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BELDERBOS, René
KU Leuven / UNU-MERIT / Maastricht University

IKEUCHI, Kenta
RIETI

FUKAO, Kyoji
RIETI

KIM, Young Gak
Senshu University

KWON, Hyeog Ug
RIETI

Research Institute of Economy, Trade & Industry, IAA

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What do R&D Spillovers from Universities and Firms Contribute to Productivity? Plant Level Productivity and Technological and Geographic Proximity in Japan*

René Belderbos (KU Leuven, UNU-MERIT, and Maastricht University)
Kenta Ikeuchi (RIETI)
Kyoji Fukao (Hitotsubashi University, RIETI, and Institute of Developing Economies, JETRO)
Young Gak Kim (Senshu University)
Hyeog Ug Kwon (Nihon University and RIETI)

Abstract

We examine the simultaneous effects of spillovers due to R&D by universities and by firms on total factor productivity in a panel of over 20,000 Japanese manufacturing plants. Estimating geographic decay functions based on the location of the universe of manufacturing plants run by R&D conducting firms and public research institutions in Japan, we find a positive influence of both private and public technologically proximate-R&D stocks, which decay in distance and become negligible at around 500 kilometers. Decomposition analyses show that declining R&D spillovers are responsible for a substantial part of the decline in the rate of TFP growth in Japanese manufacturing. The exit of geographically proximate plants operated by R&D intensive firms, which may be associated with a relocation of manufacturing activity overseas, plays a notable role in this process and is an important phenomenon in major industrial agglomerations such as Tokyo and Osaka.

Keywords: R&D, spillovers, plant productivity, distance
JEL classification: D24, O32

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Introduction

Various studies have examined the importance of R&D spillovers between firms for productivity, suggesting that these are a function of geographic and technological proximity and render the social returns to R&D much larger than the private returns (Jaffe et al., 1993; Adams and Jaffe, 1996; Aldieri and Cincera, 2009; Lychagin et al., 2016; Bloom et al., 2013; Arque-Castells and Spulber, 2018; Lucking et al., 2018; Orlando, 2004; Mairesse and Mulkay, 2008; Hall et al, 2012; Belderbos and Mohnen, 2020).[1] This literature has also suggested that R&D spillovers are enhancing the flow and use of knowledge. However, a number of limitations of prior work makes that we still know little about the (changing) relative contribution of R&D spillovers to TFP growth. First, the focus has been on inter-firm 'private' R&D spillovers while abstracting from the role of public research. A different research stream focusing on the role of knowledge spillovers from public research conducted at universities and research institutes has however suggested the importance of such spillovers, with an explicit role of geographic proximity (e.g., Jaffe, 1989; Adams, 1990; Anselin et al., 1997; Mowery et al. 2015; Hausman, 2021; Belenzon and Shankerman, 2013; Bikard & Marx 2020). We term these 'public' R&D spillovers. Second, with only some partial exceptions,[2] studies have been typically restricted to samples of publicly listed firms. Besides the selective nature of these samples, the multi-location and multi-technology nature of large publicly listed firms' operations render identification of proximity effects difficult.

This study addresses these limitations by simultaneously examining the roles of R&D spillovers due to university and firms, as they are moderated by technological and geographic

[1] Early work examined R&D spillovers at the industry level (e.g., Mohnen and Lepine, 1991; Audretsch and Feldman, 1996; Goto and Suzuki, 1989).

[2] Adams and Jaffe (1996) do analyse plant level productivity but focuses on the effects of internal R&D. The analysis of Griffith et al. (2009) for UK plants focuses on proximity effects but does not incorporate the role of R&D.

proximity, for an unusually large panel of Japanese manufacturing plants over 20 years (1987-2007). A unique feature of our data is that spillovers can be assessed by examining proximity to the universe of R&D conducting plants and public R&D institutions in Japan. To allow this, plant level data from the Census of Manufacture are matched with information on R&D expenditures from the comprehensive Survey of Research and Development in Japan covering virtually all R&D spending firms and public research institutions in the country. We carefully measure technological and proximity based on the products manufactured and the similarity in technologies used in industries. University R&D stocks are differentiated by science fields, which are mapped into technologies and industries reflecting their varying relevance for firms. Geographic distance effects are estimated using exponential decay parameters (Lychagin et al., 2016; Duranton and Overman, 2005) and are based on the population of inter-plant and plant-institution distances in Japan. The results of fixed effect panel models suggest that positive effects of both technological proximity-weighted firm and university R&D stocks, which decay in distance and become negligible at around 500 kilometres

The model and the rich data setting allow us to decompose changes in TFP in order to assess the relative contribution of R&D spillovers and to gain understanding of the declining growth in Japan's total factor productivity. Decomposition analysis shows that while the contribution to TFP growth of university R&D spillovers is stable, a major decline in the contribution of firm R&D is observed. To an important extent this is due to a decline in the growth of firm-level R&D stocks, but it is also driven by the exit of manufacturing plants of R&D intensive firms and the accompanied changing patterns of R&D agglomeration, which have reduced the size and effectiveness of the relevant pool of R&D spillovers across firms.

Model, Data, and Methods

We conduct a plant-level panel analysis of total factor productivity, relating plant-level TFP to firms' own R&D stock, other firms' R&D stocks, university R&D stocks, and a set of plant, firm and industry controls. We posit that the R&D stock of each firm is available to the firms' plants and that R&D spillovers occur between plants due to the R&D stock the plants have access to. This allows us to investigate the geographic dimension of R&D spillovers in detail, taking into account the population of R&D conducting firms and the spatial and industry configuration of their plants.

We adopt the standard knowledge stock augmented production function framework (e.g., Hall et al, 2012). We define the production function at the plant-level generally as:

$$Q_{it} = f(L_{it}, K_{it}, M_{it})g\big(R_{ift-1}, S_{ift-1}, P_{ift-1}, \mathrm{X}_{ift}\big)U_{it} \tag{1}$$

Where:

Q_{it}: Gross output of the plant

L_{it}, K_{it}, M_{it}: Inputs of plant i in year t

R_{ift-1}: firm-level R&D stock

S_{ift-1}: other firms' technological proximity weighted R&D stock

P_{ift-b}: universities technological proximity weighted R&D stock

X_{ift}: a vector of other observable factors affecting plant productivity

U_{it}: plant-year specific unobserved efficiency.

Total factor productivity (TFP) is defined as:

$$TFP_{it} \equiv \frac{Q_{it}}{f(L_{it}, K_{it}, M_{it})} = g\big(R_{ft-1}, S_{it-1}, P_{it-b}, \mathrm{X}_{ift}\big)U_{it} \tag{2}$$

Firm R&D stocks are assumed to influence production with a one-year lag to reflect that the application of new knowledge and insights due to R&D takes time. Given that university R&D focuses on (basic) academic research with long gestation lags (Adams, 1990), we take a lag of

b years, with b determined empirically by the fit of the model. If we adopt a log-linear specification for and allow $U_{it} = e^{\eta_i + u_{it}}$, where η_i is a plant specific fixed effect and u_{it} is a plant-year specific efficiency shock, we obtain:

$$\ln TFP_{it} = \alpha_R \ln R_{ift-1} + \alpha_S \ln S_{ift-1} + \alpha_P \ln P_{ift-b} + \gamma' \ln X_{ift} + \eta_i + u_{it} \qquad (3)$$

We assume that the error term u_{it} can be decomposed into industry-year specific shocks λ_{st} (with s the industry of the plant) and the idiosyncratic error ε_{it}:

$$u_{it} = \lambda_{st} + \varepsilon_{it} \qquad (4)$$

Data sources and sample

We match plant level data from the Japanese *Census of Manufacture* with information on R&D expenditures from the yearly *Survey of Research and Development* in Japan, 1987-2007. The census has a comprehensive coverage of manufacturing plants with more than 4 employees. The Survey of Research and Development in Japan is a mandatory survey of R&D performing firms and public research institutes and universities in Japan. It contains information on R&D expenditures for roughly 9,000 firms yearly and has a response rate greater than 90 percent. Larger firms are surveyed every year, smaller firms are drawn each year through stratified sampling. The survey also extends to research institutes and universities, with a response rate of close to 100 percent.

We selected those firm-year observations for which we can construct, based on the available R&D survey data, a R&D stock or for which we otherwise can ascertain that no formal R&D is taking place. This implies that firms had to be observed multiple times in the survey. We calculated R&D stocks only if there was sufficient information in the surveys to derive an R&D growth rate for a period of minimum 5 years. To accommodate firms without R&D in the logarithmic specification, the models include a dummy for non-engagement in

R&D as well a parent R&D stock variable calculated after the value 1 is added.

For the calculation of other firms' R&D stock we require estimates of spillover pools across locations. Here we obtained estimates that are as accurate as possible by using the weights provided in the R&D survey to correct for non-response and by allocating R&D stocks that could not be matched to locations on the basis of the location of the firm, rather than on the basis of the location of plants.[3]

We obtained an unbalanced panel of 9670 plants, observed for a maximum of 20 years and a minimum of 5 years, during 1987-2007. In about 3.5 percent of the plant observations, plants are owned by parent firms for which we could confirm the absence of formal R&D. The pattern of TFP growth of the sample firms appears representative of the pattern of TFP growth in the population of plants (Figure 1). Whereas in the mid-1980s TFP growth reached 2.5 percent a year, this declined to under 1 percent in the late 1990s and the early years of this century. Table 1 shows the distribution of plants over industries. There is a good distribution of plants across technology intensive industries (e.g., drugs and medicine, and information and communication equipment) as well as non-technology intensive industries (food, fabricated metal products). Reflecting Japan's strengths, parent firm R&D stocks are highest in the automobile industry, home electronics, information and telecommunication equipment industries. The lowest R&D stocks are present in the textile and fabricated metal industries

-----------Insert Figure 1 and Table 1-------------

[3] This may be a reasonable approximation as most of the unmatched firms are smaller enterprises for which the plant and administrative unit are collocated.

Variables and Measurement

Total Factor Productivity

We utilize plant level TFP data from the Japanese *Census of Manufacture* and Japan Industrial Productivity Database (JIP) 2010 (RIETI, 2018), which provides TFP estimates distinguishing 58 industries based on the index number method, following Good et al (1997): One of the main advantages of the index number method is that it allows for heterogeneity in the production technology of individual firms, while other methods controlling for the endogeneity of inputs (e.g. Olley and Pakes, 1996; Levinsohn and Petrin, 2003) assume an identical production technology among firms within an industry (Van Biesebroeck, 2007; Aw et al., 2001).

Firm R&D stocks

Firm-level R&D stocks are calculated using the following formula:

$$K_{ft} = I_{ft} + (1 - \delta_s)K_{ft-1} \tag{5}$$

where I_{ft} is R&D investment of firm f active in industry s in year t and δ is an industry-specific depreciation rate reflecting differences in the speed of obsolescence and technology life cycles. Industry specific depreciation rates are based on Japanese official surveys of the life-span of technologies conducted in 1986 and 2009 among R&D conducting firms and vary between 8 for the food industry and 25 percent for precision instruments (NISTEP, 2009). To calculate initial R&D stocks (Hall and Oriani, 2006), we use industry-specific growth rates, which we calculate from the R&D survey as average R&D growth rates per field in the 1980s. R&D investments are deflated using a deflator for private R&D from the JIP database, calculated from the price indices of the input factors for R&D expenditures for each industry. Following equation (3) the models include the natural logarithm of the firm R&D stock, for positive values of the stock. We augment the model with a dummy variable taking the value one if the parent firm's R&D stock is zero. To arrive at a plant-specific measure of R&D spillover pools, we map all R&D stocks in geographic space using the information on the location of the plants of the parent, where we distinguish more than 1800 cities, wards, towns, and villages. Figure 2 shows the 5-year moving average growth rates in the levels of nationwide R&D stocks. The growth in private R&D shows a declining trend, as the increase in overall R&D investments has slowed over time and could not compensate for the deprecation rates in particular in the most recent years of the sample period.[4]

-----------Insert Figure 2-------------

Technologically proximate R&D stocks for each specific plant are calculated based on the technological proximity between the industry of the plant and the industry of any other plants. We define the technologically relevant R&D stock (spillover pool) as the sum total of all other firms' R&D stocks available to the firms' plants nearest to the focal plant, weighted by the technological relatedness between the industry of these plants and the industry of the focal plant (e.g. Breschi, et al., 2003; Leten et al. 2007).[5]

$$\boldsymbol{S_{ifst}} = \sum_{f' \neq f} \sum_{s'} \boldsymbol{K_{f's't} T_{ss'} e^{\tau d_{if'}}} \quad (6)$$

where:

$\boldsymbol{K_{f's't}}$: R&D stock of firm $\boldsymbol{f'}$ in field $\boldsymbol{s'}$ at time *t*;

$d_{if'}$: Minimum geographic distance between plant i and the plant of firm f';

$T_{ss'}$: the technological proximity weight;

[4] We note that the declining trend in R&D stocks does not relate to the industry-specific depreciation rates. If we calculate R&D stocks based on a fixed 15 percent depreciation rate, similar patterns are observed. The United States also experienced declining growth in R&D stocks during the 1990s, but this decline was less pronounced (Fukao, et al. 2021).

[5] Hence, if firms operate multiple plants, the R&D stock is only counted once using the plant with the minimum distance to the focal plant, which avoids double counting of R&D.

τ: a decay parameter, with $\tau < 0$.

We model an exponential decay function in the effectiveness of spillovers with parameter τ to be estimated, in line with recent studies (e.g., Lychagin et al. 2016). Distance d is the distance between a pair of locations and is measured as the geo-distance between the centre of cities, wards, towns, and villages. In order to correct for differences in the geographic areas covered by the regions, distance is the radius of the region if plants are located in the same region.

Our technological relatedness measure is derived from patent citation data and based on Leten et al. (2007). The relatedness between technologies is reflected in the intensity with which technologies in a patent field build on prior art in a different patent field. Patent citation data are available at the 4-digit IPC level and are subsequently mapped onto industries using the industry-technology concordance table developed by Schmoch et al. (2003). This results in technological relatedness weights $T_{ss'}$ between industries, with weights for the own industry normalized at 1 (Appendix A).

Public R&D stocks

We differentiate university R&D by location based on the region (city, ward, town, and village) of the research institute or university and by industry/R&D field, utilizing information on science fields with varying relevance for specific industries. The deflator for public R&D is obtained from the White Paper on Science and Technology (MEXT, various years. We define the R&D stock of public research institution h in science field m as:

$$A_{hmt} = E_{hmt} + (1 - \delta_A)A_{hmt-t} \quad (7)$$

where E_{hmt} is research expenditure of public research institution h in science field m in year t and δ_A is a depreciation rate of public R&D stock, which we set at 15 percent per year. Figure

2 shows a declining trend in university R&D stocks in recent years, yet this decline is substantially smaller than the decline in the growth of firm R&D.

We estimate the university R&D expenditure by field E_{hmt} by multiplying total R&D expenditures with the share of the number of scientists in the field in the total number of scientists, for each institution and year. We arrive at a 'relevant' university R&D stock per industry using weights derived from a concordance matrix between science fields and industries. The weights are based on a study by Van Looy et al. (2004) examining citation frequencies on patent documents in different technology fields to Web of Science publications in each of the science fields. The concordance attaches to each scientific discipline probabilities that it is of relevance to each technology field (Appendix B). Applying this concordance to the university R&D expenditures per science field, and subsequently applying the concordance matrix between IPC classes and industries, we obtain technology proximity weighted public R&D stocks per industry and location (e.g., Belderbos et al., 2014).

Formally, the technologically and geographically proximate university R&D stock is defined as:

$$P_{ist} = \sum_h \sum_m A_{hmt} \tilde{T}_{sm} e^{\theta \tilde{d}_{ih}} \tag{8}$$

where:

A_{hmt}: R&D stock of university h in academic field m in year t;

$\tilde{T}_{sm}$: The proximity weight between industry s and science field m;

$\tilde{d}_{ih}$: geographic distance between plant i and the university h;

θ: the geographic decay parameter, $\theta < 0$.

Control variables and specification

The vector of time varying plant-and firm-specific characteristics X_{ift} includes plant size (number of employees), a dummy variable indicating whether the plant is active in multiple industries (at the 4-digit level). In addition, we control for parent firm size (number of employees) and the number of plants of the parent firm. As to the latter variables, on the one hand, increases in the number of a firm's plants may correlate with unobserved firm-specific advantages. On the other hand, a larger number of plants drawing on the same R&D pool may lead to reduced effective knowledge transfer (Adams and Jaffe, 1996). Finally, we conservatively include year-specific industry dummies λ_{st}, which control for industry-specific technological opportunities and demand shocks over time. [6]

We estimate plant panel fixed effects models, thus including η_i. Since the geographic decay specification introduces nonlinearity in the equation, we estimate equation (3) with nonlinear least squares. Table 2 shows descriptive statistics and correlations.[7]

--------Insert Table 2-------

Empirical results

Table 3 reports the estimation results. Model 1 only includes control variables and the two variables representing parent firm R&D stock. The dummy variable indicating the absence of parent R&D has a positive coefficient but is not significant. Because the effect of a continuous absence of R&D is-subsumed in the plant fixed effects, the dummy picks up the effect of firms conducting R&D on a non-continuous R&D basis rather than continuously. The coefficient on parent R&D suggests an elasticity of TFP with respect to R&D of 0.017 percent, which is at the lower end of the range estimated in Adams and Jaffe (1996) for plant level R&D effects.[8]

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[6] Note that the potential influence of plant age is subsumed in the industry-year and plant fixed effects. Given the limited variation of the parent number of plants measure, we include the variable in its linear form.

[7] We note that the relatedness and proximity dimensions of the model give structure to the relationship between other firms' R&D stocks and focal firm productivity, mitigating the 'reflection problem' when relating population behavior to individual outcomes (Manski, 1993). In the fixed effects model, plant locations are given and location is not a decision variable.

[8] We note that their specification was cross sectional; one may expect smaller estimated effects in fixed

Both plant size and firm size (employment) are negatively associated with TFP, which may be due to employment expansions reducing productivity or the fact that large firms can tolerate a lower productivity as they can spread costs over firm-wide operations (Cohen and Klepper, 1996).

Model 2 reports on the results with the private R&D stock and its geographic decay effect included. The elasticity of TFP with respect to the private R&D stock is larger than that of the parent firm, at 0.039, a feature that is often observed in R&D spillover studies (Hall et al., 2012). Firm R&D spillovers decay in distance with the decay parameter estimated at -0.0066.

--------Insert Table 3-------------

Model 3 adds the public R&D stock and its geographic decay parameter. Estimations of models with different lags for university R&D showed the most robust results if a lag of 3 years (b=3) was taken.[9] The elasticity of TFP with respect to the public R&D stock is somewhat larger that the elasticity with respect to private R&D, at 0.042. The decay parameter is significant and suggests a faster decay (-0.0075).

In model 4, both the private and public R&D stocks are included simultaneously. Simultaneous inclusion reduces the estimated coefficient on private R&D to 0.29 and of public R&D to 0.032, highlighting the importance of taking into account both type of R&D spillovers for accurate inference. The estimated decay parameters are similar in size. This coefficient estimates suggest that only 10 percent of the spillover effect remains at 260 kilometers, while spillover effects become negligible at about 500 kilometers.[10] This pattern for private R&D is

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effect models.

[9] Results with other lags are shown in Appendix C.

[10] We assessed the significance of the exponential decay parameter through F tests (Wooldridge, 2012; 428-430).

roughly similar to the estimates reported in Lychagin et al. (2016) for US manufacturing firms based on inventor locations.

Decomposition

With the changes over time in R&D stocks and agglomeration, we can decompose changes in TFP into several factors: firms' internal R&D effects, location-specific private R&D spillover effects, public R&D spillover effects, and industry wide effects of R&D stocks regardless of location.[11] We examine the yearly development of TFP in a balanced sample of existing 'spillover receiving' plants and calculate the contribution of the different sources of R&D.[12] The results of the decomposition analysis based on model 4 in Table 3 are presented in Figures 3 and 4 and present average yearly contributions to TFP growth in percentage points. For convenience, effects are indicated for 4 periods of 5 years. The decomposition uses plants' gross output as weights.

Figure 3a shows that declining R&D stocks and R&D spillovers, in particular declining private R&D spillovers, play an important role in the decline in TFP growth over the years. The largest decline is in industry-wide R&D effects due to the lower growth in R&D stocks. The contribution of R&D spillovers to TFP growth also reduced by a large margin, from 0.3 percent points in 1987-1992 to less than 0.1 percent points in 2002-2007. In addition, the smaller growth of R&D stocks led to a declining contribution of parent firm R&D from roughly 1.4 to 0.04 percent points. The contribution of public R&D spillovers increased up to 1997-2002 and did not show a clear declining trend, with a contribution of 0.05 in the most recent period. This is related to the more modest decline in the growth in public R&D and a changing

[11] We retrieve the contribution of industry wide R&D effects, captured by the industry-year fixed effects, by regressing these fixed effects on industry R&D and a set of year dummies.

[12] Hence, the effects of entries and exits of plants with different productivity levels on average TFP in the industry are not included, as these cannot be related to the parameters of the model. Instead, we focus on the effects of entries and exits through their influence on spillovers to existing plants.

composition of public R&D expenditures in the direction of life sciences with greater relevance for the private sector. During 2002-2007, the strong decline in private R&D spillover effects has made the contribution of public R&D spillovers to exceed the contribution of private R&D spillovers.

Figure 3b decomposes private R&D spillovers into effects due to the exit of R&D active plants, the entry of such plants, and the changing R&D stocks of surviving plants. The exit of R&D active plants reduces the R&D stock available to other plants and has a negative effect on TFP growth. In particular in the final period, this effect is dominant and reduces TFP growth by 0.012 percent points yearly. The entry of new plants of R&D conducting firms compensates, but this positive effect is only one third the size of the negative effect of exit.

Figure 4 decomposes TFP growth to prefectures in Japan, focusing on the prefectures with the largest contribution. In the first 10 years of the panel, net productivity benefits of inter-firm R&D spillovers were high in agglomerated areas. In particular in Aichi, home to a large automobile cluster responsible for about half of manufacturing output in the region led by Toyota, shows a strong contribution. The second largest contribution to TFP growth is by Kanagawa, the prefecture of the major port town of Yokohama neighboring Tokyo. This prefecture is home to an automobile cluster led by Nissan, but otherwise has a more diverse industrial structure. In the second 10-year period, Aichi remained a strong contributor to TFP growth, while the contribution of Kanagawa, where the automobile cluster underwent restructuring after the tie-up of Nissan and Renault, stalled. Notable negative contributions due to plant and firm exits are observed in the in the industrial agglomerations of Tokyo and Osaka. In Tokyo this appears a feature of the dominant electronics cluster there (focused on computers and communication equipment), which makes up half of manufacturing output; in Osaka the main manufacturing industries are likewise communication equipment, electronic parts, and household electronics.

Conclusions

This paper examined the effects of R&D spillovers on total factor productivity in a large panel of Japanese manufacturing plants matched with R&D survey data. We simultaneously analyse the role of public (universities and research institutes) and private R&D spillovers, as a function of technological and geographic proximity. We estimate geographic decay effects and take into account the differences in the relevance of academic research across industries. Our analysis confirms the simultaneous importance of positive spillover effects from R&D by firms with plants in technologically related industries and from public R&D in academic fields relevant for the plants. The magnitude of these spillover effects is roughly equal, with public R&D spillovers most discernible with longer time lag (3 years). The spillover effects are attenuated by distance and our estimates suggest that spillover effects are 90 percent reduced beyond 300 kilometres, both for private and for public R&D stocks. The results confirm that it is important to take into account both private and public R&D for accurate inference on their role in TFP growth.

Decomposition analysis shows that the contribution of private R&D to TFP growth has declined substantially since the late 1990s - in contrast with the contribution of public R&D. While the most important reason for this decline has been a declining growth in the private R&D stock, another important factor is the exit of geographically proximate plants operated by R&D intensive firms, reducing the R&D stock for spillovers. If we explore effects at the regional level, we observe that strong adverse exit effects occurred in particular in Japan's major industrial agglomerations such as Tokyo and Osaka.

Our study contributes to the literature on inter-firm R&D spillovers (Adams and Jaffe, 1996; Aldieri and Cincera, 2009; Lychagin et al., 2016; Bloom et al., 2013; Arque-Castells and

Spulber, 2018; Lucking et al., 2018; Orlando, 2004; Mairesse and Mulkay, 2008; Hall et al, 2012) and university-industry knowledge spillovers (Jaffe, 1989; Adams, 1990; Anselin et al., 1997; Mowery et al., 2015; Hausman, 2021; Belenzon and Shankerman, 2013; Bikard & Marx 2020; Toole, 2012) by for the first time simultaneously analysing the influences of private and public research on industrial TFP across fine-grained locations and industries, and comparing their influences. We confirm the importance of geographically bounded effects of university R&D and the importance of such academic research in relevant domains for the focal firm as recently observed for the U.S. (Hausman, 2021). Public R&D spillovers appear to gain in relative weight, consistent with broader observations on a declining engagement by firms in basic R&D (Arora, Belenzon, Patacconi, 2018) and an internal orientation of R&D activities by technology leaders focusing on and the in-house exploitation of technological knowledge and restricting knowledge outflows (Akcigit and Ates, 2021; Belderbos et al., 2021).

Our results increase our understanding of the particular declining pace of TFP growth in Japan. Prior studies suggest that exit rates of relatively productive plants operated by multi-plant (multinational) firms have been typically higher than the exit rates of single establishments (e.g., Fukao and Kwon, 2006; Kneller et al. 2012), due to the relocation of plants abroad by Japan's major industrial firms away from domestic regions with increasing land and wage costs. The electronics industry, which plays an important role in the prefectures with plant exits and negative TFP contributions, is known for its active foreign investment strategy. Our study suggests that this exit of plants by R&D intensive firms has reduced available R&D spillovers and has hampered TFP growth of the surviving plants. In this regard, the 'hollowing out' of the economy through major firms' offshoring of production and reliance on global value chains is likely to have more long-term effects on economic performance than a direct effect of relocation.

The findings on the decline in private R&D and its spillovers, partially linked to the exit of plants operated by R&D intensive firms provide an interesting avenue for research focusing on other countries. On the one hand, our findings may be specific to the situation of Japan with its comparatively closed economy and reliance on domestic R&D, and its relatively high-cost levels that have given rise to major plant relocations abroad. On the other hand, the relocation of manufacturing abroad has also been a feature of other industrialized economies (e.g., Kovak et al., 2021) while multinational firms based in the U.S. and Europe have been more active in relocating R&D activities abroad (Belderbos, Leten, Suzuki, 2013).

Future research should also aim to uncover how the contributions to TFP growth in Japan have developed during more recent years. Recent developments do not suggest a substantive change in TFP growth in recent years, with average TFP growth in the manufacturing sector limited to less than 0.5 percent annually during 2008- 2015 (RIETI, 2018). Research on the role of inter-firm R&D spillovers in the U.S. has similarly found remarkably stable patterns (Lucking et al. 2018). The trend in Japan's foreign direct investment also shows no abating, with the overseas manufacturing ratio continuously increasing, although after 2015 a trend of reshoring of technology intensive production to Japan may be occurring (JETRO, 2018; Park and Hong, 2017). At the same time, the Japanese government has reorganized the public university system and allowed universities to patent in an effort to increase the impact of university research on innovation (e.g., Kang and Motohashi, 2020).

While our research setup was comprehensive in coverage and the inclusion of both private and public R&D, a number of limitations are worth noting. Our analysis did not take into account potential negative spillovers effects of R&D through market stealing between firms competing in the same product market (Bloom et al., 2013; Lucking et al., 2018). In this regard, our estimates on the importance private R&D spillovers may be considered a lower bound of the spillovers to be expected for inter-firm spillovers between noncompeting firms. Second, we did not take into account market mediated channels of spillovers such as knowledge transfer through licensing and alliances, which can be prevalent both among firms (Arque-Castells and Spulber, 2018) and universities and firms (Mowery et al., 2015) and may similarly have stronger productivity effects if the actors are geographically proximate (Mowery et al., 2015). Finally, we may expect differences in inter-firm knowledge spillovers for firms that are member of industrial groups (Suzuki, 1993; Branstetter, 2000; Belderbos et al., 2015), and differences in university-industry spillovers due to differences in absorptive capacity for scientific research (e.g., Belderbos, Leten, Suzuki, 2017). Examining firm and plant heterogeneity in the receptivity to spillovers, though challenging, offers rich opportunities for future research endeavors.

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Figure 1. Trends in TFP growth: sample plants and population of Japanese plants (5-year moving average)

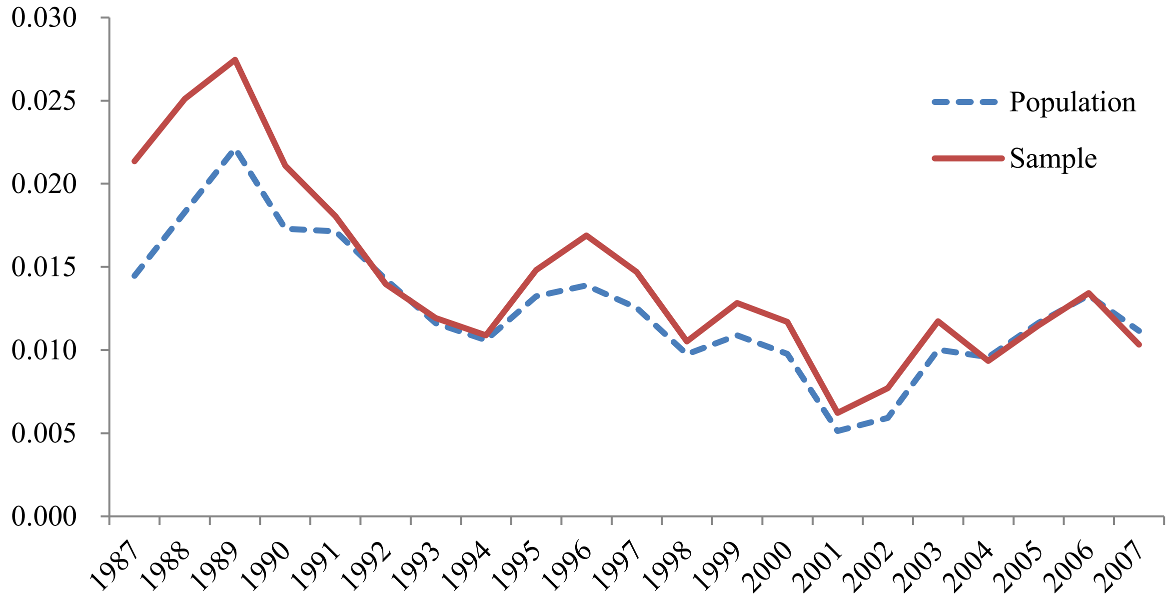


Figure 2. Growth rate in R&D stocks (5-year moving average)

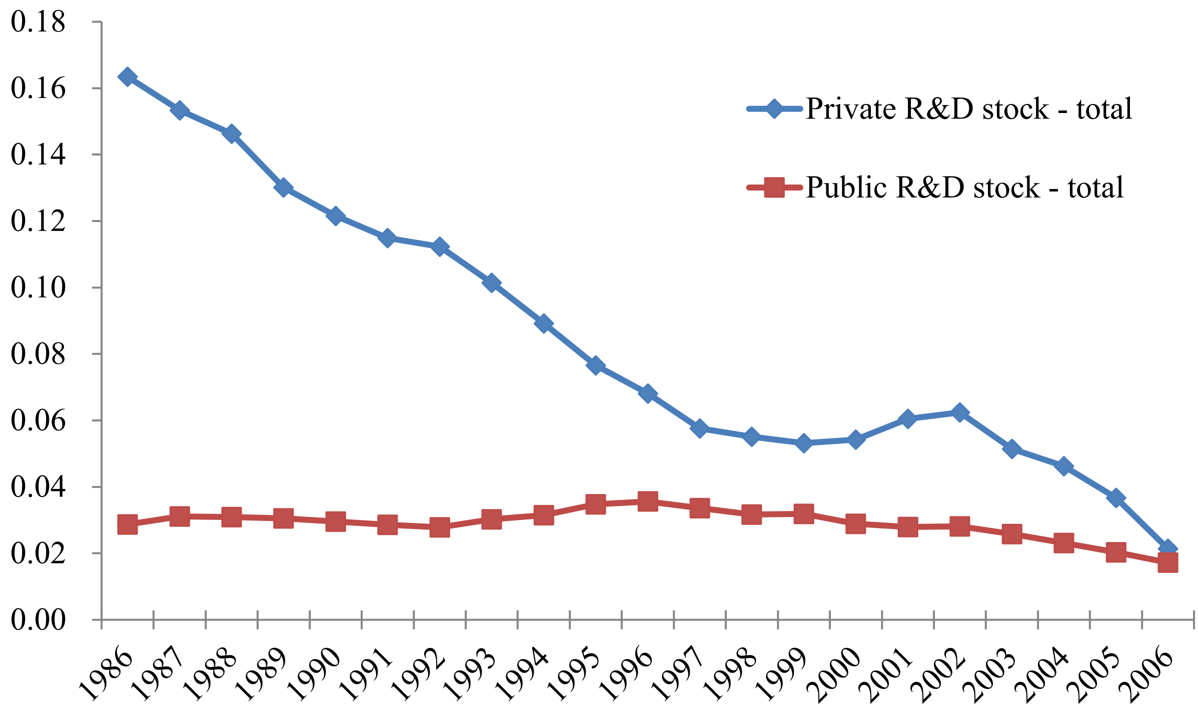
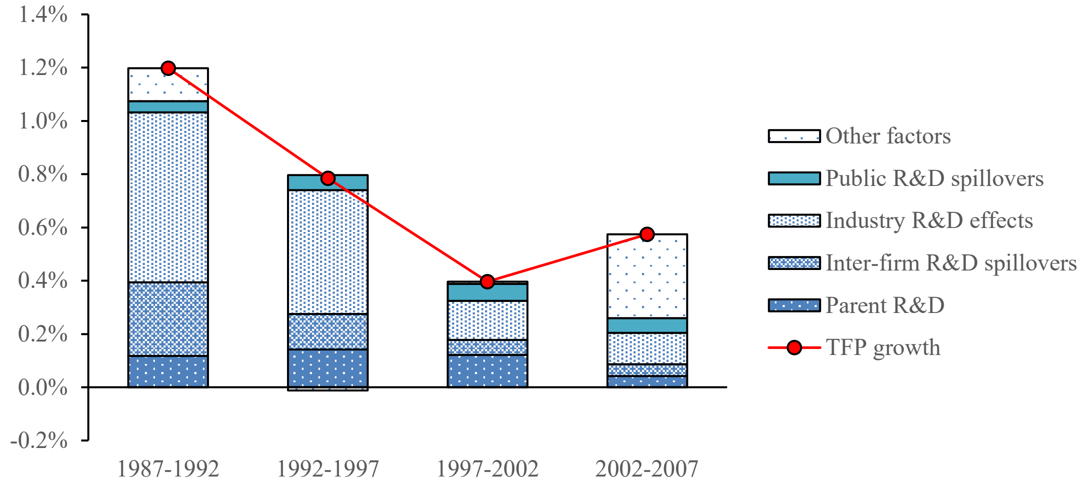


Figure 3. Decomposition Analysis: Relative Contribution of R&D (Spillovers) to TFP Growth

a. All R&D



b. Private R&D spillovers

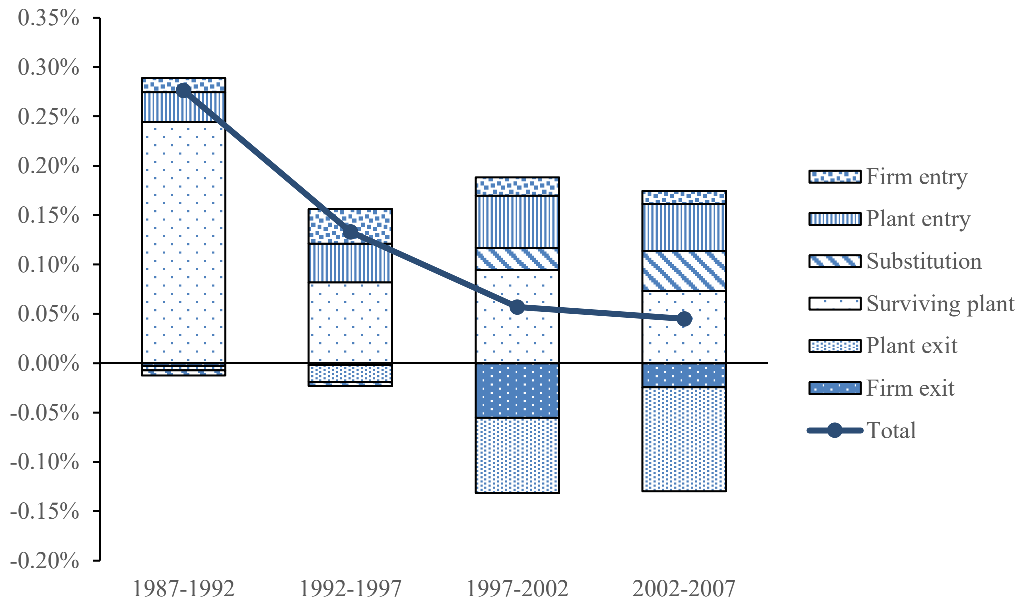
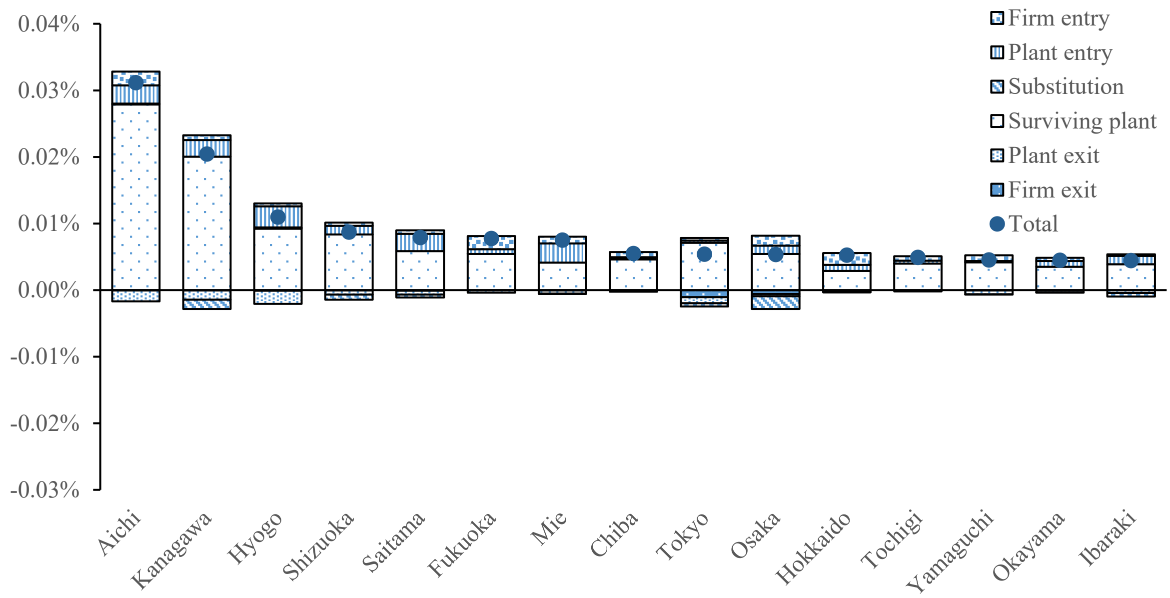


Figure 4. Decomposition Analysis: the role of entry and exit in the contribution to TFP growth of private R&D spillovers across prefectures

1987-1997



1998-2007

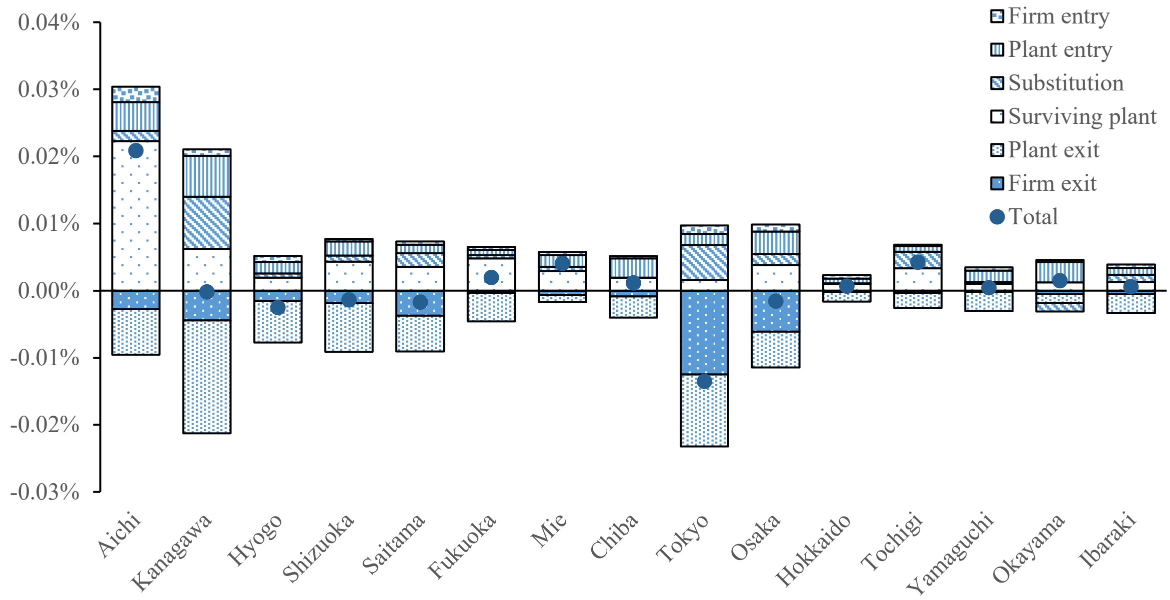


Table 1: Sample characteristics

Industries (R&D fields)	# of obs. #	# of obs. (%)	# of (unique) plants in #	# of (unique) plants in (%)	# of (unique) parent firms	Avg. parent R&D stock per plant (billion yen)	% of plants with positive parent R&D
Food products	11,678	(12.3)	1,174	(12.1)	453	9.6	98.9
Textile mill products	3,309	(3.5)	287	(3.0)	138	5.9	92.5
Pulp and paper products	3,088	(3.2)	277	(2.9)	95	7.0	96.0
Printing	945	(1.0)	93	(1.0)	30	13.3	99.0
Chemical fertilizers and industrial chemicals	6,263	(6.6)	548	(5.7)	272	21.3	99.5
Drugs and medicine	3,989	(4.2)	379	(3.9)	236	49.1	99.4
Miscellaneous chemicals	5,975	(6.3)	589	(6.1)	347	13.5	98.8
Petroleum and coal products	1,407	(1.5)	161	(1.7)	58	9.1	64.1
Rubber products	2,111	(2.2)	196	(2.0)	97	47.5	99.6
Ceramic, stone and clay products	6,504	(6.8)	616	(6.4)	217	7.2	91.7
Iron and steel	3,372	(3.5)	289	(3.0)	113	27.5	99.6
Non-ferrous metals and products	2,756	(2.9)	248	(2.6)	121	13.6	98.6
Fabricated metal products	6,778	(7.1)	754	(7.8)	350	4.5	94.4
General-purpose machinery	11,547	(12.1)	1,329	(13.7)	798	27.4	97.7
Home electronics	850	(0.9)	102	(1.1)	47	122.5	99.4
Electrical machinery	6,165	(6.5)	662	(6.8)	336	16.8	91.0
Info.&com. electronics	7,513	(7.9)	881	(9.1)	453	121.1	96.4
Motor vehicles, parts and accessories	7,309	(7.7)	703	(7.3)	255	151.0	99.1
Other transportation equipment	1,349	(1.4)	117	(1.2)	46	25.1	99.8
Precision instruments and machinery	2,204	(2.3)	265	(2.7)	161	8.2	97.2
Total	95,112	(100.0)	9,670	(100.0)	4,623	36.7	96.5

Table 2: Descriptive statistics and correlations

	Mean	SD	Min	Median	Max	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]
[1] TFP	0.197	0.428	0.118	-3.376	3.269									
[2] Non-continuous R&D (dummy)	0.035	0.184	0.000	0.000	1.000	-0.056								
[3] Parent R&D (lag=1)	1.627	1.567	1.132	0.000	8.397	0.245	-0.198							
[4] Private R&D spillover pool (lag=1)	6.968	1.192	6.941	0.069	9.569	0.224	-0.091	0.162						
[5] Public R&D spillover pool (lag=3)	1.524	1.211	1.140	0.006	5.087	0.347	-0.066	0.154	0.704					
[6] Number of plant employees	5.131	1.184	5.069	2.303	9.975	0.155	-0.145	0.531	0.212	0.098				
[7] Number of other plants	1.295	0.934	1.099	0.000	4.654	0.030	0.096	0.459	-0.198	-0.202	0.081			
[8] Number of firm employees	6.221	1.451	6.116	2.303	11.133	0.135	-0.040	0.726	0.019	-0.055	0.657	0.619		
[9] Entry plant dummy	0.009	0.095	0.000	0.000	1.000	0.004	0.007	-0.009	0.016	0.016	-0.028	0.000	-0.009	
[10] Multi-products (4digit) plant (dummy)	0.633	0.482	1.000	0.000	1.000	-0.039	-0.122	0.130	0.003	-0.012	0.241	-0.039	0.096	-0.027

Note: N=95112

Table 3. Fixed Effect Panel Estimation of Plant-Level TFP

	[1]	[2]	[3]	[4]
Parent R&D stock	0.0176	0.0177	0.0174	0.0175
	[0.000]	[0.000]	[0.000]	[0.000]
Non-continuous R&D (dummy)	0.0140	0.0142	0.0138	0.0140
	[0.052]	[0.049]	[0.056]	[0.052]
Private R&D spillover pool		0.0397		0.0298
		[0.008]		[0.026]
Public R&D spillover pool			0.0422	0.0318
			[0.002]	[0.026]
Number of plant employees	-0.0319	-0.0321	-0.0319	-0.0321
	[0.000]	[0.000]	[0.000]	[0.000]
Number of other plants of the firm	0.0029	0.0028	0.0027	0.0026
	[0.458]	[0.485]	[0.501]	[0.511]
Number of firm employees	-0.0111	-0.0110	-0.0111	-0.0110
	[0.000]	[0.000]	[0.000]	[0.000]
Entry plant (dummy)	-0.0283	-0.0282	-0.0283	-0.0282
	[0.000]	[0.000]	[0.000]	[0.000]
Multi-products plant (dummy)	0.0019	0.0018	0.0020	0.0018
	[0.482]	[0.512]	[0.471]	[0.502]
Industry-year dummies	Yes	Yes	Yes	Yes
Distance parameters:				
Private R&D spillovers		-0.0066		-0.0086
		[0.000]		[0.001]
Public R&D spillovers			-0.0075	-0.0087
			[0.001]	[0.066]
# observations	95,112	95,112	95,112	95,112
R squared	0.293	0.294	0.293	0.294

Notes: P-values based on cluster-robust standard errors in brackets; P-values of the exponential decay parameters is based on F tests.

Appendix A. Technological proximity between industries

Spillovers sources (cited) / Focal industries (citing)	[04]	[05]	[06]	[07]	[08]	[09]	[10]	[11]	[12]	[13]	[14]	[15]	[16]	[17]	[18]	[19]	[20]	[21]	[22]	[23]	[24]
[04] Food products	1.00	.003	.006	.000	.125	.359	.041	.001	.000	.004	.001	.001	.001	.094	.021	.001	.003	.002	.000	.026	.026
[05] Textile mill products	.007	1.00	.045	.024	.631	.065	.104	.001	.002	.172	.007	.006	.023	.243	.026	.013	.033	.019	.005	.148	.114
[06] Pulp and paper products	.022	.073	1.00	.126	.415	.049	.089	.002	.000	.100	.003	.003	.043	.301	.009	.008	.190	.004	.001	.123	.083
[07] Printing	.000	.011	.042	1.00	.270	.021	.095	.000	.000	.028	.008	.011	.020	.085	.003	.003	.181	.002	.000	.087	.017
[08] Chemical fertilizers and industrial chemicals	.009	.020	.008	.015	1.00	.147	.050	.012	.004	.039	.007	.007	.005	.070	.005	.010	.032	.006	.001	.041	.027
[09] Drugs and medicine	.026	.002	.001	.001	.147	1.00	.013	.000	.000	.002	.000	.000	.000	.010	.001	.000	.005	.000	.000	.076	.001
[10] Miscellaneous chemicals	.031	.032	.012	.035	.488	.128	1.00	.020	.000	.038	.008	.007	.010	.093	.010	.006	.057	.014	.003	.055	.036
[11] Petroleum and coal products	.004	.004	.002	.001	.763	.031	.143	1.00	.000	.008	.006	.005	.014	.209	.003	.036	.074	.030	.004	.130	.014
[12] Rubber products	.000	.008	.001	.001	.400	.002	.006	.000	1.00	.008	.014	.011	.004	.030	.001	.005	.028	.064	.002	.050	.116
[13] Ceramic, stone and clay products	.003	.064	.026	.021	.439	.015	.047	.001	.001	1.00	.030	.027	.073	.225	.020	.022	.108	.032	.008	.112	.197
[14] Iron and steel	.001	.006	.002	.013	.248	.011	.028	.004	.007	.120	1.00	.580	.069	.410	.030	.059	.152	.036	.008	.065	.048
[15] Non-ferrous metals and products	.001	.009	.003	.030	.392	.020	.042	.004	.010	.187	1.00	1.00	.108	.486	.034	.111	.233	.052	.009	.097	.075
[16] Fabricated metal products	.001	.009	.012	.015	.066	.006	.016	.004	.000	.104	.025	.024	1.00	.259	.027	.050	.082	.081	.025	.070	.102
[17] General-purpose machinery	.010	.012	.008	.007	.114	.019	.018	.005	.001	.040	.019	.013	.033	1.00	.018	.020	.059	.078	.014	.082	.058
[18] Household appliances	.022	.015	.003	.004	.091	.012	.022	.001	.000	.039	.014	.010	.039	.188	1.00	.057	.121	.056	.004	.079	.106
[19] Electrical machinery	.000	.003	.001	.001	.080	.003	.004	.003	.000	.019	.013	.015	.026	.084	.022	1.00	.244	.082	.009	.127	.031
[20] Info.& com. electronics	.000	.001	.003	.008	.024	.003	.005	.001	.000	.008	.003	.003	.005	.027	.005	.026	1.00	.010	.001	.068	.009
[21] Motor vehicles, parts and accessories	.000	.003	.001	.001	.028	.001	.008	.002	.003	.017	.004	.004	.029	.183	.012	.046	.055	1.00	.022	.076	.041
[22] Other transportation equipment	.000	.004	.001	.001	.032	.002	.012	.003	.000	.031	.006	.005	.064	.260	.008	.043	.041	.197	1.00	.060	.064
[23] Precision instruments and machinery	.003	.009	.004	.007	.070	.129	.011	.003	.001	.019	.003	.003	.009	.078	.007	.030	.151	.030	.003	1.00	.035
[24] Miscellaneous manufacturing	.011	.019	.009	.007	.180	.007	.024	.001	.008	.106	.007	.006	.042	.184	.034	.023	.076	.048	.009	.117	1.00

Source: calculations based on Leten et al. (2007)

Appendix B: Applied weights in the science field - industry concordance

Focal industries (citing industries) \ Spillover sources (cited science fields)		Agriculture	Biology	Medicine	Nursing	Dentistry	Chemistry	Applied-Chemistry	Physics	Geology	Engineering	Electronics	Energy	Material Science	Mathematics	Education	Art-Literature-Society	Economics-Business-Management	History-Politics-Law	Philosophy
[04]	Food products	1.5	0.5	0.1	0.2	0.0	0.1	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
[05]	Textile mill products	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
[06]	Pulp and paper products	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0
[07]	Printing	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
[08]	Chemical fertilizers and industrial chemicals	1.8	3.9	1.2	0.4	0.7	4.5	3.2	0.3	0.1	0.2	0.1	0.5	1.3	0.0	0.0	0.0	0.0	0.0	0.0
[09]	Drugs and medicine	3.4	15.6	5.8	2.3	2.1	7.0	3.2	0.3	0.1	0.2	0.3	0.4	0.3	0.0	0.1	0.2	0.0	0.0	0.0
[10]	Miscellaneous chemicals	0.2	0.1	0.0	0.0	0.0	0.2	0.5	0.1	0.0	0.0	0.1	0.1	0.2	0.0	0.0	0.0	0.0	0.0	0.0
[11]	Petroleum and coal products	0.0	0.0	0.0	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
[12]	Rubber products	0.0	0.0	0.0	0.0	0.0	0.1	0.2	0.0	0.0	0.1	0.1	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0
[13]	Ceramic, stone and clay products	0.1	0.1	0.0	0.0	0.0	0.3	0.4	0.2	0.0	0.1	0.1	0.1	1.0	0.0	0.0	0.0	0.0	0.0	0.0
[14]	Iron and steel	0.0	0.0	0.0	0.0	0.0	0.2	0.2	0.2	0.0	0.1	0.2	0.1	0.9	0.0	0.0	0.0	0.0	0.0	0.0
[15]	Non-ferrous metals and products	0.0	0.0	0.0	0.0	0.0	0.2	0.2	0.2	0.0	0.1	0.2	0.1	0.9	0.0	0.0	0.0	0.0	0.0	0.0
[16]	Fabricated metal products	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.0	0.0	0.0
[17]	General-purpose machinery	1.5	1.4	0.4	0.2	0.1	1.1	1.8	0.5	0.1	0.5	0.4	0.5	1.7	0.0	0.0	0.0	0.0	0.0	0.0
[18]	Home electronics	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.1	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0
[19]	Electrical machinery	0.0	0.0	0.0	0.0	0.0	0.3	0.1	0.6	0.0	0.3	1.0	0.4	0.7	0.0	0.1	0.0	0.0	0.0	0.0
[20]	Info. & com. electronics	0.1	0.4	0.2	0.1	0.1	0.9	0.4	2.5	0.2	1.2	12.5	0.8	2.0	0.3	2.2	0.1	0.3	0.0	0.0
[21]	Motor vehicles, parts and accessories	0.0	0.1	0.0	0.0	0.1	0.1	0.1	0.1	0.0	0.1	0.2	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
[22]	Other transportation equipment	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
[23]	Precision instruments and machinery	0.7	3.7	2.4	0.9	1.7	2.9	1.2	1.5	0.3	0.6	1.9	0.7	0.7	0.0	0.1	0.1	0.0	0.0	0.0
[24]	Miscellaneous manufacturing	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
[25]	Electricity and gas	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Source: Calculations based on Van Looy et al. (2004) and Schmoch et al. (2004)

Appendix C. Results with different lags

Table C1. Private R&D	[1]	[2]	[3]	[4]	[5]
Non-continuous R&D (dummy)	0.0142**	0.0143**	0.0142**	0.0141*	0.0138*
	[0.0493]	[0.0484]	[0.0491]	[0.0508]	[0.0565]
Parent R&D	0.0177***	0.0176***	0.0176***	0.0177***	0.0176***
	[0.0000]	[0.0000]	[0.0000]	[0.0000]	[0.0000]
Private R&D spillover pool (lag=1)	0.0397***				
	[0.0076]				
Private R&D spillover pool (lag=2)		0.0323***			
		[0.0047]			
Private R&D spillover pool (lag=3)			0.0281**		
			[0.0268]		
Private R&D spillover pool (lag=4)				0.0099***	
				[0.0003]	
Private R&D spillover pool (lag=5)					0.0029*
					[0.0528]
Number of plant employees	-0.0321***	-0.0321***	-0.0321***	-0.0323***	-0.0320***
	[0.0000]	[0.0000]	[0.0000]	[0.0000]	[0.0000]
Number of other plants	0.0028	0.0028	0.0028	0.0029	0.0029
	[0.4848]	[0.4774]	[0.4705]	[0.4642]	[0.4618]
Number of firm employees	-0.0110***	-0.0110***	-0.0110***	-0.0109***	-0.0111***
	[0.0000]	[0.0000]	[0.0000]	[0.0001]	[0.0000]
Entry plant dummy	-0.0282***	-0.0282***	-0.0282***	-0.0280***	-0.0282***
	[0.0000]	[0.0000]	[0.0000]	[0.0000]	[0.0000]
Multi-products (4digit) plant (dummy)	0.0018	0.0018	0.0018	0.0019	0.0019
	[0.5123]	[0.5098]	[0.5076]	[0.4802]	[0.4832]
Industry-year dummies	Yes	Yes	Yes	Yes	Yes
Distance parameter					
Private R&D spillover	-0.0066**	-0.0095**	-0.0082*	-0.0932***	-0.1030*
	[19.857]	[20.352]	[12.643]	[17.255]	[2.766]
# observations	95,112	95,112	95,112	95,112	95,112
R squared	0.29352	0.29352	0.29346	0.29349	0.29337

Notes: P-values based on cluster-robust standard errors in brackets; P-values of the exponential decay parameters is based on F tests.

Table C2. Public R&D	[1]	[2]	[3]	[4]	[5]
Non-continuous R&D (dummy)	0.0139*	0.0138*	0.0138*	0.0138*	0.0142**
	[0.0553]	[0.0557]	[0.0558]	[0.0556]	[0.0493]
Parent R&D	0.0174***	0.0174***	0.0174***	0.0174***	0.0176***
	[0.0000]	[0.0000]	[0.0000]	[0.0000]	[0.0000]
Public R&D spillover pool (lag=1)	0.0371***				
	[0.0058]				
Public R&D spillover pool (lag=2)		0.0395***			
		[0.0033]			
Public R&D spillover pool (lag=3)			0.0422***		
			[0.0017]		
Public R&D spillover pool (lag=4)				0.0436***	
				[0.0012]	
Public R&D spillover pool (lag=5)					0.0153**
					[0.0277]
Number of plant employees	-0.0319***	-0.0319***	-0.0319***	-0.0319***	-0.0319***
	[0.0000]	[0.0000]	[0.0000]	[0.0000]	[0.0000]
Number of other plants	0.0027	0.0027	0.0027	0.0026	0.0029
	[0.4942]	[0.4972]	[0.5006]	[0.5031]	[0.4663]
Number of firm employees	-0.0111***	-0.0111***	-0.0111***	-0.0111***	-0.0111***
	[0.0000]	[0.0000]	[0.0000]	[0.0000]	[0.0000]
Entry plant dummy	-0.0282***	-0.0283***	-0.0283***	-0.0283***	-0.0282***
	[0.0000]	[0.0000]	[0.0000]	[0.0000]	[0.0000]
Multi-products (4digit) plant (dummy)	0.0019	0.0020	0.0020	0.0020	0.0019
	[0.4741]	[0.4721]	[0.4710]	[0.4710]	[0.4866]
Industry-year dummies	Yes	Yes	Yes	Yes	Yes
Distance parameters (F-statistics in brackets)					
Public R&D spillover	-0.0064***	-0.0073***	-0.0075***	-0.0073***	0.0054***
	[7.817]	[8.984]	[10.306]	[10.948]	[6.654]
# observations	95,112	95,112	95,112	95,112	95,112
R squared	0.29342	0.29342	0.29344	0.29344	0.29341