Swiss Leading House Economics of Education • Firm Behaviour • Training Policies

Working Paper No. 164

Innovation Effects and Knowledge Complementarities in a Diverse Research Landscape

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Universität Zürich IBW – Institut für Betriebswirtschaftslehre



D UNIVERSITÄT BERN Working Paper No. 164

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January 2022 (first version: January 2020)

This paper was previously circulated under the title "Knowledge Complementarities and Patenting: Do New Universities of Applied Sciences Foster Regional Innovation?" (2020).

Please cite as:

"Innovation Effects and Knowledge Complementarities in a Diverse Research Landscape." Swiss Leading House "Economics of Education" Working Paper No. 164, 2022 (first version 2020). By Patrick Lehnert, Curdin Pfister, Dietmar Harhoff and Uschi Backes-Gellner.

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The Swiss Leading House on Economics of Education, Firm Behavior and Training Policies is a Research Program of the Swiss State Secretariat for Education, Research, and Innovation (SERI).

Innovation Effects and Knowledge Complementarities in a Diverse Research Landscape^{*}

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January 28, 2022

Abstract

We analyse the regional innovation effect of Universities of Applied Sciences (UASs)—bachelor-granting three-year colleges teaching and conducting applied research—and whether their embeddedness in the diverse landscape of research institutions in Germany creates knowledge complementarities. To account for endogeneity, we apply fixed effects estimation and implement a self-developed proxy for regional economic activity from 30 years of daytime satellite data. We find a positive UAS effect on innovation. This effect is substantially larger in landscapes with coexisting research institutions, indicating strong knowledge complementarities.

JEL Classification Numbers: I23, O31, O38, R11

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The authors would like to thank Simone Balestra, Eric Bettinger, David Deming, Simon Janssen, Edward Lazear, Paul Lewis, Jens Mohrenweiser, Samuel Mühlemann, Laura Rosendahl Huber, Paul Ryan, Guido Schwerdt, participants of the "Higher Education in Modern Ecosystems: Efficiency, Society and Policies" conference in Augsburg, participants of the ZEW/MaCCI Conference on the Economics of Innovation and Patenting in Mannheim, participants of the Munich Summer Institute, participants of DRUID19 in Copenhagen, participants of the SASE conference in New York City, participants of the EPIP conference in Zurich, participants of the RISE2 workshop in Munich and participants of the 82nd VHB Conference in Frankfurt for helpful comments, participants of the annual meeting of the Bildungsökonomischer Ausschuss des Vereins für Socialpolitik in Augsburg, participants of the Annual Conference of the Verein für Socialpolitik in Regensburg, seminar participants at the University of Zurich, seminar participants at the Julius-Maximilians-Universität of Würzburg as well as Natalie Reid for language consulting and Felix Pöge for help with data preparation. Marc Egli, Marco Henriques Pereira, Michael Niederberger, Marie-Lena Pfaff and Vanessa Sticher provided excellent research assistance. his study was partly funded by the Swiss State Secretariat for Education. Research and Innovation (SERI) through its "Leading House VPET-ECON: A Research Center on the Economics of Education, Firm Behavior and Training Policies" as well as by the German Commission of Experts for Research and Innovation.

1. Introduction

While a great number of studies have identified the positive innovation effects of basic research performed at traditional Academic Universities (UNIs) (e.g., Abramovsky et al., 2007; Che and Zhang, 2018; Demircioglu and Audretsch, 2019; Jaffe, 1989; Toivanen and Väänänen, 2016), only a few studies have investigated the innovation effects of other types of research institutions, particularly those with a more application-oriented research focus. For example, for the US Adams et al. (2003) find positive innovation effects for federal laboratories cooperating with industrial laboratories, and Popp (2017) identifies application-oriented Public Research Organizations (PROs) as more important for private firms in the energy sector than traditional UNIs. For Switzerland, Pfister et al. (2021) examine whether Universities of Applied Sciences (UASs) lead to an increase in regional patenting activities, finding strong positive effects. In this paper, we study the German context and explore if UASs also have an impact on regional innovation activities. The novel contribution of our paper is that we investigate whether—in addition to the effects of stand-alone UASs—complementarity effects between UASs and other research institutions arise in a diverse landscape of coexisting research institutions.

Thus, on top of innovation effects that stem from a single institution itself, we address the question of whether additional effects arise due to the existence of an ecosystem of UASs and other research institutions in close proximity. We expect that different types of knowledge creation in regions where research institutions coexist lead to complementarity effects, thus enhancing the capacity for innovation in regions with bundles of different research orientations. In particular, we expect UASs to foster the transfer of the scientific knowledge that basic research institutions produce into applied research, leading to a higher degree of innovation in comparison to regions with a stand-alone UAS.

This paper thus analyses the single and combined regional innovation effects of UASs and neighbouring research institutions. We are able to (a) identify the innovation effect of the establishment of UASs in Germany and (b) to separate which part of the effect goes back to UASs themselves and which part goes back to complementarities resulting from the embeddedness of UASs in a diverse landscape of coexisting research institutions. UASs in Germany have started to conduct applied research in the 1980s and offer three-year study programs awarding bachelor-level degrees. Since adapting to the Bologna Process in the 2000s, in many cases they also offer master-level degrees,¹ but do not bestow doctoral degrees. To analyse the UAS effect on regional innovation, we examine the development of patents in Germany in treated and untreated regions since the 1980s. We investigate at the regional level whether, in the regions where UASs are located, the UAS effect on innovation depends on the existence of other research institutions—UNIs and PROs. A larger UAS effect on innovation in regions with a basic research institution (i.e., a UNI or a PRO that focuses on basic research) would clearly support the existence of complementarities between basic and applied research.

For our analysis, we draw on two main data sources to compose a novel dataset covering all research institutions (more than 700) in Germany. First, we collect information on the exact locations and opening years of all research institutions. For this purpose, we augment official directories of Higher Education Institutions (HEIs) (including UNIs and UASs) and PROs with extensively researched information on the particular campus and institute locations of each HEI and PRO, and the opening years of all identified locations. Second, to measure innovation outcomes we use patent data from the European Patent Office's (EPO) Worldwide Patent Statistical Database (October 2019 version). Combining the two data sources provides us with a rich dataset that is highly suitable for analysing the impact of knowledge complementarities between different types of research institutions on innovation outcomes. As we use patent data to measure innovation outcomes, we focus on institutions specializing in Science, Technology, Engineering, and Mathematics (STEM), because patents would not adequately represent the potential innovation effects of other fields such as the social sciences or the arts.

As an identification strategy, we follow a growing literature that uses the establishment of HEIs to estimate causal effects (e.g., Eyles and Machin, 2019; Jäger, 2013; Kamhöfer et al., 2019; Toivanen and Väänänen, 2016). In so doing, we exploit variation in the

¹ In 2000, the first UASs began to offer master-level study programs and by the end of the 2000s, the large majority of German HEIs had adapted their study programs to the Bologna Process (Key and Seeßelberg, 2012; Petzina, 2005). The findings of this paper are robust to restricting the observation period to the pre-Bologna period (results available upon request).

location and the timing of UAS openings to investigate whether innovation activities increase in the treated regions.

As we do not want to claim that the spatial and temporal distribution of UASs is entirely random in Germany, we need to account for potential endogeneity in the location of UASs to identify their effect on innovation activities. That is, we need to control for time-invariant and time-variant regional economic factors that may determine both the existence of a UAS in a region and innovation activities. To control for any such time-invariant regional factors, we apply Fixed Effects (FE) estimation. To control for time-variant regional economic factors, we employ regionally disaggregated historical data. However, such disaggregated economic data is unavailable for a time period reaching as far back as the 1980s (when UASs began to conduct applied research) and at the very detailed regional level required for our analysis. Therefore, we use a novel self-developed measure based on daytime satellite data to proxy economic activity at highly disaggregated regional units, a method that studies analysing night lights data show to be valuable when other data is unavailable (e.g., Castelló-Climent et al., 2018; Henderson et al., 2012).

We derive this novel proxy in Lehnert et al. (2021) with machine-learning techniques and show that it validly proxies economic activity in an analysis using data on economic activity available for limited time series and regional units. As the proxy dates back until the 1980s, it covers a sufficiently long time series for our analysis of German UASs. Moreover, the proxy contains detailed information on different types of land cover—measured in six different surface groups (e.g., built-up land, cropland, forests)—thereby allowing a precise approximation of regional economic activity. Therefore, using the surface groups as control variables in our estimations provides a novel solution to solving endogeneity problems resulting from the non-random spatial and temporal distribution of UAS openings under the assumption that the proxy captures all factors determining regional economic activity and, in turn, UAS locations.

Our results show that stand-alone UASs have a statistically significant positive effect on patenting activities. Furthermore, the UAS effect increases substantially in regions where other research institutions exist at the time of the UAS opening. A diverse research landscape featuring different types of research knowledge thus leads to strong knowledge complementarities.

Our paper makes two contributions to the literature on the innovation effects of different types of research institutions (e.g., Intarakumnerd and Goto, 2018; Popp, 2017; Toivanen and Väänänen, 2016). First, we study UASs, a type of HEI that focuses on applied research and that only very few studies have considered so far (e.g., Pfister et al., 2021). Second, previous research has largely neglected interactions between different types of research institutions and thus the role of the surrounding research landscape. The distinct specializations among research institutions in Germany allows us to explicitly analyse such interactions.

The paper proceeds as follows. Section 2 reviews the relevant literature and develops our hypotheses. Section 3 provides detailed information on UASs in Germany and basic information on other research institutions in the German education and innovation system (UNIs and PROs). Section 4 describes the data we use for our analysis and Section 5 our methodological approach. Section 6 presents our main estimation results and provides further robustness checks. Section 7 concludes.

2. Literature Review

Many studies have emphasised the positive influence of research institutions performing basic research on regional innovation activities. In an important study, Jaffe (1989) finds evidence of spillovers from UNI research to private-sector R&D, in STEM-related industries in particular, thereby contributing to local patenting activities. Other studies attesting to the positive relationship between UNI research and the evolution of patents include Autant-Bernard (2001), Cowan and Zinovyeva (2013), Leten et al. (2014) and Toivanen and Väänänen (2016). This literature thus extensively documents the positive effect of basic research institutions on regional innovation.

In addition, other types of PROs, in particular those with a more applied research focus, positively affect innovation. In their review of the traditional linear model of innovation, Leyden and Menter (2018) argue that basic public research alone—without accompanying applied research—is insufficient for generating knowledge spillovers from the public to the private sector. A variety of PROs can serve this applied function within an innovation system, with empirical studies providing evidence for the positive effect of these PROs (e.g., Comin et al., 2019; Intarakumnerd and Goto, 2018; Popp, 2017). Case studies of regional innovation systems in Germany also show that PROs can play a key role in fostering innovation (e.g., Broekel and Graf, 2012; Graf, 2011).

A particular type of applied research institution belonging to the higher education sector are the UASs. Pfister et al. (2021) show that UASs have a large positive effect on patenting in Switzerland. For Germany, previous research has not analysed the innovation effect of UASs separately, but only in combination with other institutions in the research and innovation system. Fritsch and Slavtchev (2007) provide evidence for a positive innovation effect of HEIs (UNIs and UASs combined) using six years of patent data from the German Patent Office. Furthermore, using two waves of Community Innovation Survey data, Robin and Schubert (2013) find that collaboration between firms and public research institutions (UNIs, UASs and PROs combined) increases innovation at the firm level. Other studies use cross-sectional surveys to investigate the role of public research institutions (differentiating between UNIs, UASs and PROs) for innovation in firms, providing mixed results (Beise and Stahl, 1999; Fritsch and Schwirten, 1999).

Few studies explicitly address cooperation between research institutions. Fritsch and Schwirten (1999) find that in the regions surveyed in their analysis, cooperation with other research institutions is more common for UNIs and PROs than for UASs, which in turn cooperate more often with firms. Investigating how the number of cooperation partners affects innovation in firms (but without explicitly differentiating between different types of cooperation partners), Becker and Dietz (2004) argue that a mix of heterogeneous cooperation partners creates synergies that further increase R&D activities. However, the innovation effect resulting from knowledge complementarities between different types of research institutions remains unexplored.

In sum, based on the empirical evidence we expect that both basic and applied public research institutions increase innovation and that cooperation between the two potentially enhances this effect. In this paper, we contribute to the literature by studying the establishment of UASs, allowing us to disentangle the UAS effect on patenting from the effects of other research institutions and the joint effects.

Assuming that knowledge spillovers are geographically concentrated, as many studies argue (e.g., Audretsch and Feldman, 1996; Audretsch et al., 2012; Berkes and Gaetani, 2020; Holl et al., 2020), we expect that opening a UAS in a region where it can cooperate with a basic research institution yields a larger innovation effect than opening a UAS elsewhere. Moreover, if the two types of institutions produce complementary applied research knowledge, opening a UAS in a region where another type of applied research institution already exists might also lead to positive knowledge spillovers. In regions where no other institution exists, we expect UASs to increase innovation, but to a lesser extent. In addition to these potential effects, the applied research knowledge of UASs and their complementarities with other research institutions can help accelerate technological catch-up processes in less developed regions.

3. The German Landscape of Research Institutions

3.1. Higher Education Institutions (HEIs)

In Germany, two types of public² HEIs teach and conduct research in the STEM fields: UNIs and UASs.³ Like all education institutions in Germany, UNIs and UASs fall under the jurisdiction of the Länder⁴ governments (Federal Ministry of Education and Research (BMBF), 2018a).⁵ Although both institutions award equivalent bachelor's and master's degrees (ISCED 2011 levels 6 and 7), UNIs hold the exclusive right to award doctoral

² We restrict our analysis to public HEIs. We exclude private ones primarily because relatively fewer of them are active in STEM-related research (see Buschle and Haider, 2016).

³ In addition to UNIs and UASs, the German higher education sector also comprises universities of education (*Pädagogische Hochschulen*), of theology (*Theologische Hochschulen*), of art and music (*Kunsthochschulen*) and of public administration (*Verwaltungsfachhochschulen*) (BMBF, 2018*a*). However, as these institutions specialize in subjects unrelated to STEM and thus produce innovations that do not usually result in patents, we do not consider them in our analysis.

 $^{^4}$ $\,$ Germany is divided into 16 federal states called Länder.

⁵ Very few HEIs that train civil servants fall partly under federal jurisdiction, such as the German University of Administrative Sciences in Speyer, the German Police University in Münster or the Universities of the German Federal Armed Forces in Hamburg and Munich.

degrees throughout the years that we analyse in this paper (BMBF, 2004; Meurer, 2018).⁶ Moreover, UNIs focus on basic research and impart basic research skills to their students, whereas UASs emphasise vocational practice and applied research (BMBF, 2004).

While some UNIs have a centuries-long tradition, UASs are rather new institutions.⁷ In comparison to UNIs, teaching at UASs targets students who have completed an apprenticeship (a dual vocational education and training program) and aims at knowledge relevant for vocational practice and problem-solving (BMBF, 2004). This focus also manifests at many UASs in, for example, bachelor-degree programs that include a practical semester in the form of an internship at a firm (BMBF, 2004; Lackner, 2019).

Only in 1985 did an amendment of the German Higher Education Framework Act add applied research to the purpose of UASs (Enders, 2010; Kulicke and Stahlecker, 2004; Wissenschaftsrat, 2002). By engaging in applied research projects jointly conducted with firms, faculty members at UASs maintain their vocational practice, which they can then pass on to their students (Hinz et al., 2016; Kulicke and Stahlecker, 2004). A large part of the research projects that UASs undertake is in STEM fields such as IT, materials science or mechanical engineering (Kulicke and Stahlecker, 2004).

Due to their focus on applied research and vocational practice, UASs are an important research partner for local firms. Small and medium-sized firms in particular profit from the knowledge that UASs generate, because these firms value the application-oriented knowledge and the vocational practice, and because these firms do not possess the capacities for carrying out research projects by themselves (Hachmeister et al., 2015; Kulicke and Stahlecker, 2004). Participation in joint research projects with larger firms or in publicly funded research projects is also important for UASs (Hachmeister et al., 2015). Thus, by providing applied research knowledge to local players in the R&D ecosystem, UASs can positively contribute to regional innovation activities.

⁶ Recently, the federal state of Hesse granted research-intensive UASs a limited right to award doctoral degrees (Meurer, 2018).

⁷ The first UASs in Germany were introduced only in 1968 as teaching institutions (BMBF, 2004).

3.2. Public Research Organizations (PROs)

In addition to UNIs and UASs, which combine teaching and research, four PROs exclusively conduct research. These four PROs—the Max Planck Society, the Leibniz Association, the Helmholtz Association and the Fraunhofer Society—thus constitute another unique pillar of the German research and innovation system. They are publicly funded and act independently, serving functions that are complementary to those of HEIs (see, e.g., Commission of Experts for Research and Innovation (EFI), 2010). Each PRO maintains several research institutes throughout Germany, often employing hundreds and sometimes even thousands of researchers (BMBF, 2018b).

The four PROs serve different functions and have different ranges of activity:

- The Max Planck Society conducts basic research in the natural sciences, the life sciences, the social sciences and the humanities (BMBF, 2018a), that is, in both STEM and non-STEM fields. The Max Planck Society autonomously chooses its research subjects and aspires to scientific excellence, a goal also reflected in the organization's high degree of internationalization (BMBF, 2018a; Hohn, 2010). Examples include the Max Planck Institute for Plasmaphysics or the Max Planck Institute of Biochemistry (see BMBF, 2018b).
- The Fraunhofer Society engages in applied research projects on a range of topics (e.g., health, environment, mobility, energy), with the majority being STEM-related (BMBF, 2018a). As the Fraunhofer Society receives government funding that calls for research collaboration, both private and public demand drive the organization's choice of research projects (Hohn, 2010). Examples include the Fraunhofer Institute for Solar Energy Systems or the Fraunhofer Institute for Laser Technology (see BMBF, 2018b).
- The Helmholtz Association comprises research centres that are active in technologyintensive (i.e., STEM-related) fields with a long-term perspective, such as aeronautics and materials science (BMBF, 2018a). Therefore, the organization is involved in the transfer of basic research knowledge to technological products (Hohn, 2010).

In comparison to the Max Planck Society and the Fraunhofer Society, the public funding that the Helmholtz Association receives is tied to specific subjects or projects (Hohn, 2010). Examples include the German Aerospace Center or the Helmholtz Centre for Infection Research (see BMBF, 2018b).

The Leibniz Association originally put those institutes that did not fit into the structures of the other three organizations under one umbrella (Hohn, 2010). Consequently, the Leibniz Association has the broadest research scope of the four PROs, ranging from basic to applied research in both STEM and non-STEM fields, and having a decentralized organizational structure (BMBF, 2018a; Hohn, 2010). In addition to research institutes, the Leibniz Association also comprises non-research institutes such as museums and further education institutes (e.g., training centres) (BMBF, 2018a; Hohn, 2010). Examples include the Leibniz Institute of Polymer Research or the Leibniz Institute of Plant Genetics and Crop Plant Research (see BMBF, 2018b).

Figure 1a graphically depicts the profiles of research institutions by comparing their publication and patenting activities (EFI, 2010). Corresponding to their mandates, the Max Planck Society focuses on basic research (mainly publications) and the Fraunhofer Society focuses on applied research (mainly patents). The Helmholtz and Leibniz Associations range somewhere in between, with the Leibniz Association tending towards basic research. With respect to HEIs, the study unfortunately did not differentiate between UNIs and UASs, but the average over all HEIs locates in the middle of the spectrum. However, if one were to depict UNIs and UASs separately, their positioning would correspond to that in Figure 1b in line with the two HEIs' mandates, that is, UNIs tending towards basic research and UASs towards applied research.

In accordance with their differing profiles, PROs strategically engage in different types of research cooperation with HEIs (BMBF, 2018a). Again, such cooperation can play a key role in fostering the transfer of basic scientific knowledge to actual applications. For PROs with a basic research focus, such as the Max Planck Society, cooperation with UASs can provide an important source of applied research knowledge, while UASs, in



Fig. 1. Profiles of research institutions in Germany

Notes: Figure 1a shows an illustration based on EFI (2010, p. 40). Figure 1b shows authors' extensions based on the legal mandates of HEIs. The original analysis in EFI (2010) is based on an analysis of publications in the Science Citation Index and patent applications per researcher (in full-time equivalents) for three periods, 1994–1996, 1999–2001 and 2004–2006 (dots show averages over these three periods). The original analysis does not differentiate between UASs and UNIs. The dots for UASs and UNIs in Figure 1b represent authors' assessment of the activity of UASs and UNIs according to their legal mandates.

turn, might value such cooperation as a source of basic research knowledge. Furthermore, PROs with an applied research focus, such as the Fraunhofer Society, might also profit from knowledge complementarities with UASs.

4. Data

To analyse the innovation effect of UASs, we use three different datasets. First, we use patent data to measure innovation. Second, we use self-collected data on the locations and opening years of all HEI campuses and PRO institutes in Germany to identify regions treated by one or more of these institutions. Third, we use for the first time the proxy measure for regional economic activity that we develop in Lehnert et al. (2021) to control for endogeneity in the spatial and temporal distribution of UAS openings in our empirical analysis. Combining these three datasets provides ample information for investigating the innovation effect of UASs and the role of knowledge complementarities between UASs and other research institutions. The first dataset is the EPO Worldwide Patent Statistical Database (October 2019 version), from which we extract two measures of regional innovation as our outcome variables. This data offers complete information on patents from 1980 and thus goes back further in time than 1985, when UASs began to conduct applied research. The patent information includes, among other items, the exact geographic locations of inventors, the application date and the number of patent citations three years after publication.⁸ To assign every inventor to a German municipality, we geocode⁹ the inventor locations in the EPO data and then link the geocoded addresses to administrative geodata provided by the Federal Agency for Cartography and Geodesy (BKG).¹⁰ Using these assignments, we follow Pfister et al. (2021) and compute the fractionated¹¹ number of patents per municipality and year (patent quantity, PQUAN), as well as a patent's average number of citations per municipality and year (patent quality, PQUAL) as innovation outcomes. To ensure a complete citation window of three years for all patents in the EPO data, we end the observation period in 2015.

From the second dataset, we construct our treatment variables by determining which types of HEIs and PROs exist in each municipality at a given point in time. To create this dataset, we had to exert extensive efforts in data collection to get the location and timing of the openings of all HEI campuses and all PRO institutes.

As a starting point for the HEI data collection, we used data from the German Rectors' Conference.¹² This data contains, among other items, the name, type, main address and opening year of every HEI (i.e., every UNI and every UAS) that existed in Germany on January 1, 2017,¹³ but it does not contain their individual campus locations or study fields.

⁸ The EPO data also includes citation information for five and ten years after publication, respectively. We analyse the citation lag of three years to get a conservative estimate and to be able to use a longer time series.

⁹ We geocode addresses using the HERE application programming interface. See https://developer.here .com/ (last retrieved on November 21, 2019).

¹⁰ Available from http://www.geodatenzentrum.de/geodaten/gdz_rahmen.gdz_div?gdz_spr=deu&gdz_akt _zeile=5&gdz_anz_zeile=1&gdz_unt_zeile=15&gdz_user_id=0 (last retrieved on May 5, 2017).

¹¹ For example, if a patent lists one inventor from municipality A, one inventor from municipality B and one inventor from abroad, the patent counts as $\frac{1}{3}$ of a patent for municipality A and $\frac{1}{3}$ for municipality B. The remaining $\frac{1}{3}$ does not enter our estimations.

¹² Available from http://www.hs-kompass2.de/kompass/xml/download/hs_liste.txt (last retrieved on January 20, 2017).

¹³ We exclude HEIs that offer only distance learning, because we do not expect their innovation effects, if any, to be locally concentrated.

Furthermore, to identify HEIs that closed before January 1, 2017, (and are thus not part of the German Rectors' Conference data)¹⁴ we use data on student numbers ranging as far back as 1998 from the German Federal Statistical Office's GENESIS database.¹⁵ This data contains the names and (indirectly through disappearance in the data) the closing years of these HEIs. For the construction of our treatment variables, we had to augment these HEI data by performing extensive online searches in which we studied for every single HEI the available information on the web to nail down the HEI's individual history, campus locations, and study fields. To obtain this detailed information, we researched online the campus addresses, campus opening years¹⁶ and campus profiles (i.e., the departments or study programs that each offers),¹⁷ gathering this information primarily from the HEIs' websites. Drawing on the campus profiles, we categorize HEI campuses according to whether they are active in STEM or not. If a campus offers at least one study program in STEM or has a STEM department, we categorize it as a STEM campus.

To obtain initial information for the PRO data collection (i.e., for the collection of data on all institutes belonging to one of the four PROs Max Planck Society, Leibniz Association,¹⁸ Helmholtz Association¹⁹ and Fraunhofer Society), we draw on BMBF (2018b). This source contains the name and city of all such institutes that existed in 2018, but not the exact addresses, opening years or information on closed institutes. Again,

¹⁴ Nonetheless, we might miss some HEIs that closed before 1998. However, drawing on historical descriptions of HEIs (see also section 3.1), we find this number to be very small, therefore not biasing our estimations.

¹⁵ Available from https://www-genesis.destatis.de/genesis/online/data;jsessionid =7CF9926E22E6DDE18B248F7571AD3949.tomcat_GO_2_3?operation=abruftabelleBearbeiten &levelindex=1&levelid=1500539721416&auswahloperation=abruftabelleAuspraegungAuswaehlen&a uswahlverzeichnis=ordnungsstruktur&auswahlziel=werteabruf&selectionname=21311-0002&auswah ltext=&werteabruf=Werteabruf (last retrieved on July 20, 2017).

¹⁶ If the websites or other sources do not indicate an opening year for a campus, we assume it to be the opening year of the respective institution as indicated in the German Rectors' Conference data.

¹⁷ For example, the main campus of the Weihenstephan-Triesdorf University of Applied Sciences with the department of bioengineering sciences (among others) is in Freising. However, the Weihenstephan-Triesdorf University of Applied Sciences has a second campus in Weidenbach (more than 100 kilometres from Freising), which contains the departments of agriculture, food and nutrition and of environmental engineering.

¹⁸ The Leibniz Association, formerly named Blue List Partnership and Blue List Science Association, emerged in the 1990s from the Blue List institutes (see, e.g., Brill, 2017). Former Blue List institutes also enter our analysis as Leibniz institutes.

¹⁹ In 1995, the Association of National Research Centres was transferred into the Helmholtz Association (see, e.g., Hoffmann and Trischler, 2015). Institutes belonging to the former Association of National Research Centres also enter our analysis as Helmholtz institutes.

we perform extensive online searches to augment this data by collecting the addresses, opening years and profiles of all institutes belonging to one of the four PROs (including information on closed institutes) and categorizing the institutes according to whether they are active in STEM or not.

The second dataset thus contains the exact addresses and opening years of all UAS campuses, UNI campuses and PRO institutes. This information allows us to determine the spatial distribution of these campuses and institutes, providing us with a rich longitudinal dataset. From 1980 through 2015 (the observation period of this paper), 134 public UASs have campuses in 347 locations in Germany, 212 of which are STEM campus locations.²⁰ These STEM campus locations are geographically distributed across 142 (of a total of 11,266) municipalities.²¹ Furthermore, 99 public UNIs have 310 STEM campus locations distributed across 74 municipalities, the Max Planck Society has 145 STEM institute locations distributed across 50 municipalities, the Leibniz Association has 101 STEM institute locations distributed across 49 municipalities, the Helmholtz Association has 114 STEM institute locations distributed across 52 municipalities and the Fraunhofer Society has 161 STEM institute locations distributed across 84 municipalities. Appendix A shows the distribution of STEM campus and STEM institute locations across municipalities for the year 2015. For better readability, if not explicitly stated otherwise, we drop the specification "STEM" when we refer to UAS STEM campuses, UNI STEM campuses or PRO STEM institutes.

Third, to account for endogeneity in the spatial and temporal distribution of UAS campus locations, we use a novel proxy for regional economic activity. Using this proxy is necessary, because no other direct or indirect measure of regional economic activity or other factors related to UAS openings and patenting exists for a time series dating as far back as 1985 (when UASs began to conduct applied research), and at a sufficiently disaggregated regional level. This paper uses the novel proxy for regional economic activity based on daytime satellite imagery, a proxy that we develop in Lehnert et al. (2021).

²⁰ Here, a location comprises all departments or branches with the same postal address. Thus one location can consist of multiple departments or branches.

²¹ Throughout all observation years, we use the territorial status of January 1, 2017, because it was the most current one when we started work on this paper.

We demonstrate in Lehnert et al. (2021) that our proxy—like other satellite-based proxies such as night-light intensity (e.g. Chen and Nordhaus, 2011)—constitutes a valuable proxy for regional economic activity. Closely following the geographic literature, the proxy is constructed by applying machine-learning techniques to daytime satellite data, thereby classifying the surfaces of extremely small regional units (30 times 30 square meter pixels) into six different surface groups: built-up land (i.e., artificial materials such as buildings), grassland, forest, cropland, land without vegetation (e.g., bare rock, pure soil) and water. This information on surface groups can then be aggregated to any regional unit, including municipalities,²² to provide detailed information on regional surface structures. The proxy is available from 1984, and thus earlier than any other satellite-based proxy for regional economic activity. Using fine-grained regional data on economic activity that is only available for a limited number of years, we show in Lehnert et al. (2021) that the regional combination of surface groups is a highly valid proxy for regional economic activity. Further information on the construction of the proxy and its validation can be found in Lehnert et al. (2021).

5. Method

Combining all data sources described in Section 4, we exploit the temporal and spatial variation in the establishments of UAS campuses and estimate the following FE model:

$$Y_{i,t} = \beta_0 + \beta_1 UAS_{i,t-3} + \beta_2 UAS_{i,t-3} \times UNI_i + \beta_3 UAS_{i,t-3} \times MaxPlanck_i + \beta_4 UAS_{i,t-3} \times Leibniz_i + \beta_5 UAS_{i,t-3} \times Helmholtz_i + \beta_6 UAS_{i,t-3} \times Fraunhofer_i + i + t + X_{i,t-3} + SG_{i,t} + \mu_{i,t}$$

$$(1)$$

with *i* indicating the municipality, *t* the year ranging from 1984 (the first year in the surface groups data)²³ through 2015 (the last year in the patent data containing complete

²² On average, a German municipality consists of about 56,000 pixels.

²³ Appendix D provides the estimation results without using surface groups as control variables for the observation period 1980 through 2015. In these estimations, the pattern of the results is identical to that in our main results, but the coefficients are larger in magnitude. Therefore, surface groups do

citation information);²⁴ Y the dependent variable (patent quantity or patent quality); UAS the treatment status by a UAS campus; UNI, MaxPlanck, Leibniz, Helmholtz and Fraunhofer the existence of a campus or institute belonging to the respective institution or organization at the time of the UAS campus opening; and μ the error term. To investigate change rates instead of changes in absolute numbers, we follow previous studies that use patenting activities as an indicator for regional innovation (Feldman and Florida, 1994; Pfister et al., 2021; Schlegel et al., 2021) and take the natural logarithms of the dependent variables Y after adding the value 1, that is, we observe ln(PQUAN + 1) and ln(PQUAL + 1), respectively. The vector X includes controls for the establishments of other campuses or institutes during the observation period (i.e., the vector includes $UNI_{i,t-3}$, $MaxPlanck_{i,t-3}$, $Leibniz_{i,t-3}$, $Helmholtz_{i,t-3}$ and $Fraunhofer_{i,t-3}$). The vector SG contains the surface groups.

To estimate Equation 1 and thus to identify the innovation effect of a UAS opening, we assign each German municipality either to a treatment group or to the control group. To the treatment groups, we assign all municipalities that are treated by a UAS campus. We consider a municipality treated by a UAS campus if the municipality is located within a 25-kilometre²⁵ (15.5 miles) travel-distance²⁶ radius of the campus. For our analysis, we consider the year 1985 (i.e., when UASs began to conduct applied research according to their legal mandate) as the earliest possible treatment year, even if a UAS already existed as a teaching institution before 1985. We allow for a treatment lag of three years in Equation 1, because the regional research structures of UASs need some time to establish

indeed account for potential endogeneity in the spatial and temporal distribution of UAS locations.

²⁴ For East Germany, the patent data begin only after the German reunification in 1991. Therefore, t ranges from 1991 through 2015 for East German municipalities. The main findings of this paper are robust to excluding East German municipalities entirely from the analysis.

²⁵ We choose the threshold of 25 kilometres because in Germany, the majority of the working population (79.2 percent in 2016) commute 25 kilometres or less. See https://www.destatis.de/DE/ZahlenFakt en/GesamtwirtschaftUmwelt/Arbeitsmarkt/Erwerbstaetigkeit/TabellenPendler/Pendler1.html (last retrieved on February 19, 2019). Empirical evidence on the innovation effects of research institutions also suggests a concentration of these effects within a 25-kilometre radius of an institution (Helmers and Overman, 2017; Pfister et al., 2021). We provide estimation results with varying treatment radii as a robustness check in Appendix B to demonstrate that the choice of treatment radius does not alter our main results.

²⁶ We compute the travel distance between the geographical centre of a municipality and a campus or institute location using the HERE application programming interface. See https://developer.here.com/ (last retrieved on November 21, 2019).

after the announcement of applied research becoming a goal of UASs.²⁷ To the control group, we assign all municipalities not treated by a UAS campus.

To investigate knowledge complementarities between UASs and other research institutions, we form six treatment groups by differentiating treated municipalities according to whether they are simultaneously treated by other types of research institutions. In so doing, we apply the same 25-kilometre radius to retrieve indicators for whether a municipality is treated by a UNI campus or a PRO institute at the time of the UAS campus opening. We then interact the treatment variable UAS with these indicators to assign treated municipalities to six, non-mutually exclusive, treatment groups: municipalities treated by a UAS campus but not by any other research institution (term $UAS_{i,t-3}$ in equation 1), municipalities treated by a UAS campus and by a UNI campus $(UAS_{i,t-3} \times UNI_i)$, municipalities treated by a UAS campus and by a Max Planck institute $(UAS_{i,t-3} \times MaxPlanck_i)$, municipalities treated by a UAS campus and by a Leibniz institute $(UAS_{i,t-3} \times Leibniz_i)$, municipalities treated by a UAS campus and by a Helmholtz institute $(UAS_{i,t-3} \times Helmholtz_i)$ and municipalities treated by a UAS campus and by a Fraunhofer institute $(UAS_{i,t-3} \times Fraunhofer_i)$. These interaction terms allow us to disentangle the effect of opening a UAS in regions with no preexisting research knowledge to draw upon from the effect resulting from knowledge complementarities between UASs and other research institutions. Moreover, by including the vector X in Equation 1 we control for the establishments of UNI campuses or PRO institutes after the establishment of a UAS campus.

Figure 2 shows the distribution of treatment regions in Germany for 2015, the last year of observation in our analysis. Of the 11,266 municipalities, 3,720 (33.0 percent) lie within the 25-kilometre treatment radii of UAS campuses, 2,263 (20.1 percent) within the radii of UNI campuses, 1,842 (16.4 percent) within the radii of Max Planck institutes, 1,206 (10.7 percent) within the radii of Leibniz institutes, 1,404 (12.5 percent) within the radii of Helmholtz institutes and 2,278 (20.2 percent) within the radii of Fraunhofer institutes. Of the 3,720 municipalities treated by a UAS campus, at the time of the UAS campus

²⁷ For example, graduates are one important channel of knowledge transfer (e.g., Andrews, 2020; Lehnert et al., 2020) and the minimum number of years a UAS student needs to graduate is three years.

opening 1,364 (36.7 percent) were also treated by a UNI campus, 828 (22.3 percent) by a Max Planck institute, 337 (9.1 percent) by a Leibniz institute, 362 (9.7 percent) by a Helmholtz institute and 705 (19.0 percent) by a Fraunhofer institute.

To identify the causal UAS effect on innovation, we need to control for potential endogeneity in the locations of UAS campuses. As we cannot assume that the establishment of UASs in Germany followed a quasi-random pattern, we account for the potential endogeneity in UAS campus openings in three ways. First, to account for time-invariant municipality characteristics that determine both UAS locations and patenting activities, we use FE estimation (municipality FE *i* in equation 1). Second, to capture time trends that are common to all municipalities, we add year FE (*t*). Third, as the municipality FE and year FE still do not solve the problem of time-variant regional factors potentially determining both UAS locations and patenting, we account for (at least some of) these time-variant factors in our estimations by including the surface groups developed in Lehnert et al. (2021) in Equation 1 as proxies for time-variant regional economic activity (vector SG).²⁸ Neglecting such factors would bias our results if these factors were correlated with both the treatment (i.e., the timing and locations of UAS campus openings) and patenting.

From 1984 through 2015, a German municipality (which comprises on average about 7,800 acres), consists on average of 14.3 percent built-up land, 22.1 percent grassland, 23.5 percent forest, 30.2 percent cropland, 3.7 percent land without vegetation and 3.5 percent water.²⁹ Comparing the treatment and control groups shows that treated municipalities feature on average more built-up land (17.2 percent vs. 12.9 percent) and cropland (31.2 percent vs. 29.7 percent), but less grassland (19.9 percent vs. 23.2 percent), forest (22.2 percent vs. 24.1 percent), land without vegetation (3.7 percent vs. 3.8 percent) and water (3.4 percent vs. 3.6 percent). The treated and control regions thus differ in their regional surface structures. Therefore, our novel proxy captures differences in regional economic structures before and after UAS openings, thereby controlling for time-variant regional

²⁸ As the six surface groups are collinear, we follow Lehnert et al. (2021) and exclude the forest group as the reference. Furthermore, we add a variable indicating the percentage of unidentified surfaces to account for potential measurement error in the surface groups variables (see Lehnert et al., 2021).

²⁹ The remaining 2.7 percent are unclassified due to, e.g., cloud cover in the satellite imagery (see Lehnert et al., 2021).



Fig. 2. Municipalities treated by STEM campuses and STEM institutes in 2015 (25-kilometre travel-distance radius)

Notes: Authors' illustration with geodata from the BKG, data on HEIs from the German Rectors' Conference, data on PROs from BMBF (2018b) and self-collected data on HEIs and PROs.

heterogeneity potentially determining UAS campus locations.

6. Results

6.1. Main Results

Table 1 shows the FE estimation results for the dependent variable patent quantity.³⁰ These estimations show that UASs have a positive and significant effect on patent quantity. This effect is substantially larger in regions where other research institutions exist at the time of the UAS campus opening. According to our preferred specification in column 7, which includes the full set of interactions with UNI campuses and PRO institutes and thus considers the entire research knowledge that new UASs can draw upon, the opening of a UAS campus significantly increases patent quantity both in regions without another research institution. In comparison to regions without another research institution, the UAS effect is larger in regions with institutions focusing on basic research (Max Planck institutes), applied research (Fraunhofer institutes) or a mixture of both (Helmholtz institutes). The full set of interaction terms thus unveils that complementarities between UASs and other research institutions boost the UAS effect on patent quantity.

The FE estimation results on patent quality in Table 2 reveal the same overall pattern as the results on patent quantity. Our preferred specification with the full set of interaction terms in column 7 shows that UASs significantly increase patent quality by 2.6 percent in regions where a Max Planck institute coexists, indicating that the research knowledge of Max Planck institutes constitutes a valuable resource for the quality of innovations that UASs produce. This finding might result from the Max Planck Society's mission of aspiring to scientific excellence, suggesting that UASs need strong accompanying basic research knowledge to produce high-quality innovations.

In sum, the FE estimations suggest that UASs can tap their full potential as drivers of regional innovation in regions where other research institutions coexist. For patent

³⁰ We calculate robust standard errors in the regressions presented in this section. Our results are robust to clustering standard errors at the municipality level.

Dep. var.:							
ln(PQUAN + 1)	(1)	(2)	(3)	(4)	(5)	(9)	(2)
$UAS_{i,t-3}$	0.063^{***}	0.042^{***}	0.040^{***}	0.058^{***}	0.053^{***}	0.042^{***}	0.027^{***}
	(0.006)	(0.007)	(0.006)	(0.006)	(0.006)	(0.006)	(0.007)
$UAS_{i,t-3} \times UNI_i$		0.064^{***}					0.010
		(0.012)					(0.013)
$UAS_{i,t-3} \times MaxPlanck_i$			0.124^{***}				0.090^{***}
			(0.015)				(0.016)
$UAS_{i,t-3} \times Leibniz_i$				0.066^{***}			-0.018
				(0.022)			(0.023)
$UAS_{i,t-3} \times Helmholtz_i$					0.130^{***}		0.061^{***}
					(0.022)		(0.023)
$UAS_{i,t-3} \times Fraunhofer_i$						0.118^{***}	0.078^{***}
						(0.015)	(0.017)
Municipalities	11,266	11,266	11,266	11,266	11,266	11,266	11,266
N	341,885	341,885	341,885	341,885	341,885	341,885	341,885
R^2 (within)	0.092	0.093	0.093	0.092	0.093	0.093	0.094
R^2 (between)	0.164	0.181	0.208	0.171	0.169	0.195	0.222
R^2 (overall)	0.091	0.098	0.116	0.095	0.099	0.107	0.124
Notes: Authors' calculations ba German Rectors' Conference, c parentheses. All models include $Helmholtz_{i,t-3}$ and $Fraunhofe$	used on patent \dot{c} data on PROs f intercept, mun $r_{i,t-3}$ * $p < 0.1$	lata from the El from BMBF (20 icipality FE, yes 0, **p < 0.05, **	PO, data on sur. 118b) and self-c ar FE, surface g ** $p < 0.01$.	face groups from ollected data on roups and contre	Lehnert et al. (HEIs and PRC is for $UNI_{i,t-3}$	(2021), data on Ds. Robust stan $MaxPlanck_{i,t}$.	HEIs from the dard errors in -3 Leibniz _{i,t-3}

Table 1. FE estimation results on patent quantity (25-km travel-distance radius, 3-y. lag)

Dep. var.:							
$ln(PQUAL_{cit}+1)$	(1)	(2)	(3)	(4)	(5)	(9)	(2)
$UAS_{i,t-3}$	0.011^{***}	0.007^{**}	0.006^{**}	0.010^{***}	0.010^{***}	0.008^{***}	0.005
	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)
$UAS_{i,t-3} \times UNI_i$		0.011^{**}					0.002
		(0.005)					(0.006)
$UAS_{i,t-3} \times MaxPlanck_i$			0.027^{***}				0.026^{***}
			(0.006)				(0.007)
$UAS_{i,t-3} \times Leibniz_i$				0.008			-0.006
				(0.009)			(0.010)
$UAS_{i,t-3} \times Helmholtz_i$					0.007		-0.007
					(0.009)		(0.010)
$UAS_{i,t-3} \times Fraunhofer_i$						0.016^{**}	0.009
						(0.007)	(0.008)
Municipalities	11,266	11,266	11,266	11,266	11,266	11,266	11,266
N	341,885	341,885	341,885	341,885	341,885	341,885	341,885
R^2 (within)	0.023	0.023	0.023	0.023	0.023	0.023	0.023
R^2 (between)	0.012	0.018	0.036	0.013	0.014	0.020	0.040
R^2 (overall)	0.021	0.023	0.026	0.021	0.022	0.023	0.027
Notes: Authors' calculations ba German Rectors' Conference, \dot{c} parentheses. All models include Helmholt $z_{i,t-3}$ and Fraunhofe	sed on patent d lata on PROs f intercept, muni $r_{i,t-3} * p < 0.1$	ata from the E rom BMBF (20 cipality FE, yes 0, **p < 0.05, *	PO, data on sur 018b) and self-c ar FE, surface g *** $p < 0.01$.	face groups fron collected data or roups and contr	I Lehnert et al. I HEIs and PRC ols for $UNI_{i,t-3}$	(2021), data on Ds. Robust stan $MaxPlanck_{i,t}$	HEIs from the dard errors in -3 Leibniz _{i,t-3}

Table 2. FE estimation results on patent quality (citations) (25-km travel-distance radius, 3-y. lag)

quantity, we also consistently find positive interaction effects if UASs open in regions where they can draw upon basic research knowledge that Max Planck institutes provide, applied research knowledge that Fraunhofer institutes provide or a combination of both that Helmholtz institutes provide. For patent quality, we find a positive interaction effect of UASs only in regions where they can draw upon very strong basic research knowledge that Max Planck institutes generate. The complementarities between UASs and other research institutions can result from a variety of mechanisms, such as movements of faculty, joint research projects, or cooperation with local firms. Although we cannot determine these potential mechanisms, our results present strong evidence that knowledge complementarities between UASs and other research institutions foster regional innovation.

6.2. Robustness Checks

To check whether our main results are robust to alternative model specifications, we perform two robustness checks. First, we investigate whether these results are sensitive to decreasing or increasing the treatment radius of 25 kilometres we apply in the main specification. Second, we assess whether the main results are sensitive to choosing shorter or longer treatment lags than the three-year lag.

First, to assess the role of the radius of 25 kilometres—and thus the spatial concentration of the UAS effect on innovation—that we choose for the assignment of municipalities to the treatment and control groups, we estimate Equation 1 with (a) decreased radii of 15 and 20 kilometres, and (b) increased radii of 30 and 35 kilometres. These estimations allow us to examine the spatial persistence of the UAS effect on innovation by analysing (a) whether the effects of UASs are more locally concentrated (by decreasing the treatment radius) or (b) whether UASs exert effects on regions beyond the 25-kilometre radius (by increasing the treatment radius). Appendix B plots the coefficients of the corresponding estimations. We find the same overall pattern of effects as with the 25-kilometre radius for all specifications. For both patent quantity and patent quality, the UAS effect in regions without any coexisting research institutions becomes larger and significant when decreasing the treatment radius, but smaller and insignificant when increasing this radius. This finding suggests that the impact of a UAS campus opening concentrates in regions closer to the UAS campus.

Second, to investigate whether and, if so, how the timing of the treatment lag—and thus the persistence of the treatment effect over time—affects our results, we repeat our estimations with treatment lags varying between zero and ten years in Appendix C. Again, the overall pattern of effects remains unchanged. Interestingly, the positive UAS effect on patent quality in regions without coexisting research institutions turns significant after a lag of five years, indicating a more long-term effect. One potential explanation for this finding is that establishing processes and cooperative projects leading to higher-quality innovations takes longer time. Moreover, for patent quality, the interaction of UASs with Max Planck institutes turns insignificant after seven years, whereas the interaction with Fraunhofer institutes turns significant.

In essence, the robustness checks confirm our main finding of UASs and their complementarities with other research institutions positively influencing innovation, but also suggest heterogeneity in the underlying mechanisms. The robustness checks provide evidence that UASs yield more locally concentrated effects, indicating that spatial proximity to potential cooperation partners is important for UASs to increase innovation. Moreover, we find more long-term effects—particularly for patent quality—than specified in our main estimation parameters, implying that UASs take some time to produce high-quality innovations. Dynamic patterns in the complementarities also appear to arise over time, as the long-term positive interaction with Fraunhofer institutes for patent quality indicates. Such patterns might result from movements of faculty or changing cooperation partners. Therefore, future research needs to explore the exact mechanisms behind the complementarities between UASs and other research institutions.

7. Conclusion

This paper analyses the innovation effect of UASs in Germany and focuses in particular on the role of knowledge complementarities between UASs and other institutions coexisting in a diverse research landscape. We exploit variation in the location and timing of UAS openings in Germany to compare the development of patenting activities in municipalities with a UAS and those without one. We analyse whether the effect of UASs varies within regions in which other types of research institutions coexist to assess complementarities between these institutions and UASs. To econometrically deal with endogeneity in the location and timing decisions of the UAS openings, we (1) estimate FE models to account for time-invariant regional characteristics, (2) include year FE to capture time trends common to all regions and (3) include a novel proxy for regional economic activity based on daytime satellite data to control for time-variant regional economic factors potentially determining UAS campus locations.

Our results show that UASs have a statistically significant positive effect on patent quantity (i.e., the number of patent applications in a municipality) and on patent quality (i.e, the average number of patent citations within three years after publication). This finding is in line with previous results for UASs in Switzerland (Pfister et al., 2021). In addition, the German context allows us to show that the UAS effect is substantially larger when the scientific knowledge of other research institutions is available in a UAS region. These results confirm the view that stand-alone UASs can contribute to regional innovation, but, most importantly, our results point out that strong complementarity effects arise on top of the stand-alone UAS effect: UASs can better develop their full potential when they have the opportunity to draw upon different types of research knowledge available in the surrounding research landscape. This finding suggests that UASs have a particularly pronounced role in technology transfer and in the adaptation of basic R&D to practical needs. In light of the growing complexity of technological innovation, such regional knowledge complementarities can be a key competitive advantage for producing innovation (Balland and Rigby, 2017).

More specifically, we find strong knowledge complementarities between UASs and three other types of research institutions—Max Planck institutes (which perform basic research), Fraunhofer institutes (which perform applied research) and Helmholtz institutes (which perform a mixture of both). Complementarities between UASs and these three types of institutions lead to an additional increase in patent quantity. For patent quality, we find the same overall pattern of the effects. However, stand-alone UASs do not significantly increase patent quality and complementarities arise only between UASs and Max Planck institutes. To increase patent quality, Max Planck institutes thus provide a particularly valuable source of complementary basic research knowledge. This finding suggests that UASs can contribute to more radical innovations in regions where they can draw upon strong basic research knowledge, such as that of Max Planck institutes, and to more incremental innovations in other regions.

This paper offers a novel solution to estimating the causal innovation effect of UASs, providing evidence for a positive UAS effect and for the existence of regional complementarities between UASs and other types of research institutions. Although our methodological approach using region FE, year FE and satellite data as a proxy for regional economic activity to account for potential endogeneity in UAS campus locations might have certain limitations, we argue that by using daytime satellite imagery that provides information on six different types of surfaces related to economic activity, the proxy yields at least a more detailed insight into the overall structure of a region than, for example, simple measures of gross domestic product. Combining the proxy for regional economic activity with region FE and year FE provides at least a better solution to the problem of endogenously determined UAS campus openings than was possible with previously available data.

Future research needs to shed light on the exact mechanisms behind the regional complementarities between UASs and other types of research institutions. More specifically, the question of whether knowledge complementarities arise through direct linkages between the different types of research institutions or through indirect linkages remains open. Direct linkages, such as movements of faculty, co-patenting and co-publication, exchanges between researchers at workshops or conferences, or cooperative research projects, can lead to the knowledge complementarities we find in this paper. In addition, indirect linkages, such as local firms' drawing on the knowledge of regional research institutions by hiring their graduates, can contribute to such complementarities (e.g., Lehnert et al., 2020; Schultheiss et al., 2019). Future research needs to further explore these potential mechanisms to achieve a better understanding of how knowledge complementarities between UASs and

other research institutions arise in a diverse research landscape.

References

- Abramovsky, L., Harrison, R., Simpson, H., 2007. University research and the location of business R&D. The Economic Journal 117, C114–C141. doi:10.1111/j.1468-0297.2007.02038.x.
- Adams, J.D., Chiang, E.P., Jensen, J.L., 2003. The influence of federal laboratory R&D on industrial research. The Review of Economics and Statistics 85, 1003–1020. doi:10.1162/003465303772815899.
- Andrews, M., 2020. How do institutions of higher education affect local invention? Evidence from the establishment uf U.S. colleges. Available at SSRN: http://dx.doi.org/10.2139/ ssrn.3072565.
- Audretsch, D.B., Feldman, M.P., 1996. R&D spillovers and the geography of innovation and production. American Economic Review 86, 630–640.
- Audretsch, D.B., Hülsbeck, M., Lehmann, E.E., 2012. Regional competitiveness, university spillovers, and entrepreneurial activity. Small Business Economics 39, 587–601. doi:10. 1007/s11187-011-9332-9.
- Autant-Bernard, C., 2001. Science and knowledge flows: Evidence from the French case. Research Policy 30, 1069–1078. doi:10.1016/S0048-7333(00)00131-1.
- Balland, P.A., Rigby, D., 2017. The geography of complex knowledge. Economic Geography 93, 1–23. doi:10.1080/00130095.2016.1205947.
- Becker, W., Dietz, J., 2004. R&D cooperation and innovation activities of firms: Evidence for the German manufacturing industry. Research Policy 33, 209–223. doi:10.1016/j. respol.2003.07.003.
- Beise, M., Stahl, H., 1999. Public research and industrial innovations in Germany. Research Policy 28, 397–422. doi:10.1016/S0048-7333(98)00126-7.
- Berkes, E., Gaetani, R., 2020. The geography of unconventional innovation. The Economic Journal forthcoming. doi:10.1093/ej/ueaa111.
- Brill, A., 2017. Von der "Blauen Liste" zur gesamtdeutschen Wissenschaftsorganisation. Dokserver des Zentrums für Zeithistorische Forschung Potsdam, Potsdam. doi:10.14765/ zzf.dok.1.1115.
- Broekel, T., Graf, H., 2012. Public research intensity and the structure of German R&D networks: A comparison of 10 technologies. Economics of Innovation and New Technology 21, 345–372. doi:10.1080/10438599.2011.582704.
- Buschle, N., Haider, C., 2016. Private Hochschulen in Deutschland. Technical Report. WISTA 1, Statistisches Bundesamt.
- Castelló-Climent, A., Chaudhary, L., Mukhopadhyay, A., 2018. Higher education and prosperity: From catholic missionaries to luminosity in India. The Economic Journal 128, 3039–3075. doi:10.1111/ecoj.12551.

- Che, Y., Zhang, L., 2018. Human capital, technology adoption and firm performance: Impacts of China's higher education expansion in the late 1990s. The Economic Journal 128, 2282–2320. doi:10.1111/ecoj.12524.
- Chen, X., Nordhaus, W.D., 2011. Using luminosity data as a proxy for economic statistics. Proceedings of the National Academy of Sciences 108, 8589–8594. doi:10.1073/pnas.1017031108.
- Comin, D., Licht, G., Pellens, M., Schubert, T., 2019. Do companies benefit from public research organizations? The impact of the Fraunhofer Society in Germany. Technical Report. ZEW Discussion Paper No. 19-006, Leibniz Centre for European Economic Research.
- Commission of Experts for Research and Innovation (EFI), 2010. Research, innovation and technological performance in Germany EFI report 2010. EFI, Berlin.
- Cowan, R., Zinovyeva, N., 2013. University effects on regional innovation. Research Policy 42, 788–800. doi:10.1016/j.respol.2012.10.001.
- Demircioglu, M.A., Audretsch, D.B., 2019. Public sector innovation: The effect of universities. The Journal of Technology Transfer 44, 596–614. doi:10.1007/s10961-017-9636-2.
- Enders, J., 2010. Hochschulen und Fachhochschulen, in: Simon, D., Knie, A., Hornbostel, S. (Eds.), Handbuch Wissenschaftspolitik. VS Verlag für Sozialwissenschaften, Wiesbaden, pp. 443–456.
- Eyles, A., Machin, S., 2019. The introduction of academy schools to England's education. Journal of the European Economic Association 17, 1107–1146. doi:10.1093/jeea/jvy 021.
- Federal Ministry of Education and Research (BMBF), 2004. Die Fachhochschulen in Deutschland. BMBF, Bonn, Berlin.
- Federal Ministry of Education and Research (BMBF), 2018a. Bundesbericht Forschung und Innovation 2018: Forschungs- und innovationspolitische Ziele und Maßnahmen. BMBF, Berlin.
- Federal Ministry of Education and Research (BMBF), 2018b. Organisationen und Einrichtungen in Forschung und Wissenschaft: Organisationenband Bundesbericht Forschung und Innovation 2018. BMBF, Berlin.
- Feldman, M.P., Florida, R., 1994. The geographic sources of innovation: Technological infrastructure and product innovation in the United States. Annals of the Association of American Geographers 84, 210–219. doi:10.1111/j.1467-8306.1994.tb01735.x.
- Fritsch, M., Schwirten, C., 1999. Enterprise-university co-operation and the role of public research institutions in regional innovation systems. Industry and Innovation 6, 69–83. doi:10.1080/1366271990000005.
- Fritsch, M., Slavtchev, V., 2007. Universities and innovation in space. Industry and Innovation 14, 201–218. doi:10.1080/13662710701253466.

- Graf, H., 2011. Gatekeepers in regional networks of innovators. Cambridge Journal of Economics 35, 173–198. doi:10.1093/cje/beq001.
- Hachmeister, C.D., Duong, S., Roessler, I., 2015. Forschung an Fachhochschulen aus der Innen- und Außenperspektive: Rolle der Forschung, Art und Umfang. CHE Arbeitspapier Nr. 181. CHE Arbeitspapier Nr. 181, Centrum für Hochschulentwicklung (CHE). Gütersloh.
- Helmers, C., Overman, H.G., 2017. My precious! The location and diffusion of scientific research: Evidence from the synchrotron diamond light source. The Economic Journal 127, 2006–2040. doi:10.1111/ecoj.12387.
- Henderson, J.V., Storeygard, A., Weil, D.N., 2012. Measuring economic growth from outer space. American Economic Review 102, 994–1028. doi:10.1257/aer.102.2.994.
- Hinz, M., Gothe, K., von Polier, X., Wagner, B., Wimmer, M., Falke, U., 2016. Forschung an Fachhochschulen: Wie aus praxisorientierter Forschung Produkte und Dienstleistungen werden. BMBF, Bonn.
- Hoffmann, D., Trischler, H., 2015. Die Helmholtz-Gemeinschaft in historischer Perspektive, in: Mlynek, J., Bittner, A. (Eds.), 20 Jahre Helmholtz-Gemeinschaft. Hermann von Helmholtz-Gemeinschaft Deutscher Forschungszentren e.V., Bonn, pp. 9–47.
- Hohn, H.W., 2010. Außeruniversitäre Forschungseinrichtungen, in: Simon, D., Knie, A., Hornbostel, S. (Eds.), Handbuch Wissenschaftspolitik. VS Verlag für Sozialwissenschaften, Wiesbaden, pp. 457–477.
- Holl, A., Peters, B., Rammer, C., 2020. Local knowledge spillovers and innovation persistence of firms. ZEW Discussion Paper No. 20-005. ZEW Discussion Paper No. 20-005, Leibniz Centre for European Economic Research. Mannheim. doi:10.2139/ss rn.3543416.
- Intarakumnerd, P., Goto, A., 2018. Role of public research institutes in national innovation systems in industrialized countries: The cases of Fraunhofer, NIST, CSIRO, AIST, and ITRI. Research Policy 47, 1309–1320. doi:10.1016/j.respol.2018.04.011.
- Jaffe, A.B., 1989. Real effects of academic research. American Economic Review 79, 957–970.
- Jäger, S., 2013. The returns to higher education: Evidence from university openings in Germany. Mimeo.
- Kamhöfer, D.A., Schmitz, H., Westphal, M., 2019. Heterogeneity in marginal non-monetary returns to higher education. Journal of the European Economic Association 17, 205–244. doi:10.1093/jeea/jvx058.
- Key, O., Seeßelberg, C., 2012. Diplom war gestern: Das neue Studium an den Fachhochschulen. Beiträge zur Hochschulforschung 34, 42–65.
- Kulicke, M., Stahlecker, T., 2004. Forschungslandkarte Fachhochschulen: Potenzialstudie. BMBF, Bonn, Berlin.

- Lackner, H., 2019. Die Stellung der Fachhochschulen im deutschen Hochschulsystem, in: Cai, J., Lackner, H. (Eds.), Jahrbuch Angewandte Hochschulbildung 2016: Deutschchinesische Perspektiven und Diskurse. Springer VS, Wiesbaden, pp. 133–157. doi:10. 1007/978-3-658-22422-6.
- Lehnert, P., Niederberger, M., Backes-Gellner, U., Bettinger, E., 2021. Proxying economic activity with daytime satellite imagery: Filling data gaps across time and space. Technical Report. Swiss Leading House "Economics of Education" Working Paper No. 165.
- Lehnert, P., Pfister, C., Backes-Gellner, U., 2020. Employment of R&D personnel after an educational supply shock: Effects of the introduction of Universities of Applied Sciences in Switzerland. Labour Economics 66, 101883. doi:10.1016/j.labeco.2020.101883.
- Leten, B., Landoni, P., Van Looy, B., 2014. Science or graduates: How do firms benefit from the proximity of universities? Research Policy 43, 1398–1412. doi:10.1016/j.re spol.2014.03.005.
- Leyden, D.P., Menter, M., 2018. The legacy and promise of Vannevar Bush: Rethinking the model of innovation and the role of public policy. Economics of Innovation and New Technology 27, 225–242. doi:10.1080/10438599.2017.1329189.
- Meurer, P., 2018. Zugang von FH-/HAW-Absolventinnen und -Absolventen zur Promotion, kooperative Promotionen und Promotionsrecht. Technical Report. Studien zum deutschen Innovationssystem No. 16-2018, Commission of Experts for Research and Innovation.
- Petzina, D., 2005. Der Bologna-Prozess in Deutschland: Stand und Perspektiven. Beiträge zur Hochschulforschung 27, 18–36.
- Pfister, C., Koomen, M., Harhoff, D., Backes-Gellner, U., 2021. Regional innovation effects of applied research institutions. Research Policy 50, 104197. doi:10.1016/j.respol.2021.104197.
- Popp, D., 2017. From science to technology: The value of knowledge from different energy research institutions. Research Policy 46, 1580–1594. doi:10.1016/j.respol.2017.07. 011.
- Robin, S., Schubert, T., 2013. Cooperation with public research institutions and success in innovation: Evidence from France and Germany. Research Policy 42, 149–166. doi:10.1016/j.respol.2012.06.002.
- Schlegel, T., Pfister, C., Harhoff, D., Backes-Gellner, U., 2021. Innovation effects of universities of applied sciences: An assessment of regional heterogeneity. The Journal of Technology Transfer forthcoming. doi:10.1007/s10961-020-09839-w.
- Schultheiss, T., Pfister, C., Backes-Gellner, U., Gnehm, A.S., 2019. Tertiary education expansion and task demand: Does a rising tide lift all boats? Technical Report. Swiss Leading House "Economics of Education" Working Paper No. 154.
- Toivanen, O., Väänänen, L., 2016. Education and invention. The Review of Economics and Statistics 98, 382–396. doi:10.1162/REST_a_00520.
- Wissenschaftsrat, 2002. Empfehlungen zur Entwicklung der Fachhochschulen. Drs. 5102/02, Wissenschaftsrat, Berlin.

Appendices

Appendix A. Distribution of Campus and Institute Locations



Fig. A1. Distribution of STEM campus and STEM institute locations in 2015

Notes: Authors' illustration with geodata from the BKG, data on HEIs from the German Rectors' Conference, data on higher education institutions from BMBF (2018b) and self-collected data on HEIs and PROs.

Appendix B. FE Estimation Results on Patent Quantity and Patent Quality with Varying Treatment Radii



Fig. B1. FE estimation results on patent quantity with varying treatment radii

Notes: Authors' calculations based on patent data from the EPO, data on surface groups from Lehnert et al. (2021), data on HEIs from the German Rectors' Conference, data on PROs from BMBF (2018b) and self-collected data on HEIs and PROs. Figure plots coefficients and their 95-percent confidence intervals from separate FE estimations for each treatment radius. With the exception of the varying treatment radii, the estimations are similar to those in column 7 of Table 1.



Fig. B2. FE estimation results on patent quality with varying treatment radii

Notes: Authors' calculations based on patent data from the EPO, data on surface groups from Lehnert et al. (2021), data on HEIs from the German Rectors' Conference, data on PROs from BMBF (2018b) and self-collected data on HEIs and PROs. Figure plots coefficients and their 95-percent confidence intervals from separate FE estimations for each treatment radius. With the exception of the varying treatment radii, the estimations are similar to those in column 7 of Table 2.

Appendix C. FE Estimation Results on Patent Quantity and Patent Quality with Varying Treatment Lags



Fig. C1. FE estimation results on patent quantity with varying treatment lags

Notes: Authors' calculations based on patent data from the EPO, data on surface groups from Lehnert et al. (2021), data on HEIs from the German Rectors' Conference, data on PROs from BMBF (2018b) and self-collected data on HEIs and PROs. Figure plots coefficients and their 95-percent confidence intervals from separate FE estimations for each treatment radius. With the exception of the varying treatment lag, the estimations are similar to those in column 7 of Table 1.



Fig. C2. FE estimation results on patent quality with varying treatment lags

Notes: Authors' calculations based on patent data from the EPO, data on surface groups from Lehnert et al. (2021), data on HEIs from the German Rectors' Conference, data on PROs from BMBF (2018b) and self-collected data on HEIs and PROs. Figure plots coefficients and their 95-percent confidence intervals from separate FE estimations for each treatment radius. With the exception of the varying treatment lags, the estimations are similar to those in column 7 of Table 2.

Dep. var.:							
ln(PQUAN + 1)	(1)	(2)	(3)	(4)	(5)	(9)	(2)
$UAS_{i,t-3}$	0.111^{***}	0.079^{***}	0.080^{***}	0.107^{***}	0.099^{***}	0.081^{***}	0.058^{***}
	(0.006)	(0.007)	(0.007)	(0.007)	(0.007)	(0.007)	(0.008)
$UAS_{i,t-3} \times UNI_i$		0.095^{***}					0.024
		(0.013)					(0.015)
$UAS_{i,t-3} \times MaxPlanck_i$			0.150^{***}				0.111^{***}
			(0.016)				(0.017)
$UAS_{i,t-3} \times Leibniz_i$				0.051^{**}			-0.049^{**}
				(0.023)			(0.023)
$UAS_{i,t-3} \times Helmholtz_i$					0.151^{***}		0.064^{***}
					(0.024)		(0.025)
$UAS_{i,t-3} \times Fraunhofer_i$						0.165^{***}	0.112^{***}
						(0.017)	(0.019)
Municipalities	11,266	11,266	11,266	11,266	11,266	11,266	11,266
N	376, 305	376, 305	376, 305	376,305	376, 305	376, 305	376, 305
R^2 (within)	0.123	0.124	0.125	0.123	0.124	0.125	0.126
R^2 (between)	0.034	0.045	0.075	0.038	0.046	0.063	0.090
R^2 (overall)	0.053	0.058	0.072	0.054	0.059	0.066	0.079

Appendix D. Results without Surface Groups

Dep. var.:							
$ln(PQUAL_{cit}+1)$	(1)	(2)	(3)	(4)	(5)	(9)	(2)
$UAS_{i,t-3}$	0.023^{***}	0.017^{***}	0.016^{***}	0.023^{***}	0.022^{***}	0.019^{***}	0.014^{***}
	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)
$UAS_{i,t-3} \times UNI_i$		0.017^{***}					0.004
		(0.005)					(0.005)
$UAS_{i,t-3} \times MaxPlanck_i$			0.036^{***}				0.035^{***}
			(0.006)				(0.006)
$UAS_{i,t-3} \times Leibniz_i$				0.004			-0.017^{**}
				(0.008)			(0.008)
$UAS_{i,t-3} \times Helmholtz_i$					0.015^{*}		-0.003
					(0.008)		(0.00)
$UAS_{i,t-3} \times Fraunhofer_i$						0.025^{***}	0.015^{**}
						(0.006)	(0.007)
Municipalities	11,266	11,266	11,266	11,266	11,266	11,266	11,266
Ν	376, 305	376, 305	376, 305	376, 305	376, 305	376, 305	376, 305
R^2 (within)	0.034	0.035	0.035	0.034	0.035	0.035	0.035
R^2 (between)	0.003	0.001	0.002	0.003	0.002	0.000	0.004
R^2 (overall)	0.022	0.023	0.027	0.022	0.023	0.024	0.028

Table D2. FE estimation results on patent quality (citations) (25-km travel-distance radius, 3-y. lag, without surface