

**CLIMBING ATOP THE SHOULDERS OF GIANTS:
THE IMPACT OF INSTITUTIONS ON CUMULATIVE RESEARCH***

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ABSTRACT

While cumulative knowledge production is central to growth, little empirical research investigates how institutions shape whether existing knowledge can be exploited to create new knowledge. This paper assesses the impact of a specific institution, a biological resource center, whose objective is to certify and disseminate knowledge. We disentangle the marginal impact of this institution on cumulative research from the impact of selection, in which the most important discoveries are endogenously linked to research-enhancing institutions. Exploiting exogenous shifts of biomaterials across institutional settings and employing a differences-in-differences approach, we find that effective institutions amplify the cumulative impact of individual scientific discoveries.

“If I have been able to see further, it was only because I stood on the shoulder of giants.”

Isaac Newton, 1676

At least since the development of scientific societies and related research institutions in the 17th century, the centrality of cumulative knowledge in scientific and technical advance has been recognized.¹ However, from the perspective of economic theory, knowledge accretion has been incorporated only recently, in models of endogenous economic growth [Aghion and Howitt, 1992; Romer, 1990; Grossman and Helpman, 1991; Jones, 1995] and step-by-step technical progress within industries [Scotchmer, 1991; Gallini and Scotchmer, 2002; Aghion et al., 2008]. In order to serve as a foundation for long-term growth, scientific research and technological progress must exert a positive intertemporal spillover; to avoid diminishing returns to research investments, research itself must “stand on the shoulders” of prior knowledge [Jones, 1995].

Though extremely insightful in deriving the implications of knowledge accumulation for related economic variables (such as the equilibrium growth rate or the incentives for innovation), these models do not articulate the conditions that facilitate knowledge accumulation. As Mokyr [2002] argues, the mere production of knowledge does not guarantee that others will be able to exploit it. Effective diffusion of knowledge across researchers and over time requires that individuals be aware of extant knowledge and pay the associated costs of access. Further, since any one researcher captures a small share of the benefit from the process of certifying knowledge and making it accessible, there may be a significant gap between the private and social returns associated with investments that contribute to the diffusion of scientific knowledge. Overall, the ability of a society to stand on the shoulders of giants depends not only on generating knowledge, but also on the quality of mechanisms for storing, certifying and accessing that knowledge.

Institutions and public policy are often suggested as central to the process of knowledge accumulation.² Social scientists face a considerable challenge, however, in assessing the extent to which any one institution influences the creation, maintenance, and extension of the “knowledge stock.” It is empirically difficult to isolate the intrinsic impact of a particular piece of knowledge from the impact of the institutions in which it is embedded, although the two are conceptually distinct. While we are interested in the *marginal* impact of an institution – the incremental

¹ Newton famously acknowledged the importance of cumulative research in a 1676 letter to rival Robert Hooke: “What Des-Cartes did was a good step. You have added much several ways, & especially in taking ye colours of thin plates unto philosophical consideration. If I have seen further it is by standing on ye sholders of Giants.”

² The role of institutions in scientific research is central to the sociology of science [Merton, 1973] and the “new” economics of science [Dasgupta and David, 1994]. The linkage between institutions and knowledge accumulation has long been emphasized in the economics of technical change [Bush, 1945; Nelson, 1959; Rosenberg, 1963, 1979; Nelson, 1993; David, 2001; Mokyr, 2002].

influence of that institution on knowledge accumulation (conditional on the nature and quality of knowledge associated with it), a *selection* effect may confound our analysis if knowledge of high intrinsic importance is endogenously embedded within “high-quality” institutions.

The main contribution of this paper is to provide direct statistical evidence of the marginal impact of a specific institution – biological resource centers (BRCs) – on knowledge accumulation. BRCs collect, certify, and distribute biological organisms, such as cell lines, microorganisms, and DNA material. The ability to exploit prior research in the life sciences depends on access to the cells, cultures, and specimens used in that research. Distinct among institutional arrangements for obtaining materials for research purposes, BRCs have the explicit objective of enhancing cumulative knowledge production through biomaterials preservation, certification, and circulation. Our analysis, therefore, evaluates whether the ability to access biomaterials through a BRC amplifies the impact of the scientific research that initially described those research materials.

Our approach extends citation analysis to investigate the impact of institutions on the dynamics of cumulative scientific discovery [Jaffe, et al., 1993; Griliches, 1998]. We exploit three aspects of our empirical setting to develop and implement a differences-in-differences estimate of the impact of BRCs on knowledge accretion. First, each material deposited in a BRC is associated with a journal article that describes its initial characterization and application. Second, for specific types of BRC deposits, there is a significant lag between the initial article and the date of its deposit into a BRC; in certain cases, materials associated with “special collections” were transferred exogenously from smaller collections into a major BRC for reasons unrelated to the extent of their use. Third, detailed bibliometric data for the BRC-linked articles, a sample of control articles, *and* all of the articles citing these original research articles allow us to capture variation in how knowledge diffuses in different economic and institutional contexts.

Our empirical analysis focuses on whether articles associated with materials exogenously shifted into a BRC receive a boost in citations after their deposit into the BRC, controlling for article-specific fixed effects and fixed effects for article age and calendar year. Our setting allows us to evaluate both models that include a control sample and models that rely exclusively on variation in the timing and date of the “treatment” of the deposit of the biomaterial into the BRC. Both approaches provide evidence for the marginal impact of BRCs on subsequent knowledge; the post-deposit citation boost is estimated to be between 57 percent and 135 percent across different

specifications. Empirical checks of our key identification assumptions reinforce our overall findings. We find that the marginal impact of BRC deposit is marginally higher for articles published in less prestigious journals and that the citation boost is concentrated in follow-on research articles involving more complex subject matter. Overall, the evidence suggests that, relative to alternative institutions, BRCs play a significant role in the accumulation of knowledge in the life sciences.

I. THE IMPACT OF RESEARCH-ENHANCING INSTITUTIONS ON THE ACCUMULATION OF KNOWLEDGE

The dynamic accumulation of knowledge has become a central issue to many areas of research. The diffusion of knowledge among researchers and across generations depends on institutions and policies that facilitate low-cost knowledge transfer. Institutions may lower the costs of access to useful knowledge by enhancing “the technology of access, the trustworthiness of the sources, and the total size of the [knowledge stock about natural phenomena and regularities]” [Mokyr, 2002, p. 8]. We describe economic institutions that promote the accumulation of knowledge through these mechanisms as *research-enhancing institutions*.

Over the past two decades, a significant body of research has investigated specific research-enhancing institutions, documenting the presence of (and recognizing the difficulties of estimating) knowledge spillovers [Griliches, 1990].³ This research often employs citations to academic papers or granted patents to estimate the influence of prior knowledge on current advances. For example, Jaffe et al. [1993; Henderson et al., 1998] examine whether university patents receive citations at a higher rate and with greater geographical scope than “control” patents drawn from similar geographic and technological areas. While this prior literature has established a close empirical association between research-enhancing institutions and the impact of scientific and technical knowledge (as reflected in higher rates of citations to papers and patents, respectively), this prior research has not been able to disentangle whether these institutions facilitate knowledge accumulation *per se* or whether they are simply linked to knowledge that has a higher intrinsic impact. In the terminology of the program-evaluation literature, these prior studies conflate the marginal impact of research-enhancing institutions with the selection effect of knowledge into research-enhancing institutions. For example, university patents may be highly

³ The “search for spillovers” includes studies of university policy [Mowery et al., 2001], IP policy [Sakakibara and Branstetter, 2001], R&D consortia [Irwin and Klenouw, 1996; Branstetter and Sakakibara, 2002], national laboratories [Jaffe and Lerner, 2001], venture capital [Kortum and Lerner, 2000], patent pools [Lerner and Tirole, 2004], scientific research networks [Powell, 1998; Rosenkopf and Tushman, 1998] and the role of science in technological search [Sorenson and Fleming, 2004].

cited (relative to a control group of patents generated by private-sector laboratories) because the research reflected in the patent is more fundamental or because the norms of disclosure and openness associated with a university amplify the diffusion of university-generated knowledge.

In addition to impacting the extent to which knowledge diffuses, institutions can influence the *types* of projects drawing on particular pieces of knowledge. For example, researchers who are pursuing more fundamental (or complex) breakthroughs and whose research is itself likely to receive a high level of scrutiny (e.g., by being published in a more prestigious journal) are more likely to draw upon knowledge that is embedded within research-enhancing institutions. The long-term impact of knowledge creation depends not only on its fundamental importance, but also on whether it is embedded in institutions that facilitate low-cost knowledge diffusion.

II. BRCs AND CUMULATIVE RESEARCH IN THE LIFE SCIENCES⁴

Compared with many other scientific and technological areas, research in the life sciences has developed dramatically in recent decades. While scientific opportunity is, of course, important, the life sciences have also benefited from their ability to address a number of the constraints that may otherwise limit step-by-step progress. A central challenge is the need to maintain the integrity of biomaterials and data while sharing these materials across researchers and over time. Though seemingly simple, problems associated with biomaterials fidelity have bedeviled the life sciences research community. In one of the most startling and widespread cases of contamination, Walter Nelson-Rees and his collaborators documented that dozens of cell lines widely used in the 1970s had been contaminated by a particularly strong cell line known as *HeLa* (named after the cervical cancer donor Henrietta Lacks). This finding shed doubt on decades of cancer research, including the work of Nobel laureates [Gold, 1986].⁵ Uncertainty about biomaterials fidelity can result in considerable research delays, as scientists must undertake substantial efforts to verify each of the materials they employ. Life sciences research productivity depends on the integrity of research materials and on researchers' confidence in these materials.

The problem of maintaining the integrity of research materials is not simply technological or scientific, but is driven by the economics of research incentives. Though a robust system for validating experimental research is in the interest of all scientists, individual researchers have few incentives to invest in replication and validation. Indeed, researchers may find it worthwhile to

⁴ See Stern [2004], Cypess [2003] and OECD [2001] for detailed discussion of the function, history, and policy analysis of BRCs.

⁵ Even with recent advances in verification procedures, some researchers argue that a substantial fraction of currently circulated cell lines are still misidentified [MacLeod et al., 1999; Masters, 2002; Nardone, 2007; Chatterjee, 2007].

limit scrutiny of their published results, at least in the short term. As the integrity of the scientific process is a public good, an institutional response is essential.

Several alternative institutional arrangements exist, including peer-to-peer networks, for-profit and proprietary culture collections, and biological resource centers. Peer-to-peer networks consist of informal exchanges among researchers and are dependent on research laboratories maintaining modest-sized culture collections and fulfilling requests for distribution on an *ad hoc* basis. In a pure peer-to-peer network, it may not be possible to require researchers to exchange materials and initial discoverers may be reluctant to offer access to those whose experiments could undermine the value of the initial work [Campbell et al., 2002; Walsh et al., 2005].⁶ The potential for authentication problems is substantial in peer-to-peer networks, as labs rarely possess leading-edge verification tools and rely on (poorly paid) assistants to circulate research materials.⁷ An alternative are proprietary collections, such as those maintained by major biopharmaceutical firms, and for-profit biomaterials distribution firms. Not surprisingly, each type of collection “cherry picks” a narrow range of materials (the vast majority of which have already been accessioned at a major BRC) and focuses on materials with low storage costs and near-term commercial rewards.

BRCs, in contrast, pursue the objective of enhancing scientific research productivity by providing access to standardized biological materials. The World Federation of Culture Collections lists more than 550 of these “living libraries,” whose members’ collections exceed 1.4 million organisms [WFCC, 2009].⁸ Most countries have national collections that rely principally on government financing, helping to ensure that materials are accessioned based on their long-term scientific potential rather than near-term commercial concerns. Smaller collections then serve specialized research communities. The single largest BRC is the US-based American Type Culture Collection (ATCC, the “Library of Congress for biological materials”), which maintains a library of more than a million materials, distributes more than a quarter of a million materials annually, is supported by a mix of public and private funding, and is governed by a board that includes eminent life science researchers (ATCC, 2009). Relative to alternative institutional

⁶ Peer-to-peer transactions require researchers to contract with the developer of a particular biomaterial. In some cases, negotiations over access require the recipient to offer co-authorship or another incentive or even a Materials Transfer Agreement or patent license. While such arrangements were rarely required for academic researchers during the bulk of our study period, the use of IP in academic science has become prevalent (and controversial) over the last decade [Heller and Eisenberg, 1998; Mowery and Ziedonis, 2007; Murray and Stern, 2007; Cohen and Walsh 2008; Murray, 2009; Murray, et al, 2009; Evans, 2004].

⁷ Informal brokers may emerge in peer-to-peer networks, facilitating transactions [Lamoreaux and Sokoloff, 1999; Gans and Stern, 2003]. However, brokers are limited by the extent of their personal networks, and, since it is difficult to verify who is responsible when shared materials become contaminated, the potential for a purely reputation-based system may be limited.

⁸ Life scientists and science policy analysts have emphasized the importance of BRCS in scientific progress and suggested that their importance has increased over the past 25 years [Hunter-Cevera, 1996; OECD, 2001; Smith, 2003; Stern, 2004].

arrangements, four distinctive attributes of BRCs may be associated with enhancing the accumulation of knowledge across research generations:

(1) *Certification*: Biomaterials authentication is one of the primary functions of BRCs. When accessioning materials into their collections (and periodically thereafter), BRCs subject materials to reviews and tests to verify their identity and biological viability. This contribution is especially significant in the life sciences. As the experiences of the HeLa contaminations of the 1970s and 1980s made clear, the consequences of misidentification are far-reaching and can impose substantial costs that impede cumulative progress. In the absence of effective certification procedures, researchers must use internally-certified materials or painstakingly re-establish the validity of specific prior research findings. By enabling researchers to avoid needless and costly duplication, effective certification can enhance research productivity. Relative to the peer-to-peer network, BRCs have mission-based incentives to establish a reputation for quality across a wide range of biological materials, are able to amortize the fixed costs of certification across multiple users of a given material, and invest in the specialized equipment and skills required for the certification of biomaterials. Of course, the returns to certification may vary: in particular, the value of certification may be particularly high for biomaterials initially disclosed in less prestigious journals, since the quality signal associated with those journals may be more variable.

(2) *Independent and Open Access to Biological Materials*: BRCs ensure that their materials are equally accessible to all members of the scientific and technological community, thus encouraging *independent and open access* to the results of prior scientific research. While access through the peer-to-peer network is limited by the incentives of individual scientists to provide biomaterials access to potential scientific rivals, BRCs sever the direct tie between the researcher responsible for the initial discovery and those wanting to build upon the research. BRC collections reduce opportunities for hold-up through standardized MTA agreements. By facilitating the usage of materials by researchers in disparate scientific fields or at institutions that do not have access to a material through the peer-to-peer network, BRCs can expand the range of impact of a given scientific discovery.

(3) *Preservation of Biological Materials*: Unlike the collections of individual researchers or for-profit organizations, BRCs are dedicated to the long-term maintenance of a broad range of materials whose value may not be initially apparent. BRCs have developed capabilities to enhance the value of materials over time and enable high-impact discoveries to be made many years after the initial discovery of a particular biomaterial. For example, *Thermus aquaticus*

(*Taq*), a micro-organism discovered in the hot springs of Yellowstone National Park in the late 1960s, is an *extremophile* that can sustain enzymatic reactions during rapid heating and cooling. While no practical benefit was seen at the time of its initial deposit at ATCC, its availability and preservation were fundamental in the development of biotechnology. More than 15 years after its discovery, a private sector researcher, Kary Mullis, was able to exploit the *Taq* extremophile in the development of polymerase chain reaction (PCR) to dramatically enhance the ability to replicate and sequence genetic material (a development that brought Kary Mullis the Nobel Prize in 1993, and earned *Taq* honors as *Science's* Molecule of the Year in 1989). Whereas individual researchers focus on maintaining only those materials required for their own research needs, and for-profit distributors focus on high-volume materials with low storage costs, BRCs' explicit objective of maintaining an "option" on biomaterials leads to the active and careful archiving of a wide range of materials.

(4) *Scale and Scope Economies*: Finally, as "living libraries" that continuously collect material developed by the scientific community, BRCs are able to achieve substantial scale and scope economies that lower the costs of cumulative research. Relative to other organizational forms for preserving and circulating life science materials, BRCs maintain larger, more varied, and more balanced collections and reduce duplicative effort. As a result, BRCs are more likely to undertake the R&D and capital investments necessary to increase the quality and reduce the cost of accessing biological materials. For example, the size and breadth of their collections have enabled institutions such as the ATCC, DSMZ, the Coriell Institute, the Japan Collection of Microorganism, and the Jackson Laboratory to establish positions of global leadership in specific materials and collections, in authentication techniques, and in bioinformatics.

III. THE IMPACT OF INSTITUTIONS ON KNOWLEDGE DIFFUSION: AN EMPIRICAL FRAMEWORK

By ensuring the fidelity and lowering the costs of access to knowledge, research-enhancing institutions such as BRCs may influence the equilibrium rate and impact of a given discovery on subsequent research. Four central predictions stand out. First, consistent with the possibility of positive sorting, a selection effect implies that, on average, knowledge associated with BRCs will be of higher intrinsic scientific value than knowledge that is only available through alternative institutions, such as the peer network. Second, conditional on the intrinsic importance of a particular discovery, BRC accession confers a positive marginal impact on subsequent knowledge

diffusion. As research-enhancing institutions preserve access to knowledge for a longer time than alternative institutions, a preservation effect implies that the marginal impact will persist (or grow) rather than erode over time. Third, the marginal impact of a research-enhancing institution will be greater for knowledge associated with “poor” institutional environments. Finally, the extent of follow-on research induced by association with a research-enhancing institution will be greater among researchers and projects for which authentication and independent access are more valuable. This section briefly outlines an empirical framework to test each of these hypotheses.

Our framework is motivated by a fundamental inference problem. For a given piece of knowledge within a given institutional environment, one cannot observe the counterfactual impact that knowledge would have had had it been produced and diffused in an alternative institutional setting. From an experimental perspective, the econometrician would ideally assign discoveries randomly to distinct institutional environments and then compare the impact of different regimes on follow-on research use. While one cannot replicate this ideal experimental design, we develop an econometric strategy that takes advantage of exogenous institutional change to isolate the marginal impact of an institution on knowledge accumulation from the effect of selection into that institution. Our approach exploits two key elements of our setting. First, individual materials made available through BRCs are linked to specific scientific publications. We can therefore assess the impact of BRCs by examining the pattern of citations to articles associated with BRC deposits. Though imperfect, citations by future scientific research articles provide a useful (though noisy) index of the impact of a discovery on subsequent research.⁹ Second, while initial publication often occurs within six months (or fewer) after initial journal submission, many BRC material deposits occur long after the publication date of the associated scientific research article. Moreover, in certain instances discussed in the next section (e.g., when the principal investigator retires or switches university affiliation), the act of deposit and its precise timing are arguably econometrically exogenous (and we can apply differences-in-differences techniques to test this assumption). In other words, we can exploit the timing of the transfer of some biomaterial collections that had been maintained in academic laboratories that then get shifted into a public

⁹ Most life sciences papers are short and focused, with few extraneous references beyond those directly impacting the described findings. Thus, the principal rationale for the inclusion of a citation for a BRC-linked paper is that the material is explicitly used in a follow-on experiment or the experiment is closely connected to the findings and knowledge linked to that specific material (i.e., life sciences citations are likely more informative than social science citations). More generally, the meaning and use of academic citations has become the subject of a large body of research, including the field of scientometrics [Garfield, 1956, 1979; De Solla Price, 1976; Leydesdorff, 2001]. While recent papers suggest the potential for strategic and reputation-based citation [Simkin and Roychowdhury, 2003], the focused nature of BRC-linked citations likely mitigates this concern.

BRC. Conditional on our assumption that the timing of the deposit is exogenous, the deposit lag allows us to estimate the impact of deposit on knowledge diffusion, measured as the change in the rate of citation (between the pre-deposit and post-deposit period) to the initial article by follow-on scientific research articles.

In addition to traditional concerns about interpreting citations [Griliches, 1990; Patel and Pavitt, 1988], we are careful to consider the possibility that substitution is biasing the results. For example, *citation substitution* may arise if materials deposits lead future researchers to cite BRC-linked articles rather than other articles that reflect the same knowledge, while *materials substitution* could arise if accession leads to an increase in citations to papers using the deposited material rather than to papers using substitute materials. Switching among close but imperfect substitutes (e.g., from a mutated version of a cell line that circulates within the scientific research network to the material included in a BRC deposit) might lead to a significant increase in citations without a significant increase in overall research productivity or quality.¹⁰ For example, for very popular materials (such as HeLa), there may be several “independent” versions circulating within the scientific community. Our research design mitigates the possibility. By analyzing materials included in the “special collections,” we focus on materials that are sufficiently specialized that there are few close substitutes (other than materials in the collection itself) and for which there was a low likelihood of a “secondary market.” We nonetheless test for the possibility of substitution in our empirical analysis by examining whether exogenous deposits *negatively* affect citations to articles that are likely substitutes for BRC-deposited materials.

To apply our empirical approach, we construct a dataset composed of scientific publications linked to (delayed) BRC deposits and control articles which are comparable to our treatment articles. Because we observe citations to a scientific publication both before and after BRC deposit (and because we are able to identify a counterfactual estimate of the citation rate that would have occurred if a BRC deposit had *not* occurred), we can identify the causal impact of BRC deposit on the pattern of citations to a scientific publication. Citations data take the form of count data that are skewed to the right and over-dispersed relative to Poisson. Additionally, the rate of citation to a given piece of research will vary with the calendar year and the time elapsed since initial publication. Therefore, except where noted, we employ a conditional negative

¹⁰ It is also possible that there are multiple *identical* versions of a biological material maintained by different laboratories. Since these materials would be perfect substitutes from the perspective of cumulative knowledge production, strains that are identical to BRC deposits will be considered effectively part of the ATCC collection.

binomial model with age and year fixed effects for citations produced per year for each scientific article in our dataset.^{11,12}

We experiment with a range of alternative specifications that allow us to identify the impact of BRC deposit on follow-on research. Our initial estimator disentangles the treatment effect from the selection effect by identifying both the average differences between the treatment and control groups (where each article in the treatment group is paired with a “similar” article in a control group) and the change in citations resulting from BRC deposit:

$$(1) \text{ CITES}_{i,j,\text{pubyear}(j),t} = f(\varepsilon_{i,j,t}; \alpha_j + \beta_t + \delta_{t-\text{pubyear}} + \phi \text{BRC}_i + \psi \text{POST} - \text{DEPOSIT}_{i,t}),$$

where α_j is a fixed effect for each pair of a treatment article and control article, β_t is a year effect, $\delta_{t-\text{pubyear}}$ captures the age of the article, BRC is a dummy variable equal to one for those article linked at some point to a BRC, and POST-DEPOSIT is a dummy variable equal to one only for those years after the material linked to the article is accessioned and available from a BRC.¹³ We then modify this specification to account for heterogeneity across articles (even within matched article pairs), by including article-specific fixed effects (γ_i):

$$(2) \text{ CITES}_{i,\text{pubyear}(i),t} = f(\varepsilon_{i,t}; \gamma_i + \beta_t + \delta_{t-\text{pubyear}} + \psi \text{POST} - \text{DEPOSIT}_{i,t}).$$

This specification tests for the impact of research-enhancing institutions by calculating how the citation rate for a publication *changes* after BRC deposit, accounting for fixed differences in the citation rate across articles and relative to the non-parametric trend in citation rates for articles with similar characteristics. The structure of our data also allows us to evaluate more refined identification strategies and directly test key assumptions, such as the exogeneity of the deposit event. Specifically, we can adapt (2) to allow for a set of dummies in the years prior to and years subsequent to a deposit event; we can test for the endogeneity of deposit by examining whether there is a significant upward boost in citations prior to the deposit event.

¹¹ Panel data estimation of fixed effects count data models must address several subtle issues, including the incidental parameters problem [Hausman, et al, 1984; Allison and Waterman, 2002; Greene, 2004] and restrictions implied by distributional assumptions [Wooldridge, 2002]. We have experimented with both (a) conditional and dummy fixed effects estimators (trading off asymptotic consistency for small sample bias) and (b) quasi-ML Poisson and negative binomial estimators (trading off robustness to specification error versus a more flexible distribution). Our results are based on the traditional conditional fixed effects negative binomial estimator with bootstrapped standard errors; however, the key findings are consistent across these different procedures.

¹² When using a conditional fixed effects estimator, one citation year and one age fixed effect are not separately identified [Hall et al, 2006]. Since the main effect that we are interested in is separable from these effects, the precise specification we employ to overcome this identification issue does not at all affect our estimate of the impact of BRC deposit on citations. In our estimation, we identify differences relative to age = 0, and relative to publication in years after 1975 (though, due to data limitations, we actually impose a single regressor on the years 1975-1979).

¹³ Our empirical specifications also incorporate a “window” including the year prior to and the year after the accession of a material into the BRC to account for “announcement effects” and for potential lags in availability of materials. We abstract away from the window effect in the development of the framework in order to focus on the core identification argument.

The estimators above could be biased if the age profile of citations were systematically different for the treatment and control groups, and could overstate the impact of BRC deposit if articles ultimately associated with a BRC intrinsically had a longer-lived impact on future research. We address this in two ways. First, we continue to include the control articles to identify the impact of year effects and non-parametrically estimate the *shape* of the age profile, while also including a separate BRC-linked age trend:

$$(3) \text{CITES}_{i,\text{pubyear}(i),t} = f(\varepsilon_{i,t}; \gamma_i + \beta_t + \delta_{t-\text{pubyear}(i)}^0 + \delta^1(t - \text{pubyear}(i)) * \text{BRC}_i + \psi \text{POST} - \text{DEPOSIT}_{i,t}).$$

We can also exploit the fact that the age at time of deposit and the year of deposit vary (at least to a certain extent) and so it is possible to identify the impact of BRC deposit solely from the set of BRC-linked articles (i.e., excluding a control group). Conditioning on article-specific fixed effects, article age effects and citation year effects (through polynomials in article age and citation year), we are able to estimate:¹⁴

$$(4) \text{CITES}_{i,\text{pubyear}(i),t} = f(\varepsilon_{i,j,t}; \gamma_i + g^0(t; \beta) + g^1(t - \text{pubyear}(i); \delta) + \psi \text{POST} - \text{DEPOSIT}_{i,t}).$$

The ability to identify the impact of institutions on the accumulation of knowledge exclusively from variation in the timing of the linkage between a piece of knowledge and a particular institution is a powerful alternative to a traditional differences-in-differences approach, as it directly addresses the difficulty of constructing a synthetic control group for heterogeneous knowledge outputs such as scientific publications (or patents, in other applications).

We can also evaluate more nuanced hypotheses. First, to evaluate whether the marginal impact of BRC deposit is greater in cases where the knowledge is initially linked to an inferior institutional environment, we simply implement interaction effects between POST-DEPOSIT and measures of the underlying diffusion environment. For example, building on our discussion in Section II, we can consider whether the impact of BRC deposit is greater for articles that were published in more or less prestigious journals. Second, we evaluate whether the exploitation of knowledge embedded in research-enhancing institutions differs for different types of follow-on researchers. For example, the returns to drawing on knowledge with higher fidelity may be higher for projects that address more fundamental or more complex scientific questions. To evaluate whether the impact of BRC deposit is heterogeneous for different subpopulations of follow-on research projects, we take advantage of bibliometric measures that allow us to distinguish between

¹⁴ With enough variation in the time from publication to deposit and in the calendar year of deposit, we could, in principle, incorporate a complete set of publication age and calendar year fixed effects in (4); unfortunately, the structure of the data in this paper is not rich enough to identify POST-DEPOSIT under the most flexible specification.

different *types* of follow-on citations (e.g., citations from top-tier versus lower-tier journals). We aggregate these individual citations into counts of the number of citations received by a given “root” article in a given year by a given subpopulation of citers:

$$(5) \text{ CITES}_{i,l,\text{pubyear}(i),t} = f(\varepsilon_{i,l,t}; \gamma_{i,l} + \beta_{t,l} + \delta_{t-\text{pubyear},l} + \sum_{l=1,\dots,L} \psi_l \text{POST} - \text{DEPOSIT}_{i,t}).$$

In other words, ψ_l is the average impact of the treatment on sub-population l , conditional on a fixed effect for citations by each subpopulation for each article, and allowing for separate article age and citation year fixed effects for each subpopulation. By evaluating how the impact of BRC deposit varies across different citation subpopulations (e.g., $H_0 : \psi_l = \psi_k$), we can evaluate whether the types of citations received as the result of BRC deposit seem to be linked with the role of BRCs in enhancing certification and enabling independent access to research materials. Finally, we can evaluate how citations change after BRC deposit by calculating, for each citation-year, measures of the number of citations coming from different types of *new* sources (e.g., the number of citations from institutions or journals that had not previously cited a given article). By examining the impact of BRC deposit on citations that are *novel* to the follow-on research associated with a given article, we are able to provide evidence regarding the role of BRCs in expanding the range of follow-on research projects building on a given discovery.

III. DATA

III.A. Data Construction and Sources

To conduct the empirical analysis, we focus on a single institution, the American Type Culture Collection. Located in Manassas, Virginia, and founded in 1925, ATCC maintains the largest culture collection in the world (ATCC, 2009). Although ATCC is unusually large, its preservation, certification, and distribution functions are similar to those of other large public culture collections. We take advantage of the characteristics of ATCC in order to address four key empirical challenges associated with implementing the differences-in-differences strategy we articulate above: (a) linking BRC deposits to research publications, (b) selecting a sample of publications that can be used to identify the marginal impact of BRCs, (c) constructing a sample of control articles, and (d) accounting for ambiguity in the date on which BRC deposits are available for follow-on research.

We address the first challenge by taking advantage of the reference information maintained by ATCC on all materials deposited in its collections. For each material, ATCC documents the

name of the original depositor, date of deposit, and key scientific information associated with the deposit, including the key research article that employs or characterizes the material.¹⁵

To overcome the second challenge, we take advantage of shocks that led to the mass transfer of three *special collections* into ATCC from collections previously circulated via the peer network. These transfers occurred when scientists who maintained collections within the peer network moved or faced an institutional funding limitation unrelated to that specific collection. The first set of materials is drawn from the Tumor Immunology Bank (TIB), which was accessioned into ATCC beginning in 1982 due to funding pressures at the Salk Institute, where it had been previously maintained. The second special collection is the Human Tumor Bank (HTB), which had been operated by researchers at Sloan-Kettering until institution-wide funding considerations led to its wholesale transfer beginning in 1981. The third special collection, the Gazdar Collection, was transferred into the ATCC beginning in 1994 when Dr. Adi Gazdar left his position as Head of Tumor Cell Biology at the National Cancer Institute, and, along with his collaborator Dr. John Minna, moved to UT-Southwestern. It is important to note that the materials in each collection were (a) publicly available as part of the special collection prior to the transfer to ATCC, (b) unavailable from proprietary vendors during the sample period and (c) unencumbered by formal intellectual property claims such as patents. Together, there are 72 articles matched to materials in the TIB collection, 30 from the HTV collection, and six from the Gazdar collection.

We additionally identify a set of control articles for each BRC-affiliated article, using the most-related article in the same volume of the journal in which the BRC-linked article was published. We identify most-related articles based on a search algorithm developed by the National Library of Medicine (NLM). The NLM algorithm generates similarity rankings based on the extent to which articles in the PUBMED database share terms in their title, abstract, and Medical Subject Headings (MeSH). From the set of articles identified by the NLM algorithm as related to the focal article, we select the most-related article published in the same journal and publication year.¹⁶

¹⁵ Historically, ATCC published its catalogs in print form. Currently, ATCC maintains its catalog online at www.ATCC.org. In cases in which multiple publications are relevant for a particular material, we use the first article listed, as ATCC scientific and information technology staff report that this is the article most closely associated with the initial use of the biological material.

¹⁶ In cases in which no article in the same volume of the journal qualifies as sufficiently related according to the NLM algorithm, we use the article that immediately precedes the BRC-linked article in the specific year and issue in which the BRC-linked article was published as the control. For example, if a BRC-linked publication were the third article in the June 14, 1986 issue of *Cell*, the control article would be the second article within that same issue. We also construct an auxiliary dataset of “most related own articles,” which includes the most related article by one or more of the authors of the root publication, which we use in a robustness

The fourth challenge is to account for ambiguity in the date on which BRC deposits are available for access by other researchers. Some members of the research community become informed about collections transfer through informal communications and formal announcements prior to the official accession date. At the same time, because of the rigorous procedures used to accession materials, some materials in the HTB and TIB collections took 24 months to be declared available officially from ATCC. We explicitly account for this transition period by incorporating a “transfer window,” including the year before, the year of, and the year following the official accession date. By including this window, our analysis focuses on how the pattern of citation changes from a period prior to the deposit announcement to the period subsequent to its availability through a BRC. We also compile detailed bibliometric information, including annual citation counts and bibliometric details of cited and citing articles from the Institute for Scientific Information’s (ISI) Science Citation Index Expanded (SCI) database.¹⁷

III.B. Summary Statistics

Our core dataset consists of 108 BRC-linked articles and 108 associated control articles. We refer to these articles as “root articles” to distinguish them from the “citing articles” that reference them (Table 1 provides variable names and definitions and Table 2a reports summary statistics). We track citations to each root article from the year of its publication (mean PUBLICATION YEAR = 1979.4), yielding 4857 article-year observations. The majority of BRC-linked articles were deposited in the early 1980s, although the articles associated with the Gazdar collection were published in early 1990s. Root articles in the sample are predominantly associated with US-based authors (76 percent); 15 percent are associated with the top 50 most research-intensive US universities; and slightly more than half (56 percent) appear in journals with an ISI impact factor greater than 25.¹⁸ Our sample includes citations received by root articles between 1970 (the earliest publication year) and 2001, and the citation-years have an average AGE of 11.3 years. The key dependent variable in our analysis is FORWARD CITATIONS, which measures the number of citations received by a root article in a given year. Because publications associated with BRC deposits (and their associated control articles) tend to appear in top-tier journals, such

check below. To assemble these data, we use the NLM algorithm to identify the top 40 most-related articles for each root article, and then define the “most-related own article” as the highest-ranked article in this set that includes the root article’s last author, first author, or, if neither of these, multiple middle authors.

¹⁷ The SCI has been widely used in economics, sociology, and management research, as well as in bibliometric studies, to quantify scientists’ research output, measure research collaboration, and track the diffusion of science – prominent examples include Levin and Stephan [1991], Adams and Griliches [1998], Henderson and Cockburn [1998], and Zucker et al. [1998].

¹⁸ The average numbers of authors per article is 5.0, pages is 6.6, backward citations is 31.9, and BRC material price is \$223.

as *Science*, *Nature*, and *Cell*, the average number of forward citations is higher than would be expected for a randomly chosen life sciences article. The average number of annual FORWARD CITATIONS in our sample is 7.28, the cumulative number of citations by 2001 is 91.7, and the distribution is, not surprisingly, skewed to the right.

To examine heterogeneity in the treatment effect, we have also gathered detailed bibliometric information from the set of citing articles. We construct several measures of the number of citations that a root article receives from specific types of articles, including annual citations from papers with US-based authors (mean = 2.6), annual citations from articles associated with a Top 50 US-university (mean = 1.0), annual citations from articles appearing in top journals (mean = 3.4), and annual citations from articles with a single ISI subject category (mean = 4.1) as opposed to multiple subject categories.¹⁹ We also construct measures capturing the number of citations received from articles with identifiers that are new to the set of citations associated with a given root article. These measures are intended to reflect increases in the “breadth” of the research community drawing on the knowledge in a particular root article. Specifically, we construct three variables: CITATIONS BY UNIQUE NEW JOURNALS (mean = 2.9), CITATIONS BY UNIQUE NEW INSTITUTIONS (mean = 5.6), and CITATIONS BY UNIQUE NEW COUNTRIES (mean = 0.8). Each of these measures refers to citations in a particular year from journals, institutions, and countries, respectively, that had not yet cited the root article in previous years.²⁰

Table 2b compares key characteristics of the BRC-linked articles to those of the control sample. Articles associated with BRC deposits receive greater than 220 percent more citations than *Most-Related Article* controls, even though both control groups appear in the same journal, went through the same review process, and are matched closely by subject area. Figure A portrays the disparity between these groups over time, comparing average citations by article age. For each sample, the average number of citations increases over the first few years, peaking around the third or fourth year after publication.

¹⁹ The ISI has developed a scheme for classifying academic research into detailed scientific subject categories, including “Biochemical Research Methods,” “Cell Biology,” and “Oncology”. The Science Citation Index includes a field identifying the subject category or categories into which journals and papers have been classified. Journals and papers that cross scientific areas may be assigned multiple subject categories. Papers in our sample receive a minimum of 1 and a maximum of 5 subject categories.

²⁰ For example, if an article were to receive 10 citations in its first year after publication, all of which appeared in *Science*, and two citations in its second year after publication, one of which appeared in *Science* and the other of which appeared in *Nature*, then CITATIONS FROM UNIQUE NEW JOURNALS would equal one in the first year (since all publications appeared in the same journal, *Science*) and one in the second year (although two separate journals cited the root article in that year, only the citation in *Nature* is novel, as a citing article had appeared in *Science* in the previous year).

IV. EMPIRICAL RESULTS

IV.A. Baseline Analyses

Our analysis begins in Table 3 with a differences-in-differences analysis that separates out the marginal impact of ATCC deposit from the selection effect. We begin in (3-1) and (3-2) with OLS specifications with $\ln(\text{FORWARD CITATIONS})$ as the dependent variable. The specifications differ in that (3-1) includes AGE fixed effects, while (3-2) also includes YEAR fixed effects and fixed effects for each treatment-control pair. The results are similar: the marginal impact of BRC deposit (controlling for the selection effect) is estimated to be in excess of a 50 percent boost to the citation rate. Moreover, the BRC-ARTICLE coefficient suggest that articles that are ultimately linked to BRC deposits are associated with a 50 percent higher citation rate relative to the controls (i.e., the selection effect in this sample is large and positive). Finally, the marginal impact of BRC deposit begins to manifest itself during the window period (with an estimated 33 percent boost), and both the year and article age fixed effects are jointly significant (though the interpretation of such a test is subtle [Hall et al., 2006; Mehta et al., 2009]).

Though useful as a preliminary exercise, OLS is inappropriate for inference as citation data are composed of highly skewed count data. We therefore employ a conditional fixed effects negative binomial estimator for the remaining specifications. We report in brackets the coefficients for these models as incidence-rate ratios (a coefficient equal to one implies no effect on FORWARD CITATIONS, whereas a coefficient equal to 1.50 implies a 50 percent boost to FORWARD CITATIONS).²¹ The first of these specifications, (3-3), presents a useful comparison to (3-2), as it incorporates an essentially identical set of regressors. We can easily reject the null of no selection and no marginal effect. Indeed, the estimated coefficients are larger than those associated with the OLS specifications, and suggest the practical significance of the treatment effect: forward citation rates are estimated to increase more than 70 percent *after* BRC deposit. Moreover, BRC-linked articles receive 112 percent more citations annually than matched controls articles, implying that articles associated with the Special Collections were of greater intrinsic scientific importance than those in the control sample.²²

²¹ All models include block bootstrapped standard errors, clustered either by article pairs or article dummies, depending on the set of fixed effects included in the specification [Bertrand, et al, 2004; MacKinnon, 2002]. We do not report the significance of tests of joint restrictions on the article family or article fixed effects, as these are not computed in conditional fixed effects models.

²² It is useful to note that this estimate of the selection effect is specific to this sample and empirical design and does *not* serve as an estimate of the average selectivity of BRC-linked articles: our sample of treatment articles is not a random sample of BRC-linked articles (we chose those articles that were subject to an exogenous deposit) and the control articles are not a random sample of life sciences articles (we chose those articles to be close matches to the treatment articles).

We have, so far, abstracted away from the substantial variability among articles within article pairs. Except where noted, all remaining specifications include (conditional) article fixed effects to account fully for heterogeneity in the underlying quality of individual articles. With the control articles helping to identify the citation year and article age effects, the coefficient on BRC-ARTICLE, POST-DEPOSIT is identified from the *change* in citations (relative to expectations) after the associated biomaterial is accessioned (and after the deposit window has elapsed). The estimates in (3-4) suggest that BRC-linked articles receive a 125 percent citation boost after BRC accession, controlling for article, age and year-specific effects.²³

Of course, the interpretation of this estimate depends on the extent to which the coefficient reflects the marginal treatment impact of BRC deposit, as opposed to spurious correlation. We therefore test our key identification assumptions. We first examine whether the results in Table 3 are simply the result of a different citation age profile for BRC-linked articles compared to the controls. For example, BRC-linked articles may have inherently longer-lived citation profiles, which would result in an upward bias on the estimate of BRC-ARTICLE, POST-DEPOSIT. We address this possibility in two distinct ways. First, in (4-1), we include a separate linear time trend for BRC-linked articles; the coefficient on BRC-ARTICLE*AGE is positive but insignificant. While the coefficient on BRC-ARTICLE, POST-DEPOSIT declines relative to (3-4), the effect of BRC deposit remains statistically and quantitatively significant and similar in magnitude to (3-3). In (4-2), we consider the citation age profile more precisely by also accounting for the preservation hypothesis – the idea that the impact of BRC deposit may grow with the time elapsed from the deposit date. When we also include the regressor, YEARS SINCE BRC DEPOSIT, we cannot empirically disentangle the BRC-specific age trend from the trend that may arise after BRC deposit (the coefficient on YEARS SINCE BRC DEPOSIT is essentially zero while BRC-ARTICLE*AGE is small and statistically insignificant).

In addition, we evaluate the marginal impact of BRCs in a specification that focuses exclusively on within-variation. Conditioning on article effects, we are, in principle, able to identify the impact of BRC deposit from the fact that BRC-linked articles are both published at different times and the gap between publication and deposit varies across articles. Because the HTB and TIB special collections were accessioned at relatively similar times (1980-1983) we do

²³ These overall findings are robust across a wide range of alternative subsamples and control groups, including the exclusion or inclusion of any Special Collection (TIB, HTB, and Gazdar), a control sample composed exclusively of Nearest Neighbor Controls (the articles immediately preceding treatment articles in the journal and volume in which they appear), or a sample that only includes a treatment and control article when a Most Related Article control is available [Furman and Stern, 2006].

not observe sufficient variation in the time between publication and accession to ascertain the impact of BRC deposit with complete sets of calendar year and article age fixed effects. Thus, we include five-year grouped calendar year effects and linear and quadratic article age effects in (4-3) and a linear and quadratic term for both calendar year and article age in (4-4). In each of these specifications, the post-deposit treatment effect remains statistically significant and of a magnitude similar to (4-1). By excluding the control sample and identifying the marginal impact of BRCs solely based on variation in the treatment sample, these specifications offer a useful and alternative approach to the specifications in Table 3, as the results are in no way predicated on assumptions about the quality of the match between the treatment and control samples.

So far, our analysis has assumed that the timing of BRC deposit is exogenous. If BRC-linked articles experience a significant increase in forward citations in the years prior to accession, this would imply that the measured post-deposit effect is confounded with a pre-deposit trend, undermining our interpretation of the BRC deposit coefficient as a treatment effect. We examine this in a specification that is similar to (3-4) but includes separate dummy variables for each year preceding and following BRC-deposit (along with complete article, age, and calendar year fixed effects). Figure B plots each coefficient of this specification (in terms of the incidence-rate ratio minus one), excluding the years associated with the accession window (all effects are computed relative to the window period), along with upper and lower bounds for 95 percent confidence intervals. Two findings stand out. On the one hand, the pre-deposit citation pattern does not suggest a clear upward trend in the nine years prior to accession; while there is a slight uptick in forward citations in years two and three before the window period, this uptick is sensitive to the estimation technique.²⁴ While we cannot reject the hypothesis that all pre-deposit coefficients are equal, the results suggest some degree of caution in simply assuming that special collections deposits are econometrically exogenous. On the other hand, the sizeable and near continuous increase in the citation boost in the years following deposit is consistent with BRC-accession having a significant marginal impact on FORWARD CITATIONS. While BRC-affiliated articles experience only a 40 percent citation boost in the years immediately after accession, this effect increases to over 125 percent by ten years after deposit. In other words, while the immediate impact is positive but modest, the influence of BRC deposit does not decline over time. This is consistent with the preservation hypothesis, but can also be explained by the BRC*AGE trend in

²⁴ The pre-deposit trend has no upward trend in a specification with dummy fixed effects as opposed to conditional effects.

(4-1) and (4-2). Whereas most research is used as an input in follow-on research for only a few years following publication, BRC-linked knowledge is “forgotten” at a much lower rate.

Our citation-based analytic approach also assumes that the BRC DEPOSIT coefficient reflects real changes in follow-on research behavior, rather than citation or materials substitution. Although it is difficult to test for these practices directly, we investigate a straightforward implication of this possibility by substituting a sample of *Most-Related Own Articles* in place of the treatment articles (this sample is described in FN 16). If the listing of an article in the ATCC catalog leads simply to a shift in citation to that article and away from other articles associated with that material, related articles by authors associated with the BRC-deposit article may experience a *decline* in citations after the BRC deposit (as citations are shifted towards the BRC-linked article). This approach also addresses the possibility of *materials substitution*; since researchers often develop multiple versions of the materials they work with, the materials likely to be the closest substitutes for a deposited material are those characterized in the most-related article by the same researcher. Like citation substitution, materials substitution should, thus, yield in a decline in citations to *most-related own articles*. The results in Table 5 suggest the opposite. *Most-related own articles* experience a statistically and practically significant increase in citations after the underlying biological material is accessioned into a BRC. Overall, the result is smaller in magnitude than the baseline specification using the root articles (as expected), and allows us to reject the hypothesis that this simple form of substitution is driving the baseline results.

IV.B. Drivers of the Marginal Impact of BRC Deposit

We now turn to a more detailed investigation of the sources of the marginal citations arising from BRC deposit. We begin in Table 6 by evaluating heterogeneity in the BRC treatment effect across different types of root articles. Consistent with the theoretical model of Mukherjee and Stern (2009), we anticipate that BRC deposit will have a higher impact for articles published in journals where the “quality” signal is more ambiguous. For example, in (6-1), we estimate whether the marginal impact of BRC deposit differs for root articles associated with top-tier journals. The results imply that the marginal impact of BRC deposit is higher for articles published *outside* of top-tier journals relative to those published in top-tier journals (the difference of the coefficients is significant at the 10 percent level). This result is consistent with an interpretation in which more selective journals have a higher “bar” for the underlying quality and reproducibility of the experiment than less selective journals. As an additional check, we also test

whether the quality of the university affiliation has a significant impact on the citation boost by comparing the impact of BRC deposit on publications from reprint authors in “top 50” universities versus others.²⁵ In contrast to (6-1), we find no significant difference in the impact of university affiliation. This is, perhaps, not surprising, as the mechanism by which university quality may have a differential effect on citations is not as clear as the case for journal quality.

In a further examination of potential certification benefits, we investigate whether the impact of BRC deposit depends on an article’s level of *pre-deposit* citation. To do so, we run a first-stage OLS regression of the number of cumulative citations *at the time of deposit* as a function of calendar year fixed effects and fixed effects for “years to BRC deposit;” the residuals from this regression are then grouped into quartiles to capture differences in the level of the pre-deposit impact of different root articles. In (6-3), we report the BRC DEPOSIT coefficient for root articles in each quartile. The results suggest that the impact of BRC deposit is highest for articles from the “middle” of the quality distribution. In particular, there is a significant difference between the impact of BRC deposit on articles in the second and third quartiles, relative to the top quartile of pre-deposition citations. These findings are of particular interest to public policy: if the marginal impact of BRC deposit were concentrated exclusively among articles with the highest level of pre-deposit citations, optimal policy might simply be to ensure accessibility and integrity for those discoveries that received the highest level of follow-on work after publication; however, since BRC deposit has a positive impact for all quartiles (and the highest marginal impact is associated with articles from the “middle” of the distribution), it may be important to ensure the accessibility of knowledge and materials even for discoveries that are not deemed to be particularly important in the period immediately after their publication.

Table 7 shifts the focus by examining whether BRC deposit has a differential level of impact on *different subpopulations of potential citers*. To evaluate heterogeneity among subpopulations, we first classify each citation to each article according to bibliometric characteristics, and then calculate the total number of citations received from that subpopulation in each year after publication. For example, we calculate the number of citations to each article by articles in top-tier journals, and citations that are *not* in top-tier journals. We then specify a stacked regression, where the dependent variable in each group is the number of citations received from a given subpopulation in a given year. Each negative binomial regression includes separate fixed effects

²⁵ The Web of Science identifies each paper’s “reprint author,” as the individual to whom reprint copies of the paper are sent and to whom questions are addressed.

for each calendar year-subpopulation, article-age subpopulation, and conditional fixed effects for each root article-subpopulation. Consistent with the certification role of research-enhancing institutions, we are particularly interested in testing whether the increase in citations associated with BRC deposit are associated with higher-quality, more complex research projects.

We report results for two types of subpopulation groupings. In (7a-1), the citations from both top-tier journals and non-top-tier journals are estimated to increase after BRC deposit (the estimates imply a 110 percent citation boost from top journals and a 72 percent citation boost from non-top journal articles). Though the coefficient is larger for citations from top-tier journals, the difference between the coefficients is not statistically significant ($p = 0.40$).²⁶ In (7a-2), we investigate whether the change in citations arising from BRC deposit is associated with simple versus complex research articles. We implement this distinction by examining citations by articles that report either a single subject field (e.g., biochemical research methods) versus articles that report multiple subject fields (e.g., microscopy and parasitology). While single-subject field articles are more likely to be narrow papers on more modular topics, multi-subject papers are more likely to be broader papers on more complex topics. The results here are striking. While multi-subject articles are estimated to increase more than 150 percent after BRC deposit, single-subject articles are estimated to experience a modest decline (these coefficients are statistically different from each other). Taken together, Table 7A provides some additional evidence consistent with the certification hypothesis: the boost in citations resulting from BRC deposit is weakly associated with citations from high-quality follow-on research, and is strongly associated with more complex research projects (where the reduction in uncertainty associated with using certified biological materials may have a higher marginal benefit). These results are also consistent with the interpretation that the boost in citations in prior tables represents an expansion in follow-on research, rather than simple substitution in citations or materials. While substitution might result in higher citation counts for BRC-linked articles, the simplest forms of substitution should not significantly impact the character of follow-on research projects.

Finally, in Table 7B, we investigate whether the impact of BRC deposit is associated with an increase in the breadth of the research community building on a particular discovery. Similar to the substitution analysis in Table 5, our analysis is, in some sense, a falsification exercise, insofar

²⁶ This basic pattern of results obtains across a wide range of specifications that split citations by several different measures of perceived quality. For example, BRC deposit is estimated to result in a 98 percent increase in citations from reprint authors from top-50 universities compared with an 81 percent increase in citations by reprint authors outside of the top-50 universities. As in (7a-1), while each treatment coefficient is statistically significant, the coefficients are not statistically different from each other.

as we can evaluate whether BRC deposit simply results in an increased number of citations, without really changing the portfolio of where those citations come from. Our approach is first to calculate, for each citation year, the number of citations that come from sources that had not referenced the root article in prior years. Specifically, for each citation year, we calculate the number of unique new institutions, unique new journals, and unique new countries. Each specification in Table 7B also includes article age, calendar year, and conditional article fixed effects. In each case, BRC accession corresponds to a statistically significant and quantitatively important expansion in the sources of citations for BRC-linked root articles. For example, (7b-1) suggests that BRC accession is associated with a 98 percent increase in the number of institutions citing BRC-linked root articles that had not previously cited those root articles. Though by no means dispositive, these findings are consistent with the idea that the independent access offered by BRCs to biological materials increases the exploitation of the knowledge associated with those materials by a broadened group of follow-on researchers.²⁷

IV.C. Assessing the Cost-Effectiveness of BRCs

Our final exercise is a “back-of-the-envelope” cost-effectiveness analysis. A complete cost-benefit analysis is beyond the scope of our analysis, since we have no direct measure of the research productivity impact of BRCs. We are, however, able to undertake a simple comparison of the citation impact of expenditures targeted at accessioning biological materials into a BRC (i.e., ensuring that today’s discoveries are accessible to follow-on researchers) versus funding for an additional research project. Specifically, we compare the “cost per citation” of funding new research studies on the one hand and accessioning biological materials associated with already published research on the other. Such a counterfactual is inherently speculative; thus, we choose benchmarks that reduce our estimate of relative cost-effectiveness of marginal investment in BRCs in comparison to marginal funding for additional research projects.

Our counterfactual requires an estimate of (a) the cost per citation induced by public research funding, (b) the cost of BRC accession, and (c) the number of citations induced by BRC accession. We set the cost per citation from research funding using the lowest estimate of this metric from Adams and Griliches [1998] (corresponding to citations resulting from expenditures at a top 10 biology department) -- \$2400 in 1996 USD (which we adjust to \$2887 in 2002 USD using the

²⁷ In a related setting (mouse genetics research), Murray et al. [2009] expand on this type of analysis to evaluate the impact of a shift in openness (resulting from a relaxation of intellectual property protection) on the restrictiveness of formal intellectual property rights on the diversity and novelty of upstream scientific research.

BEA R&D price deflator). We set the cost of BRC accession to be equal to \$10,000 per material (corresponding to the maximum of the range reported from survey evidence in OECD [2001]). Finally, we draw on our estimate of the citation “boost” to compute the incremental number of citations expected to result from deposit and accession into a national BRC. Specifically, we use the estimate from (4-1) (67.7 percent, which includes a BRC-specific time trend and is lower than the baseline estimates in (3-4)). We apply this treatment effect estimate to calculate the incremental citations arising from BRC deposit for four different “types” of research articles. Adams and Griliches [1998] offer two useful benchmarks for comparison: publications from a top 10 biology department are associated with 24.6 citations during their first five years of publication, and publications from a biology department outside the top ten are associated with 14.3 citations during their first five years of publication. If we apply our treatment effect to these citation counts, BRC accession would be associated with 16.7 and 9.7 citations, respectively. Similarly, if we focus on all articles in our sample, the citation boost is estimated to be 30.1 (from a baseline of 60 citations over a five-year period), and the citation boost associated with just the treatment articles is estimated to be 41.0 (from a baseline of 60 citations over a five-year period).

Dividing the BRC Accession Cost by the BRC Citation Boost yields an estimate of the BRC Citation Cost, which can be compared with the Baseline Citation Cost. Across all counterfactuals, BRC accession is associated with a significant reduction in cost per citation. The estimates range from a factor of three (for a “random” article) to more than 10 (for BRC-linked articles). While it is important to exercise caution in interpreting these estimates (citation impact is certainly not the only criteria for research investment productivity), it is useful to emphasize that a primary funding criterion of the NIH and related agencies is the potential for impact on future research (a criterion often assessed through simple citation counts). The analysis suggests that investments in research-enhancing institutions amplify the impact of research; the marginal NIH dollar may be more effectively spent on ensuring the accessibility and authenticity of research rather than simply funding additional research.

V. CONCLUSION

In this paper, we propose a methodology to identify whether an institution exerts a positive externality on the accumulation of knowledge. We examine an institution that preserves, authenticates, and circulates life sciences research materials, and find a substantial amplification in cumulative knowledge production. Our empirical approach combines large-scale citation analysis

with a differences-in-differences approach to causal inference, allowing us to disentangle the impact of institutions on the dynamics of cumulative research, an approach that has since been adopted in an increasing number of papers [Murray and Stern, 2007; Agrawal and Goldfarb, 2009; Rysman and Simcoe, 2008; Murray et al., 2009; Furman et al., 2009]. Over the past several years, science funding agencies (including the NSF and NIH) have placed significant priority on the development of the “Science of Science Policy” (SOSP) [Marburger, 2005; Jaffe, 2006], in which the tools of program evaluation can be used to evaluate alternative institutional arrangements and science policy choices. One contribution of this paper is the introduction of the combination of citation analysis with a differences-in-differences approach as a SOSP methodology.

Our findings bear directly on public policy towards the preservation, certification, and distribution of biological materials, data, and resources. The policy issues concerning biological materials and data cut across a wide range of policy areas, including Federal funding for embryonic stem cell research (where the lack of Federal funding for new cell lines may have impacted the rate of scientific progress [Furman et al., 2009]), to public investment in freely accessible databases such as the Human Genome Project [Jensen and Murray, 2005] to the potential for conflict between national security and academic freedom in bioweapons research, illustrated most directly in the case of the identification of anthrax strains associated with the 2001 attacks [Stern, 2004]. In each of these cases, there is a significant gap between the public and private incentives to make authenticated biological materials and data available on an independent basis to follow-on researchers [Mukherjee and Stern, 2009; Häussler, 2008]. Our findings offer support for policy proposals that (a) premise public funding or publication of research on a commitment to provide access to that knowledge to future scientific researchers [Nardone, 2007] and (b) shift funding priorities on the margin away from simply funding research projects to funding research streams that accumulate a body of systematized knowledge that is available on an open-access basis. More generally, the analysis highlights the crucial role of openness and independent access as prerequisites for cumulative knowledge production and suggests the value of research identifying the economic conditions and empirical circumstances that allow Open Science to succeed as an economic institution [Mokyr, 2002; Aghion et al. 2008; David, 2008; Murray et al, 2009].

Our results are, of course, subject to well-known concerns associated with inference based on citation data. A specific concern for citations-based research employing differentiated biomaterials is the possibility that materials substitution contributes to observed changes in

citation patterns. While the evidence suggests that this is not the case in the present study, it would be extremely informative to directly assess how researchers choose among research tools when designing experiments. The case of human embryonic stem cell research seems like a plausible setting. The set of human embryonic stem cell lines is relatively small and well-defined, and it is relatively easy to observe which specific cell lines are employed in published work and to track evolution in the set of cell lines used in the research community. Using a discrete choice framework, one could, in principle, study the impact of policy shocks to stem cell research funding on the supply and demand of differentiated research tools and estimate the impact of such choices on the productivity of follow-on research.

Finally, the purpose of BRCs is to enhance access to discoveries and findings even after they are disclosed through scientific publication. Analogously, in the private sector, the patent system provides a mechanism for disclosure but does not provide a guarantee of access to the underlying technology (in the absence of a license). When research is cumulative or a single downstream innovation depends on access to multiple upstream technologies, it is possible that private contracting over technology transfer may lead to an inefficiently low level of sharing and technology transfer [Arrow, 1962; Teece, 1981; Scotchmer, 1991; Aghion et al., 2008; Heller, 2008]. While institutions such as patent pools and standard setting organizations attempt to address these challenges, a promising area for future research would be to examine empirically the consequences of alternative institutions and policies whose purpose is to unlock technology “gridlock” in a cumulative research environment.

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TABLE 1
VARIABLES & DEFINITIONS

VARIABLE	DEFINITION	SOURCE
CITATION CHARACTERISTICS		
FORWARD CITATIONS _{jt}	# of Forward Citations to Article <i>j</i> in Year <i>t</i>	Science Citation Index (SCI)
CUMULATIVE CITATIONS _{jt}	# of FORWARD CITATIONS from publication date to YEAR _{<i>t</i>-1}	SCI
YEAR	Year	SCI
AGE	Year – Article Publication Year	SCI
ARTICLE CHARACTERISTICS		
BRC ARTICLE	Dummy variable equal to 1 if Article is associated with a material deposited in the biological resource center ATCC (the American Type Culture Collection)	ATCC
BRC ARTICLE, WINDOW PERIOD	Dummy variable equal to 1 if Article is referenced by BRC deposit and YEAR = DEPOSIT YEAR or DEPOSIT YEAR plus or minus + 1	ATCC
BRC ARTICLE, POST DEPOSIT	Dummy variable equal to 1 if Article is referenced by BRC deposit and YEAR > DEPOSIT YEAR + 1 (i.e., deposit has already occurred and DEPOSIT WINDOW PERIOD already passed)	ATCC
COLLECTION	Dummy variable indicating the collection with which the article is associated (1 = Gazdar Collection; 2 = Tumor Immunology Bank (TIB); 3 = Human Tumor Bank (HTB)) <i>Gazdar Collection:</i> This collection was transferred into the ATCC when Dr. Adi Gazdar left his position as Head of Tumor Cell Biology Section at the National Cancer Institutes, along with his collaborator, Dr. John Minna, to become Professor of Pathology at the Hamon center for Therapeutic Oncology at UT Southwestern. The Gazdar collection was incorporated into ATCC over a number of years; the materials examined in this paper were accessioned into in 1994. <i>TIB Collection:</i> The Tumor Immunology Bank (TIB) was created at ATCC when a collection was transferred from the Salk Institute in 1981, and accessioned into the ATCC over the next few years. <i>HTB Collection:</i> The Human Tumor Bank was maintained at Sloan-Kettering until 1981; it was accessioned into the ATCC collection over the next few years.	ATCC
DEPOSIT YEAR	Year in which the material associated with Article <i>j</i> is “accessioned” and available for purchase through the ATCC	ATCC
PUBLICATION YEAR	Year in which Article <i>j</i> is published	SCI
US AUTHOR	Dummy variable equal to 1 if Reprint Author (corresponding author) associated with an institution located in the United States; 0 otherwise	SCI; author verification
TOP 50 UNIVERSITY	Dummy variable equal to 1 if Reprint Author (corresponding author) is associated with an institution that appears in top 50 according to the Center for Measuring University Performance (Arizona State University) 2006 Annual Report of university research rankings	CMUP (ASU)
TOP JOURNAL	Dummy variable equal to 1 if article appears in a journal with ISI Journal Impact Factor greater than 25.	SCI; author verification
CITING ARTICLE CHARACTERISTICS		
CITES FROM US AUTHOR ARTICLE	Count of citations from Reprint Author (corresponding author) associated with an institution located in the United States	SCI; author verification
CITES FROM TOP JOURNAL	Dummy variable equal to 1 if article appears in a journal with ISI Journal Impact Factor greater than 25.	SCI; author verification
CITES FROM ARTICLE WITH SINGLE SUBJECT CATEGORY	Count of citing articles associated with only a single ISI scientific subject category, based on the ISI broad subject category classification scheme.	SCI
CITES FROM ARTICLE WITH MULTIPLE SUBJECT CATEGORIES	Count of citing articles associated with more than one ISI scientific subject category, based on the ISI broad subject category classification scheme.	SCI

TABLE 2a
MEANS & STANDARD DEVIATIONS

VARIABLE	MEAN	STANDARD DEVIATION	MIN	MAX
ARTICLE CHARACTERISTICS (n=216 articles)				
BRC ARTICLE	0.50	0.50	0	1
PUBLICATION YEAR	1979.40	4.54	1970	1992
DEPOSIT YEAR*	1983.63	3.47	1981	1994
US AUTHOR	0.76	0.43	0	1
TOP 50 UNIVERSITY AUTHOR	0.15	0.36	0	1
TOP JOURNAL	0.56	0.48	0	1
ARTICLE-YEAR CHARACTERISTICS (n=4857 article*year observations)				
YEAR	1989.79	7.23	1970	2001
AGE	11.27	7.23	0	31
FORWARD CITATIONS	7.28	15.73	0	186
CUMULATIVE CITATIONS	91.67	178.86	0	2333
<i>Forward Citations received from</i>				
US AUTHOR	2.60	5.87	0	59
TOP 50 UNIVERSITY AUTHOR	0.99	2.50	0	33
TOP JOURNAL	3.37	8.02	0	99
SINGLE SUBJECT CATEGORY	4.10	10.78	0	138
UNIQUE NEW JOURNALS^	2.88	4.60	0	65
UNIQUE NEW INSTITUTIONS^	5.56	10.23	0	143
UNIQUE NEW COUNTRIES^	0.79	1.41	0	16

* DEPOSIT YEAR data only for BRC-linked articles (108 articles; 2441 article-years)

^ CITATIONS BY UNIQUE NEW JOURNALS, INSTITUTIONS, and COUNTRIES refer to citations in a particular year from journals, institutions, and countries that had not cited the root article in previous years. For example, if an article were to receive 10 citations in its first year after publication, all of which appeared in *Science*, and two citations the in its second year after publication, one of which appeared in *Science* and the other of which appeared in *Nature*, then CITATIONS FROM UNIQUE NEW JOURNALS would equal one in the first year (since all publications appeared in the same journal, *Science*) and one in the second year (although two separate journals cited the root article in that year, only the citation in *Nature* is unique, as a citing article had appeared in *Science* in the previous year).

TABLE 2b
MEANS & STANDARD DEVIATIONS, BY CONTROL GROUP

	Treatment Articles: Articles Associated with ATCC Deposits	Control Articles: Most-Related Article Control*
#PAPERS	108	108
PAPER-YEARS	2437	2437
FORWARD CITATIONS	11.13 (19.64)	3.47 (9.01)
CUMULATIVE CITATIONS	250.50 (330.00)	79.60 (125.43)
PUBLICATION YEAR	1979.40 (4.37)	1979.40 (4.36)

TABLE 3
BASELINE SPECIFICATIONS

	OLS Dep Var = ln(FORWARD CITATIONS)*		CONDITIONAL FIXED EFFECTS NEGATIVE BINOMIAL* <i>[Incidence-Rate Ratios in brackets in top line]</i> <i>Estimated coefficients in 2nd line.</i> <i>(Block bootstrapped SEs reported in parentheses)</i> Dep Var = FORWARD CITATIONS	
	(3-1) Base Model: BRC Effect with Age FEs only	(3-2) Base Model, with Article Family & Year FEs	(3-3) Baseline Count Model	(3-4) Baseline Diff-in-Diffs Specification
ARTICLE CHARACTERISTICS				
BRC-ARTICLE	0.497 (0.156)***	0.501 (0.132)***	[2.121] 0.752 (0.397)***	
BRC-ARTICLE, WINDOW PERIOD	0.332 (0.125)***	0.385 (0.106)***	[1.422] 0.352 (0.234)**	[1.759] 0.565 (0.247)***
BRC-ARTICLE, POST-DEPOSIT	0.536 (0.177)***	0.535 (0.142)***	[1.713] 0.538 (0.348)***	[2.248] 0.810 (0.360)***
CONTROL VARIABLES				
<i>Parametric Restrictions</i>				
Age FEs = 0	Sig.	Sig.	Sig.	Sig.
Article Pair FEs = 0		Sig.		
Year FEs = 0 [^]		Sig.	Sig.	Sig.
Constant	0.138 (0.087)	2.213 (0.111)***		
Observations	4857	4857	4753	4729
R-squared	0.24	0.54		
Log Likelihood	-7096.50	-5897.88	-10759.18	-9632.40
Number of Article Pairs			106	
Number of Articles				211

* Robust standard errors, adjusted for clustering by article group, are reported in parentheses in the OLS regressions in (3-1) and (3-2).

[^] Year FEs included for 1980-2001; 1970-1974 and 1975-1979 grouped.

TABLE 4
ACCOUNTING FOR THE AGE PROFILE OF BRC-LINKED ARTICLES

	CONDITIONAL FIXED EFFECTS NEG BINOMIAL <i>[Incidence-Rate Ratios in brackets in top line]</i> <i>Estimated coefficients in 2nd line.</i> <i>(Block bootstrapped SEs reported in parentheses)</i> Dep Var = FORWARD CITATIONS			
	(4-1) Interacting BRC-article*Age	(4-2) Accounting for BRC-article age & time since deposit	(4-3) Identification based only on variation within BRC-linked sample (with grouped year FEs)	(4-4) Identification based only on variation within BRC-linked sample (with polynomial expansions for year and BRC-age)
ARTICLE CHARACTERISTICS				
BRC-ARTICLE, WINDOW PERIOD	<i>[1.515]</i> 0.415 <i>(0.302)**</i>	<i>[1.514]</i> 0.415 <i>(0.361)*</i>		
BRC-ARTICLE, POST DEPOSIT	<i>[1.677]</i> 0.517 <i>(0.438)**</i>	<i>[1.676]</i> 0.516 <i>(0.474)*</i>	<i>[1.633]</i> 0.490 <i>(0.351)**</i>	<i>[1.576]</i> 0.455 <i>(0.312)**</i>
BRC-ARTICLE*AGE	[1.028] 0.028 (0.018)	[1.028] 0.028 (0.038)		
YEARS SINCE BRC- DEPOSIT		[1.000] 0.000 (0.040)		
CONTROL VARIABLES				
<i>Parametric Restrictions</i>				
Age FEs	Sig.	Sig.		
Calendar Year effects via single-year dummies [^]	Sig.	Sig.		
Calendar Year effects via 5-year dummies			Sig.	
Year				[1.130] 0.122 (0.053)***
Year-squared				[0.997] -0.003 (0.001)***
Age			[0.991] -0.009 (0.027)	[0.995] -0.005 (0.036)
Age-squared			[0.998] -0.002 (0.001)**	0.998 -0.002 (0.001)
Observations	4729	4729	2041	2041
Log Likelihood	-9620.40	-9620.40	-5124.31	-5118.40
Number of Groups	211	211	105	105

* significant at 10%; ** significant at 5%; *** significant at 1%

[^] Year FEs included for 1980-2001; 1970-1974 and 1975-1979 grouped.

TABLE 5
EXPLORING SUBSTITUTION BETWEEN ARTICLES

	CONDITIONAL FIXED EFFECTS NEG BINOMIAL <i>[Incidence-Rate Ratios in brackets in top line]</i> <i>Estimated coefficients in 2nd line.</i> <i>(Block bootstrapped SEs reported in parentheses)</i> Dep Var = FORWARD CITATIONS TO MOST-RELATED- OWN ARTICLE
Article Characteristics	
BRC-ARTICLE, WINDOW PERIOD	[1.656] 0.504 (0.261)***
BRC-ARTICLE, POST DEPOSIT	[1.748] 0.558 (0.318)***
Control Variables	
Age FEs	Sig.
Year FEs	Sig.
Observations	4197
Log Likelihood	-7550.19

* significant at 10%; ** significant at 5%; *** significant at 1%

TABLE 6
HETEROGENEITY IN TREATMENT EFFECTS ACROSS ROOT ARTICLES

	CONDITIONAL FIXED EFFECTS NEG BINOMIAL <i>[Incidence-Rate Ratios in brackets in top line]</i> <i>Estimated coefficients in 2nd line.</i> <i>(Block bootstrapped SEs reported in parentheses)</i> Dep Var = FORWARD CITATIONS		
	(6-1) Post-deposit effects for papers outside and inside top journal set	(6-2) Post-deposit effects for papers generated by authors outside & inside Top 50 Unis	(6-3) Post-deposit effects for papers classified according to pre-deposit levels of citation (using quartiles)
ARTICLE CHARACTERISTICS			
BRC-ARTICLE, WINDOW PERIOD	[1.209] 0.190 (0.107)***	[1.211] 0.191 0.124***	[1.169] 0.156 0.132***
<i>BRC-ARTICLE, POST-DEPOSIT type</i>			
BRC-ARTICLE IN TOP JOURNAL	[1.708] 0.535 (0.238)**		
BRC-ARTICLE NOT IN TOP JOURNAL	[2.155] 0.768 (0.341)***		
BRC-ARTICLE FROM TOP 50 UNIVERSITY		[1.793] 0.584 0.349***	
BRC-ARTICLE NOT FROM TOP50 UNIVERSITY		[1.870] 0.626 0.208***	
BRC-ARTICLE IN LOWEST CITATION QUARTILE AT TIME OF DEPOSIT (Q1)			[1.812] 0.594 0.365***
BRC-ARTICLE IN 2 ND LOWEST CITATION QUARTILE AT TIME OF DEPOSIT (Q2)			[2.431] 0.888 0.553***
BRC-ARTICLE IN 2 ND HIGHEST CITATION QUARTILE AT TIME OF DEPOSIT (Q3)			[2.006] 0.696 0.296***
BRC-ARTICLE IN HIGHEST CITATION QUARTILE AT TIME OF DEPOSIT (Q4)			[1.489] 0.398 0.250***
CONTROL VARIABLES			
Age FEs	Sig.	Sig.	Sig.
Year FEs	Sig.	Sig.	Sig.
Observations	4860	4860	4860
Number of Groups	215	215	215
Log Likelihood	-9911.76	-9919.14	-9905.89

* significant at 10%; ** significant at 5%; *** significant at 1%

Tests of Joint Restrictions:

(6-1): $\beta(\text{Post-Deposit BRC-Article in Top Journal}) = \beta(\text{Post-Deposit BRC-Article in Not Top Journal})$:

$chi2(1) = 2.64; Prob > chi2 = 0.10$

(6-2): $\beta(\text{Post-Deposit BRC-Article from Top50 University}) = \beta(\text{Post-Deposit BRC-Article not from Top50 University})$:

$chi2(1) = 0.06; Prob > chi2 = 0.81$

(6-3): $\beta(\text{Post-Deposit BRC-Article in Lowest Citation Quartile}) = \beta(\text{Post-Deposit BRC-Article in Highest Citation Quartile})$

$chi2(1) = 0.67; Prob > chi2 = 0.4145$

$\beta(\text{Post-Deposit BRC-Article in Lowest Citation Quartile}) = \beta(\text{Post-Deposit BRC-Article in 2nd Highest Citation Quartile})$

$chi2(1) = 0.25; Prob > chi2 = 0.6183$

$\beta(\text{Post-Deposit BRC-Article in Lowest Citation Quartile}) = \beta(\text{Post-Deposit BRC-Article in 2nd Lowest Citation Quartile})$

$chi2(1) = 1.23; Prob > chi2 = 0.2678$

$\beta(\text{Post-Deposit BRC-Article in 2nd Lowest Citation Quartile}) = \beta(\text{Post-Deposit BRC-Article in Highest Citation Quartile})$

$chi2(1) = 4.16; Prob > chi2 = 0.0414$

$\beta(\text{Post-Deposit BRC-Article in 2nd Lowest Citation Quartile}) = \beta(\text{Post-Deposit BRC-Article in 2nd Highest Citation Quartile})$

$chi2(1) = 0.75; Prob > chi2 = 0.3875$

$\beta(\text{Post-Deposit BRC-Article in 2nd Highest Citation Quartile}) = \beta(\text{Post-Deposit BRC-Article in Highest Citation Quartile})$

$chi2(1) = 3.33; Prob > chi2 = 0.0682$

TABLE 7A
EXPLORING HETEROGENEITY IN TREATMENT EFFECTS BY CITING ARTICLES

	CONDITIONAL FIXED EFFECTS NEG BINOMIAL <i>[Incidence-Rate Ratios in brackets in top line]</i> <i>Estimated coefficients in 2nd line.</i> <i>(Block bootstrapped SEs reported in parentheses)</i>			
	(7a-1)		(7a-2)	
	<i>DV = Forward Citations by articles not in top journals</i>	<i>DV = Forward Citations by articles in top journals</i>	<i>DV = Forward Citations by articles with a Single Subject field</i>	<i>DV = Forward Citations by articles with Multiple Subject fields</i>
ARTICLE CHARACTERISTICS				
BRC-ARTICLE, POST-DEPOSIT	[1.721] 0.543 (0.193)***	[2.098] 0.741 (0.401)***	<i>[0.728]</i> <i>-0.318</i> <i>(0.137)*</i>	[2.543] 0.933 (0.353)***
CONTROL VARIABLES				
Age FEs	Sig.		Sig.	
Year FEs	Sig.		Sig.	
Observations	9596		7294	
Log Likelihood	-14891.16		-13256.34	
Number of Groups	426		323	
Test for equality of regression BRC-ARTICLE, POST-DEPOSIT coefficients				
	chi2(1) = 0.70 Prob > chi2 = 0.404		chi2(1) = 32.91 Prob > chi2 = 0.000	

*Coefficients for BRC-Window articles included in regressions but suppressed in order to focus on key variables in the analysis. IRRs reported in brackets; raw coefficients reported in middle line.
* significant at 10%; ** significant at 5%; *** significant at 1%*

TABLE 7B
EXPLORING THE IMPACT OF DEPOSIT ON UNIQUE NEW CITATIONS

	CONDITIONAL FIXED EFFECTS NEG BINOMIAL <i>[Incidence-Rate Ratios in brackets in top line]</i> <i>Estimated coefficients in 2nd line.</i> <i>(Block bootstrapped SEs reported in parentheses)</i>		
	(7b-1)	(7b-2)	(7b-3)
	<i>DV = Post-deposit impact on annual count of Unique New Institutions in set of citing papers</i>	<i>DV = Post-deposit impact on annual count of Unique New Journals in set of citing papers</i>	<i>DV = Post-deposit impact on annual count of Unique New Countries in set of citing papers</i>
ARTICLE CHARACTERISTICS			
BRC-ARTICLE, POST-DEPOSIT	[1.976] 0.681 (0.281)***	[1.737] 0.552 (0.223)***	[1.909] 0.647 (0.250)***
CONTROL VARIABLES			
Age FEs	Sig.	Sig.	Sig.
Year FEs	Sig.	Sig.	Sig.
Observations	4860	4860	4860
Log Likelihood	-9255.01	-7305.66	-4304.69
Number of Groups	216	216	216

*Coefficients for BRC-Window articles included in regressions but suppressed in order to focus on key variables in the analysis. IRRs reported in brackets; raw coefficients reported in middle line.
* significant at 10%; ** significant at 5%; *** significant at 1%*

TABLE 8
BRC DEPOSIT COST-EFFECTIVENESS ANALYSIS

Calculation	Baseline Cost Per Citation*	BRC Accession Cost	BRC Citation Boost	Cost per Citation for BRC-linked Articles	BRC Cost-Effectiveness Index[‡]
BRC-Deposited Articles Citation Boost	\$2,887	\$10,000	40.96	\$244.12	11.83
Sample Article Citation Boost	\$2,887	\$10,000	30.14	\$331.80	8.70
Top Ten University Citation Boost[^]	\$2,887	\$10,000	16.65	\$600.45	4.81
Random University Citation Boost[^]	\$2,887	\$10,000	9.68	\$1,032.94	2.79

* Based on Adams-Griliches (1986) estimate of cost per citation.

[^] Based on Adams-Griliches (1986) estimate of citations received by articles authored by member of Top Ten Biology departments and other university Biology departments.

[‡] BRC Cost-Effectiveness Index = (Baseline Citation Cost)/(BRC Citation Cost)

FIGURE A
AVERAGE ANNUAL CITATIONS BY AGE,
BRC VS. CONTROL ARTICLES

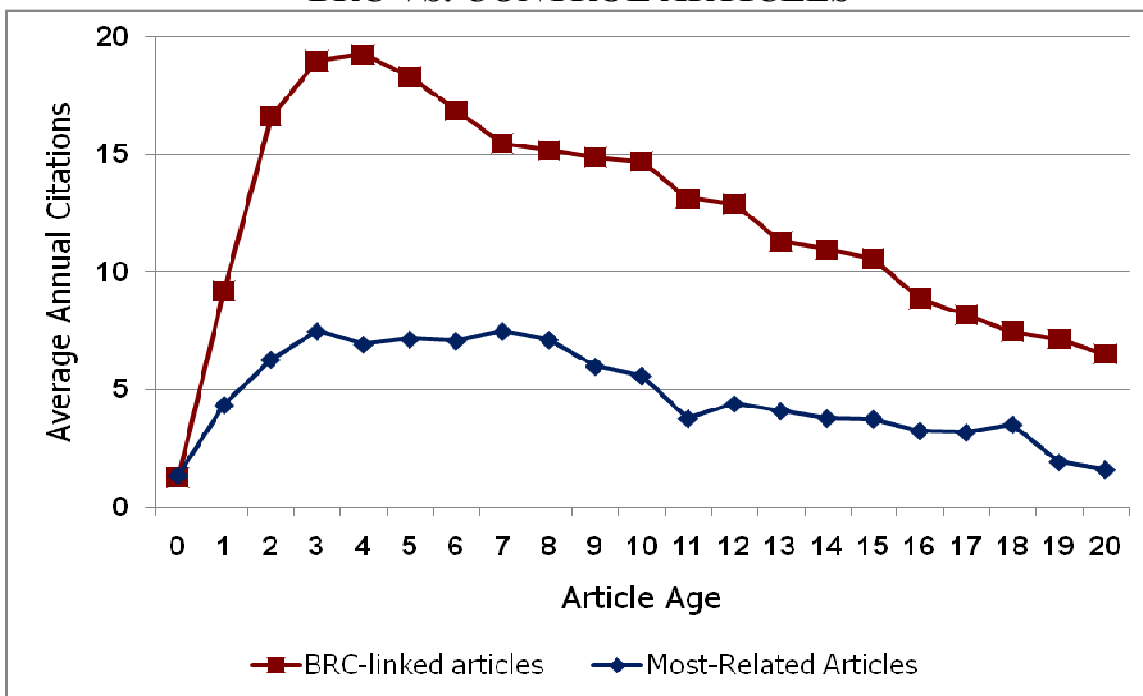


FIGURE B
PRE- AND POST-DEPOSIT EFFECTS ON FORWARD CITATIONS

