The citation impact of research collaboration in science-based industries : a spatial-institutional analysis

The citation impact of research collaboration in science-based industries: A spatial-institutional analysis

Koen Frenken, Roderik Ponds and Frank van Oort

Working Paper 10.02

Eindhoven Centre for Innovation Studies (ECIS),
School of Innovation Sciences,
Eindhoven University of Technology, The Netherlands

The citation impact of research collaboration in science-based industries:

A spatial-institutional analysis

Koen Frenken [a,b,*], Roderik Ponds [c], Frank van Oort [b,c]

[a] Eindhoven Centre for Innovation Studies (ECIS)

School of Innovation Sciences

Eindhoven University of Technology

P.O. Box 513

NL-5600MB Eindhoven

The Netherlands

[*] corresponding author, k.frenken@tue.nl

[b] Section of Economic Geography

Urban & Regional research centre Utrecht (URU

Utrecht University

P.O. Box 80115

NL-3508TC Utrecht

The Netherlands

[c] Netherlands Environmental Assessment Agency

Oranjebuitensingel 6, 2511VE, The Hague

The Netherlands

The citation impact of research collaboration in science-based industries:

A spatial-institutional analysis

Abstract: This study shows for eight science-based industries that the citation impact of research collaboration is higher for international collaboration than for national and regional collaboration. A further analysis of institutional affiliations shows that university-industry-government collaborations profit from being organised at the regional scale only in the cases of biotechnology and organic fine chemistry. The alleged importance of physical proximity for successful interaction between university, industry and government thus is not robust across industries. We discuss the policy implications that follow.

Keywords: proximity, citation, globalisation, university-industry-government collaboration, triple helix

JEL codes: O30 - R10

The citation impact of research collaboration in science-based industries: A spatial-institutional analysis

1. Introduction

An increasing number of industries rely heavily on science as an input for innovation. Following Pavitt (1984), we characterise science-based industries by a high number of innovations based on scientific knowledge. Electronics, the pharmaceutical industry, and more recently, biotech and nanotech industries are among the most important examples. As these industries are responsible for the larger part of innovative activity in society, they constitute the central object of innovation policies in advanced economies.

An important feature of science-based industries concerns the distributed nature of the innovation process. The complexity of the technologies involved is so high that most innovations stem from inter-organisational collaboration. Consequently, inter-organisational networks are increasingly regarded as the 'locus of innovation' in science-based industries (Powell et al. 1996; Bonaccorsi 2008). Apart from inter-firm alliances, collaboration between firms and universities is central to innovation processes in these industries. And, in contexts with a strong public interest, governmental organisations are pivotal to innovation networks as well. Metaphorically, the innovations networks in science-based industries have been characterised as a "triple helix" of university-industry-government relations (Etzkowitz and Leydesdorff 2000).

A second feature of science-based industries is their strong tendency towards spatial concentration (Audretsch and Feldman 1996; Paci and Usai 2000). The importance of face-to-face interaction in research collaboration is often considered to be an important agglomerative force in these industries. In particular, regional university-industry collaboration is seen as an important carrier of knowledge spillovers from the global science system to the 'regional innovation system' (Cooke et al. 1998). Accordingly, regional policies in science-based industries typically aim to stimulate collaboration between firms and universities. Empirical studies on research collaboration in science-based industries, however, have shown that research collaborations, including university-industry collaborations, occur most often at national and international scales (McKelvey et al. 2003; Coenen et al. 2004; Ponds 2009). Thus, science-based industries are characterized, somewhat paradoxically, by a spatial concentration in a limited number of regions on one hand and collaborative knowledge networks that span the globe on the other (Asheim and Isaksen 2002; Owen-Smith and Powell 2004).

The question we ask in the current study holds whether research collaboration at different spatial scales is characterised by different quality levels. For science policy purposes, it is useful to understand the determinants of the quality of output of research collaboration. Here, citation impact is used as a proxy for the quality of a scientific publication.[1] One of the data sources that have been used to analyse research collaboration are co-publications where a co-publication is defined as a publication with two or more institutional affiliations (Katz and Martin 1997). An earlier study by Ponds (2009) showed that most publications in science-based industries stem from co-publications.

It is known for a while that international co-publications involving organisations from different countries tend to receive more citations than national co-publications (for a review, see Frenken et al. 2009). The citation impact of sub-national research collaboration, however, has not been researched so far. Below, we compare the citation impact of regional, national and international collaboration for publications in eight science-based technologies involving at least one Dutch organisation. We will further distinguish between collaborations within academia, collaborations between academia with actors outside academia, and collaborations outside academia altogether. This allows us to test the central thesis underlying the regional innovation system concept that university-industry-government collaboration benefits from physical proximity.

[1] This interpretation of citations is heavily debated. We go into this debate in the section on data.

We proceed as follows. Section 2 provides the theoretical background of our study drawing on recent literature in the geography of innovation. In section 3 we formulate a number of hypotheses concerning the expected citation impact of different types of spatial and institutional collaboration. Section 4 presents the data we used on publications in eight science-based technologies. In section 5 we discuss the regression results. We end with a discussion of our results in section 6 in the light of future research questions and regional policy debates.

2. Theoretical motivation

Since the path-breaking study by Jaffe (1989), knowledge-production-function studies have shown that knowledge spillovers from public research are highly geographically localized. Systematic evidence for such spillovers from public research has been found for regions in the United States, France and Germany, among other countries.[2] These studies provided one of the empirical pillars for regional innovation policies aimed to promote regional development through local knowledge spillovers.

More recently, studies applying network analysis have put the consensus on localised knowledge spillovers from public research into question. Methodologically, the focus is no longer on estimating the geographical localisation of knowledge spillovers, but, more generally, on the accessibility to knowledge through any form of network through which knowledge spillovers may flow including social networks, labour mobility, professional associations or inter-organisational networks (Saxenian 1994, 2006; Zucker et al. 1998; Almeida and Kogut 1999; Breschi and Lissoni 2001; Maggioni et al. 2007; Gallie 2009; Graf and Henning 2009; Massard and Mehier 2009). The role of social networks in knowledge spillovers, for example, has been analysed by looking at patent citations. Breschi and Lissoni (2003, 2006, 2009) repeated a study by Jaffe et al. (1993) who showed that USPTO patent citations – as indicators of knowledge spillovers – are highly geographically localized. Breschi and Lissoni obtained the same result on EPO patent citations in their studies on Italy and the United States. Yet, once social proximity among inventors is taken into account, which is measured by the social

[2] A recent survey can be found in Fritsch and Slavtchev (2007).

(‘geodesic’) distance in the co-inventor network, the effect of physical proximity on patent citations vanishes. Their study thus shows that co-location itself does not lead to knowledge spillovers, but social ties between inventors do. And, since most network ties are local, the resulting knowledge spillovers are to an important extent geographically localized. Singh (2005) carried out a similar study providing further support for the results obtained by Breschi and Lissoni. The results on patent citations are consistent with studies applying a knowledge-production-function approach including an inter-regional spillover matrix based on the frequency of collaboration. It was found that inter-regional collaboration networks indeed have an independent effect on the innovative output of regions though its effect seems less robust for EU subsidised networks (Maggioni et al. 2007) than for networks as indicated by co-publications (Ponds et al. 2009).

The importance of networks as carriers of knowledge spillovers has raised interest in the geographical determinants of R&D networks. Studies on R&D networks as funded by the European Commission under the Framework Programmes found that geographical distance plays a significant, yet minor, role in the creation of such networks - understandably so - because international partnering is a condition to access these funds (Autant-Bernard et al. 2007; Maggioni and Uberti 2009; Scherngell and Barber 2009). By contrast, studies analyzing joint patents and joint publications found that both geographical distance and country borders play a very important role in the establishments of such collaborations (Katz 1994; Liang and Zhu 2002; Ejermo and Karlsson 2006; Ponds et al. 2007; Hoekman et al. 2009; Maggioni and Uberti 2009).

A research question that follows from the current interest in the geography of networks concerns the spatial differentiation of networks. Actors choose to collaborate at different spatial scales at the same time. This raises the question whether collaboration at different scales are different in their nature and effects. The question we ask in the current study is whether research collaboration at different spatial scales has different citation impact. We will follow the research design adopted in previous studies (Frenken et al. 2005; Singh 2007), which compared the citation impact of domestic versus international collaborations in the field of biotechnology and applied microbiology. Our contributions hold that we expand the number of industries being analysed from one to eight and that we add a regional variable to the analysis. By further distinguishing between collaborations within academia, collaborations between academia with actors outside academia, and collaborations outside academia altogether, we further test the widely held thesis that university-industry-government collaboration benefits from physical proximity within the region.

3. Hypotheses

It has been observed a long time ago that scientific publications stemming from international research collaborations receive on average more citations than publications stemming from national research collaborations (Narin et al. 1991). Subsequent statistical research on this topic found that after controlling for other factors affecting the number citations to scientific publications, the original finding still holds (Katz and Hicks 1997; Frenken et al. 2005; Singh 2007).

There are two types of interpretations for the finding that international research collaboration has a larger citation impact than national research collaboration. First, it is argued that international collaboration leads to research with higher quality than national collaboration, which explains why it is cited more often than national collaboration. International collaboration connects distant knowledge bases that generally have less overlap than knowledge bases within a single country. Furthermore, the costs involved in international projects (travel costs, coordination costs) generally exceed the costs of national project, other things being equal. This could mean that in order to legitimate these higher costs, the expected returns must also be higher. A second possible interpretation, which does not necessarily exclude the first one, holds that the result may reflect that international collaboration helps the authors to diffuse the results to a wider audience. This interpretation, though less common than the first interpretation, is in line with the domestic citation bias that researchers display (Paris et al. 1998; Wong and Kokko 2005; Pasterkamp et al. 2007). The domestic bias implies that international collaboration, especially involving authors from countries with many researchers such as the United

States, will obtain more citations as it becomes preferentially cited in multiple home countries. Below, we will follow the first interpretation, but the analysis in itself would be not affected if one would prefer the second interpretation to the first.

Generalizing the national/international distinction to a hierarchical spatial system, we argue that the higher the spatial level of research collaboration, the higher the citation impact of a publication is expected to be. Thus, our first hypothesis holds that *the citation impact of research collaboration increases with the spatial scale of collaboration (hypothesis 1)*. Below, we will test this hypothesis by distinguishing between regional, national and international collaboration. Regional collaborations stand for publications involving at least two organisations that are located in the same NUTS3 region; national collaborations stand for publications involving at least two organisations that are located in The Netherlands, but in different NUTS3 regions; and, international collaborations stand for collaborations between at least one Dutch organisation and at least one foreign organisation.

The type of institutions involved in collaborative research is also expected to affect the citation impact of publications (Hicks 1995). Collaboration within academia will more often involve the production of more basic knowledge, which is most relevant to future academic research, and, hence, will tend to be cited more often. Furthermore, university researchers are explicitly oriented towards impacting their peers and will put more effort in rendering their work relevant to colleagues. Researchers working for firms and governments, by contrast, tend to produce more specific knowledge that is useful to the specific goals of the organisation they work for. Thus, the institutional type of research collaboration is expected to affect its citation impact. Our second hypothesis holds that *the citation impact of research collaboration increases with the extent to which academic organisations are involved (hypothesis 2)*. Below, we will test this hypothesis by distinguishing between collaborations within academia, collaborations between academia with actors outside academia, and collaborations outside academia altogether.

Hypothesis 1 may seem at odds with the central thesis in geography of innovation, which holds that physical proximity between actors favours innovation. Physical proximity allows for frequent face-to-face interaction through which tacit knowledge can be exchanged and complex project can be managed, while physical proximity generally also involves a shared culture and language further facilitating interactive learning. The rationale for face-to-face interaction equally applies to scientific research, because tacit knowledge plays an important role in scientific research as well, both in using equipment and in achieving a common understanding (Collins 1985; Hicks 1995; Balconi et al. 2007). Yet, one expects the importance of physical proximity to collaboration in academic collaboration to be lower than to collaboration involving academic and non-academic organisations. Within academia expert languages and cultural norms are fairly standardised and interaction can take place relatively easy over long distance. What is more, face-to-face interaction is realised through 'temporary proximity' (Torre 2008) through conferences and workshops where most members of a particular discipline regularly meet. By contrast, in the case of university-industry-government collaborations, permanent physical proximity is expected to be important. In such 'hybrid' collaborations, incentives are not aligned as university, industry and government have different objectives and operational logics (Hicks 1995; Etzkowitz and Leydesdorff 2000). Universities are primarily interested in the production and disclosure of generic knowledge in the form of timely, detailed publication, firms in appropriating commercially relevant knowledge through secrecy or patenting, and governments in the use of knowledge to solve societal problems.

To overcome incentive problems in university-industry-government relations, face-to-face encounters – before and during the project – will be important to create trust and to handle conflicts effectively. One can expect that those who are co-located in the same region can manage such complex university-industry-government collaborations more effectively than those located in different regions, for two reasons. First, co-located partners will generally have more regular face-to-face meetings than partners who are not co-located for the simple reason that co-location reduces the time and costs to organize such meetings. Second, co-located partners share a common regional cultural context and are more often part of the same social network than partners who are not co-located (Saxenian 1994). These forms of regional embeddedness facilitate the establishment of trust among heterogeneous partners (Uzzi 1996; Boschma 2005) and hereby to the success of projects involving universities, firms and government agencies. In terms of proximity, we thus expect that the lack of institutional proximity in university-industry-government relations can be compensated by physical proximity (Ponds et al. 2007). *Mutatis mutandis*, the same reasoning holds for national collaboration, but to a lesser extent. We thus expect that for research collaborations within academia the citation impact increases with the spatial scale of collaboration as in hypothesis 1, while *the citation impact of university-industry-government collaboration decreases with the spatial scale of collaboration (hypothesis 3).*

4. Data

We use data from Web of Science, a product offered by Thomson Scientific. It covers three databases: the Science Citation Index (SCI) including Science journals, the Social Science Citation Index (SSCI) including social science journals, and the Arts and Humanities Citation Index (A&JCI) including journals belonging to the arts and humanities. Web of Science covers all major journals in the world for 1988 onwards with a known bias towards Anglo-Saxon journals.

The dependent variable in our study is the number of citations that a scientific publication has received at the time we collected the publication data. The use of citations as an indicator of quality is contested. Citation data have a number of advantages, in particular, comparability across time and across spatial units. Nonetheless, the idea that the number of citations is an appropriate proxy for the quality of a scientific publication has been criticised for a number of reasons (MacRoberts and MacRoberts 1996; Wouters 1998; Moed 2005):

- Citation behaviour differs across disciplines, which implies that publications from different disciplines should not be compared in terms of the number of citations they received.

- Many citations to publications do not necessarily reflect true intellectual debt, but point to publications that are only loosely related to the citing publication.
- Those who provided important ideas through informal encounters are not necessarily cited (though they may be acknowledged in the first footnote).
- Some citations are 'miscitations' in the sense that the cited publication contains a different claim than what the citing publication suggests that the cited publication claims.
- Not all citations are recorded in the database used as citation databases tend to be biased towards Anglo-Saxon journals.

The first criticism does not apply to our study since we study scientific fields separately.[3] The remaining criticisms deserve serious attention. In particular, to compare a small set of publications in terms of citations will provide little information about the underlying quality. However, in aggregate analyses involving thousands of publications, the criticisms are much less problematic as 'distortions' are treated as noise. Furthermore, it can be assumed that our two sets of variables of interest (spatial scale variables and institutional origin variables) are largely unaffected by these distortions, since we have no reason to believe that the complex motivations underlying citation behaviour are influenced by the spatial scale and institutional origins of the cited publication. Finally, the ISI Web of Science covers most peer-reviewed journals and proceedings in the natural sciences. This means that the citation impact of a publication in ISI Web of Science is likely to be highly correlated to the citation impact of a publication in a database that would include even more journals and proceedings.[4]

The independent variables are based on the address information contained in each publication referring to the institutional affiliation of each author. We refer to publications with multiple addresses as co-publications, which can be considered as a tangible result of a successful collaboration. The underlying assumption is that researchers from the organisations listed on the publication have in some way

[3] Admittedly, however, some fields may be internally quite heterogeneous. On this, see Rafols and Leydesdorff (2009).

[4] Monographs are not included in the ISI database, but these are rarely cited in science publications.

pooled resources and knowledge (Katz and Martin 1997; Cockburn and Henderson 1998). Since individuals and their affiliations are generally only mentioned on a publication after a substantial contribution, publications with multiple authors and multiple organisations are considered good indicators for collaborative research (Katz and Martin 1997). However, whereas almost all co-publications might be considered to represent some form of collaboration, not all collaboration in research ends up in a co-publication. Consequently, not all research collaboration is measured by the use of co-publications. Laudel (2001) showed that this is most often the case for collaborative research between individual researchers within the same organisation. Research collaboration between different organisations (which is the focus of the present study) does generally lead to a joint publication.

In order to identify the addresses and define different types of organisations we developed an algorithm. The location of an organisation was determined by using the country name and, for Dutch organisations, by linking the postal code to the region. The postal codes were used since in the spelling of organisation names and cities several mistakes exist in Web of Science. In order to identify the different types of organisations we made a list of abbreviations and words to assign each organisation. We distinguished between three types of organisations; academic organisations, firms and governmental/non-profit organisations. Universities and national academic research organisations (such as the Max Planck institutes in Germany) have been labelled as academic organisations. In the Netherlands the largest national academic research organisations are NWO (Netherlands Organisation for Scientific Research), KNAW (the Royal Netherlands Academy of Arts and Sciences) and academic hospitals. Research organisations such as TNO in the Netherlands or the National Institutes of Health in the USA and non-profit organisations are labelled governmental organisations. Based on a primary classification of organisations into these three categories an algorithm was designed to assign each organisation to one category. This algorithm was then tested and improved several times on a changing subset of 2,000 articles until more than 99 percent of the organisations were assigned correctly to one of the three types of organisations and to the location.

Collaboration is defined as the co-occurrence of two or more addresses on a publication. Although collaboration in its essence takes place between people, our focus is on organisations since our interest in the impact of the type of organisations. Addresses attached to the publications refer to institutional affiliations and not to single persons per se. In the ISI Web of Science database, it is not possible to link the individual authors to organisations. This means that a single-author paper with two or more affiliations is also counted as collaboration whereas a multi-authored paper with one address (i.e. an intra-organisation collaboration) is not regarded as collaboration (Katz and Martin, 1997). The share of papers with multiple affiliations and one author in the overall number of papers with multiple affiliations, however, never exceeds one percent.

The focus in our study lies on collaboration in scientific research related to science-based technologies. Our selection of science-based technologies is based on a study of Van Looy et al. (2003). They analysed the citations from patents to scientific publications in different technological classes.[5] The science-intensity of a technology, as defined as a set of technology classes, is indicated by the average share of citations from its patents to scientific publications in the total number of citations for each technology. Technologies with a high share of citations from patents to scientific publications are considered to be science-based technologies. In the second stage, the scientific fields that belong to each technology are determined by assigning a set of scientific journals to each technology. A journal is attributed to a technology on the basis of the frequency with which publications in these journals are cited in the patents belonging to a technology.

Using this methodology, we choose to analyse the eight science-based technologies also studied by Ponds et al. (2007): (1) Agriculture & food chemistry, (2) Biotechnology, (3) Organic fine chemistry, (4) Analysis, measurement & control technology, (5) Optics, (6) Information technology, (7) Semiconductors and (8) Telecommunications. For all these technologies it holds that patents cite a relative high number of scientific publications. *Table 1* shows the relevant scientific fields for each

[5] Based on the OST-INPI/FhG-ISI technology classification.

technology, where fields here refer a set of journals that are often cited in patents beloning to the respective technology. Note that there is some overlap between the science bases of various technologies in the sense that some journals are attributed to multiple technologies. In the following, a distinction is made between life science-based technologies (1, 2 and 3) and physical science-based technologies (5, 6, 7 and 8) as introduced by Marsili (2001). Life sciences and physical sciences are based on different knowledge bases as well as on different organisational structures with the average size of research units in the life sciences based technologies typically being smaller than in physical sciences based technologies. We did not group the remaining technology Analysis, control and measurement technology (4), since it is a technology with a more mixed science base.

TABLE 1 AROUND HERE

Based on the lists of journals belonging to each technology, all publications relevant to the eight selected technologies with at least one address in the Netherlands have been retrieved from the Web of Science data base in March 2005 for the period 1988-2004. Using the address information from each publication, we define research collaboration as a publication with two or more addresses. Based on the addresses of the organisations the spatial scale(s) of the underlying collaboration, if any, are determined. A distinction is made between the regional level (collaborating organisations located in the same NUTS3 region in the Netherlands[6]), the national level (collaborating organisations located in the Netherlands but in different NUTS3 regions) and the international level (involving at least one Dutch and one foreign organisation). The latter is further sub-divided into collaboration with the EU15, USA and the rest of the world (denoted as ‘Other international’).

[6] The NUTS3 regions in The Netherlands correspond closely to the labour market regions (Cörvers et al. 2009). There are forty NUTS3 regions, most of which are characterized by a single city and its surroundings from which people commute. The scale thus reflects fairly small regions in which frequent face-to-face can be organized at low cost.

The institutional type of collaboration is determined by distinguishing between academic and non-academic organisations. Universities and other academic research organisations[7] are labeled as 'academic organisations', while the remaining organisations, mostly firms and government agencies, are labeled as non-academic organisations. Three types of collaborations can now be distinguished: collaborations between academic organisations ('Academic'), collaborations between non-academic organisations ('Non-academic') and collaborations between an academic and a non-academic organisation ('hybrid'). The hybrid category refers to university-industry and university-government relations jointly.

For each technology, the final dataset consists of all publications (both single and co-publications) with dummy variables for different spatial scales and different type of collaborations. Note that a single publication can be classified at multiple spatial scales and in multiple institutional types. For example, a publication involving a Dutch academic organisation in a particular NUTS3 region collaborating with a Dutch non-academic organisation located in another NUTS3 region and a Chinese non-academic organisation, has a value of one for dummies 'Netherlands', 'Other international', 'hybrid' and 'non-academic', and has a value of zero for all other dummies. We also constructed dummies for all possible combinations between a spatial scale variable and an institutional variable. Following the example, the combined dummies that get a value of one would be 'Netherlands hybrid' and 'Other international hybrid' and 'Other international non-academic'.

5. Results

We first computed the number of co-publications as a percentage of all publications for each year and each technology. *Figure 1* shows that the trend towards co-publications is pervasive for all

[7] In the Netherlands the largest academic research organisations are NWO (Netherlands Organisation for Scientific Research) and KNAW (the Royal Netherlands Academy of Arts and Sciences). Academic hospitals are also classified as an acandemic organisation.

technologies. Whereas co-publications accounted for less than half of all publications in 1988 its share has grown to about 70 percent in 2004. The rapid increase in the share of co-publications underlines the importance of research collaboration in knowledge production in science-based technologies.

Table 2 provides the descriptive statistics of our data for the publications in the eight science-based technologies. A number of patterns are visible. First, the number of international collaborations clearly exceeds the number of domestic collaborations for all technologies. This reflects the global nature of knowledge production in science-based technologies. Second, university-industry and university-government collaboration as captured by the Hybrid variable is very common and only slightly less frequent than collaboration within academia. This reflects the strong reliance on scientific knowledge by non-academic organisation in science-based technologies. Third, the number of hybrid collaborations at the regional level, indicative of interactions within 'regional innovation systems', is particularly high for agriculture and food chemistry, biotechnology and organic fine chemistry. For these technologies based on life sciences, the regional innovation systems are relatively well developed compared to technologies based on physical sciences.

TABLE 2 AROUND HERE

Table 3 provides the regression results for each of the eight technologies explaining the number of citations received by each scientific publication. The methodology is replicated from Frenken et al. (2005) and Singh (2007) using a negative binomial regression, which is an estimation technique suitable for analyzing count data such as citations (Long 1997). In all regressions, we use dummies for the year of publication, since more recent publications have had a shorter time frame available to collect citations than older publications. In our presentation of the results, we will only refer to the last column for each technology containing the full model including all independent variables.

TABLE 3 AROUND HERE

The main 'input' variables to control for are the number of authors and the number or organisations involved in the research projects leading to a scientific publication. The number of authors has a positive impact on citation in all models, which reflects that projects involving more researchers generally result in higher impact, as expected. To some extent, this result may also reflect that publications with many authors are also better promoted in the communication to peers who subsequently cite them. *Mutatis mutandis*, the number of organisations can be expected to affect the citation impact in the same way. However, this result is not obtained, as the number of organisations does not seem to affect citation impact, and in many technologies even exerts a negative impact. This shows that what matters for successful collaboration is the number of people (brains) involved and not whether these people work for different organisations. Given the negative impact of the number of organisations in some technologies, one can further conclude that for these technologies research collaborations benefits from organisational proximity (Boschma 2005).

Turning to the dummy variables, which are of main interest here, the coefficients can be interpreted as reflecting whether a particular type of collaboration receives more or less citations than the reference case of publication produced by a single organisation. For example, a coefficient of 0.28 for USA would mean that a Dutch organisation publishing with an American organisation receives exp(.28)=1.323 times more citations, all else being equal.

We first observe that collaborations taking place at international scales tend to receive more citations than collaborations at national or sub-national levels. More specifically, collaborations between Dutch organisations with organisations in the United States and, to a lesser extent, in the EU, tend to yield the highest number of citations. By contrast, collaborations with other foreign countries typically have a negative effect on citation impact. These results may well reflect the dominance of Western countries at both sides of the Atlantic in the global science system. At the same time, given the bias in the ISI Web of Science database towards Anglo-Saxon journals, this dummy can also be considered as controlling for this bias. Unexpectedly, national collaboration tends to receive fewer citations than regional (NUTS3) collaboration in life sciences, while the opposite result is obtained for two out of the four physical sciences. Thus, life sciences seem to have a ‘glocal’ spatial structure (Coenen et al. 2004; Moodysson et al. 2008), while physical sciences display the expected hierarchical spatial structure. In conclusion, our results only partially confirms hypothesis 1, which stated that the citation impact of a joint scientific publication increases with the spatial scale of collaboration.

The second main result holds that if academic organisations are involved in collaboration, the impact on citation tends to be higher. The academic variable is significant and positive for six out of eight technologies. For three technologies we find that hybrid collaborations also obtain a citation premium, which is roughly equal to the premium obtained for academic collaboration except for Analysis, measurement and control technology, in which academic collaborations outperform hybrid collaborations. We can conclude that hypothesis 2 is confirmed for six out of eight technologies in the sense that academic collaboration performs better than non-academic collaboration.

Table 3 shows the effects on citation impact of collaboration at different spatial scales and of different institutional types. The spatial and institutional classifications are combined into a spatial-institutional classification as in *Table 4*. Looking at the effects of the co-occurrence of a spatial level of collaboration with an institutional type of collaboration on citation impact, we observe clearly that academic collaborations benefit from higher spatial scales. In particular, high-impact academic research takes place primarily at European level and in collaboration with the United States. By contrast, academic collaboration at national or regional levels has a relatively low impact in terms of citations. We can therefore re-confirm hypothesis 1 in the sense that for academic collaboration at the international level performs best, but only in so far EU countries or the United States are involved.

TABLE 4 AROUND HERE

Hybrid collaborations, which are the main focus of regional policies aimed at supporting spillovers from public research to companies in the region, tend to profit from physical proximity only for specific technologies. The NUTS3 Hybrid variable in *Table 4* is significant and positive for biotechnology and organic fine chemistry, while being insignificant in all other cases. Interesting, the *share* of hybrid collaborations at the NUTS3 level is also found to be highest for biotechnology and organic fine chemistry (*Table 2*), which suggests that actors in these technologies act according to the opportunities to produce high-impact research in these technologies. Judging from these results, the alleged importance of physical proximity to enhance high-tech innovation in the region through knowledge spillovers is only visible in specific technology contexts. One such context is biotechnology, which is indeed often mentioned as an example of a technology where geographical clustering of universities and companies is important to spur innovation through university-industry collaboration (Coenen et al. 2004; Moodysson et al. 2008). However, the majority of the technologies studied here show no positive impact of physical proximity, through permanent co-location in the region, on the citation impact of hybrid collaborative research. This does not to deny the role of physical proximity *per se* for successful collaborations in these technologies, but rather that in so far physical proximity plays a role, it is organised on a temporal basis, that is, through temporary proximity (Torre 2008).

A further result, which has been unexpected, is that hybrid collaborations at international scales tend to have a positive effect on citation impact in the three life sciences. Though this effect is mostly small, in some case the effect is substantial, particularly, in the cases of hybrid collaboration with the US. This result contradicts the logic of the proximity approach, which predicts that a lack of institutional proximity in hybrid collaborations is best dealt with at the regional level. We thus find only limited evidence for the popular assumption that university-industry and university-government relations would profit from being organised regionally rather than nationally or internationally. We therefore do not confirm hypothesis 3, which stated that the citation impact of university-industry-government collaboration decreases with the spatial scale of collaboration.

6. Discussion

Our study showed that research collaboration in life sciences – as indicated by co-publications involving multiple organisations – has a higher citation impact if organised at the regional level than the national level, while the opposite is found for the physical sciences. At the same time, in both sciences the citation impact of international collaboration exceeds the citation impact of both national and regional research collaboration. A further analysis of the institutional affiliation of researchers shows that the success of regional research collaboration in the life sciences is specific to university-industry-government collaborations highlighting the importance of physical proximity in such complex collaborations. Regional university-industry-government collaborations in physical sciences had no additional citation impact, suggesting that the specific importance of regional university-industry-government collaboration may be limited to life sciences only.

Our mixed results suggest that the role of physical proximity may be sensitive to the technological context in question. Further research should find technology-specific variables such as the level of codification of the underlying knowledge base and the relative share of multinational companies in research collaboration, which may affect the benefits that partners can realize from regional collaboration compared to national or international collaboration. Furthermore, it must be reminded that we deal with regions in The Netherlands, where the geographical area covered by NUTS3 regions is relatively small and the distances between regions are relatively short. Repeating our study for other countries would shed more light on our results. In particular, such studies can be used to verify the differences in results for life sciences compared to physical sciences.

Innovation policy, in particular those designed by regional policymakers, tends to privilege regional collaboration over international collaboration. Our study suggests that such emphasis is not justified as high-impact research takes place at many different spatial scales, in particular, at the international scale. Policies that fix the spatial scale of collaboration run the risk of under-exploiting opportunities provided by collaboration with partners outside the region. This conclusion is in line with earlier studies in economic geography stressing the complementary between global and local linkages (Asheim and Isaksen 2002; Bathelt et al. 2004; Coenen et al. 2004; Moodysson et al. 2008).

Having said this, it should be reminded that regional collaboration is not limited to scientific research that leads to publication in international journals. More targeted forms of collaboration aimed at the creation of technological infrastructures or the exploitation of scientific knowledge for commercial use may well profit from regional collaboration. Such initiatives, however, will generally yield less knowledge spillovers compared to scientific research collaboration, and, correspondingly, should involve private funding from those firms that are likely to profit.

References

Almeida P, Kogut B (1999) Localization of knowledge and the mobility of engineers in regional networks. *Management Science* 45: 905-917

Asheim BT, Isaksen A (2002) Regional innovation systems: the integration of local 'sticky' and global 'ubiquitous' knowledge. *Journal of Technology Transfer* 27: 77-86

Audretsch DB, Feldman, MP (1996) R&D spillovers and the geography of innovation and production. *American Economic Review* 86(3): 630-640

Autant-Bernard C, Billand P, Franchisse D, Massard N (2007) Social distance versus spatial distance in R&D cooperation: empirical evidence from European collaboration choices in micro and nanotechnologies. *Papers in Regional Science* 86(3): 495-519

Balconi M, Pozzali A, Viale R (2007) The "codification debate" revisited: a conceptual framework to analyze the role of tacit knowledge in economics. *Industrial and Corporate Change* 16(5): 823-849

Bathelt H, Malmberg A, Maskell P (2004) Clusters and knowledge: local buzz, global pipelines and the process of knowledge creation. *Progress in Human Geography* 28: 31-56

Bonaccorsi A (2008) Search regimes and the industrial dynamics of science. *Minerva* 46(3): 285-315

Boschma RA (2005) Proximity and innovation: A critical assessment. *Regional Studies* 39(1): 61-74

Breschi S, Lissoni F (2001) Knowledge spillovers and local innovation systems: a critical survey. *Industrial and Corporate Change* 10(4): 975-1005

Breschi S, Lissoni F (2003) Mobility and social networks: Localised knowledge spillovers revisited. *CESPRI Working Paper* 142. http://www.cespri.unibocconi.it/

Breschi S, Lissoni F (2006) Mobility of inventors and the geography of knowledge spillovers. New evidence on US data. *CESPRI Working Paper* 184. http://www.cespri.unibocconi.it/

Breschi S, Lissoni F (2009) Mobility of skilled workers and co-invention networks: an anatomy of localized knowledge flows. *Journal of Economic Geography* 9(4): 439-468

Cockburn IA, Henderson RM (1998) Absorptive capacity, coauthoring behavior, and the organisation of research in drug discovery. *Journal of Industrial Economics* 46(2): 157-182

Coenen L, Moodysson J, Asheim BT (2004) Nodes, networks and proximities: On the knowledge dynamics of the Medicon Valley biotech cluster. *European Planning Studies* 12(7): 1003-1018

Cohen WM, Nelson RR, Walsh JP (2002) Links and impacts: the influence of public research on industrial R&D. *Management Science* 48(1): 1-23

Collins HM (1985) *Changing Order: Replication and Induction in Scientific Practice*. Sage, London

Cooke P, Uranga MG, Extebarria G (1998) Regional innovation systems: an evolutionary perspective. *Environment and Planning A* 30: 1563-1584

Cörvers F, Hensen M, Bongaerts D (2009) Delimitation and coherence of functional and administrative regions. *Regional Studies* 43(1): 19-31

Ejermo O, Karlsson C (2006) Interregional inventor networks as studied by patent coinventorships. *Research Policy* 35(3): 412-430

Etzkowitz H, Leydesdorff L (2000) The dynamics of innovation: from national systems and 'mode 2' to a triple helix of university-industry-government relations. *Research Policy* 29(2): 109-123

Frenken K, Hardeman S, Hoekman J (2009) Spatial scientometrics: Towards a cumulative research program. *Journal of Informetrics* 3(3): 222-232

Frenken K, Hölzl W, De Vor F (2005) The citation impact of research collaborations: The case of European biotechnology and applied microbiology (1988-2002). *Journal of Engineering Management and Technology* 22(1-2): 9-30

Fritsch M, Slavtchev V (2007) Universities and innovation in space. *Industry and Innovation* 14(2): 201-218

Gallie EP (2009) Is physical proximity necessary for knowledge spillovers within a cooperative technological network? The case of the French biotechnology sector. *Regional Studies* 43(1): 33-42

Gertler M, Levitte YM (2005) Local nodes in global networks: the geography of knowledge flows in biotechnology innovation. *Industry and Innovation* 12: 487-507

Graf H, Henning T (2009) Public research in regional networks of innovators: A comparative study of four East-German regions. *Regional Studies* 43(10): 1349-1368

Hicks D (1995) Published papers, tacit competencies and corporate management of the public/private character of knowledge. *Industrial and Corporate Change* 4(2): 401-424

Hicks DM, Katz JS (1996) Where is science going? *Science, Technology and Human Values* 21(4): 379-406

Hoekman J, Frenken K, Van Oort F (2009) The geography of collaborative knowledge production in Europe. *Annals of Regional Science* 43(3): 721-738

Jaffe AB (1989) Real effects of academic research. *American Economic Review* 79(5): 957-970

Jaffe AB, Trajtenberg M, Henderson R (1993) Geographic localization of knowledge spillovers as evidenced by patent citations. *Quarterly Journal of Economics* 108(3): 577-598

Katz JS (1994) Physical proximity and scientific collaboration. *Scientometrics* 31: 31-43

Katz JS, Hicks D (1997) How much is a collaboration worth: a calibrated bibliometric model. *Scientometrics* 40(3): 541-554

Katz JS, Martin BR (1997) What is research collaboration? *Research Policy* 26(1): 1-18

Laudel G (2001) Collaboration, creativity and rewards: why and how scientists collaborate. *Journal of Technology Management* 22 (7-8): 762-781

Liang LM, Zhu L (2002) Major factors affecting China's inter-regional research collaboration: Regional scientific productivity and physical proximity. *Scientometrics* 55(2): 287-316

Long JS (1997) *Regression Models for Categorical and Limited Dependent Variables. Advanced Quantitative Techniques in the Social Sciences* (Volume 7). Sage, Thousand Oaks CA

Lundberg J, Thomson G, Lundkvist I, Skar, J, Brommels, M (2006) Collaboration uncovered: exploring the adequacy of measuring university-industry collaboration through co-authorship and co-funding. *Scientometrics* 69 (3): 575-589

MacRoberts MH, MacRoberts BR (1996) Problems of citation analysis. *Scientometrics* 36(3): 435-444

Maggioni MA, Nosvelli M, Uberti TE (2007) Space versus networks in the geography of innovation: A European analysis. *Papers in Regional Science* 86(3): 471-493

Maggioni MA, Uberti TE (2009) Knowledge networks across Europe: which distance matters? *Annals of Regional Science* 43(3): 691-720

Marsili O (2001) *The Anatomy and Evolution of Industries: Technological Change and Industrial Dynamics*. Edward Elgar, Cheltenham

Massard N, Mehier C (2009) Proximity and innovation through an 'accessibility to knowledge' lens. *Regional Studies* 43(1): 77-88

McKelvey M, Alm H, Riccaboni M (2003) Does co-location matter for formal knowledge collaboration in the Swedish biotechnology–pharmaceutical sector? *Research Policy* 32(3): 483-501

Moed HF (2005) *Citation Analysis in Research Evaluation*. Springer, Dordrecht

Moodysson J, Coenen L, Asheim B (2008) Explaining spatial patterns of innovation: analytical and synthetic modes of knowledge creation in the Medicon Valley life-science cluster. *Environment and Planning A* 40(5): 1040-1056

Owen-Smith J, Powell WW (2004) Knowledge networks as channels and conduits: the effects of spillovers in the Boston biotechnology community. *Organization Science* 15(1): 5-21

Paci R, Usai S (2000) Technological enclaves and industrial districts: an analysis of the regional distribution of innovative activity in Europe. *Regional Studies* 34(2): 97-114

Paris G, De Leo G, Menozzi P, Gatto M (1998) Region-based citation bias in science. *Nature* 396: 210

Pasterkamp G, Rotmans J, Kleijn D, Borst C (2007) Citation frequency: A biased measure of research impact significantly influenced by the geographical origin of research articles. *Scientometrics* 70(1): 153-165

Pavitt K (1984) Sectoral patterns of technical change: towards a taxonomy and a theory. *Research Policy* 13: 343-373

Ponds R (2009) The limits to internationalization of scientific research collaboration. *Journal of Technology Transfer* 34(1): 76-94

Ponds R, van Oort F, Frenken K (2007) The geographical and institutional proximity of research collaboration. *Papers in Regional Science* 86(3): 423-443

Ponds R, van Oort F, Frenken K (2009) Innovation, spillovers, and university-industry collaboration: An extended knowledge production function approach. *Journal of Economic Geography* 10(2): 231-255

Powell WW, Koput K, Smith-Doerr L (1996) Interorganisational collaboration and the locus of innovation: networks of learning in biotechnology. *Administrative Science Quarterly* 41: 116-145

Rafols I, Leydesdorff L (2009) Content-based and algorithmic classifications of journals: Perspectives on the dynamics of scientific communication and indexer effects. *Journal of the American Society for Information Science and Technology* 60(9): 1823-1835

Saxenian A-L (1994) *Regional Advantage: Culture and Competition in Silicon Valley and Route 128*. Harvard University Press, Cambridge MA

Saxenian A-L (2006) *The New Argonauts. Regional Advantage in a Global Economy*. Harvard University Press, Cambridge MA

Scherngell T, Barber M (2009) Spatial interaction modelling of cross-region R&D collaborations. Empirical evidence from the 5th EU framework programme. *Papers in Regional Science*, 88(3): 531-546

Singh J (2005) Collaborative networks as determinants of knowledge diffusion patterns. *Management Science* 51(5): 756-770

Singh J (2007) External collaboration, social networks and knowledge creation: Evidence from scientific publications. INSEAD, mimeo

Stuart TE (2000) Interorganisational alliances and the performance of firms: A study of growth and innovation rates in a high-technology industry. *Administrative Science Quarterly* 43: 668-698

Torre A (2008) On the role played by temporary physical proximity in knowledge transmission. *Regional Studies* 42(6): 869-889

Uzzi B (1996) The sources and consequences of embeddedness for the economic performance of organizations: The network effect. *American Sociological Review* 61(4): 674-698

Van Looy B, Zimmerman E, Veugelers R, Verbeek E, Mello J, Debackere K (2003) Do science-technology interactions pay off when developing technology? *Scientometrics* 57(3): 355-367

Wagner-Doebler R (2001) Continuity and discontinuity of collaboration behaviour since 1800 – from a bibliometric point of view. *Scientometrics* 52: 503-517

Wong BBM, Kokko H (2005) Is science as global as we think? *Trends in Ecology and Evolution* 20: 475-476

Wouters PF (1998) The signs of science. *Scientometrics* 41(1-2): 225-241

Zucker LG, Darby MR, Armstrong JS (1998) Geographically localized knowledge: spillovers or markets? *Economic Inquiry* 36(1): 65-86

Table 1. Relevant science-fields* for the selected technologies

Agriculture & food chemistry *(Life sciences)* Biochemistry & Molecular Biology Plant Sciences Microbiology Genetics & Heredity Food Science & Technology Agriculture Dairy & Animal Science Nutrition & Dietetics **Analysis, measure & control technology** *(Not classified)* Biochemistry & Molecular Biology Applied Physics Instruments & Instrumentation Electrical & Electronical Engineering Immunology Analytical Chemistry **Biotechnology** *(Life sciences)* Biochemistry & Molecular Biology Microbiology Genetics & Heredity Immunology Virology Biophysics Biotechnology & Applied Microbiology **Information technology** *(Physical sciences)* Electrical & Electronical Engineering Computer Applications Computer Cybernetics Telecommunications Acoustics	**Optics** *(Physical sciences)* Optics Electrical & Electronical Engineering Applied Physics Polymer Science **Organic fine chemistry** *(Life sciences)* Biochemistry & Molecular Biology Organic Chemistry Pharmacology & Pharmacy Immunology Genetics & Heredity Microbiology **Semiconductors** *(Physical sciences)* Electrical & Electronical Engineering Physics Condensed Matters Crystallography Applied Physics Nuclear Science and Technology Material Science **Telecommunication** *(Physical sciences)* Electrical & Electronical Engineering Telecommunications Optics Applied Physics Computer Applications Computer Cybernetics

* Fields consist of a set of journals as defined by the Institute for Scientific Information (ISI). See Van Looy et al. (2003) and Ponds et al. (2007)

Figure 1. The share of co-publications in the total number of publications

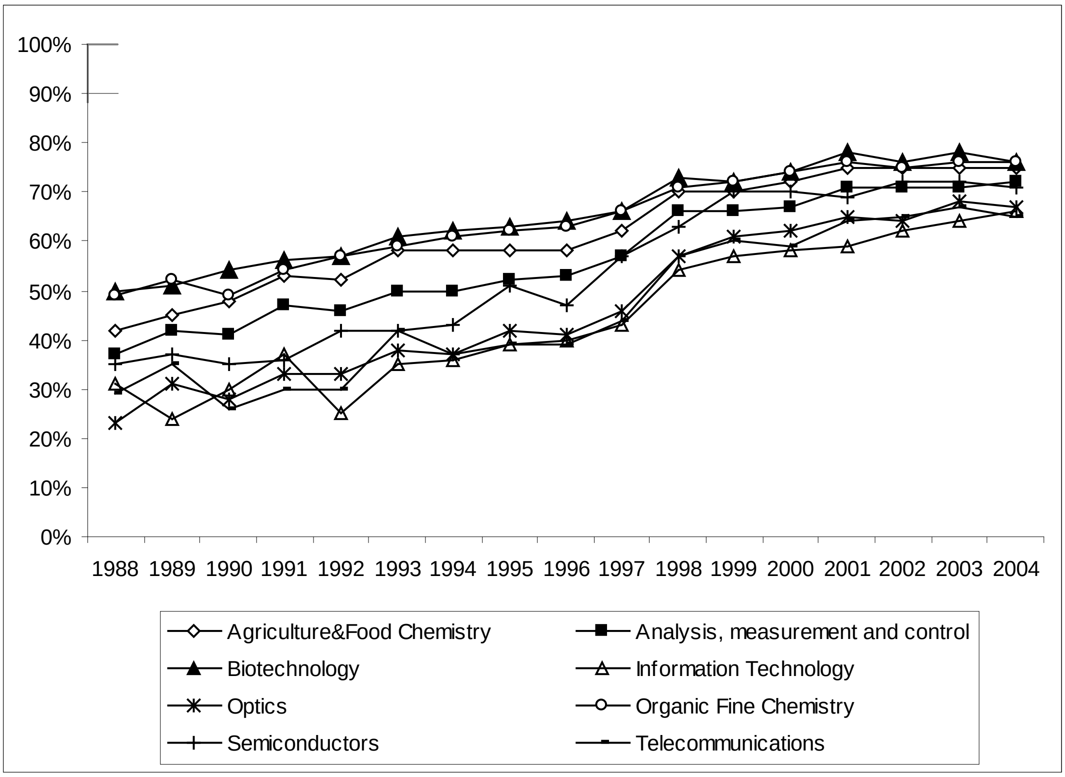

Table 2. Descriptive statistics

	Agriculture & food chemistry				Biotechnology				Organic fine chemistry			
	(N=32534)				(N=33501)				(N=36133)			
	Min.	Max.	Mean	Std. Deviation	Min.	Max.	Mean	Std. Deviation	Min.	Max.	Mean	Std. Deviation
Times cited	0	2695	19.10	42.65	0	2695	21.04	45.78	0	2765	20.07	43.84
Authors	1	97	4.73	3.06	1	151	5.22	3.53	1	114	5.10	3.39
Addresses	1	28	2.11	1.72	1	99	2.23	1.94	1	99	2.18	1.91
NUTS3			0.10				0.12				0.12	
Netherlands			0.10				0.10				0.10	
EU			0.25				0.27				0.25	
USA			0.11				0.12				0.11	
Other international			0.10				0.10				0.09	
Academic			0.30				0.31				0.30	
Hybrid			0.22				0.24				0.23	
Non-academic			0.08				0.09				0.09	
NUTS3 academic			0.04				0.05				0.05	
NUTS3 hybrid			0.05				0.07				0.06	
NUTS3 non-academic			0.03				0.05				0.03	
Netherlands academic			0.06				0.06				0.06	
Netherlands hybrid			0.05				0.04				0.04	
Netherlands non-academic			0.02				0.02				0.02	
EU academic			0.14				0.15				0.14	
EU hybrid			0.10				0.11				0.11	
EU non-academic			0.03				0.04				0.04	
USA academic			0.07				0.08				0.07	
USA hybrid			0.04				0.05				0.05	
USA non-academic			0.01				0.02				0.02	
Other international academic			0.07				0.06				0.06	
Other international hybrid			0.05				0.04				0.04	
Other international non-academic			0.01				0.02				0.01	

Table 2 (cont.)

	Analysis, measurement & control technology				Information technology				Optics			
	(N=26353)				(N=8409)				(N=14714)			
	Min.	Max.	Mean	Std. Deviation	Min.	Max.	Mean	Std. Deviation	Min.	Max.	Mean	Std. Deviation
Times cited	0	2064	16.43	37.89	0	470	6.49	16.52	0	1225	9.96	22.15
Authors	1	596	4.72	6.50	1	98	3.26	3.38	1	98	3.78	2.91
Addresses	1	43	1.94	1.68	1	21	1.66	1.20	1	21	1.69	1.09
NUTS3			0.07				0.05				0.04	
Netherlands			0.07				0.07				0.07	
EU			0.25				0.17				0.21	
USA			0.10				0.08				0.07	
Other international			0.10				0.08				0.10	
Academic			0.28				0.19				0.21	
Hybrid			0.20				0.16				0.18	
Non-academic			0.06				0.07				0.06	
NUTS3 academic			0.03				0.02				0.01	
NUTS3 hybrid			0.04				0.03				0.03	
NUTS3 non-academic			0.02				0.01				0.01	
Netherlands academic			0.05				0.04				0.04	
Netherlands hybrid			0.03				0.03				0.04	
Netherlands non-academic			0.01				0.01				0.01	
EU academic			0.14				0.08				0.10	
EU hybrid			0.10				0.06				0.09	
EU non-academic			0.03				0.03				0.03	
USA academic			0.06				0.04				0.04	
USA hybrid			0.04				0.03				0.03	
USA non-academic			0.01				0.02				0.01	
Other international academic			0.07				0.05				0.07	
Other international hybrid			0.04				0.03				0.04	
Other international non-academic			0.01				0.01				0.01	

Table 2 (cont.)

	Semiconductors				Telecommunications			
	(N=14149)				(N=12685)			
	Min.	Max.	Mean	Std. Deviation	Min.	Max.	Mean	Std. Deviation
Times cited	0	1228	10.52	23.74	0	478	8.65	19.67
Authors	1	98	4.25	3.12	1	98	3.62	3.09
Addresses	1	21	1.82	1.20	1	21	1.70	1.15
NUTS3			0.03				0.04	
Netherlands			0.07				0.07	
EU			0.25				0.19	
USA			0.07				0.09	
Other international			0.14				0.10	
Academic			0.26				0.21	
Hybrid			0.18				0.17	
Non-academic			0.05				0.06	
NUTS3 academic			0.01				0.01	
NUTS3 hybrid			0.02				0.03	
NUTS3 non-academic			0.01				0.01	
Netherlands academic			0.04				0.04	
Netherlands hybrid			0.04				0.03	
Netherlands non-academic			0.01				0.01	
EU academic			0.14				0.10	
EU hybrid			0.09				0.08	
EU non-academic			0.03				0.03	
USA academic			0.05				0.05	
USA hybrid			0.03				0.04	
USA non-academic			0.01				0.01	
Other international academic			0.10				0.06	
Other international hybrid			0.05				0.04	
Other international non-academic			0.01				0.01	

Table 3. Regression results for spatial and institutional variables (* indicates significance at 0.01 level)

	Life-sciences-based technologies															
	Agriculture & food chemistry				Biotechnology				Organic fine chemistry				Analysis, measurement & control technology			
Authors	0.093* (0.003)	0.091* (0.003)	0.093* (0.003)	0.091* (0.003)	0.072* (0.003)	0.070* (0.003)	0.072* (0.003)	0.070* (0.003)	0.066* (0.003)	0.064* (0.003)	0.066* (0.003)	0.064* (0.003)	0.061* (0.004)	0.060* (0.004)	0.063* (0.004)	0.060* (0.004)
Addresses	-0.011* (0.006)	-0.035* (0.007)	-0.022* (0.006)	-0.033* (0.007)	0.009 (0.006)	-0.021* (0.007)	-0.007 (0.006)	-0.020* (0.007)	0.015* (0.005)	-0.022* (0.007)	-0.001 (0.006)	-0.020* (0.007)	0.022* (0.008)	-0.056* (0.011)	-0.024* (0.010)	-0.047* (0.012)
NUTS3		0.104* (0.026)		0.082* (0.029)		0.130* (0.024)		0.095* (0.027)		0.052* (0.024)		0.025 (0.026)		0.261* (0.037)		0.189* (0.040)
Netherlands		-0.130* (0.026)		-0.155* (0.028)		-0.189* (0.026)		-0.220* (0.028)		-0.152* (0.025)		-0.183* (0.027)		-0.035* (0.036)		-0.131* (0.040)
EU		0.170* (0.021)		0.142* (0.024)		0.193* (0.020)		0.161* (0.023)		0.219* (0.019)		0.185* (0.022)		0.282* (0.026)		0.190* (0.030)
USA		0.254* (0.026)		0.228* (0.029)		0.248* (0.024)		0.218* (0.026)		0.304* (0.025)		0.274* (0.027)		0.392* (0.033)		0.297* (0.036)
Other international		-0.168* (0.027)		-0.194* (0.029)		-0.095* (0.027)		-0.125* (0.029)		-0.053* (0.027)		-0.086* (0.029)		-0.196* (0.033)		-0.294* (0.037)
Academic			0.084* (0.017)	0.055* (0.021)			0.092* (0.017)	0.052* (0.020)			0.104* (0.017)	0.057* (0.020)			0.238* (0.022)	0.190* (0.026)
Hybrid			0.031 (0.019)	0.016 (0.021)			0.078* (0.018)	0.047* (0.020)			0.090* (0.018)	0.058* (0.019)			0.082* (0.024)	0.058* (0.026)
Non-academic			0.001 (0.029)	-0.005 (0.030)			0.033 (0.027)	0.011 (0.029)			-0.027 (0.026)	-0.043 (0.028)			-0.022 (0.039)	-0.081* (0.040)
Constant	3.114* (0.038)	2.917* (0.038)	2.933* (0.038)	2.911* (0.038)	3.111* (0.039)	3.105* (0.039)	3.099* (0.039)	3.096* (0.039)	3.007* (0.036)	3.015* (0.036)	2.995* (0.036)	3.005* (0.036)	2.897* (0.046)	2.946* (0.046)	2.905* (0.046)	2.924* (0.046)
Alpha	1.643* (0.013)	1.600* (0.013)	1.587* (0.013)	1.599* (0.013)	1.639* (0.013)	1.624* (0.013)	1.636* (0.013)	1.624* (0.013)	1.664* (0.013)	1.648* (0.013)	1.661* (0.013)	1.647* (0.013)	1.849* (0.017)	1.825* (0.016)	1.839* (0.017)	1.820* (0.016)
N	32534	32534	32534	32534	33501	33501	33501	33501	36133	36133	36133	36133	26353	26353	26353	26353
Log likelihood	-120039	-119910	-120026	-119906	-126465	-126316	-126444	-126312	-135817	-135646	-135787	-135637	-92842	-92675	-92778	-92640
Log likelihood R2	0.232	0.238	0.232	0.238	0.229	0.236	0.230	0.236	0.199	0.207	0.201	0.207	0.193	0.203	0.197	0.205

Table 3 (cont.) (* indicates significance at 0.01 level)

	Physical-sciences-based technologies															
	Information technology				Optics				Semiconductors				Telecommunications			
Authors	0.038* (0.008)	0.041* (0.008)	0.047* (0.008)	0.046* (0.008)	0.030* (0.006)	0.031* (0.006)	0.031* (0.006)	0.032* (0.006)	0.013* (0.005)	0.014* (0.005)	0.014* (0.005)	0.015* (0.005)	0.064* (0.006)	0.067* (0.006)	0.069* (0.006)	0.069* (0.006)
Addresses	-0.009 (0.018)	-0.063* (0.028)	-0.070* (0.022)	-0.058* (0.028)	-0.014 (0.012)	-0.024 (0.021)	-0.010 (0.015)	-0.018 (0.021)	-0.002 (0.011)	-0.026 (0.019)	0.000 (0.014)	-0.023 (0.020)	-0.058* (0.014)	-0.140* (0.023)	-0.103* (0.018)	-0.119* (0.024)
NUTS3		-0.070 (0.080)		-0.157 (0.088)		-0.032 (0.062)		0.051 (0.070)		-0.103 (0.066)		-0.032 (0.072)		-0.072 (0.068)		-0.075 (0.074)
Netherlands		0.151* (0.069)		0.007 (0.077)		0.074 (0.050)		0.089 (0.058)		0.198* (0.050)		0.221* (0.056)		0.299* (0.056)		0.202* (0.063)
EU		0.167* (0.058)		0.037 (0.068)		0.062 (0.039)		0.082 (0.049)		0.059 (0.037)		0.082 (0.045)		0.228* (0.045)		0.140* (0.054)
USA		0.343* (0.070)		0.215* (0.077)		0.190* (0.051)		0.199* (0.058)		0.310* (0.051)		0.329* (0.056)		0.273* (0.053)		0.183* (0.060)
Other international		-0.260* (0.072)		-0.414* (0.078)		-0.265* (0.047)		-0.288* (0.054)		-0.246* (0.041)		-0.248* (0.047)		-0.160* (0.052)		-0.286* (0.059)
Academic			0.301* (0.048)	0.315* (0.058)			0.051 (0.032)	0.042 (0.041)			0.044 (0.031)	0.019 (0.038)			0.265* (0.036)	0.227* (0.044)
Hybrid			0.047 (0.049)	0.045 (0.054)			-0.007 (0.033)	-0.028 (0.038)			-0.007 (0.032)	-0.037 (0.037)			0.004 (0.038)	-0.021 (0.042)
Non-academic			-0.032 (0.072)	-0.046 (0.077)			-0.233* (0.051)	-0.305* (0.055)			-0.223* (0.054)	-0.287* (0.057)			-0.112 (0.058)	-0.189* (0.063)
Constant	2.147* (0.085)	2.196* (0.086)	2.171* (0.085)	2.171* (0.086)	2.663* (0.059)	2.676* (0.060)	2.656* (0.059)	2.668* (0.060)	2.822* (0.056)	2.834* (0.056)	2.819* (0.056)	2.831* (0.057)	2.468* (0.068)	2.537* (0.070)	2.493* (0.069)	2.510* (0.069)
Alpha	1.824* (0.032)	1.808* (0.032)	1.813* (0.032)	1.798* (0.032)	1.630* (0.020)	1.621* (0.020)	1.627* (0.020)	1.617* (0.020)	1.637* (0.021)	1.623* (0.021)	1.634* (0.021)	1.619* (0.020)	1.744* (0.024)	1.729* (0.024)	1.734* (0.024)	1.721* (0.024)
N	8409	8409	8409	8409	14714	14714	14714	14714	14149	14149	14149	14149	12685	12685	12685	12685
Log likelihood	-22813	-22783	-22790	-22762	-46308	-46271	-46293	-46251	-45378	-45316	-46293	-45301	-37917	-37868	-37881	-37837
Log likelihood R2	0.162	0.168	0.167	0.172	0.160	0.164	0.161	0.166	0.149	0.157	0.161	0.158	0.161	0.168	0.166	0.172

Table 4. Regression results for combined spatial-institutional variables
(* indicates significance at 0.01 level)

	Life-sciences-based technologies			
	Agriculture & food chemistry	Biotechnology	Organic Fine Chemistry	Analysis, measurement & control technology
Authors	0.091* (0.003)	0.071* (0.003)	0.064* (0.003)	0.060* (0.004)
Addresses	-0.029* (0.007)	-0.012 (0.006)	-0.009 (0.006)	-0.034* (0.010)
NUTS3 academic	0.060 (0.032)	0.025 (0.028)	-0.013 (0.027)	0.228* (0.045)
NUTS3 hybrid	0.053 (0.036)	0.062* (0.024)	0.080* (0.032)	0.036 (0.049)
NUTS3 non-academic	0.053 (0.051)	0.024 (0.023)	-0.063 (0.043)	0.276* (0.074)
Netherlands academic	-0.049 (0.033)	-0.115* (0.033)	-0.080* (0.032)	0.012 (0.044)
Netherlands hybrid	-0.141* (0.038)	-0.164* (0.041)	-0.124* (0.039)	-0.104 (0.056)
Netherlands non-academic	-0.147* (0.055)	-0.175* (0.057)	-0.241* (0.054)	-0.226* (0.087)
EU academic	0.158* (0.022)	0.184* (0.022)	0.195* (0.022)	0.262* (0.027)
EU hybrid	0.049 (0.027)	0.052* (0.026)	0.087* (0.026)	0.116* (0.033)
EU non-academic	0.085 (0.044)	0.069 (0.041)	0.068 (0.040)	-0.023 (0.054)
USA academic	0.181* (0.031)	0.146* (0.030)	0.192* (0.030)	0.380* (0.039)
USA hybrid	0.189* (0.041)	0.182* (0.037)	0.157* (0.037)	0.199* (0.050)
USA non-academic	0.046 (0.068)	0.111* (0.057)	0.157* (0.057)	-0.179 (0.080)
Other international academic	-0.195* (0.033)	-0.162* (0.034)	-0.147* (0.033)	-0.240* (0.039)
Other international hybrid	0.000 (0.042)	0.078 (0.043)	0.101* (0.043)	-0.013 (0.052)
Other international non-academic	-0.142* (0.070)	-0.147* (0.068)	-0.135* (0.068)	-0.098 (0.098)
Constant	2.930* (0.038)	3.109* (0.039)	3.010* (0.036)	2.941* (0.046)
Alpha	1.589* (0.013)	1.625* (0.013)	1.648* (0.013)	1.824* (0.016)
N	32534	33501	36133	26353
Log likelihood	-119926	-126328	-135652	-92667
Log likelihood R2	0.237	0.235	0.207	0.204

Table 4 (cont.)
(* indicates significance at 0.01 level)

	Physical-sciences-based technologies			
	Information technology	Optics	Semiconductors	Telecommunications
Authors	0.044* (0.008)	0.032* (0.006)	0.015* (0.005)	0.068* (0.006)
Addresses	-0.053* (0.024)	-0.034 (0.016)	-0.023 (0.015)	-0.098* (0.019)
NUTS3 Academic	-0.019 (0.099)	-0.090 (0.130)	-0.013 (0.093)	-0.226* (0.104)
NUTS3 Hybrid	-0.094 (0.101)	0.113 (0.075)	-0.032 (0.089)	-0.120 (0.084)
NUTS3 Non-academic	0.111 (0.157)	-0.114 (0.110)	-0.219 (0.130)	0.046 (0.130)
Netherlands Academic	0.205* (0.086)	0.166* (0.063)	0.179* (0.063)	0.375* (0.069)
Netherlands Hybrid	0.014 (0.098)	-0.010 (0.063)	0.157 (0.064)	-0.001 (0.074)
Netherlands Non-academic	-0.382* (0.156)	-0.240 (0.107)	-0.211* (0.120)	-0.164 (0.126)
EU academic	0.278* (0.064)	0.161* (0.041)	0.098* (0.036)	0.305* (0.046)
EU hybrid	0.076 (0.073)	0.051 (0.044)	0.049 (0.044)	0.030 (0.053)
EU non-academic	0.013 (0.101)	-0.097 (0.069)	-0.199* (0.072)	-0.096 (0.079)
USA academic	0.434* (0.087)	0.254* (0.060)	0.361* (0.060)	0.273* (0.062)
USA hybrid	0.139 (0.099)	0.051 (0.072)	0.040 (0.075)	0.069 (0.074)
USA non-academic	0.190 (0.143)	0.076 (0.110)	0.138 (0.128)	0.117 (0.118)
Other international Academic	-0.165* (0.083)	-0.248* (0.051)	-0.242* (0.044)	-0.197* (0.058)
Other international Hybrid	-0.354* (0.112)	-0.029 (0.066)	-0.101 (0.056)	-0.077 (0.073)
Other international Non-academic	-0.362 (0.187)	-0.687* (0.139)	-0.167 (0.137)	-0.685* (0.161)
Constant	2.186* (0.085)	2.684* (0.060)	2.835* (0.056)	2.499* (0.069)
Alpha	1.799* (0.032)	1.616* (0.020)	1.622* (0.020)	1.720* (0.024)
N	8409	14714	14149	12685
Log likelihood	-22764	-4624	-45312	-37837
Log likelihood R2	0.172	0.166	0.157	0.172