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Influencing scientists' collaboration and productivity patterns through new institutions: University research centers and scientific and technical human capital☆

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ABSTRACT

This paper analyzes the effect of university research centers on the productivity and collaboration patterns of university faculty. University research centers are an important subject for policy analysis insofar that they have become the predominant policy response to scientific and technical demands that have not been met by extant institutions, including academic departments, private firms, and government laboratories. Specifically, these centers aim to organize researchers from across the disciplines and sectors which, collectively as a research unit, possess the scientific and technical capacity relevant to scientific and technical goals of the sponsoring agencies. In this paper, we measure the productivity and collaboration patterns of university researchers affiliated with a relatively large-scale and "mature" university research center to discern the effects, if any, of the center mechanism on individual scientists and engineers. Based on an analysis of longitudinal bibliometric data, the results from this case study demonstrate affiliation with the center to be effective at enhancing overall productivity as well as at facilitating cross-discipline, cross-sector, and inter-institutional productivity and collaborations.

1. Introduction

University research centers and comparable arrangements constitute a key mechanism for the strategic use of science and technology for solving problems (Stokols et al., 2008). Policy scholars' interest in university research centers began after the establishment in the 1980s of the large-scale (in terms of budget and length of funding cycle) centers programs sponsored by the National Science Foundation, most notably the Engineering Research Centers (ERC) program. The original program was authorized by the US Congress in 1985, with an initial budget of $10 million (Bozeman and Boardman, 2004).[1] The creation of the ERC program was an explicit policy response to the perceived economic competitiveness crisis with Japan (Suh, 1986) and was one of a number of mechanisms employed during those years to help bridge the divides between university research, education, and industrial innovation.[2] Today, the ERC program is still considered in such a strategic light, having recently been modified in response to current concerns over US competitiveness (Lal et al., 2007). Accordingly, assessments of university research centers and their effects,

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[1] Currently NSF allocates more than $250 million (or about 6% of the NSF total budget) per year to different center programs, and the ERC program is among the biggest, costing more than $50 million per year. Twenty-seven ERCs have graduated from the program, of which currently there are 16 who have become self-sustaining. There are 15 ERCs that are currently within their 10 year funding cycles. Depending on size and nature of research, ERCs may receive annual funding of up to $4 million per year. The ERC program is considered a success by NSF, and recently (November 2008) 5 third generation ERCs were launched, with a budget of $92 million for the next five years.

[2] Other policy mechanisms during the 1980s aimed at facilitating technology transfer to industry included Cooperative Research and Development Agreements wherein (per the Stevenson–Wydler Act) government laboratories and private companies could collaborate to commercialize technology developed with federal monies and the Bayh–Dole Act affording universities intellectual property control over their inventions (see Dai et al., 2001). Bozeman and Boardman (2003) and Corley et al. (2006) argue that the advent of "multipurpose, multidiscipline university research centers" (including NSF ERCs) constitutes a chief policy mechanism for facilitating technology transfer to industry.

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including but not limited to ERCs, have focused predominantly on the benefits afforded industry partners, including the conduct of applied and commercially relevant research (Gray et al., 2001) and access to upstream modes of knowledge and to students for hire upon graduation (Feller et al., 2002).

Few studies have addressed the publication patterns of center-affiliated university faculty. This is surprising for a number of reasons. First, the predominant mode of knowledge dissemination for university faculty is publishing, and aggregate statistics on scientific output generally are considered valuable for assessing the rate and quality of scientific production (van Raan, 1996), including for assessment of R&D organizations (Geisler, 1994).[3] Changes in the publication patterns of scientists, particularly ones triggered (whether deliberately or not) by new institutions, are of great interest to science policy makers (National Academy of Science, 2007; Stokols et al., 2008). Second, the primary operationalization of research collaboration in science and technology policy analysis and research evaluation is co-authorship (e.g., Katz and Martin, 1997). As university research centers are policy tools for fostering collaborative networks that create cross-disciplinary and cross-sector synergies to further a field of research and development (Boardman and Corley, 2008), one would expect bibliometric study of university research centers and their scientists, especially regarding center scientists' publications that are co-authored across institutional, disciplinary, and sectoral boundaries.

Perhaps one reason there has been so little study of the publishing patterns of university research centers and their scientists is that the manner in which centers may affect individual publishing activities is not sufficiently clear. On one hand, many researchers choose to affiliate with centers to increase their publishing productivity (among other motivations, see Landry and Amara, 1998). In affiliating with a center, researchers may augment their "scientific and technical human capital" (Bozeman et al., 2001) and, with it, their respective abilities to conduct research of different types and publish the results. On the other hand, many centers are focused on modes of knowledge production that may not be as conducive to publishing as to other forms of dissemination, such as informal knowledge exchange (Ponomariov and Boardman, 2008) and patenting (Dietz and Bozeman, 2005). Moreover, the problem of "additionality" (Georghiou and Roessner, 2000) is omnipresent in the evaluation of policy mechanisms like university research centers. An essential but thorny evaluation question is precisely the extent to which changes in publication patterns may be attributed to the operations of university research centers, versus alternative explanations.

The purpose of this paper is to assess the effect of affiliating with a "mature" university research center – the Mid-America Earthquake (MAE) Center, an ERC established in 1997 and headquartered at the University of Illinois at Urbana-Champaign – on the publication patterns of the faculty affiliated with this center. The MAE Center provides an excellent opportunity for bibliometric analysis given that it has reached successfully the conclusion of its funding cycle with the NSF (ten years, with a review and renewal at 5 years) and therefore has had the maximum time (at least under the auspices of the ERC program) to have an effect on the university faculty working there. Another reason the MAE Center provides a particularly good case for developing a better understanding of how the center mechanism may affect the publishing patterns of university faculty is that the MAE Center is part of what many consider in the ERC program to be the flagship university research centers program in the US and abroad.[4]

Thus, as a singular case study, the MAE Center is of significant "instrumental" value (Stake, 1995; Yin, 2003) insofar that the knowledge produced by an examination of how this center has altered the publication patterns and rates of its affiliated faculty can inform policy and management decision making for centers and centers programs more broadly. There are currently thousands of research centers on American campuses to date, and centers and centers programs have become the hallmark of national- and regional-level science and technology policies in most developed countries. While a single case like the MAE Center will not allow for broad conclusions regarding the general effects of the center mechanism, it can be instrumental in developing policies and management strategies for centers and centers programs insofar that so little is known about how centers alter the knowledge production patterns and rates of university faculty.

In this paper, we assess changes in the publishing of university faculty once they affiliate with the MAE Center, using longitudinal data from before and after the faculty joined the center (the analysis is based on scientists' complete publication histories). We combine bibliometric and survey data[5] to assess publishing patterns in a number of ways that speak directly to the primary goals of centers like the MAE Center and instrumentally to centers programs like the ERC program: cross-discipline, cross-sector, and inter-institutional research collaborations. We operationalize collaborations as publications authored conjointly by university faculty and other same-university researchers, researchers in industry, and at other universities as well as number of collaborators of different type.[6]

In addition to the collaboration goals of centers, we also use the MAE Center case to assess the effect of center affiliation on the productivity of university faculty. Therefore, the longitudinal analysis also includes overall yearly publication rates. This additional focus is important for addressing the extent to which center affiliation detracts from or enhances traditional academic behaviors and outputs, which has been an ongoing debate regarding not just university research centers with industry-related missions but also regarding other policies and institutions aimed at facilitating university–industry interactions (see Slaughter and Rhoades, 1996). While this case study is not general enough to resolve the debate, it constitutes one of the first direct empirical tests of the claim that centers detract from traditional modes of dissemination by university faculty.

The perspective that guides our analysis is the scientific and technical human capital perspective (Bozeman et al., 2001), which emphasizes individual-level research capacity and how it may be affected by professional linkages and network ties, including but not limited to linkages and ties made by way of affiliation with a university research center. Given the general purpose of government centers programs to facilitate collaboration (Boardman and Corley, 2008) and to develop research capacity that is different from that developed in traditional academic departments (Bozeman and Boardman, 2004; Ikenberry and Friedman, 1972), and given that we

[3] While many centers employ researchers who are not employed on the tenure track in an academic department, it is a requirement of most NSF centers programs, including the ERC program that center researchers hold tenured or tenure track appointments in academic departments (Bozeman and Boardman, 2003).

[4] The ERC program is considered the advent of multidiscipline university–industry centers and has served as archetype for numerous subsequent centers programs in the US, South Korea, and Ireland (Bozeman and Boardman, 2004).

[5] From a survey administered to MAE faculty as a part of the external evaluation of the center in 2006.

[6] While this study is in the tradition of most prior study of research collaboration by focusing on co-authorship (Katz and Martin, 1997), other studies operationalize research collaboration using survey responses focused on self-reports of time allocation (Bozeman and Corley, 2004) insofar that not all collaboration, especially that between university and industry scientists, result in publications.

focus on collaboration patterns and publication rates that are not standard practice for academics (e.g., papers authored conjointly with industry researchers), the scientific and technical human capital approach is appropriate for the current analysis.[7]

The next section provides a brief case description of the institutional composition of the MAE Center over time, demonstrating that, since the ERC's establishment in 1997, its participant base has been comprised consistently of researchers with divergent disciplinary backgrounds working at numerous universities or in private companies. Such a description is prerequisite to presenting the scientific and technical human capital (S&T human capital) framework we propose in the next section, which includes hypotheses regarding the impact of affiliation with the MAE Center on individual publishing patterns and rates. The following section describes the data and methods and includes discussion of how our research design accounts for all of the key threats to internal validity. After presentation of the empirical results, which show affiliation with the MAE Center to influence both the patterns (e.g., university–industry, interdisciplinary) and rates of publishing by university faculty, we conclude with a discussion of the policy and management implications of these findings, as well as directions for future research.

2. The "institutional composition" of the MAE Center[8]

University research centers like the MAE Center are designed to achieve scientific and technical goals by including in the center fold participants and stakeholders from divergent contexts and backgrounds who collectively possess the scientific capacity (e.g., knowledge, skills, and resources) appropriate for achieving those goals.[9] Accordingly, a brief description of the "institutional composition" of the MAE Center is in order, specifically of the universities, academic disciplines, and private firms that have contributed personnel and other resources to the center over time. After describing the institutional composition of the MAE Center from the perspective of universities, academic disciplines, and industry, we discuss some center- and program-level mechanisms and structures implemented by center management and program officials to facilitate cross-institution interactions.

2.1. University composition

The MAE Center is comprised of faculty from 8 universities (see Table 1). The university composition of the center has not changed over time—these core universities have been active throughout the 10 years of operation of the center (though the number of faculty from each university has fluctuated slightly, e.g., in cases when new faculty join the center). Also, scientists from other universities also regularly collaborate with MAE Center-affiliated researchers (although their home universities are not necessarily a part of the center).

Table 1 lists the MAE Center universities and total number of personnel that each university contributes to the center as of 2006. Six of the universities are categorized as universities with very high research intensity (Carnegie Foundation for the Advancement of Teaching, 2004), based on the number of doctorates awarded and R&D funding, with the exceptions of the University of Puerto Rico, Mayaguez and the University of Memphis. In terms of personnel, the MAE Center's home institution nearly doubles the personnel contribution of any other university.

2.2. Disciplinary composition

MAE Center faculty[10] come from numerous disciplinary backgrounds, including seismology, geotechnical engineering, civil engineering, information technology, public policy, geography, and computer science.[11] Correspondingly, multidisciplinarity is evident in the organization and management of the center's research. Specifically, the MAE Center organizes its research using three divisions or research thrusts—Engineering Engines, Information Technology, and Social Sciences. These thrusts are integrated by the consequence based engineering framework that guides the overall research priorities of the center and faculty routinely interact and collaborate across thrust areas.

A majority of faculty on the research projects come from civil engineering (46%), about a quarter come from the geophysical sciences (25%), with the rest coming from the social and computer sciences. This disciplinary composition is also reflected in the total peer-reviewed journal output of the center-affiliated faculty. Looking at the subject categories[12] with more than one paper under which center-affiliated faculty publish their work (approximately the top 30 subject categories), reveals that 59% of the publications are under civil engineering-related subject categories, about 20% are under subject categories relating to geophysical sciences, 6% under information technology-related subject categories, and 13% under social science-related subject categories.

2.3. Industry composition

All ERCs are required to incorporate private companies and other non-academic stakeholders into their research and educational activities. The approach most common across ERCs is the "membership model" whereby the centers solicit private companies to "join" the center by paying annual dues in exchange for access to center research and personnel (Lal et al., 2007).

The industry/stakeholder composition of the center is diverse and includes a wide range of actors with interests in managing or mitigating the consequences of earthquakes and in earthquake engineering: government agencies, utility companies, engineering firms, and infrastructure owners. Finally, in addition to the membership mechanism, private sector companies may also interact with the MAE Center as "customers", i.e., purchase access to center products and services, or enter contract research agreements on an individual basis.

[7] Boardman (2009) compares alternate perspectives of research collaboration, including the resource-based, institutional, and scientific and technical human capital views. While he acknowledges conceptual overlap among the perspectives, he argues that the latter view is most appropriate for explaining institutional arrangements intended to facilitate new behaviors and outcomes. This is discussed further below.

[8] Here we provide a brief description of the institutional composition of the MAE center. Such a description is important for understanding the context to which university faculty who are affiliated with the center are exposed. We address the potential mechanism with which this context operates to affect publication patterns in the following section on scientific and technical human capital (Bozeman et al., 2001). We do not provide background on the ERC program beyond that provided in the introduction (see Suh, 1986 and Bozeman and Boardman, 2004 for histories of the inception and evolution of the ERC program, respectively).

[9] The mission of the MAE Center is to create new knowledge and methodologies for the field of hazard loss assessment and consequence-based risk management.

[10] Faculty who participate in ERCs and comparable university research centers do so on a voluntary basis (Boardman and Bozeman, 2007) and typically are recruited at the proposal phase. Some centers may distinguish between "core faculty" (i.e. the group that actually wrote and submitted the proposal for the center, and "affiliated faculty" (i.e. faculty who may affiliate with the center at different points in time, as is the case with many of the MAE faculty. Centers typically draw on faculty from the universities they are located in, thus the "recruitment process is" not typically a formal one.

[11] See http://mae.ce.uiuc.edu/faculty/index.html. Viewed on 05/05/08.

[12] Standard headings under which publications and journals are classified in the WOS database. Please see the data and methods section for more detailed explanation.

Table 1
Universities participating in the MAE Center.

University name	Carnegie classification	Number of faculty and staff (2006)
University Illinois at Urbana Champaign (MAE Center Headquarter)	Research, very high	44
Georgia Institute of Technology	Research, very high	19
Texas A&M University	Research, very high	10
University of Memphis	Research, high	25
University of Michigan	Research, very high	1
University of Puerto Rico, Mayaguez Campus	Masters	6
University of Texas, Austin	Research, very high	1
Washington University	Research, very high	6
Total		112

Note: The faculty counts include postdocs and research staff who are not included in the bibliometric analysis presented in the current study. Graduate students are not included.

2.4. Facilitating interactions and collaboration

2.4.1. Mechanisms at the center level

It is clear that the MAE Center is influenced by participants and stakeholders from multiple institutions—from multiple universities as well as spanning across disciplinary and sectoral boundaries. But interactions and collaborations do not necessarily occur just by putting people in the same room with one another (though when mutual interests become apparent, collaborations can occur, see Melin (2000b)). While many of the participants and stakeholders described above are co-located, many are not. To ensure that the MAE Center facilitates cross-sector, cross-discipline, and multi-university interactions – some but not all of which may result in co-authored (or any) publications – the center provides its affiliated faculty, industry partners, and other stakeholders and participants with various resources and opportunities to interact. For instance, to facilitate interactions among scientists from different disciplines and universities, the MAE Center has populated the ranks of its research thrusts with scientists from multiple disciplines and institutions. In addition, the MAE Center holds an annual meeting as well as weekly video conferences for all institutions involved.

Among the various ways in which inter-institutional interactions are catalyzed by the MAE Center, perhaps the most explicit are the mechanisms for facilitating interactions with external stakeholders, including industry. The center has a management unit called Industry Collaboration, Outreach, and Technology Transfer (referred to internally as "ICOTT") to facilitate access by industry partners and other external stakeholders to the center's faculty and research results. The MAE Center also has an external consultant group called the Stakeholder Advisory Board (SAB), which is organized to provide the opportunity for industry, government, and non-profit entities to collaborate with the center and to access to center faculty and resources. As mentioned earlier (Table 2), some common types of stakeholders that have been involved with SAB include private sector insurance and utility companies, engineering and design services firms, and building and infrastructure owners, as well as public sector organizations such as transportation and mission agencies (e.g., USGS, NOAA). Other mechanisms for external access and participation include software programs to help stakeholders perform analysis in earthquake engineering related topics and also seminars to enhance public awareness of earthquake related matters (MAE, 2005).

2.4.2. Mechanisms at the program level

Though the ERC program leaves considerable managerial flexibility to the MAE Center, it has specific expectations (for all ERCs, not just the MAE Center) regarding the key components and mechanisms of the center that additionally may help to ensure interactions and collaboration across institutions and sectors. One example is the requirement that center management articulate a strategic plan for achieving the knowledge and technology goals of the center. Importantly, the strategic plan is not the research proposal, nor is it focused on explicating the knowledge and technology goals per se, but rather it is intended to articulate the organizational structures (e.g., research thrusts, vertical oversight and management layers) and personnel and resource flows (e.g., projects, timeline) required to achieve the knowledge and technology goals. These plans become the managerial "blueprint" of the center for coordinating and fostering collaboration among center participants within and across universities, industry, and government. Another mechanism implemented at the program level is for project selection and funds allocations. Though the practice may vary across ERCs, a common requirement is that, unlike with individual investigator grants, center-affiliated faculty members do not have complete control over their research resources. To receive center support (either through a proportion of their salary or through resources for their research), faculty must commit to projects consistent with a particular focus area or thrust within the center.

3. Center affiliation as scientific and technical human capital

Having described the institutional composition of the MAE Center and the structures and processes it has in place to facilitate collaboration among its multiple participants, it becomes imperative to explain how such an environment may influence the publication productivity and patterns of the MAE Center-affiliated university faculty. To guide our thinking about the effects of affiliation with the MAE Center on individual-level research collaboration and productivity, we draw conceptually from the S&T human capital perspective, which has guided a number of recent inquiries into university-based research collaboration and production (Boardman and Corley, 2008; Bozeman and Corley, 2004; Bozeman, et al., 2001; Dietz and Bozeman, 2005; Gaughan and Robin, 2004; Lin and Bozeman, 2006).

One of the fundamental steps in designing inter-organizational collaborations like the MAE Center is the identification and recruitment of participants who, by working together, may achieve the goals of the collaboration (Agranoff and McGuire, 2001). As described in the above section, the MAE Center has recruited researchers and participants from industry, government, multiple universities, as well as from multiple scientific and engineering disciplines, who together are working to develop integrated approaches for minimizing the consequences of future earthquakes across hazard-prone regions in the US and elsewhere. Participants in centers like the MAE Center are usually selected due to the S&T human capital they possess, which has been defined as "the sum of an individual researcher's professional network ties, technical knowledge and skills, and resources broadly defined" (Bozeman, et al., 2001, p. 636).

The overarching premise of the S&T human capital perspective is that *social capital begets human capital*. Upon joining a center, one's individual S&T human capital "constitution" may be enhanced by

Table 2
Industry/stakeholder composition of the MAE Center.

SAB members	Sector/industry	Practitioner group	Sector/industry
Federal Highway Administration	Government agency	ABS Group, Inc.	Engineering firm
Illinois Emergency Management Agency	Government agency	American Family Insurance	Insurance firm
Marriott International	Private sector infrastructure owner	American Institute of Steel Construction	Private Sector interest group
NOAA Coastal Services Center	Government agency	American Re-Insurance Company	Insurance firm
Pacific Gas and Electric	Private utility company	Aon Corporation	Insurance firm
Skidmore, Owings and Merrill	Engineering firm	Bowman, Barrett and Associates, Inc.	Engineering firm
The World Bank		Brick Industry Association	Private sector interest group
		Construction Technology Laboratories, Inc.	Engineering firm
		Earthquake Hazards Solutions	Engineering firm
		Federal Highway Administration	Government agency
		Geomatrix Consultants, Inc.	Engineering firm
		IBHS	Private research entity
		Kinemetrics, Inc.	Engineering firm
		Risk Management Solutions, Inc	Insurance firm
		Servdrup Civil, Inc.	Engineering firm
		Siebold Sydow Elfanbaum	Engineering firm
		State Farm Insurance	Insurance firm
		US Army CERL	Government research laboratory
		Willmer Engineering, Inc	Engineering firm

other center participants and also by access to center resources, given that a new participant is exposed by way of center affiliation to collaborators and resources that he or she did not have access to prior to joining the center. In other words, the concept of S&T human capital helps to explain how researchers continue over time and beyond their formal training (e.g., usually after completing a doctoral program) to enhance their research capacities, not only by gaining access to resources but also by learning.

Specifically, after they have achieved their doctorates, academic researchers continue to expand their research capacities, or *human capital*, as they progress through their careers. Though some of this capacity development may occur through outlets such as journals and perhaps also via additional training and development, because these researchers are at the forefronts of their fields, much of this development also occurs as they expand their *social capital* by making connections, formal and informal, to collaborators both within and outside of their fields and professions. These connections (e.g., with researchers within and outside their fields, with industry and government researchers) may enhance their abilities by facilitating the transfer of both formal and tacit knowledge, thus enhancing not only what they know, but additionally how they approach scientific and technical problems analytically (e.g., cognitively) and operationally (e.g., discrete skill or craft).

Thus, the overarching premise of this paper is that university research centers constitute organizational reservoirs of S&T human capital – based on the knowledge, skills, abilities, and resources (broadly defined) of the participants to which faculty gain access by affiliating with the center and by which these faculty may enhance their own research capacities. A more specific premise of this paper is that center-enhanced research capacities for individual faculty will be evident behaviorally, including but not limited to publication patterns (e.g., co-authorship between university and industry researchers) and rates (e.g., quantity of publications per annum). Given that a university research center is an organization with a particular combination of resources and relationships (one shaped by a center's mission and goals), the enhancement of the S&T human capital of affiliated researchers should not be random, but rather should correspond to the goals of the center. For example, a scientist joining a center conducting multidisciplinary research will be more likely to collaborate with researchers from other disciplines after joining the center than before, because the resources that the center offers (in this case the faculty themselves) provide such an opportunity for capacity development and scientific production (to which the new center researcher may not have been privy before joining the center).

Of course, there are numerous alternate perspectives of scientific production and research collaboration (Melin, 2000a). For instance, the resource-based view of collaboration and productivity (Van Rijnsoever et al., 2008), if applied explicitly here, would posit essentially the same expectations as the S&T human capital perspective-increased publication activity after affiliation with the MAE Center than before.[13] However, the S&T human capital perspective does not preclude the resource-based view (Boardman, 2009). The two perspectives are complementary: *social capital* is a *resource* that faculty use to develop *research capacities (or human capital)* and increase and alter productivity. The S&T human capital perspective is emphasized here because it is more direct in its accounting for the nature of the center affiliation "treatment" by specifying the types of resources (e.g., social capital, such as industry collaborators) that enable not only increased productivity, but also specific types of collaboration and production patterns (e.g., co-authorship with industry) that are relatively "non-standard" for academia (Ikenberry and Friedman, 1972), based on the participants in the center. This is not to say that motivation does not play an important role – it certainly does – but rather just that professional linkages and network ties such as those available in the MAE Center are instrumental for harnessing resource-motivated faculty towards particular types of collaboration and productivity.

3.1. Hypotheses: center affiliation and publishing productivity rates

Accordingly, we expect that the "institutional composition" of the MAE Center presented above (in Section 2) to be reflected by the publication patterns of MAE Center faculty. Due to its participant base in academia and industry across multiple academic disciplines, and also due to its mechanisms to facilitate interactions between those actors, MAE Center affiliation should see higher individual-level rates of papers co-authored across universities, disciplines, and sectors than occurred before affiliation. Further, publishing productivity rates may be increased due to the exposure to and in all probability the use of additional resources (e.g., funds, students, equipment, and support staff) that MAE Center affiliation constitutes. Specifically:

[13] Though, this is not always the case. Boardman (2009) suggests that the resource-based and S&T human capital perspectives of research collaboration may diverge, based on the qualitative nature of the dependent construct.

H1. Center affiliation positively affects faculty publication productivity. Specifically, the publication output of faculty is higher in the years after they affiliate with the MAE Center than in the years before they affiliated with the center.

H2. Center affiliation positively influences the extent to which affiliated scientists collaborate. Specifically, faculty has more co-authors during the years they are affiliated with the MAE Center than during the years they are not affiliated.

These hypotheses rely on the idea of S&T human capital, albeit in a general way when compared to the hypotheses below regarding boundary-spanning co-authored papers (see Section 3.2.). Here the general rationale is that the more resources and collaborators a researcher has, the more productive will that researcher become. Since MAE Center affiliation in all likelihood increases a faculty member's access to both collaborators and resources, we expect her to publish more, and with more co-authors, after joining the center than before. There is some empirical precedent using this reasoning. For example, Dietz and Bozeman (2005) demonstrate that scientists with former career experience in the private sector publish more than scientists who are career academics (having never worked in the private sector or outside academia) because of the access to new social networks and resources afforded by their private sector work experience.

Isolating the impact of research policies like boundary-spanning centers on scientific productivity and professional network development is a typical challenge when assessing the effects of specific policies, like the MAE Center, on scientific productivity (Georghiou and Roessner, 2000). However, the structure and content of the data used in the bibliometric analysis for this study helps to isolate the impact of affiliation with the MAE Center.[14]

Another challenge to positing and demonstrating a positive relationship between publication productivity and MAE Center affiliation is that ERCs have organizational goals other than producing publications (e.g., applied research, technology transfer, educational and community outreach). However, while the overarching mission of the ERC program is to transform the engineering research and education by rendering both more relevant to industry, the core mission of the MAE Center remains furthering understanding of earthquake engineering. Accordingly, ERCs like the MAE Center do not necessarily supplant fundamental knowledge dissemination activities (such as publishing) with alternate activities (such as applied research), but rather such institutional arrangements alter the properties of conventional outputs like published papers (e.g., by way of industry participation in writing papers, see below) in addition to seeing university faculty participate in less conventional (for academe) activities like applied research and transfer.[15] Moreover, given that researchers affiliated with ERCs are required to hold primary appointments that are tenured or tenure-track in academic departments, – which continue to value publishing above all else in tenure and promotion decisions, despite the changing roles of the professoriate (Arreola et al., 2003) – some have reported increased publication productivity as an incentive to join institutional arrangements like the MAE Center (Landry and Amara, 1998).

3.2. Hypotheses: center affiliation and boundary-spanning publishing productivity

There are a number of observations about the MAE Center that suggest affiliation would see an increase in university researchers' "boundary spanning" (Aldrich and Herker, 1977; Meyer and Rowan, 1977) collaborations—with industry and across academic disciplines and universities. First, as the institutional composition of the MAE Center indicates, the center has nearly 40 private and government stakeholders as paying members of the center and the core faculty has training in multiple academic disciplines and is spread across 8 universities in 6 US states and one unincorporated US territory (Puerto Rico). Second, many federally funded centers programs, including ERCs like the MAE Center, require centers to articulate processes and engage in activities for facilitating faculty interactions and for transferring center-produced knowledge and technology to industry clients and partners (Bozeman and Boardman, 2004). Last, it is clear that the MAE Center expects its faculty to collaborate with one another and with industry, having implemented organizational structures and mechanisms designed explicitly for facilitating such collaborations (e.g., weekly video conferences, annual meetings, ICOTT—see the section on institutional composition above). Thus:

H3. Center affiliation positively affects faculty collaboration with industry. Specifically, faculty co-author more papers with industry during the years they are affiliated with the MAE Center than during the years they are not affiliated.

H4. Center affiliation positively affects faculty the interdisciplinarity of faculty research. Specifically, faculty publications fall under more subject categories during the years they are affiliated with the MAE Center than during the years they are not affiliated.

H5. Center affiliation positively affects the extent of cross-institutional collaborations of affiliated scientists. Specifically, faculty collaborate with co-authors from more institutions during the years they are affiliated with the center than in the years they are not affiliated.

These hypotheses rely on the idea of S&T human capital in a more specific way when compared to the hypotheses above regarding publication productivity rates (see Section 3.1.). Per the social capital component of the S&T human capital perspective outlined above, the probability of university researchers who are affiliated with boundary-spanning centers co-authoring papers with researchers in industry, in different fields, and/or at other universities is likely higher after joining the center than before, even if affiliated faculty have a history of working with a diverse set of researchers (Lee and Bozeman, 2005). Per the human capital component of the S&T human capital perspective, upon joining a research center, faculty members interact and collaborate with one another insofar that no single center scientist can alone meet the scientific and technical goals of their center (Boardman and Corley, 2008). Accordingly, the "composition" of MAE Center faculty members' collaborative behaviors, measured here as co-authored publications, should correlate positively with center-level features, including ties to industry, other universities, and multiple academic departments (Dietz and Bozeman, 2005).

Across the hypotheses for this study, we are proposing that the MAE Center serves, among other functions, as a professional networking portal providing university faculty with access to opportunities with "outside" researchers—rendering among other outcomes co-authored papers among these researchers. Though

[14] First, we use longitudinal bibliometric data, capturing the entire publication histories of the affiliated faculty – both before and after they had become affiliated with the MAE. Second, every faculty member is observed at multiple points before and after the affiliation, thus improving the reliability of any evidence of differential patterns. Third, the set of faculty in question is very diverse, featuring faculty from different disciplines, different institutions, different educational and career paths, and of different cohorts, so the errors in such a diverse set are likely to be uncorrelated rather than show similar underlying trends, for instance owing to being at similar career stages. Last, supplementary variables derived from survey data allow us to control for multiple factors that correlate with collaboration and productivity, such as academic rank, age, gender, among other factors.

[15] Extending this argument, there is consistent evidence of a positive relationship between relatively commercial modes of dissemination such as patenting and "open" modes like publishing. See Baldini (2008) for a review of this literature.

center scientists may have engaged in, for instance, joint research with industry absent the center, center affiliation might no less trigger additional collaborations that would not have materialized because of the costs involved in identifying and establishing additional contacts with industry researchers with common research interests. Center affiliation increases an individual's S&T human capital to the extent that they can "afford" more readily these additional collaborations, which may result in co-authored papers.[16] The degree to which our research design and methodology account for alternate explanations (besides center affiliation) of center faculty affiliates' bibliometric productivity is discussed in the next section.

4. Data and design

4.1. Data

Longitudinal bibliometric data – the primary data source used for this study – are well positioned to address the above hypotheses. We downloaded the comprehensive publication histories for all tenured tenure-track faculty affiliated with the MAE Center from the Institute for Scientific Information's Web of Science database (WOS). WOS is the most comprehensive scientific database, indexing articles in peer-reviewed journals from all scientific fields.

Databases such as the WOS allow the operationalization and construction of multiple indicators characterizing scientific activity, and particularly the behaviors of interest in this paper. The primary record in such databases is the individual publication (journal article). However, every publication is then characterized by a wealth of properties, such as author names, author affiliations and addresses, journal, number of times the paper has been cited, the references cited by the paper, the subject categories the paper has been published under, etc. This structure of the bibliometric data allows aggregation and analysis at many different levels and thus the construction of multiple indicators. In the present paper, the data are aggregated and analyzed at the level of the individual faculty member, on a yearly basis.

The first step in the data collection effort was the retrieval of publication records for fifty-one MAE Center-affiliated faculty members who were either tenured or tenure-track. We based this retrieval on a list of affiliated faculty provided by the MAE leadership in 2006. Postdocs, research staff, graduate students or government scientists were excluded from the analysis because their publication paths are either too short (or non-existent, e.g., for some research staff) and not directly comparable to those of tenured or tenure track faculty and because these groups are of peripheral interest for the current study. Eliminating those records resulted in the 51 tenured or tenure track scientists who are the subject of the analysis that follow.

Having the complete publication histories of MAE Center-affiliated faculty – i.e., observing the publication behavior of faculty over multiple years – allows discerning if affiliation with the MAE Center has had any effect on the publication and collaboration patterns of faculty over time. Because faculty became affiliated with the MAE Center at different times and at different stages in their careers, comparing these patterns in the years before and after center affiliation makes it possible to discern whether MAE Center affiliation has independent direct effects on publication activity. Thus, the longitudinal analysis offers a robust assessment of the effects of MAE Center affiliation on scholarly productivity patterns and rates versus, for example, cross-sectional before-and-after comparisons (this is discussed in detail in Section 4.2. below).

A total of 1142 publication records for the fifty-one faculty were collected. Retrieval of these publication records was complemented by reference to the CVs of the affiliated faculty. CVs assisted in the data collection process by (1) allowing verification of the publication data downloaded from WOS, and (2) by providing auxiliary information about the career path of faculty (e.g., timing of appointments, particularly obtaining "tenured" status) relevant to the bibliometric analysis. The first year of publication on record in the WOS database provided a reasonable date of the beginning of the researchers scholarly career (pre-MAE Center affiliation),[17] while the year after the year a scientists affiliated with the MAE Center, obtained from an online survey conducted in 2006 as a part of a 3-year evaluation of the center, served as the end of the pre-affiliation period and the beginning of the researchers affiliation with the center.[18]

The resulting data set is a panel data set containing observations of the same set of individuals across multiple years over the course of their careers, up until 2006.[19] During some of these years, faculty are affiliated with the center and during others they are not. Since there were 3 observations for which data were available only during their affiliation with the MAE Center,[20] they were dropped from the data set (because no before and after comparisons are possible for them). The resulting final panel data set consists of 777 observations (i.e., faculty-year records), of which 446 have at least one or more publication records (i.e., given that not all faculty publish in all years, 446 is the number of person-year records characterized with at least one publication). Based on the publication records for each year, it is possible to construct similar yearly variables, such as number of individuals with whom one has collaborated in a given year, number of collaborations with industry, etc. The average number of observations (i.e., years) per group (i.e., per respondent) is 16 with a minimum of 4 and a maximum of 21. The average number of years for which individuals are observed while affiliated with the MAE Center is 6, with a minimum of 2 and maximum of 10.

4.2. Design

The design for this study is a single group interrupted time-series quasi-experiment. This design is relatively strong in that it accounts for many of the common threats to internal validity,

[16] The precise way in which centers like the MAE Center may do this, for instance by creating "innovation spaces" (see the section on mechanisms for facilitating inter-institutional interactions above), is reviewed in a recent paper by Toker and Gray (2008).

[17] However, the earliest publication year is in WOS was 1987, at the time of the data collection. The records for a limited number of individuals with particularly long publication records are truncated at 1987. This does not pose problems for the primary goal of the analysis, since even with this cut off, it allows for up to 10 years of pre-MAE Center publication activity for such scientists.

[18] The present paper uses very limited subset of the variables retrieved in this survey. In addition to the "demographic" variables we use (such as rank, year of affiliation, university, year of doctoral degree, etc.), the survey asked MAE faculty to provide information on the nature of their involvement with the center, their collaborations in the center, their student related activities (e.g. mentoring), and their attitudes and perceptions of the type of interdisciplinary research at MAE. The survey was administered in August 2006, by means email invitation and reminders.

[19] The "start" of the presence of each faculty in the data set is the first year in which he or she has published. This is an arbitrary decision, made to facilitate clear comparisons in the publication patterns before and after the affiliation. Other scenarios are conceivable as well. For example, a junior scientist could start on a tenure-track position and not publish his first paper for several years into his new job, in which case it would be legitimate to have yearly observations for this individual even before his first publication. However, there is insufficient data to establish decision criteria for recognizing such scenarios. Moreover, from a practical point of view, the majority of the MAE Center-affiliated faculty are tenured, and all of them are employed in top-ranked research intensive universities where extended periods with no publications are unlikely, even for junior scientists.

[20] A typical scenario for such cases could be junior assistant professors who affiliated with MAE simultaneously with accepting their first tenure-track job.

including maturation, statistical regression, and testing (Campbell and Stanley, 1963).[21] The threats that are typically problematic for the design are instrumentation, mortality, and history. However, instrumentation is not a problem here, since the data are retrieved from a standardized publication database (i.e., WOS). Mortality is not an issue as well, because the study only covers faculty that were affiliated with the MAE Center in 2006. By collecting historical bibliometric data for this set of faculty, we ensure that no changes in the publication output and patterns can be explained by attrition, since the data consistently capture the publication behavior of the entire affiliated group, rather than of a group with individual members that dropped out.

The absence of a non-equivalent comparison group from the design makes history the most formidable challenge for establishing the internal validity of the findings below. For instance, it is conceivable that some historical event other than MAE Center affiliation could be the cause of changes in publication rates and patterns. However, several features of the data alleviate the history threat. First, the operationalization of MAE Center affiliation is not discrete, i.e., affiliation is not a single or one-shot "treatment" (i.e., a single exposure to the MAE Center), but rather a continuous experience. It is difficult to anticipate an alternative historical event that could as consistently influence the behaviors of affiliated faculty. But, we acknowledge that as one-shot treatments wane, so may wane the impact of university research centers on faculty affiliates.

A much stronger safeguard against the history threat present in the current design is that for each of the MAE Center faculty, center affiliation occurred at different points in time. Unlike typical assessments of treatments or interventions using a single-group time-series design, multiple historical events at different points in time rather than a singular historical event must be conceived as alternate explanations of faculty publishing patterns and productivity rates. Any consistent effect of MAE Center affiliation in the analysis below is much more easily attributed to center affiliation than to a series of unrelated historical events that coincide across individuals with center affiliation. Thus, the design used in this study, along with the time-variant nature of the intervention or treatment of MAE Center affiliation, approaches the "multiple-baseline" approach used in clinical trials, i.e., an interrupted time-series using data from multiple participants and staggering the intervention to occur at different times to alleviate the history threat to internal validity (Barlow and Hensen, 1984; Ferron and Scott, 2005).

5. Variables and method

5.1. Variables

After compiling all the faculty publications from the aforementioned database, these records were exported to the VantagePoint™ text-mining software, which is used for processing, extracting, and summarizing field-tagged textual data. After parsing and extracting the relevant variables, they were compiled into a standard spreadsheet data set. Table 3 provides the descriptive statistics for the set of 48 respondents in the panel.

The key independent variable of interest is "MAE Center affiliation." It is a dummy variable coded 1 if a respondent was affiliated with the MAE Center in a given year, zero otherwise. In the panel data set used here, this is a variable characterizing a particular year for a particular respondent. For example, if a respondent becomes affiliated with the MAE Center in 1999, all years from 2000 onwards will be coded 1 for this respondent, while all previous years will be coded zero. Thus, at the aggregate, this variable allows for assessment of the differences (if any) in the patterns and rates of bibliometric output of MAE Center-affiliated faculty in the set of years before and after they became affiliated with center. Information about the first year of affiliation with the MAE Center for each faculty member was retrieved from faculty responses to an online survey conducted in 2006.

Table 3
Descriptive statistics-tenured or tenure-track faculty in the bibliometric data set ($n = 48$).

Variable	Mean	Standard deviation	Range
Year of affiliation with the MAE Center	2000	3.1	1997–2005
Publications	19.1	17.3	2–71
Collaborators	30	56	2–427
Papers with industry collaborators	2.5	3.1	0–11
Distinct institutions collaborated with	12.8	9.8	1–43
Number of subject categories	24	17.1	3–68
Georgia Tech	20%	–	0–1
UIUC	34%	–	0–1
Social scientist	22%	–	0–1
Male	86%	–	0–1
Tenured before MAE Center affiliation	70%	–	0–1
Year of the PhD degree	1986	11.6	1954–2005

The above statistics describe the data at the level of individual faculty for all years combined.

The five hypotheses for this study (see Sections 3.1 and 3.2.) are tested on the basis of the five dependent constructs included in Table 4.

While the first four variables are self-explanatory from a behavioral point of view, it should be emphasized that additionally the dependent constructs operationalize the S&T human capital of MAE Center-affiliated faculty. Discussed above, the theory emphasizes individual researchers' accumulation of social capital – specifically heterogeneous linkages between researchers and institutional contexts – as an important mechanism for the enhancement of individual research capacity. Thus, the dependent constructs may be interpreted not only as productivity outcomes but additionally as measures of the social capital linkages of MAE Center-affiliated researchers that help to enhance individual research capacity, at least to the extent that the researchers may publish different kinds of papers after center affiliation than before. This is a critical point to our analysis insofar that while the independent construct is perhaps "blunt" by accounting for center affiliation dichotomously but not for variable levels of exposure to particular aspects of the MAE Center that we propose will enhance the S&T human capital of center affiliates (see Section 2 above), the dependent constructs are reflective of the specific types of social capital that faculty gain when they affiliate with the MAE Center (e.g., in terms of co-authorship patterns) and also of the human capital of MAE Center affiliates (e.g., in terms of publication productivity rates and publication subject matter).

Because there is not a universally accepted way to operationalize research interdisciplinarity (Porter and Cunningham, 2005), the dependent construct for publication interdisciplinarity requires explanation. The WOS database assigns journals to standard subject categories that allow for coherently classifying journals and papers into subject categories. These subject categories are not identical to "disciplines" in that they are more granular.[22] Overall, the set of

[21] The design is long-known (Campbell and Stanley, 1963) to be strong against these threats due to the multiple observations over time. Moreover, no matter the design, the testing threat does not apply to studies conducting bibliometric analysis.

[22] For example, the top subject categories under which MAE Center-affiliated faculty publish under are: Engineering, Civil; Construction & Building Technology; Engineering, Geological; Geochemistry & Geophysics; Geosciences, Multidisciplinary; Engineering, Mechanical; Materials Science, Multidisciplinary; Mechanics; Environmental Studies; Computer Science, Interdisciplinary Applications.

Table 4
Dependent constructs, per hypothesis.

Hypothesis	Dependent construct
H1. Center affiliation positively affects faculty publication productivity.	Publication productivity—number of publications published by scientist *j* in year *i*
H2. Center affiliation positively influences the extent to which affiliated scientists collaborate.	Collaboration activity—number of distinct co-authors with which scientist *j* has co-authored in year *i*
H3. Center affiliation positively affects faculty collaboration with industry.	Publication activity with industry—number of publications with industrial collaborators published by scientist *j* in year *i*
H4. Center affiliation positively affects faculty the interdisciplinarity of faculty research.	Interdisciplinarity of research—number of distinct subject categories under which scientist *j* published in year *i*
H5. Center affiliation positively affects the extent of cross-institutional collaborations of affiliated scientists.	Cross-institutional collaborations—number of distinct institutions with which scientist *j*'s co-authors are affiliated in year *i*

Table 5
Summary of the control variables.

Control variable	Summary
Social science	This variable is coded 1 if the faculty member is in one of the social sciences present in the center (e.g., sociology, public policy, geography), zero otherwise. This control is necessary simply because different scientific fields (e.g., engineering vs. social sciences) may have different publication and collaboration norms and practices. In addition, center affiliation may have differential impacts on faculty from the engineering disciplines and sciences and on faculty from the social sciences. Related, we also include an interaction term between "Social science" and "Affiliated with MAE Center in year *i*" to control for such possible differential impacts
Male	This variable is coded 1 if the faculty member is male, zero otherwise. Including gender as a control variable is warranted by the ongoing policy debate if women face different constraints and challenges than men in academia, particularly in their publication and collaboration productivity.
Tenured before MAE Center affiliation	This variable is coded 1 if the faculty member had attained the rank of Associate or Full Professor prior to the year he or she affiliated with the MAE Center, zero otherwise. Including this variable is related to the possibility of divergent constraints and expectations faced by junior and senior faculty affiliated with ERCs and particularly in their traditional home academic departments. For example, given that the goals of the ERCs may diverge from, or be broader than, the goals of the traditional academic departments, it is important to assess the impact of affiliating with the center on junior faculty, particularly in regard to productivity—a primary criterion for tenure. Related, we introduce an interaction term between "Tenured before affiliating with the MAE Center" and "affiliated with MAE Center in year *i*." to capture the differential impact, if any, that affiliation with the MAE Center has on junior and senior faculty.
Year of the PhD degree	Including the year of the PhD degree helps to indirectly control for possible cohort effects in collaboration and productivity patterns. For example, scientists who have received their degrees more recently may have been socialized in behaviors more accepting of industrial collaborations versus scientists who have received their degrees in earlier periods when such concerns have not been as visible in academia.
Publication productivity (lagged 1 year)	One's own lagged publication productivity is an important control variable for at least two reasons: (1) Past productivity is one of the best predictors of future productivity and (2) Collaborative behaviors and opportunities are to a large extent contingent on publication productivity (for example, more productive scientists are more likely to be both more capable of collaborating with more colleagues and of being more sought after as collaborators).
MAE Center core institution	This variable is coded 1 if the faculty member works in one of the two dominant universities in the center (University of Illinois at Urbana Champaign—the center headquarter) and Georgia Tech. This control is warranted insofar in a multi-institution center there are inevitably some inequities in terms of contributions and access to resources.

subject categories under which a scientist publishes can be used as a proxy for the diversity of topics on which that scientist works. Subject categories have been used in prior research, with various degrees of sophistication, as indicators of the extent of interdisciplinarity (Porter et al., 2007). In the analysis below we use the number of distinct subject categories under which MAE Center-affiliated faculty publish every year to assess whether the affiliation has resulted in a body of work with a broader scope and generality, as would be evidenced by publishing in more subject categories. Specifically, an increase in the number of subject categories can be interpreted as a proxy increase in interdisciplinarity, since interdisciplinary research may be considered relevant to a broader range of topics and disciplines than perhaps work falling under but a single subject category (Porter et al., 2007). Although this measure is simple and arguably crude, it is accepted as an at least partially valid indicator of interdisciplinarity, and since it is reliable and consistent, in a time series design the marginal changes would still convey relevant information such as the degree to which the scope of the scholarly work produced by the center scientists expands over time (or not).

Several control variables are also used in the estimation, including variables for discipline, gender, tenure status, cohort, past bibliometric productivity, and whether the respondent is employed at one of the two core universities for the MAE Center or at an affiliated university. Table 5 summarizes the controls.

5.2. Method

Since the analysis is based on panel data, and since all of the dependent variables are count variables, we analyze this data using random-effects Poisson regressions[23] using the xtPoisson procedure in the Stata 9.0 statistical package. This procedure is both flexible and robust and has been used previously in longitudinal analysis of bibliometric data (e.g., Zucker et al., 2007).

[23] We also separately estimate fixed model regressions (not presented here). The effect of MAE affiliation in those models is virtually identical to the random effect model in magnitude and significance; since all other independent variables are time invariant (and are therefore dropped in a fixed effect model) we only present the random effect models.

Table 6
Effects of MAE Center affiliation on faculty productivity and collaborations. Poisson regression ($n = 777$).

	(1) Number of publications in year *i*	(2) Number of collaborators in year *i*	(3) Number of publications with industrial collaborators in year *i*	(4) Number of subject categories published under in year *i*	(5) Number of institutions collaborated with in year *i*
Affiliated with MAE Center in year *i*	0.423***	0.492***	1.433**	0.259*	0.628***
	(0.160)	(0.125)	(0.588)	(0.157)	(0.122)
Number of publications in year *i–1*	0.062***	0.032**	0.171***	0.042**	0.031**
	(0.019)	(0.015)	(0.050)	(0.017)	(0.014)
Year of the PhD degree	−0.005	0.051***	0.021	0.009*	0.043***
	(0.013)	(0.017)	(0.024)	(0.005)	(0.014)
Affiliated with a core MAE Center institution	0.035	−0.994***	0.241	0.123	−0.502**
	(0.213)	(0.278)	(0.414)	(0.088)	(0.222)
Tenured before MAE Center affiliation	0.364	1.715***	1.027	0.273*	1.032***
	(0.312)	(0.370)	(0.714)	(0.164)	(0.304)
Interaction term: *tenured before MAE affiliated with MAE in year i*	−0.334*	−0.315**	−0.762	−0.095	−0.112
	(0.180)	(0.143)	(0.625)	(0.174)	(0.137)
Social science	−0.374	−0.806**	−0.984	0.150	−0.244
	(0.260)	(0.348)	(0.668)	(0.118)	(0.270)
Interaction term: *social science affiliated with MAE in year i*	−0.036	0.046	−0.904	−0.229	−0.186
	(0.198)	(0.163)	(0.913)	(0.165)	(0.147)
Male	0.028	0.472	−0.422	0.332**	0.388
	(0.326)	(0.437)	(0.705)	(0.145)	(0.347)
Constant	10.206	−100.962***	−44.701	−18.296*	−85.236***
	(26.523)	(33.717)	(48.096)	(10.712)	(27.011)
Observations	729	398	729	398	398
Number of id	48	48	48	48	48

Note: Models 2, 4 and 5 include years with publications only. Standard errors are in parentheses.
* Significant at 10%.
** Significant at 5%.
*** Significant at 1%.

The general form of the population averaged xtPoisson model is expressed as follows:

$$\log(\lambda_{ij}) = \beta_{0j} + \sum_{k=1}^{K} \beta_k X_{kij} \quad (1)$$

$$\beta_{0j} = \eta_{00} + \alpha_{0j} \quad (2)$$

Combining the two equations above:

$$\log(\lambda_{ij}) = \eta_{00} + \sum_{k=1}^{K} \beta_k X_{kij} + \alpha_{0j} \quad (3)$$

where λ_{ij} is the expected number of events occurred for the *j*th individual at the *i*th year, β_{0j} indicates an intercept that is random for each individual, and α_{0j} is an error term for the *j*th individual.

6. Regression results

Table 6 summarizes the results of five regressions – one per hypothesis – investigating the effect of MAE Center affiliation on publication productivity (Model 1), overall collaboration activity[24] (Model 2), publication activity with industry (Model 3), interdisciplinarity of research (Model 4), and cross-institutional collaboration (Model 5). Since the dependent variables in each of the models are derived from publication data, the number of observations in Models 2, 4 and 5 are smaller than in Models 1 and 3, as the variables are meaningful only if the individual has also published in a given year. For example, while having zero publications in a given year is analytically meaningful, having zero collaborators in a year in which one has not published has no substantive meaning in this particular data set unless a more 'aggressive' approach, based on much looser behavioral interpretation of the data derived from publication records is adopted.[25]

Across all models, the estimated impacts from center affiliation support the proposed hypotheses. During the years in which faculty are affiliated with the MAE Center, they are more likely to be more productive (Model 1), to produce more papers with industrial collaborators (Model 2), to collaborate more with colleagues and with other institutions (Models 3 and 4), and to produce more interdisciplinary research (Model 5). Exponentiating the raw Poisson coefficients (which in their raw form represent the logs of the expected counts of the dependent variable) allows for easier interpretation, as it produces estimates of incidence rate ratios, i.e., the extent to which the "rate" of events (e.g., publications, collaborators, etc,) changes proportionately as a function of the independent variables. Thus, we can observe that affiliation with the MAE Center increases the rate of publication incidence by a factor of 1.5, the number of collaborators by a factor of 1.6, the publications with industry by a factor of 3.7, the cross-institutional collaborations by a factor of 2, and the number of subject categories by a factor of 1.4. Rank ordering these estimates suggests that MAE Center affiliation has had the strongest effect on likelihood of collaborating with industry, followed by cross-institutional

[24] A standard caveat in assessing collaboration activity my means of bibliometric data is that the assumption that co-author on a paper necessarily are collaborators is not always valid, especially in scientific or engineering papers that may involve tens of co-authors, who, although contributing to the same project, do not necessarily even know each other. Nevertheless, at the aggregate, using co-authorships as proxy for collaboration is an adequate and widely accepted method in bibliometric analysis.

[25] Of course, one could have zero collaborators in a given years because he/she published only single-authored papers. Such records are considered in the analysis.

collaborations and collaborators in general, and publication productivity.

In addition, there are notable results regarding the effect of affiliation with the MAE Center on junior and senior faculty. In particular, faculty who were tenured before affiliating with the MAE Center have, on average, more collaborators and are more actively engaged in cross-institutional collaborations in all years relative to faculty who were not tenured before joining the MAE Center. This is to be expected given that senior faculty are more likely to already have more extensive and well-developed professional and collaborative networks.

Further, while all faculty on average benefit from affiliation with the MAE Center, junior faculty have experienced greater gains than senior faculty in terms of publication productivity and collaborations, as evidenced by the interaction term between tenured status prior to affiliation and MAE Center affiliation in a given year. In other words, the overall positive effect of center affiliation on productivity and overall collaboration is stronger for junior faculty. This finding suggests that the center-related activities are not a distraction for junior faculty, e.g., by taking their time and effort away from pursuing tenure in their departments, but rather that center affiliation enhances the ability to publish and to find new collaborators, and the effect is even stronger than for more senior faculty. These results imply that university research centers are able to offer not only various collaboration opportunities resulting from the affiliation, but also other resources and opportunities that seem to be particularly helpful for enhancing junior faculty's productivity.

A caveat in interpreting this mechanism is that the differential impact on junior and senior faculty may also be the result of junior faculty being less selective than their senior colleagues in the type of publication projects and collaborations they undertake in the center. However, this behavior is likely of junior faculty in any context, thus it does not diminish the relevance of the finding that the positive effect of center affiliation is stronger for junior faculty (in terms of gains in publication productivity and collaborations).

The results also suggest that the senior faculty affiliated with the MAE Center (e.g., tenured before affiliating with the center) generally have broader research portfolios. This is not surprising given that senior scholars have had more opportunities to develop their interests and competencies that would enable them to pursue broader research portfolios and integrate broader range of topics in their research while junior faculty are perhaps more likely to "start out" in more specialized subject areas.

7. Discussion and conclusions

The results presented in this study suggest that affiliation with a university research center affects the behavior of affiliated faculty in ways consistent with the common emphases and goals in such center programs: increased productivity, collaboration (including with industry and with colleagues from other institutions), and interdisciplinarity. Though co-authorship and university-industry co-authorships are by now widespread and well-known phenomena (NSB 2008, Vol. 1, NSF-SRS 2004), the findings presented above are among the first to attribute these trends – albeit just for the specific case of the MAE Center – to institutional arrangements like university research centers.

Though access to opportunities and resources provided by the center has positively affected publication productivity overall, the strongest impact seems to be in the collaborative behaviors underlying this publication activity. This set of effects is important to emphasize, as it is precisely the *combination* of these effects that enhances the claim that university research centers represent mechanisms to influence the behavior of scientists towards ends deemed desirable by the sponsoring mission agencies. While these results are "positive" in terms of the direction of effect of MAE Center affiliation on faculty collaboration and productivity, it is important to note that we report these results agnostically. Whether the outcomes we find here constitute benefits (e.g., increased co-authorship) or costs (e.g., decreased research autonomy, "free rider" co-authorship) remains an open debate, one we are unable to engage with the data and design used for this study.

The mechanism for such effects was articulated through the lens of S&T human capital. Specifically, the overarching expectation of the study was that the effects of affiliation would be discernible in faculty affiliates' respective scientific activities, with the particular configuration of S&T human capital provided by the center being reflected in these activities. The findings support such a mechanism and suggest that the S&T human capital concept is not merely descriptive, but additionally is relevant for designing and evaluating policy mechanisms aimed at influencing scientists' behaviors and production. However, we acknowledge that the S&T human capital perspective draws heavily on alternate approaches to understanding research collaboration and scientific production (e.g., the resource-based view), and that multiple perspectives and levels of analysis must be considered when explaining the impacts of institutional arrangements like the MAE Center on university faculty behaviors and outputs.

To the extent that implications for broader policy can be drawn from a single case study, we feel the demonstration that the behaviors and production of scientists can be changed within relatively short spans of time instructive. Such a finding is notable in the context of scientific community, notorious for its adherence to its strong traditional norms of self-regulation and unrestrained intellectual freedom. While such norms and traditions are indeed rigid and resistant to change, the scientific community seems to respond to appropriately designed sets of incentives and constraints. University research centers, at least those similar to the MAE Center, may be such a set. While providing discernible incentives to scientists in way of enhancing their S&T human capital – e.g., access to grant funding, equipment and instrumentation, collaborators, graduate students, partnership opportunities with other institutions and with industry, the ability to work on large and complex projects beyond the reach of individual investigators (Boardman and Bozeman, 2007; Landry and Amara, 1998) – centers like the MAE Center seem to offer these incentives in a fashion commensurate with center and programmatic priorities to steer scientists towards utilizing center resources and opportunities in ways consistent with these priorities.

Future research on the effects of the center mechanism on the conduct of scientists will benefit from better data, for sets of centers, either for the same centers program or across programs for the same agency. Such research would be greatly facilitated by uniform requirements from the sponsoring agencies for collecting appropriately structured bibliometric data. Moreover, while bibliometric data have numerous advantages (e.g., they are standardized and therefore reliable), future research could benefit by pairing bibliometric approaches with other methods and data, such as qualitative and survey-based research, to further elaborate the mechanism suggested by the MAE Center case here. While there has been extensive case study of singular centers, there has not been multi-case comparison using both bibliometric and qualitative approaches.

Future research could also benefit by new research questions. An important issue that needs to be addressed relates to how durable or lasting are center effects. Though centers and centers programs attempt to facilitate lasting changes in how scientific and engineering education and research are conducted in the long term, the demonstration of relatively short term impacts (e.g., in this study, in external evaluations) tells very little about the sustainability of center impacts. Perhaps it is too early for this sort of assessment. But probably not. ERCs, like the MAE Center, date back to the mid-1980s, and there are other centers programs that date earlier than

ERCs. The challenge of course is that for many of these historic centers that are no longer under the auspices of their founding centers programs, data are scarce, which reinforces our concern that centers programs begin to approach data collection and storage more systematically. While we do not advocate the use of standardized performance measures and metrics across all centers, even within the same centers program, currently there is a dearth of information for systematically assessing the sustained impact (or lack thereof) of the predominant science and technology policy mechanism in the US and many countries in Europe and Asia.

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