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RESEARCH PAPER

Analyzing research outcomes and spillovers at a US nanotechnology user facility

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Abstract This paper maps research outcomes and identifies spillover effects at a US University Research Center (URC) that offers user facilities for nanotechnology research. We use scientometric and network science approaches to analyze measures of topical orientation, productivity, impact, and collaboration applied to URC-related Web of Science abstract publications records. A focus is on the analysis of spillover effects on external organizations (i.e., non-affiliated users). Our findings suggest the URC's network relies on external organizations acting as brokers, to provide access to the facilities to other external organizations. Analysis of heterophily indicates that collaboration among internal and external organizations is enhanced by the facilities, while articles written by a mix of co-authors affiliated with internal and external organizations are likely to be more cited. These results provide insights on how URCs with user facilities can create conditions for diverse collaboration and greater research impact.

Keywords Nanotechnology · User Facilities · University Research Centers · Spillovers · Networks

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Introduction

A University Research Center (URC) is an organization created in a university to address a research need within, across, or separate from departments [1]. Such organizations have the potential to increase research capacity by creating and strengthening professional ties, increasing skills, and expanding access to specialized resources [2]. This article focuses on a particular type of URC, one that provides facilities for research and development for users both within and outside of the hosting university. These types of URCs are believed to create environments that encourage collaboration among researchers at internal and external organizations (i.e., those that operate the facilities vs. those that have access but do not operate the facilities) but little research has been done to support this belief.

This paper develops a set of research indicators to provide insights on the extent to which a US URC with user facilities fosters research productivity,

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impact, and especially collaboration among users. We explore the dynamics among internal and external researchers that derive from the URC's facilities to analyze the interaction of research outcomes with organizations' typologies. Results suggest the URC provides good opportunities for diverse organizations to collaborate and relies on a group of brokers to connect the facilities with external organizations. In addition, productivity, impact, and collaboration intensity are bolstered with mixed (i.e., internal and external) co-authorship instances.

For our case, we examine the Southeastern Nanotechnology Infrastructure Corridor (SENIC), which offers specialized services through user facilities spread over two university locations. These user facilities include open-access cleanrooms with nanofabrication and nano-characterization tools for research in nanoscience and nanotechnology. SENIC provides users from academia, companies, and government with access to fabrication and characterization tools, instrumentation, and expertise across multiple disciplines of nanoscale science, engineering, and technology. These facilities are located at Georgia Institute of Technology (Georgia Tech) and the Joint School of Nanoscience and Nanoengineering (JSNN), the collaborative academic facility of North Carolina Agricultural and Technical State University (N.C. A&T) and the University of North Carolina, Greensboro (UNCG). SENIC is a member site of the National Nanotechnology Coordinated Infrastructure (NNCI), a program sponsored by the National Science Foundation (NSF) which supports 16 user facility sites in the USA.

An approach common among research managers for showing and reporting the research contributions of NNCI user facilities (as with other URCs) is to present counts of publications by affiliated researchers. Facilities may also note accrued citations or highlight papers from affiliated researchers that appear in high-impact journals. We seek to demonstrate how facilities can go beyond these standard measures to employ metrics, using readily available publication data that could add value to assessments of NNCI facility research activities and their achievement of program justification and improvement objectives. Examples of these objectives include (1) stimulating more published research, (2) encouraging more authors from more diverse institutions to access user facilities for collaborative research, (3) encouraging research in "non-traditional fields" (in this case, outside of materials science, chemistry, nanoscience, and physics), and (4) encouraging higher-impact research. In this article, we identify indicators that can inform assessments of such objectives and undertake analyses that more fully map research outcomes.

Our contribution stems from studying interactions among internal and external organizations associated with a URC with user facilities. This approach differs from URC studies that focus exclusively on relationships and impacts among their own center members. We suggest widening the scope of study to include external associates since the spillover effects that facilities generate for external researchers is a particular feature of research centers, such as those that are part of the NNCI program, where user facilities are made publicly available to outside users. Other insights arise from the comparison of SENIC's research to the overall field of nanoscience and technology, and a description of its research profile based on its geographical distribution, types of organizations, map of science, and aggregate impact indicators. These analyses provide evidence of the performance of the center and could be undertaken by other URCs, especially those with user facilities and access by external researchers.

The next section discusses the literature on the effects of university research centers and user facilities on scientific outcomes. This is followed by descriptions of the data and methodology used to access, download, and clean publication records and the approaches used to produce research publication indicators, generate a map of science for the focal URC, and perform network analyses. A presentation of results shows the distributions, summary statistics, and analysis of variance (ANOVA) of the main indicators. A map of science is presented to characterize the research profile of the center within the overall fields of science. A network analysis examines SENIC's organization co-authorship network, from which inferences are made about the network's structure, the ability of the center to promote collaboration between different types of organizations, how communities are created within it, and the identification of key organizations within (i.e., central in each community) and between them (i.e., with the ability to create bridges between communities). The final section discusses conclusions and limitations.

Theoretical framework: user facilities and research outcomes

Scientific and technical human capital (STHC) theory [2] is a particularly relevant strand in the literature on approaches to understanding outcomes from investments in research and the mechanisms through which those outcomes are generated and diffused. STHC theory contends that the accumulation of human capital in a researcher comes from the sum of network ties, access to resources in a broad sense, and individual technical knowledge and skills. We draw on this notion to test how URCs influence collaboration, productivity, and impacts for and among affiliated researchers.

Additionally, the STHC framework advances a link between collaboration and productivity, with the implication that this can be enhanced through affiliation with a URC. There is extant evidence that collaboration is positively correlated with research productivity for research scientists affiliated with a URC [3]. Another possible mechanism guiding the effect of URCs on research outcomes is the accumulation of trust, governance, and cooperation among researchers affiliated with a center, which leads to more effective research outcomes [4].

Studies using the STHC framework to investigate the impacts of research center affiliations have found that, after joining a research center, typically an individual's human capital is enhanced through knowledge exchange and cooperation with other participants and access to a center's resources. Results show that affiliation with a URC increases researchers' productivity, collaboration (with industry and colleagues from other institutions), and interdisciplinarity [5]. Center-affiliated researchers have more links with industry compared to exclusively department-based colleagues [6] and are more productive than non-center-affiliated faculty members, with particularly large benefits for senior tenured faculty [7].

Research on the macro effects of research centers provides insights into the mechanisms that augment affiliated researchers' human capital. Analysis of the NSF Nanoscale Science and Engineering Centers (NSECs) finds that these centers signal new research areas, decrease the transaction costs of interdisciplinarity work, develop dense networks, enhance collaboration among different types of organizations, and accelerate the careers of young researchers [8]. Comparable findings emerge from the Energy Frontier Research Centers within the US Department of Energy, which generate new co-authorship instances, increase the intensity of the existing ones, and improve the quality of research among its members [9].

Building on the above literature, we seek to understand the dynamics between center affiliation and researchers' levels of research collaboration, productivity, and impact, mediated by human capital enhancements through creating new social ties and accessing new resources, as the STHC theory proposes. The contribution we make to this literature is by focusing on—and examining the effects of—a URC that offers user facilities. This increases the diversity of potential users (including external and internal users) and may influence the potential for prospective effects on their human capital.

The available research on the impacts of user facilities is limited but does suggest that these facilities enable the realization of collaborative experimental and research work, stimulate interdisciplinary research, and positively affect researchers' careers [10]. Additionally, more complex tasks can be performed at user facilities due to the specialized equipment available (compared to what is typically available in individual laboratories). This means that the facilities themselves, and the overall host URC, can play a role not only in research but also in training and the development of sophisticated skills in a field of science [11].

A feature of a URC with open user facilities is its potential to generate knowledge spillovers for external users (i.e., researchers that are not employed by the organization hosting the URC). This creates distinctive internal–external dynamics, potentially leading to new patterns of collaboration and gains for research productivity and impact. For instance, given that most university researchers tend to collaborate mostly with others in the same home laboratory or research center [12], expanding access to external researchers through user facilities may generate new links and positively affect the research outcomes of its users. It can also attract knowledge from different institutions in different geographical locations, which can enhance research outcomes by exploiting recombinatorial potential [13]. These effects might well be larger than those produced solely by intra-university internal collaboration, since inter-organizational collaborations (which user facilities promote) tend to provide multiple opportunities for productive interactions, notwithstanding transaction costs associated with trust building, incentive alignment, and distance [14, 15].

Access by external users of URCs facilities promises to produce gains for both internal and external organizations, mediated by their collaboration dynamics. On the one hand, internal (university academic) researchers could produce more discoveries, with more variety, as they interact with researchers from industry who have higher propensities to patent [16]. On the other hand, external users in general, and firms in particular, can benefit from accessing URC facilities. This is supported by evidence suggesting that firms seek to locate close to clusters of academic innovative activity [17] and those that collaborate with universities have higher R&D productivity and levels of patenting [18]. Rather than academics assuming primary roles in collaborations with the industry, university-industry interactions in nanotechnology research have been found to result in lead authorships from academia and industry in similar proportions [19].

Some scientific and technical problems require collaboration and cannot be addressed individually (e.g., due to problem complexity or the need for complementary capabilities or equipment). Academic and industry links can emerge to conjointly handle such problems [20]. URCs with user facilities that promote internal–external collaborations are likely to be conducive arrangements for cooperatively working on these types of problems.

Informed by insights from both STHC theory and available URC studies, we develop an approach for research outcome mapping and analyzing the spillover effects of the facilities on non-affiliated users. We apply this approach to examine the patterns of research collaboration, productivity, and impact on internal and external researchers affiliated with a specialized user facility for nanotechnology research.

Data and methodology

Data source and cleaning

The main data source used to retrieve publication records is the Web of Science (WoS), a widely available scientific publication and citation database currently comprising about 75 million publication records from over 21,000 peer-reviewed journals [21]. A few records, not available in the WoS, were retrieved from Scopus, a database with similar characteristics. Records included manuscript-level information (e.g., authors, organizations, funders) and their cited references.

As an initial step, we implemented a search strategy to identify records associated with SENIC, the target URC. We extracted and collated all SENIC's peer-reviewed paper titles as publicly posted in annual reports by the center for the 6-year period from 2015 to 2020 [22]. This resulted in a list of 1644 publication titles (with author and other publication details), which we then queried in the WoS. Scientists typically publish their latest research in peer-reviewed papers in scientific journals, hence we focused on these publications and did not include SENIC's 2015–2020 reported book chapters [$N=48$] as book chapters are often not peer-reviewed for quality and this category also included encyclopedia entries and handbook chapters. Using a fuzzy matching algorithm, we compared the list of publication records identified in the WoS with the original SENIC list. We found a few false positives (i.e., records downloaded from the WoS, but not in the original list) and a few false negatives (i.e., records in the original list that were not downloaded from the WoS). To deal with the former issue, we submitted a new query in the WoS, including a "NOT" condition with the set of false positives. After following this procedure, we confirmed 1390 SENIC records in the WoS. To deal with the issue of false negatives, we corrected misspellings and special characters and submitted a new query in the WoS with the remaining 254 records. This resulted in confirming 154 additional records. The remaining 100 records were searched in Scopus, and 56 were found. Overall, following these search processes, 1600 records were retrieved.

We then used a fuzzy matching algorithm (in VantagePoint text analytics software) to remove duplicates and to clean and validate author and organization names. We also conducted further manual reviews to avoid inclusion and exclusion errors. Regarding inclusion errors, every matched name was analyzed by inspecting the WoS subject categories in which the matched authors published and the organizations with which they were affiliated to validate the matching process. This was supplemented by web searches to identify publications associated with matched authors, where checking of the algorithmic results did not provide sufficient information. Exclusion errors were addressed by inspecting every author with two or more records in the sample. Where an author's name was similar to another unmatched author, a further process of analyzing each author's publications, organizations, and web search results was used. An analogous operation was implemented to match and clean organization names. The outcome of these processes was a definitive and cleaned final dataset of 1565 SENIC peer-reviewed publication records (a return rate of 95.2% based on the original list of 1644 titles).

URC research profile

For this final publication dataset, we examined distributions and summary statistics for productivity, impact, and collaboration measures. We expected that the distribution of publication outputs and citations would be skewed, with a relatively small set of authors responsible for a relatively high proportion of publications, and a relatively set of publications responsible for a relatively large share of total citations [23]. We probed for evidence of such patterns in SENIC's publications. We compared SENIC's distributions with those from the overall field of nanoscience and nanotechnology.

Additional analyses were undertaken to characterize the research profile of the center, including the geographical distribution of publication records and the author organization type. The former was already encoded in the data downloaded from the WoS, based on the country and city of organizations of affiliated authors. The type of organization was created using a thesaurus (in VantagePoint) that classified each organization as academic, government, corporate, other nongovernmental organization (NGO), or hospital. The classifier results required post-classification review and reassignment to ensure that some organizations were appropriately grouped.

To show disciplinary clustering and interdisciplinary links, we visualized data from the publication records in a "map of science" format [24]. A standard map of science is a network representation of the visual relationship of scientific fields to one another. The nodes in the map of science are scientific fields (or groupings of journals in WoS subject categories such as "Engineering, biomedical" or "Physics, applied") and links are co-citations among fields. Fields with more co-citations are more similar and get clustered closer together. The standard map of science can be used as a "base map" and a dataset of publications can be overlaid on the base map to visually identify which fields have more or fewer publications based on the size of the "nodes" in the dataset.

In our case study, we overlay SENIC publications onto the standard map of science, such that nodal size represents the number of SENIC publications in each journal subject category. The base map and overlay method as in Rafols et al. [25] is used to profile SENIC's research outputs on the map of science. VOSviewer is used for visualizing this analysis [26]. The base map comprises predetermined links and clusters given by a similarity matrix (generated by co-citations among subject categories), to which we overlay SENIC publications' subject categories. This analysis allows us to understand from a visual standpoint which SENIC publications have the largest nodes and thus which fields or subject categories SENIC publications are concentrated in.

URC's internal and external dynamics

We studied the differences in collaboration, productivity, and impact among organizations that are formal SENIC partners, which we denote as internal organizations, and those that are not, which we designate as external organizations. We are interested in identifying whether more diverse collaboration in terms of internal and external organizations is associated with greater overall collaboration and higher impact. We rely on analysis of variance (ANOVA) to examine statistical differences in these variables.

We used a co-authorship network—which consisted of organizations as nodes and co-authorship instances as links, where the size of the nodes varied according to the number of publications, and the size of the links varied according to the number of publications co-authored—to examine the collaboration patterns among different types of organizations (e.g., industry links) and between internal (i.e., those in which there are facilities) and external organizations. The network analysis also identifies communities of organizations co-authoring together, relevant organizations according to their closeness and betweenness centrality, and brokers that bridge the gap between internal and external organizations.

We compute an assortativity coefficient to understand the extent to which authors in similar types of organizations collaborate. The assortativity coefficient ranges from − 1 to 1, from most heterophily (author-affiliated organizations only collaborate with those different from them) to most homophily (author-affiliated organizations only collaborate with those like them). The two attributes employed to measure similarity are whether the organization is (1) academic, corporate, government, other NGO, or hospital, and (2) internal or external.

A second analysis identifies communities of relevant organizations. A community is formed when organizations are more densely connected to one another than to the rest of the network. For the three largest communities, we identify the central organizations; those with the shortest path lengths to all other organizations (measured with closeness centrality) and those that are in between the maximum number of the shortest paths (measured with betweenness centrality). The results of this analysis contribute to identifying groups of organizations working together and the way they connect to the rest of the network through their pivotal nodes.

A third metric is constraint, which provides insights into the organizations that connect different communities. The constraint of a node measures how much the collaborators of an organization are also connected among themselves. Nodes with low constraints have access to disparate information by connecting different organizations. They are potential brokers; intermediaries between nodes that do not have direct access to each other. Computing the constraint of the nodes in SENIC reveals those organizations that connect communities without facilities with the communities that do have facilities.

Results

This section presents the results of the analyses, based on the approaches described in the preceding section on data and methodology.

URC research profile

There are 4575 unique authors in the dataset of 1565 SENIC publication records. As anticipated, the productivity distribution is positively skewed. While the median number of publications is 1, the mean is 1.77, being pulled by high values at the right end of the distribution. The bottom 72% of authors have one publication each, with the top 10% accounting for 42% of the publications. There is heterogeneity above the 99% percentile, ranging from 16 to 65 publications per author.

In terms of citation impacts, the 1565 publications in the dataset accumulated a total of 40,937 citations. The top 10% of cited works accounted for 35% of total citations, while the bottom 5% of the publications had zero citations. The average publication received 26 citations, although this figure is skewed by a few articles with numerous citations, as the much lower median of 12 citations suggests. We compared SENIC-associated publications with a dataset for the whole nanotechnology field (888,539 WoS publication records from 2016 to 2019, retrieved following the search strategy described in Wang et al. [27]). Both mean and median levels of citations are greater for SENIC than the equivalent values for the overall nanotechnology field (4.7 and 2, respectively). The SENIC publication set includes publications from 2020 and early 2021, which will have had less time to accrue citations than the overall nanotechnology dataset. Although we have not controlled for other factors that could influence citations (such as number of authors, which we control for later in this paper), this comparison suggests that SENIC's research has a high citation impact compared to all nanotechnology publications.

The number of citations also exhibits great heterogeneity above 99% of the distribution, ranging from 236 to 962 citations. The top 10 most cited records show that research produced with the use of SENIC's facilities is published in top journals in the fields of nanoscience and nanotechnology, chemistry, materials science, electric and electrical engineering, mechanical engineering, and physical chemistry. The list of journals includes *Chemical Reviews*, *Nature Energy*, *Nature Materials*, *Nature Communications*, *ACS Nano*, *Advanced Materials*, *Advanced Functional Materials*, *Energy and Environmental Science*, *Nano Letters*, and *Small.*

Usage count, a measure of viewing and downloading records from the WoS platform, is over three times larger than the citations count in our sample, with an accumulated count of 46,524 instances. Its distribution has a mean of 64, a median of 30, and a maximum value of 1586. Publications with zero usage account for only 1% of the distribution. In terms of usage count, SENIC also exhibits a greater impact when compared to the overall field. The latter has a mean of 37 and a median of 19 by this measure.

The number of authors per publication—a measure of team collaboration—is less skewed in the SENIC publication dataset than for the productivity and impact variables. There are few single-authored publications (only eight); most of the articles are written by six co-authors (median = 6 and mean = 6.1), the top 5% includes 12 or more co-authors in each publication, and the publication with the largest number of co-authors is written by 39 co-authors. These figures are slightly higher than those from the overall field of nanoscience and nanotechnology, where the average number of authors per publication is 5.5 and the mean is 5.

In terms of types of organization and geographical distribution, most papers are dominated by academic and US authors. Ninety-nine percent of SENIC-associated publications have at least one academic author, followed by government (13%), and corporate (13%). Likewise, 89% of publications have at least one author affiliated with a US organization, and 14% have at least one non-US author. The top non-US authors are based in China (8% of SENIC publications have at least one Chinese author) and South Korea (2% of SENIC publications have at least one South Korean author).

To analyze SENIC's topical orientation, we use a map of science, where each node is a WoS subject category, and links are based on co-citation instances. The position of each node in the figure and clusters (in colors) are pre-defined by a similarity matrix. Overlaying SENIC's research data changes the size of the nodes, such that larger nodes represent subject categories in which a greater proportion of SENIC's articles are published. The map shows that SENIC's research is concentrated in a few fields, grouped mostly in three clusters: materials science, physics, and nanotechnology (in green), biochemistry and other biosciences (in red), and electrical and electronic engineering (in blue). Out of 117 subject categories, the following six account for 62% of the total record frequency in the sample: materials science, multidisciplinary (17%); nanoscience and nanotechnology (11%); physics, applied (10%); chemistry, physical (9%); chemistry, multidisciplinary (8%); and engineering, electrical and electronic (7%) (Fig. 1).

Besides the categories mentioned above, SENIC generates knowledge in other areas, including nontraditional fields, such as bioscience, environmental science, energy and fuels, and experimental medicine research. There are, for instance, 124 records

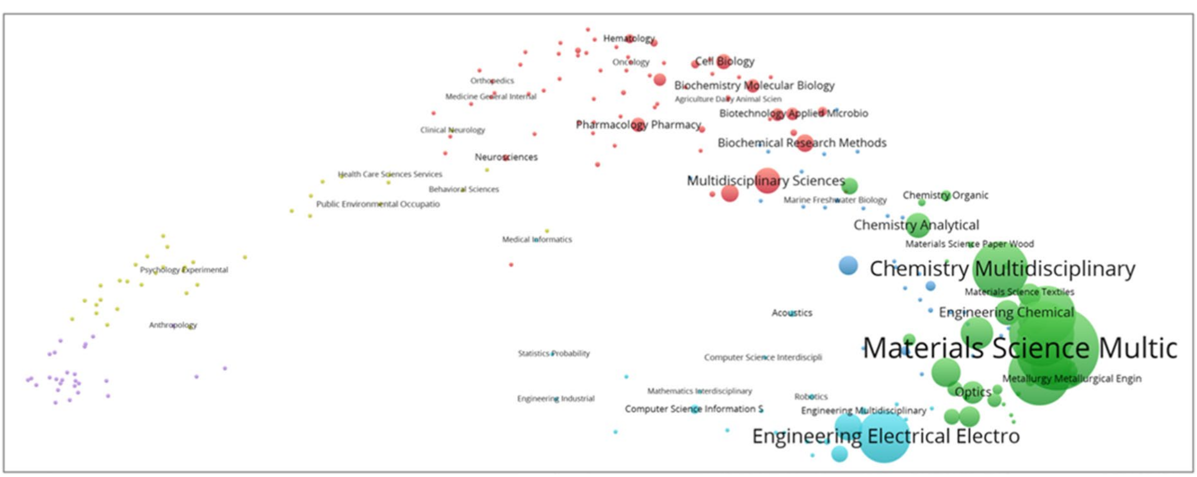

Fig. 1 SENIC—Map of science. Source: authors' VOSviewer analysis of 1565 peer-reviewed SENIC publications from 2016 to 2020. Nodes represent subject categories with their size determined by the number of publications. Edges and clusters are predetermined using a similarity matrix from co-citations among subject categories

in bioscience, appearing in biomedical engineering, biomedical research methods, and biotechnology and applied microbiology. Research on environmental science is also produced with the use of the facilities, contained in 38 records from environmental sciences and 11 records in environmental engineering. Energy and fuels with 98 records is another field in which SENIC has made contributions, as well as experimental medicine with 16 records.

While the map of science is a representation of the research profile of SENIC in terms of its location in the overall field patterns of science, it does not provide information about the quality and impact of this research. To gain an idea of the quality of this research, we considered the impact factors of the top 20 journals in which SENIC's records are most published. These journals include *Chemical Reviews* (impact factor = 52.7), Nature Energy (46.5), Nature Materials (38.6), *Advanced Materials* (27.4), *Advanced Functional Materials* (16.8), *ACS Nano* (14.6), *Angewandte Chemie-International Edition* (12.9), *Small* (11.5), *Journal of Materials Chemistry A* (11.3), *Nano Letters* (11.2), and *Proceedings of the National Academy of Sciences of the United States of America* (9.4). Overall, we find that a significant portion of SENIC's research is published in leading journals in the fields of nanoscience and nanotechnology, materials science, and chemistry. This finding is robust to measuring impact in alternative ways (e.g., Eigenfactor Score).

In summary, SENIC's publications follow a regular pattern in research whereby a small subset of authors accounts for most publications, and a few publications account for most citations and usage counts. Overall, SENIC's research exhibits a higher impact, in terms of citations and usage, when compared to the overall nanoscience and nanotechnology field. It demonstrates a slightly higher collaboration intensity as measured by the number of authors per publication. In terms of topical orientation, SENIC's publications focus on materials science, physics, nanoscience and nanotechnology, and electrical and electronic engineering.

URC's internal and external dynamics

We further explored differences in the main variables depending on the organization type, whether it is internal (i.e., Georgia Tech, JSNN, N.C. A&T, UNCG) or external (not a primary or partner SENIC organization). Using publications as the unit of analysis we find that out of the total 1575 publications, 948 (60%) are mixed (i.e., are written by both, internal and external authors), 524 (34%) are internal only and 90 (6%) are external only.

There are more authors per publication in mixed articles, followed by external and internal publications (a median of 7, 4.5, and 4 respectively). An analysis of variance suggests that these differences between the groups in the sample are statistically significant at a 5% significance level; a Tukey pairwise comparison test indicates that mixed publications have more authors per paper than external and internal, while the difference between external and internal is not statistically significant.

We analyze the differences between these organizational types based on the number of citations. Mixed publications garner more citations than internal and external publications, with a median of 13 citations for mixed publications compared to a median of 10 for internal and 9 for external publications. The analysis of variance suggests that these differences are statistically significant at a 5% significance level. A Tukey pairwise comparison test indicates that this effect is attributed to the significant difference between the more highly cited mixed versus the less highly cited external-only publications. In sum, within SENIC's records, mixed articles are also the ones with more collaboration and impact.

To study in more depth the interplay among different types of organizations, we created a co-authorship network at the organization level. SENIC's co-authorship network is made of 777 nodes (organizations) and 2698 edges (co-authorships). With the igraph R package, we also generated network benchmarks by averaging 1000 simulations using the Erdős–Rényi model [28] which selects a similar graph at random from all possible graphs with the same number of nodes (777) and edges (2698). A comparison provides an indication of how SENIC's network characteristics differ from a typical network with the same nodal and co-authorship patterns. Compared to the averaged random network with the same features, SENIC's network is characterized by a relatively small diameter (i.e., fewer steps to connect any two organizations), lower average path length (i.e., the typical organization can be reached in fewer steps by any other organization), and a higher average clustering coefficient (i.e., there is a higher number of complete triangles, meaning that if organization X collaborates with Y and with Z, Y also collaborates with Z) (see Table 1). This structure suggests that SENIC has created a "small-world network" [29]; a network where most organizations relate to each other, suggesting that information flows readily, and any organization can be quickly reached. This network structure facilitates collaboration and can have positive effects on productivity and impact on the facility's users.

To explore the degree of collaboration among different types of organizations in SENIC, we first estimated an assortativity coefficient and visualized the co-authorship network using the following categories as an attribute: academic, corporate, government, other NGO, and hospital. We obtained an assortativity coefficient of 0.22, which implies that organizations have a weak preference for collaborating with the same type. The visualization of the co-authorship network illustrates this pattern by showing that most of the organizations are academic, and the rest are scattered over the graph without strong segregation patterns (see Fig. 2). While organizations of the same type are still pulled to each other, the strength of their attachment is relatively low given the predominance of academic organizations in the dataset.

A second assessment based on the assortativity coefficient aims at answering whether internal organizations in SENIC collaborate more with external organizations or prefer to work among themselves. In this case, the assortativity coefficient is − 0.14, indicating that internal organizations have a weak preference for collaborating with external organizations. The pattern is observed by coloring the internal and external organizations in the co-authorship network. This shows that internal organizations take a central role in their communities and collaborate with several external organizations (see Fig. 3), meaning that SENIC spurs collaboration between internal organizations and the rest of the network.

We identify the main communities and central organizations within and between them. The Louvain algorithm for community detection [30] creates 48 communities in SENIC's network. The top three most populated communities contain 79% of all the author's organizational affiliations. Georgia Tech leads the most populated community (the blue community in Fig. 4). It has the greatest betweenness centrality (i.e., serves as a bridge to other author affiliation nodes) and closeness centrality (i.e., shortest path length to all other author affiliation nodes) (Table 2). The Georgia Tech-centered community is characterized by numerous external author organizational affiliations collaborating with Georgia Tech authors in a clear internal–external collaboration pattern.

Table 1 SENIC network structural characteristics

Measure	SENIC	Random graph	Interpretation
Average degree	6.9	6.8	The typical organization is connected to about seven other organizations
Average weighted degree	20.6	7.0	There are plenty of repeated collaborations
Diameter	6.0	6.8	Any two organizations in the network can be connected in six or fewer steps
Radius	4	5	At least four steps are required to get from an organization to its farthest organization
Average path length	2.34	3.65	The typical organization is about two steps away from any other organization in the network
Graph density	0.01	0.01	1% of the potential connections among the organizations in the network are realized
Number of communities	48	17	Three SENIC communities comprise about 70% of the organizations
Average clustering coefficient	0.85	0.01	The network is cohesive. Most organizations tend to be related to each other. There is a high proportion of complete triangles (x and y, x and z, and y and z). Together with a short average path length, it suggests a small-world network
Nodes	777	777	
Edges	2698	2698	

Source: analysis of 1565 peer-reviewed SENIC publications from 2016 to 2020 compared with averages from 1000 Erdős–Rényi random graph simulations with the same number of nodes (representing organizations) and edges (representing co-authorship instances)

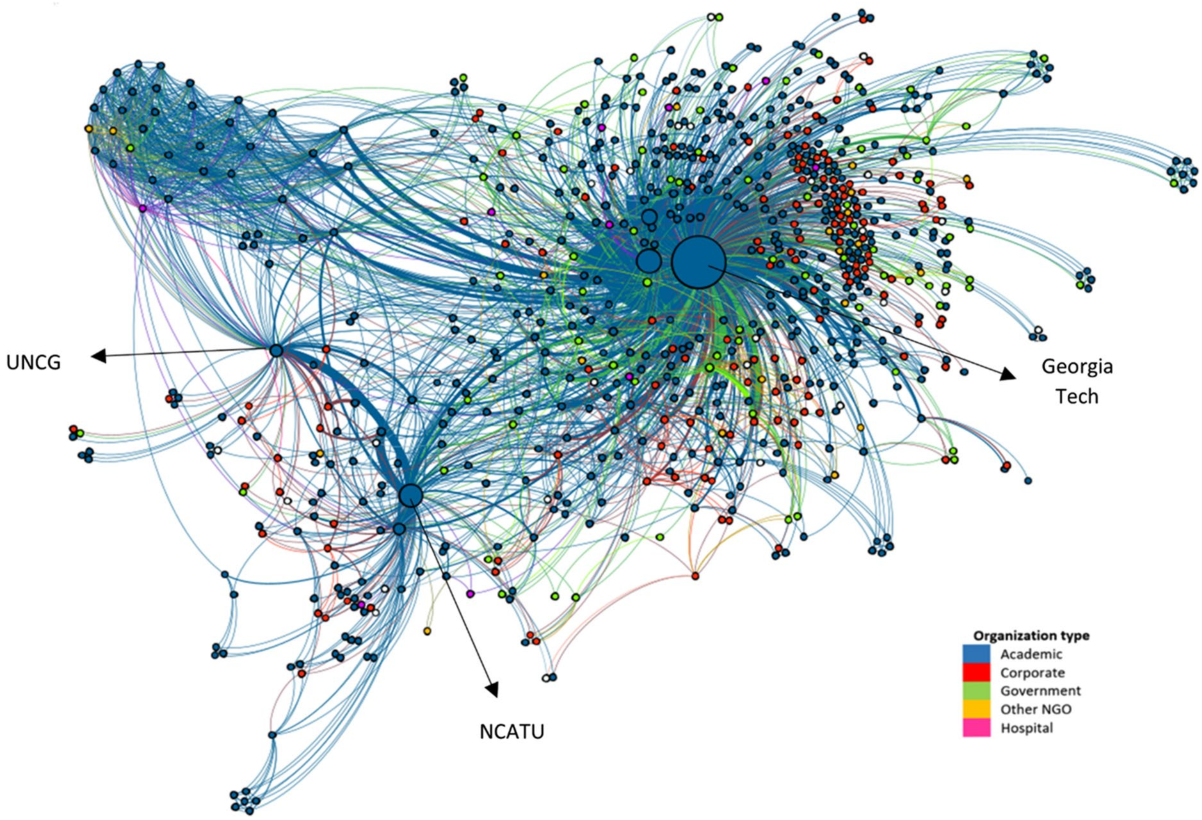

Fig. 2 Co-authorship network by type of organization. Source: analysis of 1565 peer-reviewed SENIC publications from 2016 to 2020. Nodes represent organizations and links are co-authorship instances. The size of the nodes varies according to the number of publications of each organization. The width of the links varies according to the number of publications co-authored between pairs of organizations. Colors vary by organization type (see legend)

The second-largest community is centered on JSNN, N.C. A&T, and UNCG (the purple community in Fig. 4). The community indicates strong collaboration among N.C. A&T, UNCG, the University of North Carolina at Chapel Hill (UNCCH), and North Carolina State University (NCSU). These organizations are also the most central. UNCCH, N.C. A&T, and UNCG have the highest betweenness centrality (serving as bridges) in the community and UNCCH and NCSU the maximum closeness centrality (Table 2). The rest of the community is made of external organizations, many of which are international.

The third most populated community (the green community in Fig. 4) is an interesting case since this community does not have internal SENIC facilities, but it still has research production and collaboration within the network. It is made of 49 organizations appearing in 111 records, including publications from the following organizations: Penn State University, Peking University, MIT, Rice University, Harvard University, Carnegie Mellon University, University of Bordeaux, University of Tokyo, University of Maryland, and the University of Strasbourg. Penn State has the highest betweenness and closeness centrality (Table 2). It also has co-authorship connections with other organizations. It is a low-constrained organization, which implies that it can connect information and resources from diverse external to internal organizations (i.e., it functions as a broker in the network). This community has most of the low-constrained organizations of the entire network, meaning that it relies on brokers (i.e., organizations connecting different parts of the network) to bring external

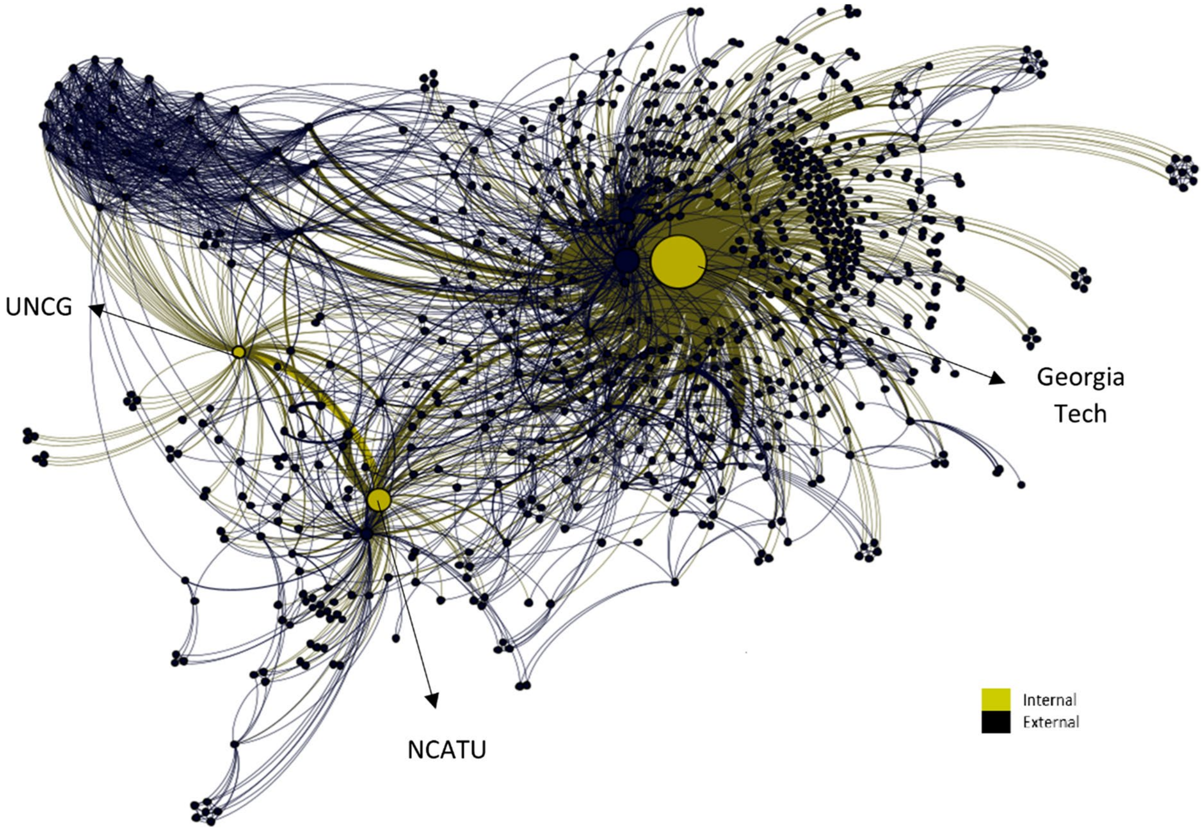

Fig. 3 Co-authorship network, internal and external organizations. Source: analysis of 1565 peer-reviewed SENIC publications from 2016 to 2020. Nodes represent organizations and links are co-authorship instances. The size of the nodes varies according to the number of publications of each organization. The width of the links varies according to the number of publications co-authored between pairs of organizations. Colors vary by whether the organization is internal or external (see text for definitions)

organizations into the user facilities. Other than Penn State, organizations playing this role within the community are Harvard University, the University of Tokyo, and the University of Strasbourg. These organizations act as links between the user facilities and the rest of their community.

Discussion and conclusions

We have presented a case study of a university research center (SENIC) with specialized user facilities for nanoscience and nanotechnology research, to develop and test an approach for research outcomes mapping using scientometric and network science tools. We find that SENIC's research outcomes distributions are skewed. We compare these distributions with those in the overall field of nanotechnology and nanoscience and find that SENIC's papers have a greater impact, both in terms of citations and usage count. They also exhibit slightly higher collaboration intensity, as measured by their number of authors. This suggests that SENIC has met its objective to strengthen and accelerate the discovery in nanoscience and nanoengineering across the southeastern USA.

SENIC is a national research center where most researchers are affiliated with US organizations that are predominantly academic (although there are strong government and corporate collaborators). In terms of its research orientation, SENIC's research is focused on materials science, chemistry, physics, and nanotechnology. However, we also found an emerging interest in other fields, including biosciences and

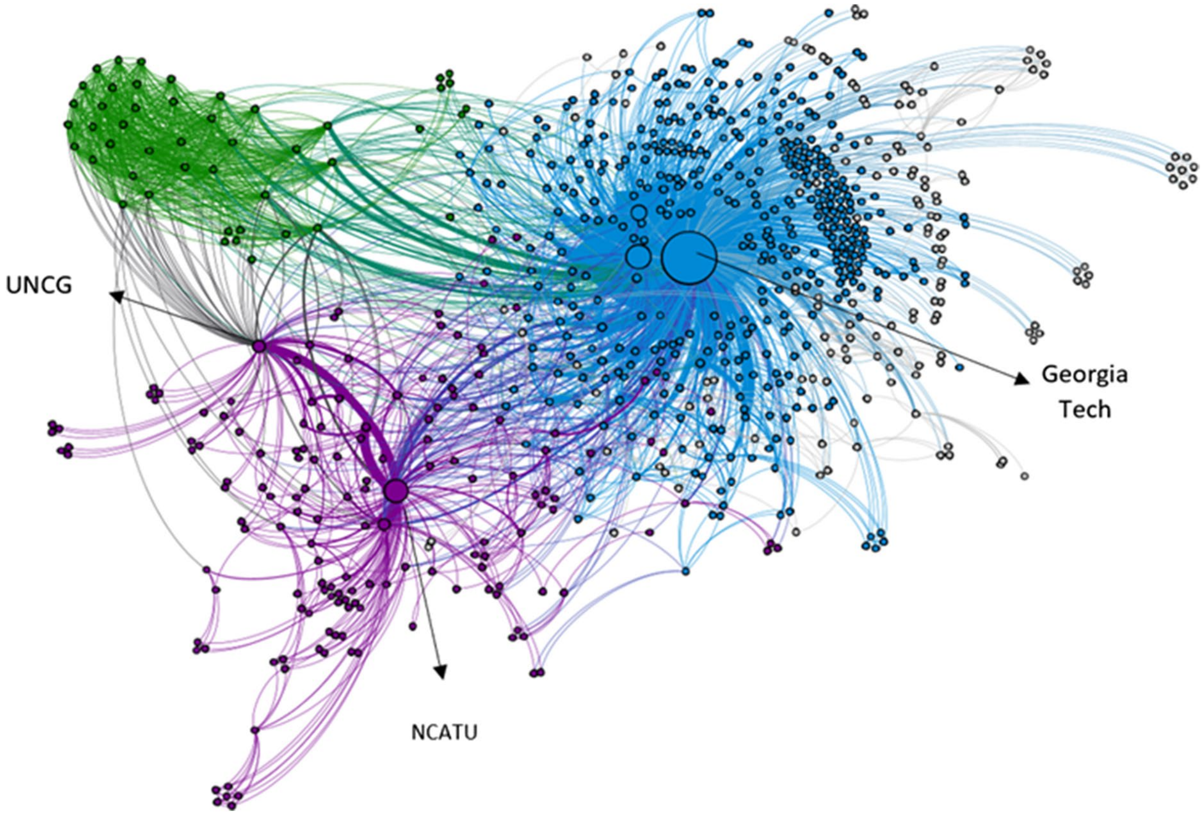

Fig. 4 Co-authorship network by communities. Source: analysis of 1565 peer-reviewed SENIC publications from 2016 to 2020. Nodes represent organizations and links are co-authorship instances. The size of the nodes varies according to the number of publications of each organization. The width of the links varies according to the number of publications co-authored between pairs of organizations. Colors represent the three co-authorship network communities as discussed in the text

energy, which are linked to SENIC's aim of serving a broad range of domains.

The differential effects and dynamics of internal and external organizations (i.e., the principal organizations that have facilities located at their campuses and those that do not) suggest a characteristic of these types of research facilities in bringing together diverse users. Mixed articles (i.e., those written by both internal and external authors) are co-authored by a greater number of researchers, indicating that collaboration between different types of organizations is related to higher overall collaboration. Mixed articles are also more cited than internal and external articles. This provides evidence of positive feedback mechanisms among the number of co-authors, the diversity in the organizations involved, and the impact of the research.

To understand SENIC's collaboration patterns, we analyzed its organizations' co-authorship network. Assessing the homophily in the network, we found that organizations have a low tendency to collaborate with others of the same type (e.g., academic, government, corporate). Also, authors from internal organizations tend to collaborate more with authors from external organizations than with their home organizations. These findings indicate that SENIC provides opportunities for different types of organizations to collaborate and access its specialized facilities, supporting its objective to translate discoveries into commercial products by enterprises. A complementary finding for the third most populated community in the network, where there are no internal user facilities, demonstrates reliance on brokers—unconstrained organizations linking

Table 2 Top 15 organizations by closeness and betweenness centrality

Closeness centrality		Betweenness centrality	
Top 15 organizations	Score	Top 15 organizations	Score
Georgia Tech	0.813	Georgia Tech	249,192
Univ N Carolina at Chapel Hill	0.521	Univ N Carolina at Chapel Hill	21,499
Emory Univ	0.518	North Carolina A&T State Univ	18,464
Penn State Univ	0.516	Univ North Carolina Greensboro	13,099
Arizona State Univ	0.507	Emory Univ	7173
Univ Washington	0.506	Wake Forest Univ	5555
Wake Forest Univ	0.505	Penn State Univ	4197
Harvard Univ	0.500	Chinese Academy of Sciences	3071
N Carolina State Univ	0.500	N Carolina State Univ	2644
Univ Illinois	0.498	Arizona State Univ	2600
Chinese Academy of Sciences	0.498	Georgia State Univ	2288
Oak Ridge Natl Lab	0.497	Harvard Univ	2031
MIT	0.494	Shanghai Jiao Tong Univ	1716
Shanghai Jiao Tong Univ	0.493	Univ Strasbourg	1648
Univ Calif Irvine	0.492	MIT	1512

Source: analysis of 1565 peer-reviewed SENIC publications from 2016 to 2020

different types of nodes and parts of the network—to get access to the facilities.

The structural features of SENIC's co-authorship network suggest it has certain elements of a small-world network, meaning that any organization affiliated with the center can be reached by any other in a few steps. This entails that SENIC is a cohesive research center, where most organizations relate to each other, information flows easily, and any organization can be readily reached. This pattern might suggest that URCs with user facilities can bring organizations together around a common research theme, taking advantage of specialized resources not available in individual laboratories, and creating a fertile research interaction where collaboration and productivity flourish.

An important contribution of this study is its focus on understanding the effects of specialized user facilities. We highlight a range of research outcomes that can emerge from user facilities. User facilities provide capabilities for researchers at institutions operating the facilities but also for researchers at other institutions. This study finds a spillover effect of these user facilities on research outside of the operating institutions. One of the key objectives of SENIC, as expressed in the abstract of its NSF award, is to create a "research ecosystem that is strengthened by collaboration, sharing of best practices, scholarly interaction, and mutual support" [31]. The evidence from our analysis of SENIC's networks and collaborations indicates that the center has established a collaborative and scholarly interactive research ecosystem.

We acknowledge limitations in the study. The case study is based on one URC user facility in a particular field (nanotechnology). The study also focuses on a set of research outcomes that can be readily measured using available publication databases. Other outcomes, including for research training and capability enhancement or for patenting, innovation, and business performance, are not measured. Nonetheless, while the study has provided findings for a specific case study, we suggest that this approach for mapping research outcomes and analyzing dynamics among internal and external researchers is a tool that can be replicated and refined by other NNCI user facilities. More generally, this framework could be useful as a tool to inform and enhance the assessment of research indicators for centers, organizations, and networks in other technological domains and programs.

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Declarations

Conflict of interest One of the authors is the Coordinator of Social and Ethical Implications at the Southeastern Nanotechnology Infrastructure Corridor (SENIC). The authors do not have other competing interests to declare.

Disclaimer Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

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