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DISCUSSION PAPER

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Are Firms Withdrawing From Basic Research? An Analysis of Firm-Level Publication Behaviour in Germany

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Are firms withdrawing from basic research?

An analysis of firm-level publication behaviour in Germany

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Abstract

Previous research has expressed concerns about firms engaging less in basic research. We contribute to this debate by studying trends in the scientific publishing activities of firms located in Germany. Our results do not confirm a declining trend in raw numbers with numbers indicating that firms' aggregate volume of scientific publications stayed constant between 2008 and 2016. However, the number of publishing firms declined, in particular in high-tech and knowledge-intensive industries. Beyond that, we observe positive trends in publishing in basic research journals compared to journals focused on applied research, and publishing in collaboration with academic partners compared to publishing alone. Thus, our results paint an ambiguous picture. While they do not confirm a decrease in firms' basic research engagement in the aggregate, the figures document a concentration of publishing activities on fewer firms. We argue that this concentration of basic research activities in firms may pose a threat to the longer term innovativeness of the German economy.

Keywords Corporate publishing - Basic research - R&D strategy

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Introduction

Firms make important contributions to scientific knowledge. However, there are concerns that firms' contributions to scientific progress are diminishing. Recent studies report a downward trend in scientific publications co-authored by firm-affiliated researchers (Arora et al. 2018; Larivière et al. 2018; Tijssen, 2004). The proportion of firm publications in scientific output significantly declined over the last decades (Larivière et al. 2018). Arora et al. (2018) find that large US firms grew less likely to publish since the 1980s, and conclude that large firms are withdrawing from basic research. At the same time, other studies, which use alternative methodologies and examine other countries (Archambault and Larivière 2011; Chang 2014; Sun et al. 2007) or samples of firms (Camerani et al. 2018; Simeth and Raffo 2013; Simeth and Cincera 2016), show a rise in firms' publication activities. Thus, there seems considerable ambiguity in current trends, which requires deeper analysis.

By matching Scopus to the Mannheim Enterprise Panel, we provide detailed results on the population of scientific publications originating from firms located in Germany for the years 2008-2016. On the one hand, we find that the aggregate numbers of scientific publications of all firms, patenting firms, and large firms in Germany stay constant over this period. In addition, firm publications are increasingly published in journals focusing on basic research, as opposed to applied research. Moreover, we find that an increasing number of firm publications is published in collaboration with German research institutes or universities. On the other hand, despite the constant publication volume, our analysis confirms that the number of publishing firms has declined. This indicates that firms, on the whole, are not withdrawing from basic research, but publication activities are concentrating on fewer firms. Thus, although the overall publication numbers may stay constant and their basicness may increase, our findings indicate that increasingly many firms indeed withdraw from science.

The contribution of our paper is threefold. First, our generated dataset allows the analysis of the publication activities of the population of German firms, avoiding a sample bias inherent to most other studies that start from a selected subsample of firms. Second, we update the analyses of trends in firm publishing to the period 2008 to 2016 and are thus more recent than existing studies. Third, we compare directly the overall publication trends of frequently used subsamples of firms, such as large firms and innovation active firms. We also provide detailed insights by sector.

Literature review

To frame our results in the broader literature, we review the existing work on the motivations behind firms' scientific publishing activities. This stream of research highlights several motives to publish, such as to keep connected to the scientific community, to signal stakeholders, as complement to intellectual property, or as a commercialization strategy. We also review previous studies on the development of firm publishing. To further put our analysis into context, we examine prior results as well as differences in methodologies, time frames and samples.

Why do firms publish?

In its seminal treatment of incentives for science, Nelson (1957) claimed that basic research needs to be funded by the state because knowledge, as a public good, is subject to spillovers. Firms will therefore underinvest in basic science because they are unable to appropriate the full returns associated with the knowledge they create. Nonetheless, empirical evidence shows that firms are active in publishing nonetheless, which seems to contradict this simple wisdom. Many scholars have therefore provided additional reasons which can explain why firms rationally invest in basic science and become active publishers.

The literature on firm publishing reveals five broad, and to some extent interrelated, motivations (Camerani et al. 2018). First, firms publish in order to stay involved with the scientific community. From that perspective, publishing is a signal that the firm complies with academic standards and can contribute to scientific research (Almeida et al.

2011; Fini and Lacetera 2010; Hicks 1995; Simeth and Raffo 2013; Zucker et al. 2002). Such collaborations make it easier for industrial scientists to stay abreast of developments in the field (Kinney et al. 2004; Zucker et al. 2002), and to access potentially useful external knowledge (Furukawa and Goto 2006; Gittelman and Kogut 2003). Engaging in scientific research also strengthens the firm's absorptive capacity (Cohen and Levinthal 1989), leading to better innovation outcomes (Cockburn and Henderson 2003; Jong and Slavova 2014; Li et al. 2015; Simeth and Cincera 2016).

Second, and closely related, publishing helps firms to attract and retain scientists for their research departments. For many scientists, being able to contribute to the scientific literature is an important perk, and the opportunity to do so is perceived as a non-monetary reward (Sauermann and Roach 2014; Stern 2004). Publishing moreover signals that the firm provides a science-oriented work environment, which can help to attract scientists from academia (Cockburn and Henderson 2003; Fini and Lacetera 2010; Gans, Murray, and Stern 2017; Gittelman and Kogut 2003; Stern 2004).

Third, publications can be useful signals to other stakeholders (Hayter and Link 2018; Hicks 1995). Publications signal market potential towards investors, especially for start-ups that might lack other forms of intellectual property (Almeida et al. 2011; Belenzon and Patacconi 2014; Hicks 1995; Kinney et al. 2004). They can also inform suppliers, customers, and competitors about future technological developments (Godin 1996; Harhoff 1996; Hicks 1995; Kinney et al. 2004; Muller and Pénin 2007; Tijssen 2004), and, more generally, signal openness for mutually beneficial disclosure (Alexy et al. 2013; Pénin 2007). Indeed, previous studies have found a relation between publications and stock market valuation (Arora, Belenzon, and Patacconi 2018; Pellens and Della Malva 2018; Simeth and Cincera 2016).

Fourth, publications can be complementary to other forms of intellectual property. By publishing in scientific literature, firms add their work to the prior art, which prevents it from being claimed by competitors in a patent. This practice, called defensive publishing, is an effective intellectual property strategy in situations where the firm might otherwise have difficulties exploiting its innovations, or when rivals might otherwise limit the firm's operations by claiming intellectual property rights on key technologies (Barrett 2002; Gans et al. 2017; Hayter and Link 2018; Johnson 2014; Della Malva and Hussinger 2012; Pénin 2007). Defensive publishing is also effective in patent races for leaders as well as laggards (Baker and Mezzetti 2005; Parchomovsky 2000).

Fifth, publishing in the scientific literature can support the commercialisation of new products by generating interest (Godin 1996; Pénin 2007; Simeth and Cincera 2016). Especially in the pharmaceutical industry, publications are complementary to marketing efforts by signalling effectiveness to doctors (Azoulay 2002; Hicks 1995; Rafols et al. 2014). They can also act as scientific evidence for regulators when products need to be approved (Arora et al. 2018; Penders and Nelis 2011; Pénin 2007; Simeth and Raffo 2013).

Because firm publications mirror a sort of high-end knowledge, it is believed that they mirror a firm's competitive edge in high-tech or knowledge-intensive fields, which are typically also more disruptive. Because of this crucial importance, an increasing number of scholars have analysed trends in firms' publishing behaviour. We summarize the existing results in the next subsection.

Trends in the publication activities of firms

Evidence is mixed on the question whether firm publishing is increasing or decreasing. Camerani et al. (2018) show that the number of publications by the 2,500 most R&D active firms worldwide grew by 2.3% per year between 2011 and 2015. Studies of firm publications in Canada (Archambault and Larivière 2011), Japan (Sun et al. 2007), and Taiwan (Chang 2014) also document that their number is increasing. This is also found in analyses of innovative French firms (Simeth and Raffo 2013), large international firms listed in Compustat (Simeth and Cincera 2016), and other samples of firms (e.g. Godin 1996; Halperin and Chakrabarti 1987). Others have documented increasing numbers of firm publications in the pharmaceutical and electronics industries (Hicks et al. 1996; Narin and Rozek 1988), in the semiconductors industry (Pellens and Della Malva 2018), and in the field of artificial intelligence (Hartmann and Henkel 2020).

Other studies conclude that the number of firm publications decreases. Tijssen (2004) shows that the number of worldwide firm publications between 1996 and 2001 declined by 12%, starkly contrasting increases in the number of industrial researchers and patent applications. Studying large pharmaceutical firms, Rafols et al. (2014) finds a drop of 9% in the period between 1995 and 2009. The authors interpret this as a general reduction of effort in traditional core research fields, rather focusing more on health services and clinical research, and an increased reliance on external research partners for basic research. In a case study of publishing at IBM, Bhaskarabhatla & Hegde (2014) show that IBM's publications dropped from 1989 onwards. However, this was the result of changing incentives schemes for inventors, and not necessarily indicative of a broader trend.

Some of the differences in the findings are clearly due to different methodological approaches and databases. Despite this ambiguity in the overall numbers, it is clearer that the share of firm publications among the whole body of scientific output is decreasing. Camerani et al. (2018) find that the number of publications by top R&D spenders grew less quickly than the number of publications in other institutions. Larivière et al. (2018) document that the proportion of worldwide industry-authored papers more than halved between 1980 and 2014. Thus, in relative terms the importance of firm publications is decreasing.

Relatedly, some studies show that firms become less likely to publish research results, keeping other factors equal. While a decrease in the total number of scientific publications by firms could be primarily driven by a drop in the aggregate level of R&D investment, these analyses show that also the number of corporate publications has decreased even when R&D investments are factored in. Conditional on other firm characteristics, among which R&D expenditures, Arora et al. (2018) find firms on average generate 20% fewer publications per decade between 1980 and 2006, and Arora et al. (2020) report a decline of 44% between 1980 and 2015. Arora et al. (2018; 2020) interpret these shifts as a decreasing engagement in scientific research. This trend seems to be heterogeneous across and within sectors. In the semiconductor industry, for instance, Pellens & Della Malva (2018) estimate that fabless firm's propensity to publish grows by 4% yearly, whereas that of manufacturing firms remains constant.

In total, even though firms are in aggregate publishing large quantities of scientific publications, the number of publications per unit of R&D expenditures is dropping. This indicates that firms are contributing a smaller proportion of the knowledge they generate to the scientific literature (Arora et al. 2018; 2020; Larivière et al. 2018; Tijssen 2004). Arora et al. (2018) argue this trend is driven by a decline in the private value of science or by an increase in the cost of doing research. In fact, the latter idea is in line with the findings of Bloom et al. (2020), who document decreasing returns to R&D in many settings. One possible explanation is that firms are increasingly motivated to keep research findings secret, in order to maintain a knowledge advantage (Larivière et al. 2018). Arora et al. (2018), however, argue that this is unlikely, as they find that firms are especially disconnecting from high-impact science, which they argue contains mostly basic research. If firms increasingly valued the ability to appropriate findings, they should be proportionally less likely to publish commercially valuable applied research findings.

Amid these trends, the manner in which firms are publishing is also changing. Firms are less inclined to publish by themselves or in collaboration with other firms, and publish more in collaboration with scientific institutes (Camerani et al. 2018; Hartmann and Henkel 2020; Hicks et al. 1996; Larivière et al. 2018; Sun et al. 2007; Tijssen 2004). These shifts match positive trends in industry-science collaborations in general (Calvert and Patel 2003; Tijssen 2012). One interpretation of this changes is that firms shift their priorities, increasingly conducting basic research with external partners and focusing more intensely on applied research and commercialisation (Arora et al. 2018; Pisano 2010; Sun et al. 2007; Tijssen 2004; Rafols et al. 2014). An alternative interpretation are increased collaborations which are the result of firms seeking out external knowledge or high-potential recruits in universities (Hicks et al. 1996).

In summary, the evidence on the trend in firm publishing is mixed, and depends on the time period under consideration, the nature of the sample, and the exact outcome measure analysed. What most studies appear to agree on, however, is that the contributions of firms to scientific knowledge are increasingly manifesting in collaboration with scientific institutions.

Data

To analyse the publication activities of German firms, we draw on the Scopus database provided by Elsevier. We further make use of the Mannheim Enterprise Panel generated by the ZEW - Mannheim, and the German Patent Office's patent database.[1] The three datasets are matched and aggregated at the firm-year level. The final dataset comprises yearly information on firms' publishing and patenting activities by industry and size.

In using Scopus to identify scientific firm articles, we follow Simeth and Cincera (2016). Scopus is the largest abstract and citation database of peer-reviewed literature.[2] It comprises information on scientific journals, books and conference proceedings. We use the disambiguation strategy proposed by Rimmert et al. (2017) to identify articles, letters, notes, reviews, and conference proceedings published by at least one author affiliated to a German firm between 2005 and mid-2017. These publications are defined as firm publications and we extract information on their authors' affiliations, their composition of authors, their citations and type of research.

We enrich this data with information on firms' industry and employment numbers. For this, we draw on the Mannheim Enterprise Panel. This dataset contains the complete data pool of the largest German credit rating agency - *Creditreform e.V.* - and is maintained by the ZEW Mannheim since 1992. It is the most comprehensive firm-level database in Germany next to the official Business Register of the Federal Statistical Office and provides a representative picture of the German corporate landscape, covering almost the entire population of firms in Germany (Bersch et al., 2020). Firms are defined as legally independent enterprises.[3] The patent database stems directly from the German Patent Office and covers the received patent applications from 1896 onwards. Inter alia, the database contains information on the names and addresses of patent applicants.

To match Scopus records and firm information, we extract affiliation names and addresses from the authors affiliated to a firm in our publication sample and aggregate them to unique firm name-address combinations. These name-address combinations are matched to the enterprise panel. In the resulting dataset, 99.6% of all combinations are matched to 2,455 enterprise panel firms. Individual firm publications are then attributed to firms over the generated affiliation-firm match. Firm-address combinations were either matched exactly, or, in case the exact affiliation information from Scopus was not found in the firm panel, matched to the most similar firm-address combination. To avoid mismatches arising from this, all matches were also manually checked. If a publication had two or more authors of different German firms, the publication was attributed to each firm. Our dataset covers 82,550 distinct publications, whereby each publication was allocated to 1.2 firms on average. The match between the Mannheim Enterprise Panel and the patent database is directly provided by the ZEW - Mannheim. It is based on matching patent applicant names and addresses to firm-level data and applies the same procedures as used in studies such as Crass et al. (2019) or Czarnitzki et al. (2016).

All information is aggregated to the firm-year level. For our analysis, we restrict the sample to publishing firms within industries covered by the European Community Innovation Surveys of the European Commission.[4] The surveys are used to estimate official statistics on the business enterprise sector's innovativeness and thus cover the same target population as our examination.[5] Furthermore, we focus on citable items (see Garfield, 1978; Moed, 2005) and, thus, abstract from conference proceedings. The reason for this is that conference proceedings in many cases only list the presenting author (Michels and Fu, 2014). Therefore, they cannot be attributed to all their authors reliably and, in addition, underestimate joint publications. Finally, we do not consider the pre-economic-crisis years

[1] All three databases were prepared in 2017. Thus, reliable information on patent applications and scientific publications are only available until 2016. Therefore, 2016 is the upper bound of our observed time period. To ensure the reliability of the Scopus database, we choose 2005 as lower bound of our observed time period.

[2] For a comparison between the coverage of Scopus and Web of Science in Germany see Schmoch et al. (2012).

[3] Detailed information on data collection, processing and definitions are provided in Bersch et al. (2014).

[4] The current European Community Innovation Surveys cover the sections B, C, D, E, H, J and K, the divisions 46, 69 to 74 (without the group 70.1) as well as the divisions 78 to 82 of the Nace Rev. 2 Classification (see Eurostat, 2008) .

[5] The Community Innovation Surveys follow the OECD's Oslo Manual and abstract from firms which are part of industries not or barely related to the business enterprise sector. Example industries are the sections *T - Households*, *U - Extraterritorial bodies* or *S - Membership organisations*.

before 2008. After applying these three restrictions, our panel represents 1,584 distinct firms. Table 1 provides descriptive statistics on our constructed balanced firm-year panel dataset, and describes the different variables which are used to examine aggregate trend statistics in the following section. Table 2 displays descriptive statistics on firms' publication volume for different industry subsamples. Technical details about the sample and the variables' generation are included as notes below the tables and figures.

Table 1 shows that the average yearly publication volume of a firm which published at least once within 2008 and 2016 is 2.93 on average, whereas the largest observed yearly publication volume accounts to 337 publications. Moreover, the average yearly publication volume in basic research journals of 1.68 is more than twice as high as the average yearly publication volume in applied research journals of 0.73. More than half of our sample firms applied at least once for a patent at the German patent office and around a third of our sample employs 500 persons or more. In addition, firms publish more in cooperation with German academia than alone or with other German firms, or German firms and academia. We limit our co-author composition classes to domestic collaboration as we cannot reliably distinguish between co-authors from academia, firms or other organizations for other countries than Germany. The average publication volume of highly cited publications is 0.59 and thus makes around 20.14% of a firm's entire publication volume.

- **Table 1** -

Table 2 suggests that knowledge and technology-intensity have a strong influence on firms' publication activities: Firms in technology-intensive manufacturing and knowledge-intensive services contribute a much higher number of firm publications. Firms part of high-tech manufacturing publish the most on average, whereas firms from medium-high-tech manufacturing add the most to the aggregate publication volume of all German firms. Firms in more low-tech manufacturing or other less knowledge-intensive services have fewer publications despite their high importance in terms of employment.

- **Table 2** -

Aggregate trends in scientific publishing of German firms

Increasing publication intensity of firms

As can be seen in Figure 1, there does not seem to be a clear trend in the number of firm publications. With some annual fluctuations, the overall volume of firm publications stays close to between 4,700 and 5,000, with a slight dip to 4,185 during the financial crisis in 2009 and 2010. However, the figures return quickly to the pre-crisis level afterwards. This finding contrasts the results presented by Arora et al. (2018; 2020), who argued for a downward trend in publishing by large US firms over the last decades. Neither do our results match those of Camerani et al. (2018), who document growing publication volumes by the world's top R&D spenders from 2011 to 2015. These variations may reflect differences in the sampling and methodology, as our sample includes all publishing German firms, whereas the other studies are based on large firms active in innovation.[6] However, the general trend in our data is also present when only considering large or patenting firms. Our analysis is closest to that of Archambault and Larivière (2011), who study the population of Canadian firms. Compared to this study, we document a more stagnant pattern.

- **Fig.1** -

[6] Compared to Arora et al. (2018; 2020), for instance, our study also differs in that we consider trends in the aggregate number of publications, whereas Arora et al. (2018; 2020) report trends in publication activities conditional on other characteristics, such as R&D expenditures.

Despite a constant trend in the absolute number of publications, the core of publishing firms has decreased. Figure 2 shows that while the overall number of publishing firms was above 700 in 2008, the number decreased to below 600 in 2016. Thus, while the overall number of publications did not shrink, they originated from fewer firms, which on their side increased their publication activities. This increasing concentration of publication activities is in line with findings by Rammer and Schubert (2018) who showed that the innovation activities in Germany, although on the rise, were due to a declining core of innovation active firms - a trend that started already in the early 2000s. Our results, therefore, strongly suggest that the concentration tendencies observable in general innovation activities are also paralleled by an increase in the concentration of the publication activities.

- **Fig.2** -

When disentangling the trends in publications by industry, we see that firms in technology-intensive manufacturing (Figure 3a) and knowledge-intensive services (Figure 3b) contribute a much higher number of publications than firms in other industries at any point in time. In addition, aggregate publication volumes have remained more or less unchanged in most industries with only small annual fluctuations. One exception is medium high-tech manufacturing, where publication numbers have steadily increased since 2009. Figures 4a and 4b show the development of the number of publishing firms by industry. The drop in publishing firms is driven by diminishing numbers of publishing firms in technology-intensive manufacturing and knowledge-intensive services. Thus, given the constant or increasing publication volumes in Figure 3a and Figure 3b, the concentration of publishing is increasing in particular in these industries.

- **Fig.3a,b** -

- **Fig.4a,b** -

Increasing ratio of basic research publications

Figure 5 shows that the ratio of basic to applied research publications by German firms has grown from 1.7 in 2008 to 2.6 in 2016. Hence, while there is a general stagnation of the overall publication volume as shown in Figure 1, the amount of basic research publications has risen compared to applied research publications. Thus, in contrast to US firms (Arora et al. 2018), we find that publications by German firms have become more basic over the last 10 years.[7] One reason for such a relative decline in applied publishing might be that firms are increasingly reluctant to publish commercially relevant information, in order to maximise opportunities for appropriation. Another driver might be related to changes in the composition of firm publishing, where collaborations with universities account for an increasing share of firms' publications (Camerani et al. 2018; Hartmann and Henkel 2020; Hicks et al. 1996; Larivière et al. 2018; Sun et al. 2007; Tijssen 2004). Under the assumption that collaborations with universities are more basic in nature than research conducted solely by firms, an increase in collaborations with universities might explain the trend towards basic research.

- **Fig.5** -

Joint publications and their impact

Figure 5 shows, in line with prior studies (Camerani et al. 2018; Hartmann and Henkel 2020; Hicks et al 1996; Larivière et al. 2018; Sun et al. 2007; Tijssen 2004), that the stagnation in the number of firm publications is driven by, on the one hand, a decrease in the number of publications published only by authors from the same firm, and,

[7] Part of the difference between our finding and the conclusion of Arora et al. (2018), who find that firms are particularly decoupling from basic science, might be one of definition: whereas we make use of a journal-level classification to differentiate basic and applied work (see also Lim 2004), the analysis by Arora et al. (2018) considers high-impact journals as basic.

on the other hand, an increase of publications including co-authors from academia. Since the number of publications including other firms, as well as other firms and academia stayed about the same in the period between 2008 and 2016, we find that science-industry co-publications were generally growing at the expense of publications not co-authored with any other organization. This pattern is consistent with the increasing share of basic research publications documented in the previous section.

- **Fig.6** -

These patterns are especially relevant as there is a clear relation between the nature of science collaboration and scientific impact. In Figure 7, we plot the excellence rate, the share of a firm's publications in the 10% most cited publications by type of co-publication. Consistently, the publications authored only by the focal firm rank lowest with an excellence rate between 12% and 17%. Highest, in particular in the most recent periods, are the publications with academia (20% in 2016) and academia and other firms (19% in 2016). Similar trends can also be observed when using the citation rate - the number of citations per publication - as a benchmark. Here too, co-publications with academic involvement rank highest.

- **Fig.7** -

Conclusion

Our comprehensive analysis of the scientific publications of German firms adds to the still limited body of literature on the development of firm publications. Our results indicate that German firms, in aggregate, are not publishing significantly less in scientific literature over the last decade. At the same time, the number of firms that engage in publishing is decreasing, indicating that firm publishing is concentrating. This pattern mirrors a more general concentration of innovation activities in Germany revealed by Rammer and Schubert (2018). This trend is accompanied by a tendency towards publishing in journals focusing on basic research, and in co-authorship with German scientific institutes.

An important implication of our finding is that we are unable to subscribe to a simple “yes” or “no” on the question of whether firms are withdrawing from science. On the one hand, our results indicate that the total number of publications remains relatively stable, implying limited reason for concern. Also, the observation that publications’ degree of basicness is increasing indicates that, on the whole, firms do not appear to leave basic research. On the other hand, the number of publishing firms is decreasing, especially in high-tech and knowledge-intensive industries. This concentration on fewer firms indicates that some firms leave scientific research, which may be worrisome for these industries and pose a thread on Germany’s future innovativeness. Likewise, the fact that scientific publishing is occurring to a higher degree in collaboration with academia hints that scientific, and in particular basic, research increasingly requires a division of labour (Arora et al. 2018; Pisano 2010; Sun et al. 2007; Tijssen 2004; Rafols et al. 2014).

We have to acknowledge the following data limitations. First, our results are restricted to the publications collected by the Scopus database. In recent years, new publication outlets, like ArXiv, are gaining relevance in new areas, like Artificial Intelligence. Moreover, we abstract from conference proceedings, because they cannot be reliably attributed in case of multiple authorship. However, in particular in the fields of informatics and electrical engineering, conference proceedings play a vital role for science communication (Michels and Fu 2014). Incorporating conference proceedings and alternative information would lead to a more complete picture of firm publishing, but is outside the scope of this analysis. Second, some researchers employed by industry are also affiliated with scientific institutes (Yegros-Yegros and Tijssen 2014) and might only use this affiliation for their publication activities. We are not able to identify these firm publications. Finally, when focusing on joint publications with other firms or academia, we can only identify German organizations and are bound to an analysis of domestic collaborations.

We are aware that our results only present descriptive statistics, which reflect aggregate patterns in firm publishing. They do not capture causal relationships, nor do they take into account changes in underlying factors, such as R&D expenditures. As such, our analysis does not make a statement on the economic impact of the developments in firms' publication activities for the publishing firms themselves, the German innovation system, or the German economy as a whole.

These limitations provide ground for future research. For one, future research should consider how shifts in firms' publication behaviour affect innovation and long-term economic performance. While these topics have been considered before (e.g. Arora 2018, Simeth and Cincera 2016), little attention has been paid to those firms that stop engaging with scientific publishing. Moreover, considering the way in which firms' different motives for publishing, for instance the aim of engaging with the scientific community compared to supporting the intellectual property strategy, interact with economic outcomes would be valuable. Understanding these relationships is key for the derivation of managerial implications for firms, which might be put for example in the context of open innovation, or intellectual property right management.

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Tables

Table 1 Variable definitions and pooled descriptive statistics

short name	description	mean	s.d.	max	sum
publication volume	Firm's yearly publication volume. It is calculated as the sum of yearly published articles, letters, notes, and reviews from authors affiliated to the firm.	2.93	13.64	337	41,834
applied research publications[a]	Firm's yearly publication volume in applied research journals.	0.73	3.22	84	10,371
basic research publicationsa[a]	Firm's yearly publication volume in basic research journals.	1.68	9.56	267	23,926
publications w/o partners[b]	Firm's yearly publication volume without co-authors from any other organizations.	0.41	1.82	47	5,786
publications with German academia[b]	Firm's yearly publication volume with co-authors affiliated to German academia.	1.19	5.80	130	16,997
publications with German firm(s)[b]	Firm's yearly publication volume with co-authors affiliated to other German firms.	0.19	1.30	32	2,710
publications with German firm(s) & German academia[b]	Firm's yearly publication volume without co-authors affiliated to other German firms and co-authors affiliated to German academia.	0.20	1.27	45	2,812
highly cited publications	Firm’s yearly publication volume in top ten percent highest cited publications according to Schmoch et al. (2016).	0.59	3.72	108	8,437
large firm	Dummy variable for being a large firm. We define firms with more and equal to 500 employees as large. (large = 1, not large = 0)	0.29	0.45	1	4,186
patenting firm	Dummy variable for being a patenting firm. We define firms applying for at least one patent at the German patent office as patenting. (patenting = 1, not patenting = 0)	0.58	0.49	1	8,223

Descriptive statistics refer to a balanced firm-year panel dataset. It covers 14,256 observations, which can be attributed to 1,584 individual firms that publish at least once between 2008 and 2016. Individual firms are all part of the industries used in the European Community Innovation Surveys.

[a]Publications are classified according to the journal classification scheme by Archambault et al. (2011). 18% of the aggregate firm publication volume of 41,834 cannot be classified into applied or basic research as their journal cannot be clearly attributed to basic or applied research.

[b]Co-author groups were identified based on Rimmert et al. (2017). 32% of the aggregate firm publication volume of 41,834 cannot be attributed to one of the four displayed co-author groups.

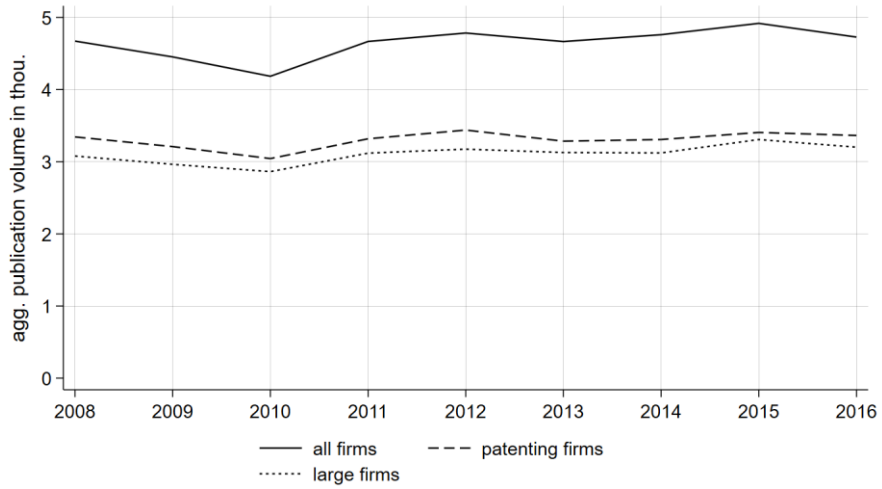
Table 2 Firms' publication volume by industry

Industry	mean	s.d.	max	sum
High-tech manufacturing	5.70	25.91	276	8,974
Medium-high-tech manufacturing	4.39	20.50	337	11,769
Medium-low-tech manufacturing	0.64	1.69	15	921
Low-tech manufacturing	0.75	2.04	26	541
Knowledge-intensive high-tech services	2.86	5.96	56	7,052
Knowledge-intensive market services	2.49	8.77	124	7,728
Knowledge-intensive financial services	2.09	4.41	33	917
Other knowledge-intensive services	2.00	4.95	32	431
Other industries	2.16	7.51	88	3,501

Descriptive statistics refer to a balanced firm-year panel dataset. It covers 14,256 observations, which can be attributed to 1,584 individual firms that publish at least once between 2008 and 2016. Individual firms are all part of the industries used in the European Community Innovation Surveys. The industry classification displayed follows the definition of high-tech and knowledge-intensive industries by Eurostat (2016).

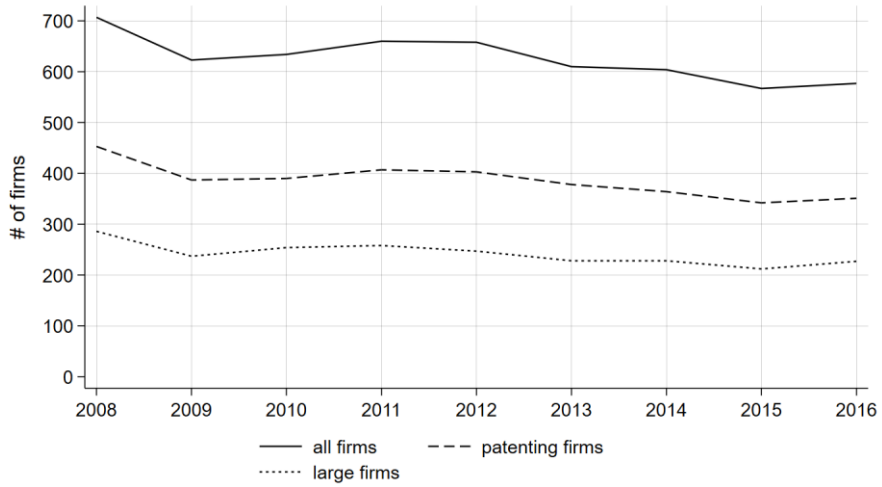
Figures

Fig.1 Trends in the aggregate firm publication volume



The yearly publication volume is calculated by summing up the publication volumes over all firms within a given year. Publications authored by several firms are thus counted once for each firm. Large firms are defined as firms with >= 500 employees. Patenting firms are defined as firms which applied for a patent at the German patent office at some point in time.

Fig.2 Trends in the aggregate number of publishing firms



The yearly number of publishing firms is calculated by counting the number of firms with a publication volume of at least one in a given year. Large firms are defined as firms with >= 500 employees. Patenting firms are defined as firms which applied for a patent at the German patent office at some point in time.

Fig. 3a Trends in the aggregate firm publication volume by industry

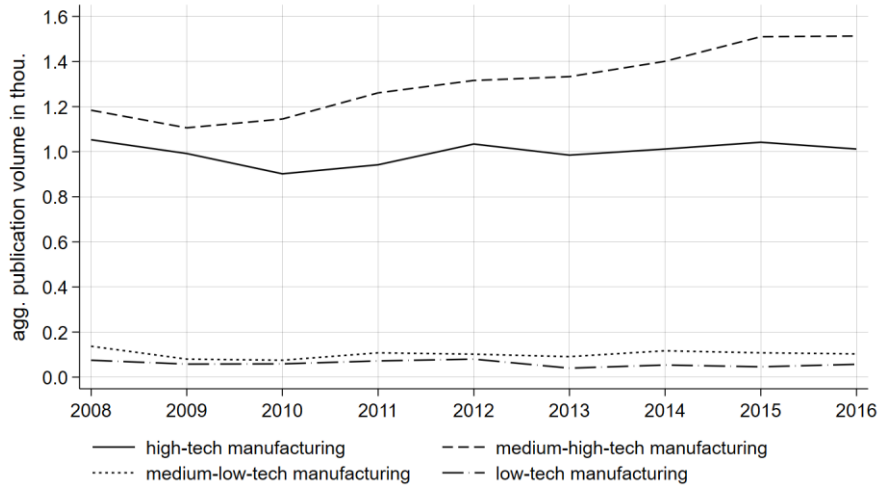
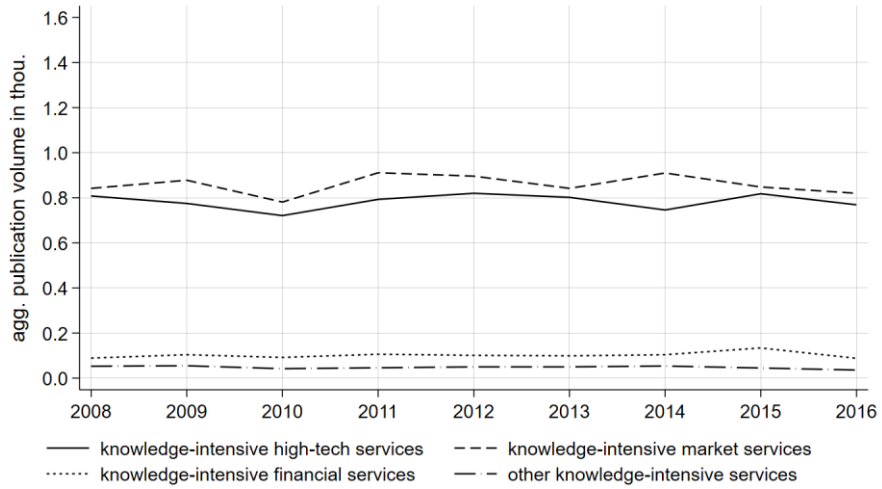


Fig. 3b Trends in the aggregate firm publication volume by industry



The yearly publication volume by industry is calculated by summing up the publication volumes over all firms within a given year and industry. Publications authored by several firms are thus counted once for each firm. The industry classification displayed follows the definition of high-tech and knowledge-intensive industries by Eurostat (2016).

Fig.4a Trends in the aggregate number of publishing firms by industry

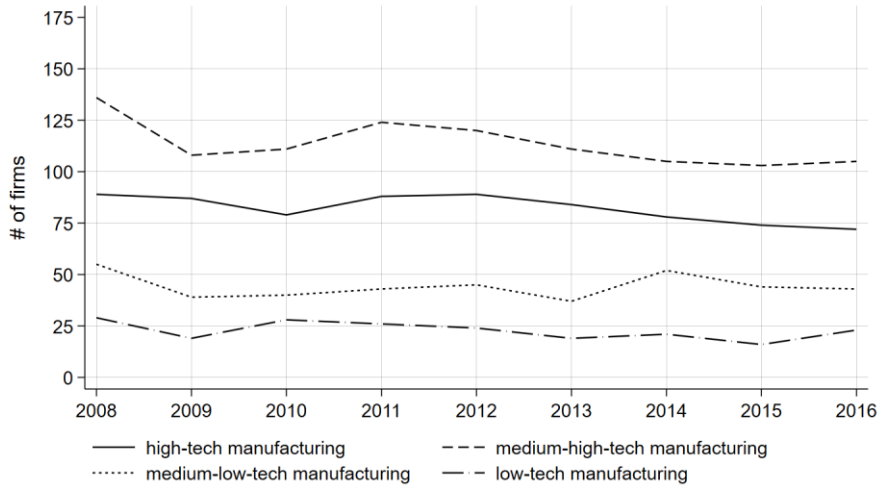
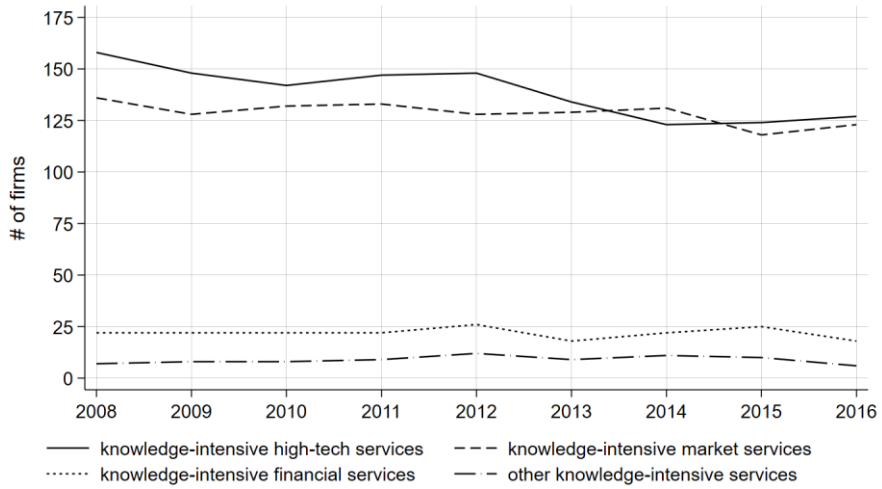
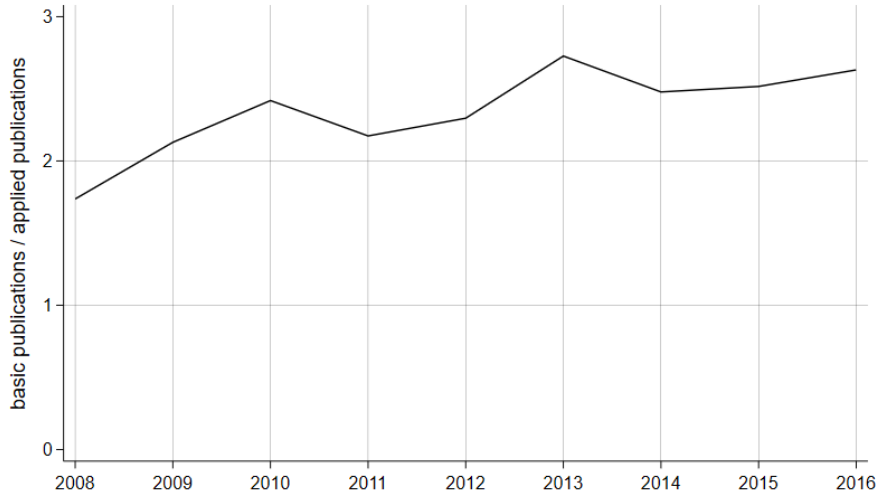


Fig.4b Trends in the aggregate number of publishing firms by industry



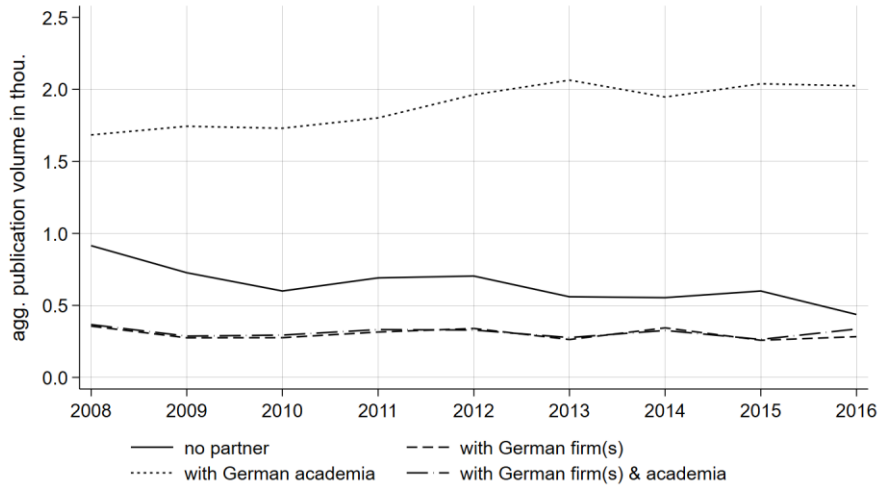
The yearly number of publishing firms is calculated by counting the number of firms with a publication volume of at least one in a given year and industry. Publications authored by several firms are counted once for each firm. The industry classification displayed follows the definition of high-tech and knowledge-intensive industries by Eurostat (2016).

Fig.5 Development of the ratio between applied and basic research publications



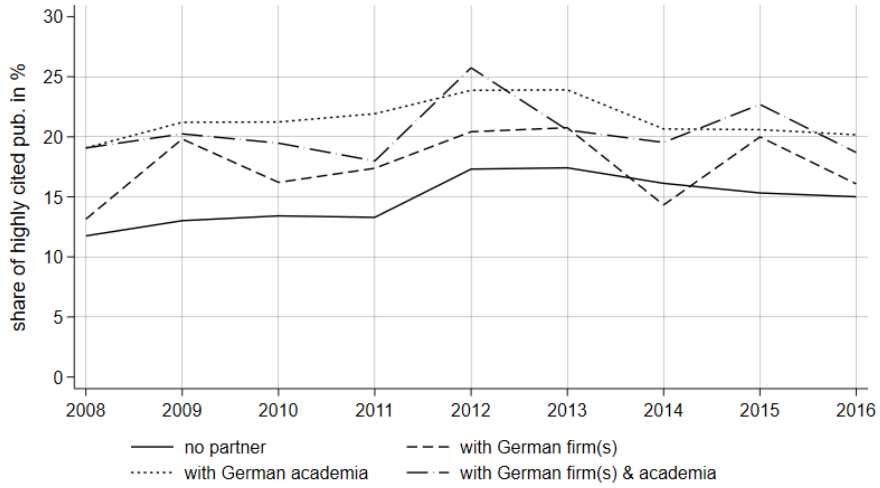
The ratio equals the aggregate yearly publication volume of all firms in basic research divided by the yearly publication volume of all firms in applied research. 18% of the overall aggregate publication volume cannot be classified into applied or basic research and is not taken into account for the calculation.

Fig.6 Trends in the aggregate publication volume by domestic cooperation partner



The yearly publication volume by domestic cooperation partner(s) is calculated by separately summing up the different publication volumes over all firms within a given year. Publications authored by several firms are thus counted once for each firm. We limit our cooperation partner classes to domestic cooperation as we cannot reliably distinguish between academia, firms or other organizations for other countries than Germany.

Fig.7 Trends in the aggregate shares of highly cited publications by domestic cooperation partner



1) The yearly publication volume of highly cited publications is allocated to the four domestic co-author groups for each firm individually. The allocation is proportional to a co-author group's share on a firm's yearly overall publication volume. 2) The yearly publication volume of highly cited publications by domestic co-author group is calculated by separately summing up the different allocated publication volumes over all firms within a given year. 3) The yearly overall publication volume by domestic co-author group is calculated by separately summing up the publication volumes over all firms within a given year. 4) The yearly share of highly cited publications by domestic co-author group is calculated by dividing the yearly publication volume of highly cited publications by the overall publication volume.

Normal and highly-cited publications authored by several firms are counted once for each firm. We limit our collaboration partner classes to domestic cooperation as we cannot reliably distinguish between academia, firms or other organizations for other countries than Germany.

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