(1)	(2)	(3)	(4)
	q25	q55	q75	q95
ExposGNRD (t-1)	0.0086 [0.3442]	0.5219*** [0.1658]	0.5100*** [0.1506]	0.5881*** [0.1860]
AvRD	14.5409*** [0.3720]	12.2362*** [0.2837]	11.4198*** [0.2535]	10.6719*** [0.2916]
ExposGNRD (t-1) * AvRD	-0.7501 [2.3069]	-3.8693*** [1.2562]	-3.7336*** [1.1886]	-4.3249*** [1.5168]
GDP (t-1)	0.0394** [0.0158]	0.0470*** [0.0071]	0.0540*** [0.0049]	0.0598*** [0.0049]
Constant	1.7434*** [0.1656]	2.0743*** [0.0750]	2.1421*** [0.0525]	2.2224*** [0.0512]
Observations	3,085	3,085	3,085	3,085
Year FEs	YES	YES	YES	YES
NUTS-2 FEs	YES	YES	YES	YES

Notes. Dep. Var: Extent of regional diversification, the (log) number of new RTA of region r at time t with respect to time $t-1$. All models are estimated using a panel two-way fixed effects quantile regression, weighted by population density. Models report the estimates for selected quantiles: the 25th (column 1), the 55th (column 2), the 75th (column 3) and the 95th (column 4). Regional exposure to GNRD (ExposGNRD) and (log) GDP are lagged by one year. Bootstrapped standard errors are reported in parentheses.

FIGURES

Figure 1. Geographic distribution of average GNRD exposure across NUTS2 regions (quintiles), 2004-2008 in panel (a), 2014-2018 in panel (b)

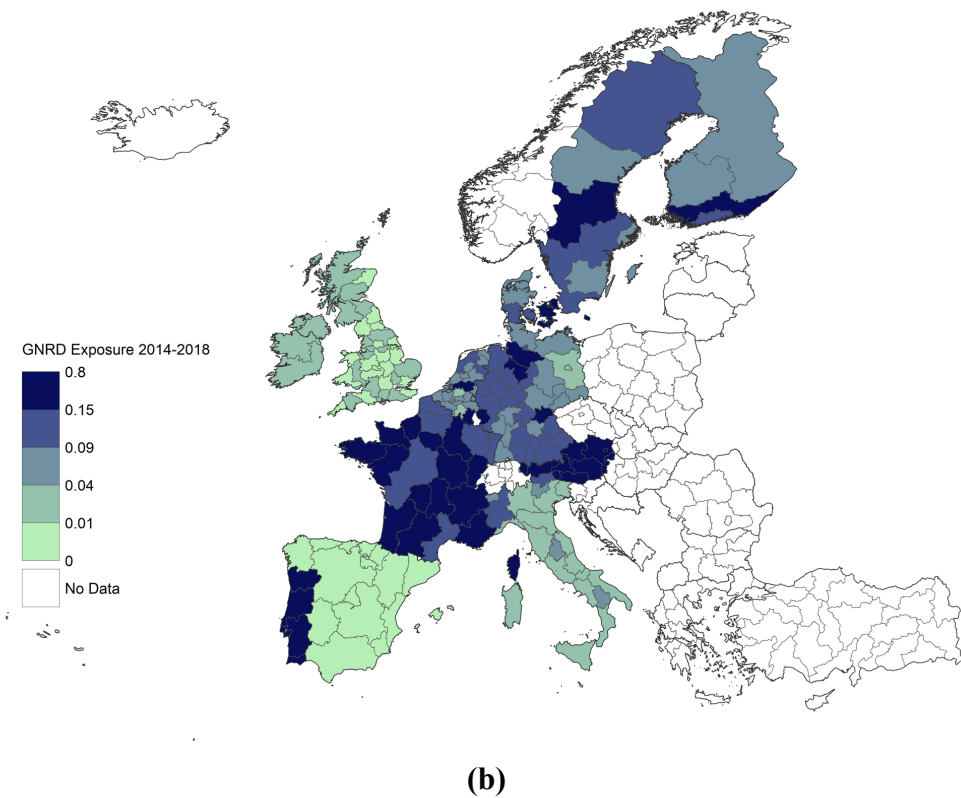
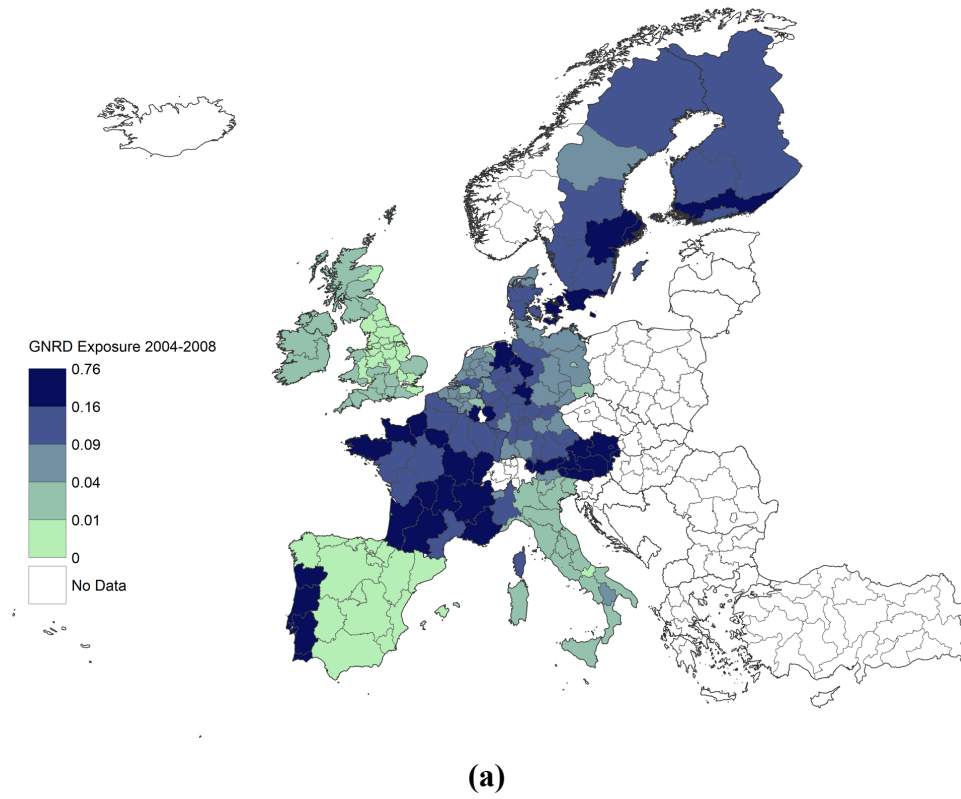
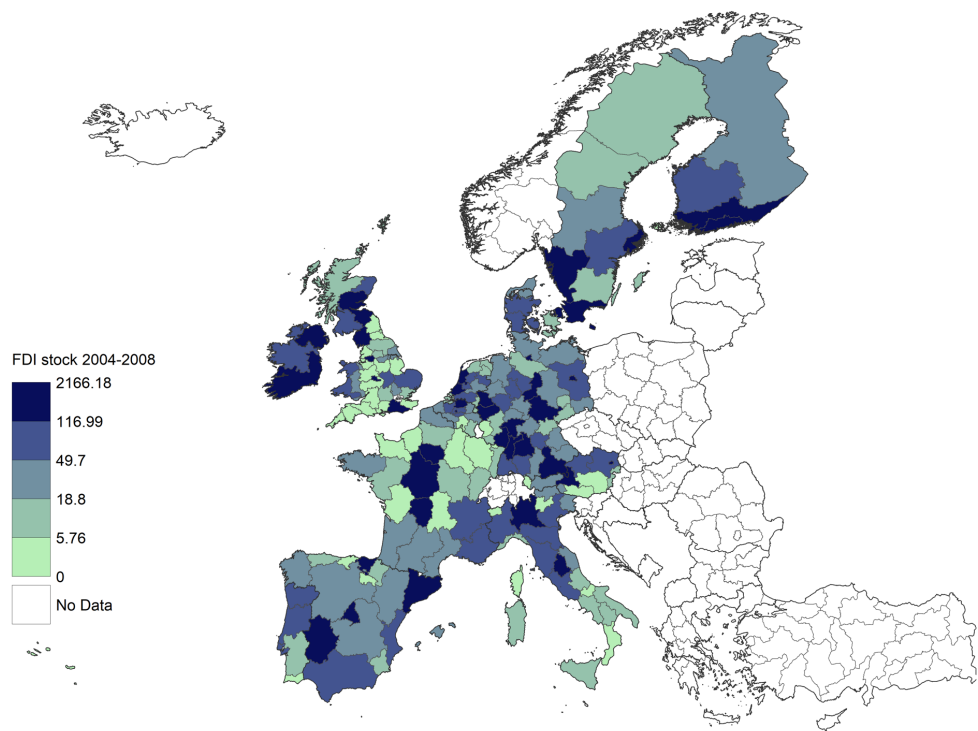
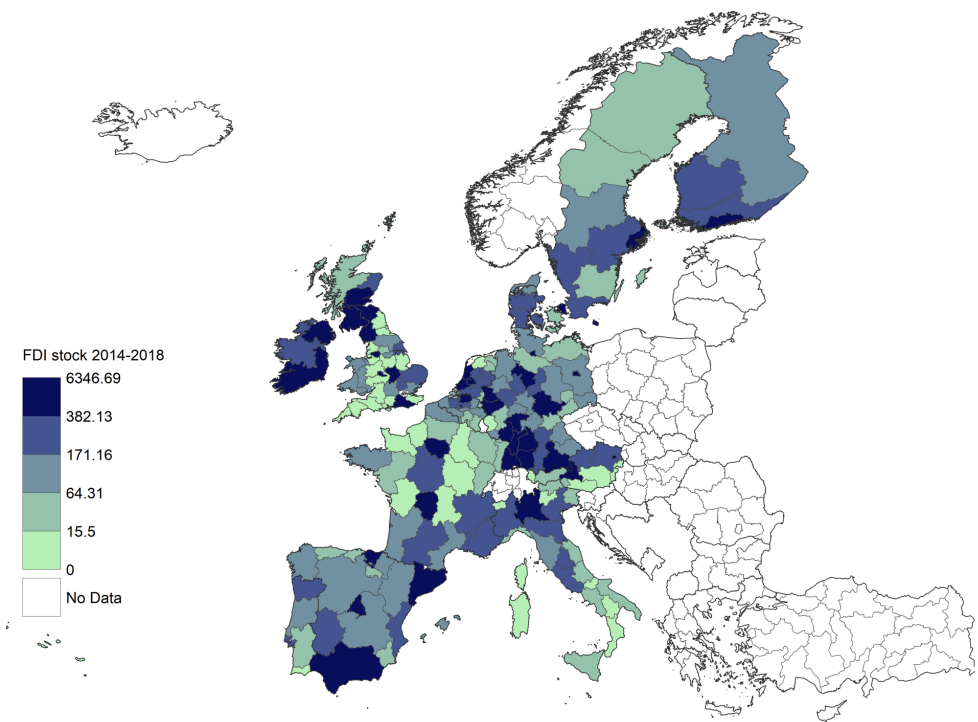


Figure 2. Geographic distribution of average FDI stock (inward and outward) across NUTS2 regions (quintiles), 2004-2008 in panel (a), 2014-2018 in panel (b)



(a)



(b)