Received: 21 June 2023 | Revised: 15 December 2023 | Accepted: 6 February 2024

DOI: 10.1111/ssqu.13339

ORIGINAL ARTICLE

Translating interdisciplinary knowledge for gender equity: Quantifying the impact of NSF ADVANCE

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Alexander J. Gates and Jessica R. Gold shared lead authorship.

Funding information
National Science Foundation Directorate for STEM Education (EDU), Grant/Award Numbers: 1836671, 2000713

Abstract

Background: Interdisciplinarity is often hailed as a necessity for tackling real-world challenges. We examine the prevalence and impact of interdisciplinarity in the NSF ADVANCE program, which addresses gender equity in STEM.

Methods: Through a quantitative analysis of authorship, references, and citations in ADVANCE publications, we compare the interdisciplinarity of knowledge produced within the program to traditional disciplinary knowledge. We use Simpon's Diversity Index to test for differences across disciplines, and we use negative binomial regression to capture the potential influences of interdisciplinarity on the long-term impact of ADVANCE publications.

Results: ADVANCE publications exhibit higher levels of interdisciplinarity across three dimensions of knowledge integration, and cross-disciplinary ties within ADVANCE successfully integrate social science knowledge into diverse disciplines. Additionally, the interdisciplinarity of publication references positively influences the impact of ADVANCE work, while the interdisciplinarity of authorship teams does not.

Conclusions: These findings emphasize the significance of interdisciplinarity in problem-oriented knowledge production, indicating that specific forms of interdisciplinarity can lead to broader impact. By shedding light on the interplay between interdisciplinary approaches, disciplinary structures, and academic recognition, this article contributes to programmatic design to generate impactful problem-solving knowledge that also adds to the academic community.

Interdisciplinarity has long been an academic ideal (Abbot 2001, pp. 131–32). Yet, despite targeted attention from funding agencies and universities encouraging interdisciplinary collaboration (Jacobs and Frickel, 2009; Sá, 2008), disciplinary knowledge is still privileged across many metrics and interdisciplinary collaboration still faces challenges (Kniffin and Hanks, 2017; MacLeod, 2018; Rhoten and Pfirman, 2007; Zhao and Tsatsou, 2018). One framework capturing the tension between interdisciplinary and disciplinary knowledge suggests that disciplinary knowledge excels in abstract, theory-driven academia, while interdisciplinary knowledge is vital for generating practical knowledge (Ledford, 2015; Okamura, 2019).

This distinction is reflected in solicitations from funding agencies that champion interdisciplinary collaboration to solve real-world problems, such as international migration (Bommes and Morawska, 2005), obesity and other public health issues (Tiffin, Bruce Traill, and Mortimer 2006; Von Lengerke, 2006) and natural resource management (Freudenburg and Gramling, 2002). Because translational endeavors have different epistemic goals and potentially different reward structures compared to traditional academia (Bianco and Schmidt, 2017), interdisciplinarity may be best positioned for institutionalized acceptance in applied science.

However, there remain many questions around the applicability of interdisciplinary knowledge production in the translation of abstract concepts to solutions. For example, if interdisciplinary knowledge is not well suited for producing abstract theory-driven knowledge, is it indeed successful at generating problem-oriented knowledge? How does interdisciplinarity manifest in large grant-funded programs, and which forms of interdisciplinarity matter most for specific programmatic or problem-solving goals? Is interdisciplinarity equally prevalent across fields, and how might field epistemic differences align with problem-solving goals to affect knowledge integration? Given that both interdisciplinarity and engaged scholarship may have adverse career impacts, especially on scholars already marginalized in academia (Ellison and Eatman, 2008; Gonzales and Rincones, 2012; Kniffin and Hanks, 2017), does the scientific community acknowledge this interdisciplinary knowledge at commensurate levels? How might we structure funding programs to both produce important problem-solving knowledge while maintaining academic impact that is so important to careers?

To begin to address these questions, we use a case study of a multidecade National Science Foundation (NSF) funded program called ADVANCE, which supports interdisciplinary projects aimed at addressing a real and complex issue: gender equity in academic science, technology, engineering, and math (STEM) fields. Within the translational context of a knowledge-producing program such as ADVANCE, we address the following questions:

First, does the ADVANCE program succeed at integrating knowledge across disciplines compared to a disciplinary approach?

Second, does the ADVANCE program successfully integrate knowledge between social science and STEM fields, overcoming epistemic barriers that hinder cross-field interdisciplinary knowledge production?

Finally, given that disciplinary knowledge and organization continue to be rewarded according to more traditional academic measures (e.g., citations, journal impact, and tenure and promotion), which forms of interdisciplinary knowledge produced in this problem-oriented setting, if any, achieve higher impact vis-à-vis traditional academic measures of success?

To address these questions, we quantify the author, reference, and citational interdisciplinarity of academic publications in the ADVANCE program, comparing the scope, dimension, and impact of these three dimensions within ADVANCE publications and to publications in academia more broadly. First, we find that affirmatively, ADVANCE publications are indeed more interdisciplinary than traditional disciplinary knowledge across all three forms of interdisciplinarity. While not unexpected given the ADVANCE program's interdisciplinary nature, this confirmation sets the stage for a deeper investigation into the different contexts and impacts of ADVANCE interdisciplinarity. Second, we find that for cross-disciplinary ties, ADVANCE publications in all disciplines integrate knowledge from social science fields, increasing interdisciplinarity overall. At the same time, social science ADVANCE knowledge has a much broader impact across disciplines (including STEM) than in academia more generally. Finally, we find that the interdisciplinarity of publication references increases the impact of ADVANCE work, while the interdisciplinarity

of authorship teams does not. Together, these findings highlight the importance of interdisciplinarity in problem-oriented knowledge production for broader impact and demonstrate a framework to understand which forms of interdisciplinarity, and across which disciplines, may be most successful at doing so.

DISCIPLINARITY VERSUS INTERDISCIPLINARITY

Interdisciplinarity is increasingly discussed by the scientific community (including funding agencies) as a means to increase the rate of innovation and discovery and to solve complex real-world problems. Yet scientific knowledge production, training, dissemination, and career reward structures continue to operate within relatively siloed disciplines (Becher, 1994; Harris and Shaffer, 2022; Posselt et al., 2020; Sá, 2008). The organization of modern academia into disciplines, departments, and institutions forms a relatively rigid set of constraints which, despite "talking the talk," continually struggles to "walk the walk" in support of interdisciplinary work (Rhoten, 2004). Instead, interdisciplinary work is often accomplished through researchers' intrinsic commitments. However the cost to researchers can be high since interdisciplinary work is often on the margins of the traditional measures of scholarly productivity that matter most for legitimacy, recognition, and career advancement (Gonzales and Rincones, 2012; Rhoten, 2004).

Despite these barriers and risks, many researchers continue to pursue interdisciplinary work, especially in research contexts directly connected to real-world problem solving (Haynes and Leonard, 2010). Yet little is known about how *much more* interdisciplinary work in an applied setting may be, nor what forms of interdisciplinarity are most used in such a context. Scholars studying the science of science recognize multiple forms of interdisciplinarity—that is, the ways in which knowledge is blended across disciplines (Gates et al., 2019; Wagner et al., 2011; Wang and Schneider, 2020). We focus on three of the most common forms. First, *authorship interdisciplinarity* captures the diversity of disciplines among authors on a paper, assuming collaborative efforts blend ideas, theories, and methods. While common in funding calls, this does not ensure integration of diverse knowledge in the resulting publications.

Second, interdisciplinarity can be conceptualized as the extent to which a single publication combines ideas from many different disciplines, generally indicating that the publication has been *influenced by* other disciplines. This is commonly measured by the diversity of disciplines covered in the publication's references, indicating that regardless of the authors' disciplinary expertise, the knowledge presented in the publication draws from multiple disciplines.

Finally, interdisciplinarity can be conceptualized as the impact the publication has on other disciplines. This *interdisciplinary impact* does not necessarily reflect how a single publication has integrated knowledge from different disciplines, but how useful that knowledge is across multiple disciplines in future work. It is commonly measured by the diversity of disciplines that cite the publication.

Together, these three forms of interdisciplinarity cover a wide range of knowledge integration: the combination of experts in collaboration, the span of referenced disciplines within a publication, and how broadly that knowledge impacts future work in different disciplines. To address our first question—is the ADVANCE program more interdisciplinary compared to academia broadly?—we compare these three forms of interdisciplinarity in publications produced via the ADVANCE program to the corpus of all publications in the Microsoft Academic Graph (MAG), a large database of scientific publications. As interdisciplinary knowledge has been theorized to be better suited for problem-oriented tasks, we hypothesize that interdisciplinarity of all forms will be higher in ADVANCE compared to academia as a whole. Furthermore, as ADVANCE, similar to many funding agencies running such programs, encourages interdisciplinarity by expecting STEM faculty to work with social science experts, we expect that co-author interdisciplinarity will be high in outcome publications.

Hypothesis 1a. (H1a): All three forms of interdisciplinarity will be higher in ADVANCE publications compared to publications in academia more broadly.

Hypothesis 1b. (H1b): Co-author interdisciplinarity will have the largest difference between ADVANCE publications and publications in academia more broadly, compared to reference and citation interdisciplinarity.

FIELD DIFFERENCES IN INTERDISCIPLINARITY

Beyond institutional challenges, cognitive obstacles can arise from disciplinary differences in epistemologies and socialized ways of doing science (MacLeod, 2018). For example, the disciplines of sociology, psychology, and political science have the same epistemological origins, developing into relatively independent disciplines over time due in large part to political, social, and scientific evolutions (Ross, 1991). These social science disciplines thus may collaborate with and cite one another more often than with disciplines in STEM fields, which have different epistemic and methodological traditions (Sigelman, 2010). Even within problem-oriented settings, research has repeatedly shown that social science and STEM collaborations—such as clinical medicine or biophysical sciences paired with sociology—face epistemic challenges as well as social challenges around perceptions and stereotypes (Freudenburg and Gramling, 2002; Olsen, 2021). Yet, it is in these problem-oriented settings, with explicit monetary and institutional support for cross-field collaboration and with different reward structures, that we might expect more successful cross-field interdisciplinarity.

As the mission of ADVANCE is to create knowledge about systemic gender inequities in science through organizational transformation with the explicit integration of social science knowledge into gender equity frameworks in STEM disciplines, we expect ADVANCE publications to draw on more social science knowledge compared to other fields. At the same time, because ADVANCE seeks to apply social science insights to a pressing problem within STEM, we expect ADVANCE publications to be more successful at disseminating knowledge to diverse fields compared to traditional disciplinary knowledge. We measure the extent to which publications from one discipline draw their references to and citations from another discipline, controlling for the varying discipline sizes, through a measure of reference/citation strength.

Hypothesis 2a. (H2a): After controlling for a publication's discipline, ADVANCE outcome publications will reference social science fields more strongly than academia (broadly) references social science fields.

Hypothesis 2b. (H2b): After controlling for a publication's discipline, ADVANCE outcome publications will more strongly impact all disciplines compared to publications in academia more broadly.

IMPACT OF INTERDISCIPLINARITY

Disciplines not only structure systems of knowledge production but also systems of legitimacy and rewards in academia. Academic careers are largely constrained by disciplines: in departments that regulate hiring and promotion, journals with high impact factors, service through professional associations, and teaching university courses (Kniffin & Hanks, 2017). This disciplinary organization often poses challenges and risks to both interdisciplinary scholars and problem-oriented knowledge, as papers that integrate knowledge across disciplines and/or address real-world problems are seen as harder to review or find a home in the mostly disciplinary, theoretically oriented landscape of top-tier journals (Bianco and Schmidt, 2017; Ellison and Eatman, 2008; Gonzales and Rincones, 2012; Rhoten and Pfirman, 2007).

Problem-oriented scholarship has historically been devalued in academia, receiving less recognition than traditional academic work by tenure and promotion committees (Ellison and Eatman, 2008; Gold, 2021; Hutchinson, 2011; O'Meara, 2001), and facing more resistance when evaluated for publication in traditional academic journals (Posselt et al., 2020; Settles et al., 2020). These disadvantages tend to be further compounded for women and scholars of color, who are more likely to engage in problem-oriented work

(Antonio, Astin, and Cress 2000; Gold, 2021; O'Meara, 2002; Vogelgesang, Denson, and Jayakumar 2010) and are already underrepresented at all levels of academia (Nelson and Brammer, 2010). As such, academic scholars engaged in problem-oriented knowledge creation still need to consider how their work may be valued vis-à-vis traditional academic metrics.

Research suggests that, over the long term, interdisciplinary papers have higher citation impact than disciplinary papers (Chen et al., 2022; Leahey et al., 2017), though this is often coupled with findings that interdisciplinarity leads to fewer publications for authors or grant teams (Leahey et al., 2017; Park et al., 2023; Wang et al., 2015). We do not yet know, however, if reference interdisciplinarity may lead to higher academic impact for applied scholarship, and it is not clear how author interdisciplinarity might shape academic impact, particularly in applied settings. Understanding the impact of different forms of interdisciplinary outputs is important if problem-oriented programs are to successfully encourage impactful interdisciplinary knowledge creation in academic communities. Despite the well-documented inequities produced by reliance on these measures (Bell & Chong, 2010; Bernal and Villalpando, 2002; Gonzales and Rincones, 2012; Posselt et al., 2020), citation impact in particular remains a consequential form of academic capital, which scholars must pursue to attain and maintain faculty positions (Apple, 1999; Leahey, 2006; Slaughter and Leslie, 1997; van den Brink and Benschop, 2012).

Based on research on interdisciplinary impact in academia more broadly, we expect that problem-oriented research will have a greater long-term impact with increasing reference interdisciplinarity. Less is known about the potential impacts of author interdisciplinarity. On the one hand, a paper with authors from different fields may garner more citations, as each author may attract citations from their respective fields. On the other hand, papers produced by an interdisciplinary author team may not categorically fit into any one discipline (a common challenge with interdisciplinary scholarship), adversely impacting citation counts overall.

Hypothesis 3a. (H3a): Reference interdisciplinarity will be positively associated with citation counts in ADVANCE publications.

Hypothesis 3b. (H3b): Author interdisciplinarity will be positively associated with citation counts in ADVANCE publications.

DATA: THE ADVANCE PROGRAM

To examine interdisciplinarity in a problem-oriented setting, we use publication data from the NSF ADVANCE program. Since 2001, ADVANCE has funded institutional change projects to promote gender equity in academic STEM fields to increase the representation and advancement of women in the professoriate. We focus on ADVANCE specifically because if there were a space to encourage interdisciplinarity in a way that was generally supportive of women and underrepresented racial and ethnic groups in science, this would be a program well suited to do so. The main focus of the ADVANCE program is to design and implement innovative institutional transformation projects to promote gender equity at universities and in STEM organizations. But as an NSF-funded initiative, the awards also require that the projects be both evidence-based and grounded in social scientific theories, as well as *produce* knowledge based on the lessons learned from implementation and data gathered during the award period (Nelson and Zippel, 2021; Zippel and Ferree, 2019).

Prospective awardees are asked to build on prior ADVANCE work with best practices from the interdisciplinary literature on systemic gender inequities in science when designing interventions and programs on their campuses and in organizations (Gold et al., 2022). Awardees are then also expected to contribute to new knowledge on gender equity and organizational change in STEM organizations and universities.

Our study draws upon a manually curated data set capturing an important aspect of ADVANCE knowledge production: publication in peer-reviewed journals. For the 273 ADVANCE-funded awards between 2001 and 2018, we collected detailed information on all ADVANCE-related publications listed

as ADVANCE award outcome publications as defined by three primary sources: publications listed as outcomes on the NSF website, those on Google Scholar acknowledging any of these ADVANCE award numbers, and those listed as outcomes on ADVANCE awardees' program websites. As authors may overlook crediting NSF funding, our data represent a conservative count of the total knowledge published by ADVANCE teams.

These sources resulted in 838 unique outcome publications from 172 ADVANCE awards. We matched 561 of these publications to publication metadata available in the MAG. The MAG is a massive bibliometric database containing information on over 240 million papers, proceedings, book chapters, theses, etc. Computer scientists have further enhanced the available publication metadata by algorithmically tagging each publication with keyword labels from a hierarchical field-keyword ontology. We focus only on the highest level of the ontology that aligns well with the common perception of academic disciplines (19 disciplines at level 0), albeit with a few caveats: there is no "educational sciences" discipline and many of the traditional humanities disciplines are poorly captured or missing altogether.

The MAG also algorithmically disambiguates the authors on each publication, allowing us to identify the same individual across all publications in our data set. We leverage this disambiguation to assign the 1782 outcome publication authors to 991 authors. Of these authors, we found that only 671 were principal or co-principal investigators (PIs) (37.7 percent). Thus, while the ADVANCE teams of PIs are highly interdisciplinary, the authorship teams may be less interdisciplinary. We then infer each author's field as the most frequent field in their entire publication history (including both ADVANCE and non-ADVANCE publications).

To provide context for the levels of interdisciplinarity in the ADVANCE outcome publications, we compare them to academia more broadly as captured by the full MAG corpus. Critically, we control for publication year and discipline, so, for example, ADVANCE outcome publications in sociology are compared to all other publications in sociology that year. This follows other research that controls for disciplinary differences in interdisciplinarity over time and at the field level (Porter et al. 2008; Leahey et al. 2017; Gates et al. 2019; Ke et al. 2023). For this, we limit to the 81,493,122 journal articles assigned to at least one field and published after 1950, processed using the pySciSci bibliometric software package (Gates and Barabási, 2023).

MEASURING FORMS OF INTERDISCIPLINARITY

To quantify interdisciplinarity we use Simpson's Diversity Index (Simpson, 1949; Stirling, 2007) corrected for finite sample sizes. This measure was originally proposed to quantify ecological diversity but has since been adopted into the science of science. Given a distribution over bins, for example, the fraction of authors that come from each discipline, Simpson's Diversity Index is the probability that two samples come from different bins (i.e., two randomly selected authors come from different disciplines). In this version, 0 reflects a distribution that has no diversity and every author comes from the same discipline, while 1 captures the case that all authors come from different disciplines. Specifically, given a collection of N items into K bins with counts n_k in bin k, Simpson's Diversity Index corrected for finite sample sizes is given by

$$1 - \sum_{k=1}^{K} \frac{n_k \left(n_k - 1\right)}{N \left(N - 1\right)}.$$

While this measure of interdisciplinarity captures the diversity of fields integrated in ADVANCE outcome publications (H1), it does not indicate which disciplines are "strongly" tied (H2). To examine how the knowledge is combined, we use a measure of reference/citation strength between disciplines, defined as the proportion of references/citations from publications in one discipline to publications in another discipline, normalized by the size (total number of publications) of the target discipline (Frank et al., 2019).

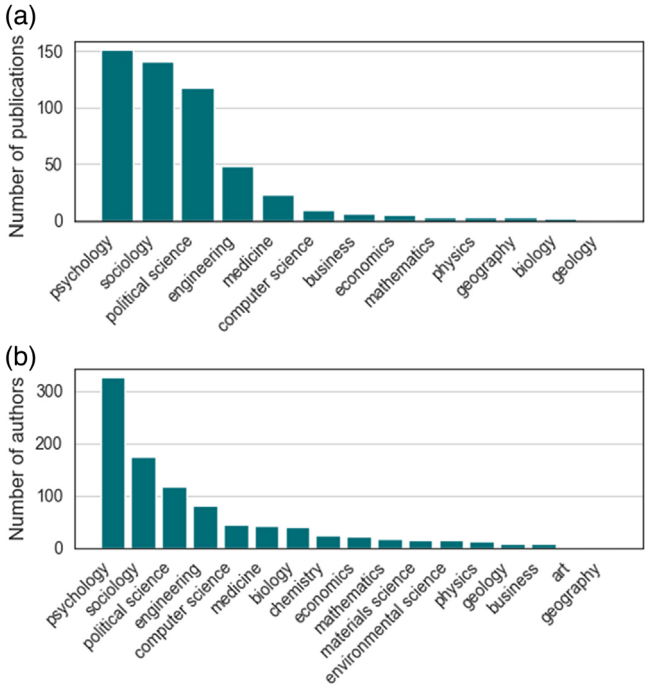

FIGURE 1 ADVANCE outcome (A) publication and (B) author multidisciplinarity.

Best understood on a log scale, a value of 1 means the source discipline references/cites the target discipline proportional to its size (i.e., as if randomly). If a value is greater than 1, it indicates that more references/citations were made to the discipline than expected by the discipline's size, while a value below 1 reflects fewer references/citations were made than expected by the discipline's size. We bootstrap 1000 sample sets of the same size as the ADVANCE discipline subset to assess the statistical significance of differences between the set of ADVANCE outcome publications and a field overall.

Finally, to capture the potential influences of interdisciplinarity on the long-term impact of a scientific publication, we use linear regression to assess the relationship between our interdisciplinary measures and citation impact. As our outcome variable is a count of citations but is also overdispersed, we use negative binomial regression rather than Poisson, and we check our results using an OLS regression model with a logged transformation of the outcome variable (reported in the Supporting Information Appendix). We include several control variables that may also be related to citation impact, such as publication year, the publication's discipline, author team size, gender-diverse author team, whether the publication was co-authored by an ADVANCE PI, and ADVANCE topic expertise (for details, see Supporting Information Appendix).

FINDINGS

We begin by looking at the disciplinary distribution of ADVANCE outcome publications and authors. As shown in Figure 1A, ADVANCE outcome knowledge was primarily published in the fields of psychology (151), sociology (141), and political science (118), followed by engineering (48) and medicine (23). This eclectic mix of primary publication disciplines reflects the diverse target audiences for ADVANCE outcome publication knowledge. While most publications are in social science journals, important messages and experiences related to STEM disciplines are still present. The "real-world" application of this knowledge attends to gender equity in STEM fields, while rooted in social science, clearly spans disciplinary boundaries in regard to the publication venues and audience. As shown in Figure 1B, almost a third of

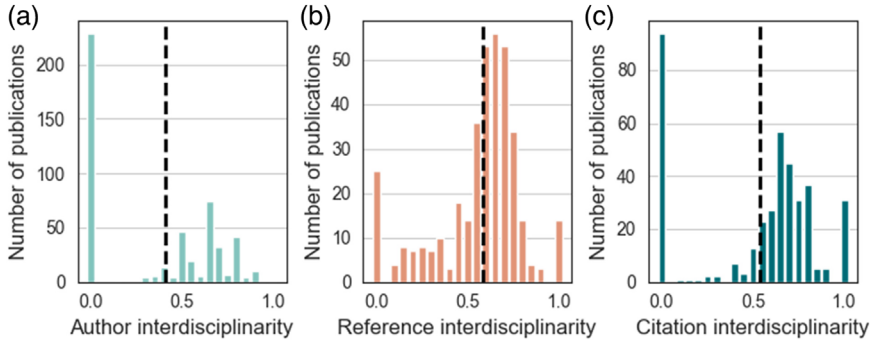

FIGURE 2 ADVANCE outcome interdisciplinarity. The distribution over ADVANCE outcome publications of Simpson's Diversity Index for (A) authorships, (B) references, and (C) citations.

authors come from psychology (326), followed by sociology (175), political science (117), engineering (80), computer science (45) and medicine (42). This predominance of psychology authors and articles is unsurprising, as compared to social science fields broadly, psychology is more likely to have published articles about sex and/or gender (Fox et al. 2022).

How interdisciplinary is ADVANCE knowledge?

To address our first research question, we assess the levels of interdisciplinarity across three forms: author interdisciplinarity, reference interdisciplinarity, and citation interdisciplinarity. As shown in Figure 2A, the distribution of authors' interdisciplinarity shows a substantial spike at 0, reflecting that a third of ADVANCE outcome publication teams are composed of a single discipline. At the same time, the distribution also shows a second set of publications with high interdisciplinarity, reflecting that about half of the ADVANCE outcome publications were authored by a team with expertise from different disciplines. Overall, the average author team interdisciplinarity is 0.41.

To establish a baseline scale for whether this amount of author interdisciplinarity is significant compared to "normal" disciplinary collaborations, and because different disciplines have varying norms and expectations for the integration of knowledge in authorship teams, we aggregate all ADVANCE publications within specific disciplines and compare the observed levels of author interdisciplinarity with a measurement over all publications in the MAG since 2000. As shown in Figure 3A, we find that overall, the disciplines with the least diverse authorship teams on average are medicine, physics, and psychology, while the most diverse are sociology, political science, and engineering. Comparing the ADVANCE outcome publications to the discipline averages, we find that ADVANCE publications in psychology, sociology, political science, engineering, medicine, and computer science had a more diverse author team than expected in the MAG (statistically significant). Thus, in fields where author team diversity is relatively high in general (e.g., sociology and engineering), ADVANCE author teams are *even more* interdisciplinary, and in fields where author team diversity is generally relatively low (e.g., psychology and medicine), ADVANCE author teams stray far from the norm.

While diverse author teams indicate that ADVANCE has successfully brought people from different fields together in the production of knowledge, it does not tell us the extent to which any produced knowledge actually draws on the fields of its authors. To measure the interdisciplinary influences on a publication, we examine a second form of interdisciplinarity: reference diversity.

The distributions for reference diversity and citation diversity of the ADVANCE outcome publications (Figure 2B,C) share many of the same features as author diversity. Comparisons within disciplines show that ADVANCE publications in psychology, sociology, political science, and medicine are the only subject areas that are statistically significantly more diverse than expected in the MAG. Similarly, the citation

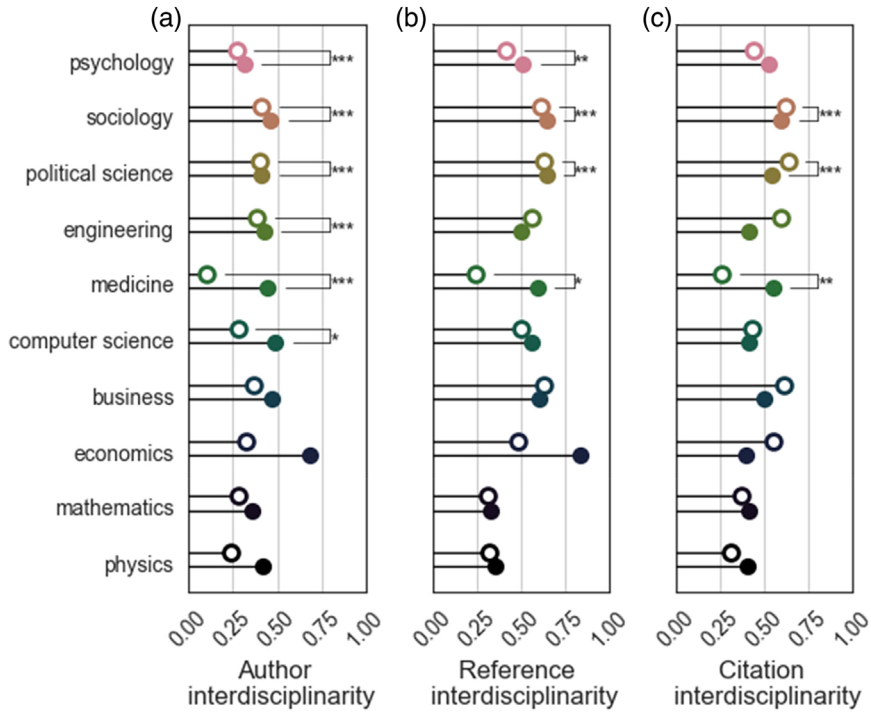

FIGURE 3 ADVANCE outcome interdisciplinarity for each field. Average Simpson's Diversity Index for all ADVANCE publications in each field (solid dots) compared to the average over the entire field (open dots) when focusing on (A) authorships, (B) references, and (C) citations. The Mann–Whitney *U*-test for differences in distributions is statistically significant at the corresponding levels: $*p < 0.05$; $**p < 0.01$; $***p < 0.001$.

diversity for ADVANCE publications in sociology, political science, and medicine is statistically significantly more diverse than expected in the MAG.

In summary, we find that ADVANCE was successful in stimulating interdisciplinary authorship teams, publications influenced by interdisciplinary references, and publications with interdisciplinary impact across most of its outcome disciplines. In support of H1a, we found that in all forms of interdisciplinarity, ADVANCE outcome publications in sociology, political science, and medicine were much more interdisciplinary than their disciplines overall. In support of H1b, we also found that co-authorship interdisciplinarity in ADVANCE was greater than the MAG baseline for six disciplines—more disciplines than reference or citation interdisciplinarity (four and three disciplines, respectively). Many funding agencies, including the NSF, encourage interdisciplinarity specifically through diverse-discipline research teams, and that encouragement appears to have been successful in the case of ADVANCE.

Are some disciplines more coupled with each other?

The analysis of reference strength suggests that the significant reference interdisciplinarity we found in ADVANCE outcome publications is largely driven by references to social science disciplines. Namely, compared to all MAG publications, ADVANCE publications in sociology are equally likely to cite sociology and political science publications but are significantly more likely to cite psychology (Figure 4A). On the other hand, ADVANCE sociology publications are less likely to reference publications from other STEM disciplines than the MAG baseline suggests: for example, computer science is a 10th as likely to

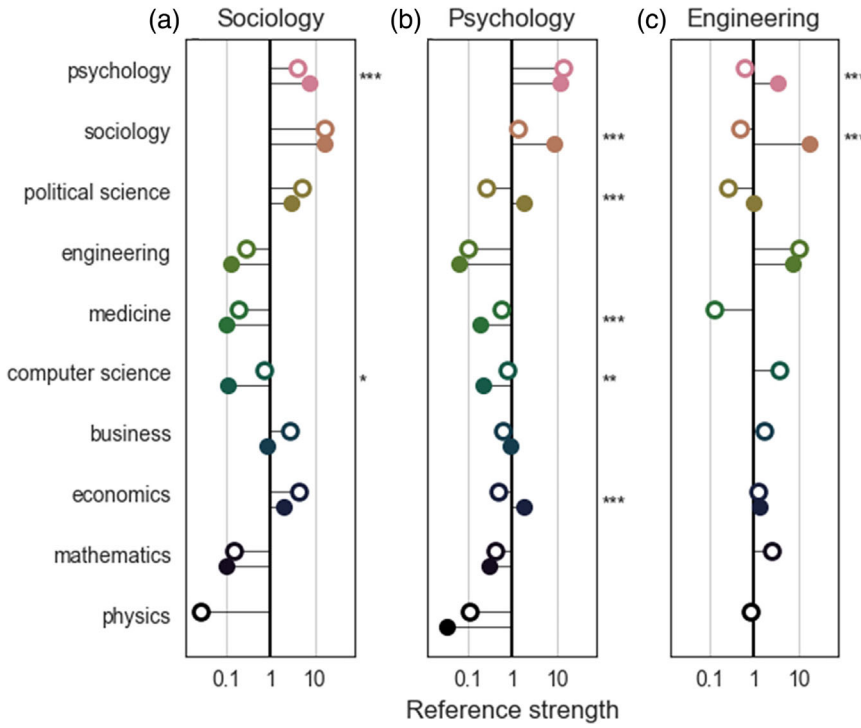

FIGURE 4 Reference strength. The reference strength for all ADVANCE publications (solid dots) in (A) sociology, (B) psychology, and (C) engineering compared to the entire field overall (open dots). Statistical significance are found from 1000 bootstrap samples are statistically significant at the corresponding levels: *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

be referenced than in non-ADVANCE sociology publications. We see a similar pattern in psychology (Figure 4B), where ADVANCE psychology publications are significantly more likely to reference sociology, political science, and economics publications than in the field of psychology in general, but less likely to reference other STEM fields such as medicine and computer science.

Outside of the social sciences, we similarly see a strong reference dependency on social science publications. This is exemplified by the reference strength for the 48 ADVANCE outcome publications in engineering (Figure 4C). First, even though these publications are focused on issues of gender equity, these ADVANCE engineering publications are still tightly coupled to the engineering literature (no statistically significant difference in reference strength between ADVANCE and all engineering publications). At the same time, these publications also strongly referenced the sociology literature (18 times the random baseline) in stark contrast to the engineering literature overall, which is half as likely to reference sociology as would be expected under the random baseline for all publications.

Taken together, these results support H2a, where the cross-disciplinary reference strength of ADVANCE publications is stronger to the social sciences overall. As these disciplines are also the most published-in fields in the ADVANCE corpus, this suggests that much of the interdisciplinarity in ADVANCE is driven by social science citations. Importantly, while social scientists are not citing STEM fields in ADVANCE publications, ADVANCE STEM publications do draw from the social science disciplines significantly more than expected in those disciplines, representing a relatively successful story of overcoming epistemic barriers. This may be in large part due to the specific problem-solving nature of the ADVANCE program, where the "problem" is widely recognized to be largely rooted in social inequalities.

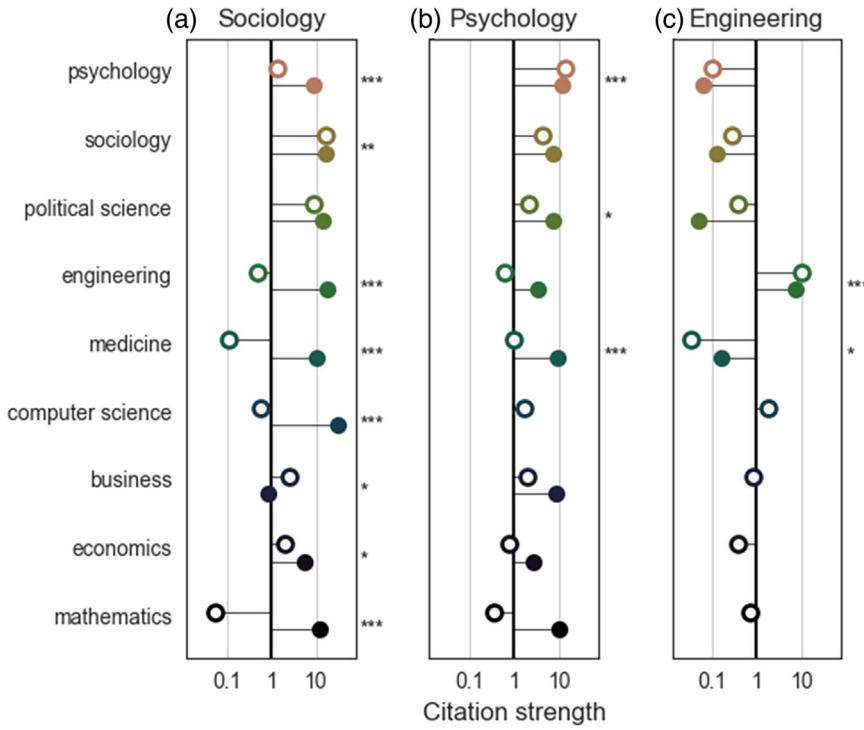

FIGURE 5 Citation strength. The citation strength for all ADVANCE publications (solid dots) in (A) sociology, (B) psychology, and (C) engineering to other disciplines, and compared to the entire field overall (open dots). Statistical significance from 1000 bootstrap samples with the corresponding levels: $*p < 0.05$; $**p < 0.01$; $***p < 0.001$.

Problem-focused programs may thus be key to identifying spaces where interdisciplinarity may not be as limited by cognitive barriers across fields.

As expected in H2b, we find that the cross-disciplinary citation strength of ADVANCE publications is more successful at disseminating knowledge to diverse disciplines compared to traditional disciplinary knowledge—but mostly for ADVANCE work published in sociology. For example, while general sociology publications produce greater impact in sociology than the ADVANCE sociology publications, ADVANCE publications in sociology are more likely than their MAG baselines to impact future work in psychology, engineering, medicine, computer science, and even mathematics (Figure 5A). However, this pattern is not as strong for ADVANCE publications in psychology, which only show statistically significant greater impact on political science and medicine publications (Figure 5B). And finally, unlike the reference strength, we do not see broad impact for ADVANCE work in STEM fields (Figure 5C).

While these patterns demonstrate some inequity in the ways disciplines integrate and impact knowledge across disciplines, they fit within the goals and operation of our case study. The ADVANCE program aims to integrate social science knowledge into gender equity frameworks in STEM disciplines while simultaneously addressing a pressing problem within STEM careers. Together, this suggests that ADVANCE publications might draw on more social science knowledge while also disseminating knowledge across diverse fields compared to traditional disciplinary knowledge. In an interdisciplinary framework, we expected that disciplines with lower epistemic barriers, such as between sociology and psychology compared to sociology and engineering, would be more tightly coupled. We found that the reference strength among social science disciplines reflected this tighter coupling, but not the citation strength. This is a crucial distinction, suggesting that epistemic similarities may have eased interdisciplinary knowledge production, but were not necessarily tied to impact.

Are some forms of interdisciplinarity more impactful?

What forms of interdisciplinarity have an effect on the traditional citation impact of ADVANCE publications? To operationalize citation impact, we use the number of citations a publication accrues over 5 years. Caution is required when using citation-based measures to assess the importance of individual papers or authors, as research shows considerable bias by race, gender, and research topics in citation patterns; still, the accessibility and quantity of such data provide one view—among many—of how scientific knowledge accumulates.

There are many factors known to potentially affect the impact of publications, including the year of publication, the publication's discipline, and the number of authors (i.e., team size). Our first model predicts publication citation impact using these three control variables (see Table 1, Model 1), and we find that publications from psychology have a statistically significant tendency to be more highly cited than other ADVANCE outcome publications. Year and team size have no effect on the impact of ADVANCE publications. Regardless, this model explains very little variance in the publications' impact.

Next, we add a few ADVANCE-specific controls (see Table 1, Model 2). Specifically, we tag publications that have at least one ADVANCE PI in the authorship team, and, since the outcome publication authors are overwhelmingly women, we tag those publications with at least one male author. Additionally, since most of the focus of ADVANCE knowledge is built upon expertise in Gender Studies or Race and Ethnicity Studies, we tag publications that contain at least one author with Gender or Race and Ethnicity expertise (see Supporting Information Appendix). This extended control model explains significantly more variance in the publications' impact. It also shows that having a PI, a gender-diverse team, or a Gender Studies Expert does not influence the publication's impact, but having Race and Ethnicity studies expertise is statistically significant and positively related to the impact of ADVANCE outcome publications. With these baselines in place, we create a third model that includes our measures of interdisciplinarity: author interdisciplinarity and reference interdisciplinarity (see Table 1, Model 3). The model coefficients show that all previously significant predictors of impact (psychology, and having a Race and Ethnicity Studies expert on the author team) remain. Author team interdisciplinarity is not a significant predictor of impact for ADVANCE outcome publications, but reference interdisciplinarity is statistically significant, has the largest standard error of any of our independent variables, and its inclusion in the model nearly doubles the explained variance while reducing the Bayesian information criterion. In other words, the interdisciplinarity of a publication's influences is a more important signature of impactful ADVANCE work than any other dependent variable, including the interdisciplinarity of a publication's authorship team.

These findings support H3a (reference interdisciplinarity will be positively correlated with citation counts) but do not support H3b. Author interdisciplinarity had no significant effect, while reference interdisciplinarity was the most important predictor of citation impact (see Supporting Information Appendix for a robustness check of these findings using OLS).

CONCLUSION

Academia is extraordinarily successful at generating disciplinary knowledge; its reward structure is almost solely focused on doing so. At the same time, many funding agencies are interested in promoting knowledge that addresses practical issues and that has an impact beyond disciplines, and beyond academia. These funding agencies recognize that successfully confronting the biggest and most complex problems—global climate crises, pandemics, extreme inequality, political violence, and extremism—requires interdisciplinary collaboration. Institutions and foundations continue to struggle, however, to support and promote interdisciplinarity within an academic system so rigidly organized—institutionally, epistemically, and methodologically—around disciplines. Nevertheless, funders persistently strive for this lofty ideal: scholars from diverse disciplines collaborating harmoniously to tackle significant problems and generate groundbreaking knowledge for others to build upon. But do these programs live up to this ideal? We found that

TABLE 1 Negative binomial regression coefficients for the three models of impact to predict C5.

Negative binomial			
	Model		
	(1)	**(2)**	**(3)**
Intercept	2.32***	2.22***	2.1***
	(2.15, 2.48)	(2.06, 2.39)	(1.94, 2.26)
	SE 0.09, $p = 0.0$	SE 0.08, $p = 0.0$	SE 0.08, $p = 0.0$
Year	−0.09	−0.09	−0.12
	(−0.27, 0.08)	(−0.27, 0.08)	(−0.3, 0.06)
	SE 0.09, $p = 0.3044$	SE 0.09, $p = 0.2966$	SE 0.09, $p = 0.1897$
Team size	−0.1	−0.16*	−0.22*
	(−0.27, 0.06)	(−0.33, −0.0)	(−0.41, −0.04)
	SE 0.08, $p = 0.2244$	SE 0.08, $p = 0.0479$	SE 0.09, $p = 0.0153$
Psychology	0.33**	0.26*	0.31**
	(0.13, 0.53)	(0.05, 0.46)	(0.11, 0.51)
	SE 0.1, $p = 0.0014$	SE 0.1, $p = 0.013$	SE 0.1, $p = 0.0027$
Sociology	0.18	0.21*	0.31**
	(−0.02, 0.39)	(0.0, 0.42)	(0.11, 0.51)
	SE 0.1, $p = 0.0815$	SE 0.11, $p = 0.0486$	SE 0.1, $p = 0.0028$
Political Science	−0.01	−0.06	0.05
	(−0.22, 0.2)	(−0.26, 0.15)	(−0.15, 0.25)
	SE 0.11, $p = 0.9313$	SE 0.11, $p = 0.5912$	SE 0.1, $p = 0.633$
Has PI		0.03	−0.07
		(−0.15, 0.21)	(−0.25, 0.11)
		SE 0.09, $p = 0.7716$	SE 0.09, $p = 0.4434$
Has man		0.01	0.03
		(−0.16, 0.18)	(−0.14, 0.2)
		SE 0.09, $p = 0.9049$	SE 0.09, $p = 0.7165$
Has gender expert		0.17	0.11
		(−0.03, 0.37)	(−0.09, 0.31)
		SE 0.1, $p = 0.0922$	SE 0.1, $p = 0.288$
Has race expert		0.33***	0.41***
		(0.14, 0.52)	(0.22, 0.59)
		SE 0.1, $p = 0.0007$	SE 0.09, $p = 0.0$
Reference interdisciplinarity			0.6***
			(0.41, 0.78)
			SE 0.09, $p = 0.0$
Author interdisciplinarity			−0.1
			(−0.29, 0.1)
			SE 0.1, $p = 0.3307$
Observations	408	408	408
Pseudo-R^2	0.0068	0.0169	0.0315

(Continues)

TABLE 1 (Continued)

Negative binomial			
	Model		
	(1)	**(2)**	**(3)**
Log-likelihood	−1256.95	−1244.2	−1225.67
BIC	2555.98	2554.52	2529.48
F-statistic	31.91*** (d.f. = 402.0)	21.41*** (d.f. = 398.0)	20.2*** (d.f. = 396.0)

Note: *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

one such program, the NSF ADVANCE program, has made important steps toward this goal. In particular, we identified three empirical patterns across the knowledge produced through this program that have implications for our understanding of both interdisciplinary and problem-oriented scholarship.

First, ADVANCE has produced publications that are more interdisciplinary than comparable published articles across three types of interdisciplinarity: authorship, references, and citations. Second, this interdisciplinarity was not driven by all disciplines equally collaborating or integrating knowledge. Both social science and STEM fields were more likely to integrate knowledge from across the social sciences, but the social sciences, in particular sociology, had broader interdisciplinary impact compared to the average publication. Third, a publication's reference interdisciplinarity, not the disciplinary composition of its author team, was positively associated with its 5-year impact in academia more broadly.

The ADVANCE program is uniquely situated at the nexus of the social sciences and STEM fields and even more so, the program has explicitly emphasized the importance of social science knowledge in addressing gender equity in STEM, requiring social science research statements in funding proposals. Interpreting these three empirical patterns in the context of the ADVANCE program structure has important implications for the sociology of higher education and the dynamics of knowledge production.

First, while the ADVANCE program does not have guidelines around publications coming out of their program, ADVANCE's focus on interdisciplinary teams and on the importance of social science knowledge at the proposal stage likely had downstream effects on the knowledge-production stage. This finding is neither obvious nor trivial: foundations can create an environment that encourages a particular type of knowledge production without explicit requirements in the publication process.

Second, the three forms of interdisciplinarity we measured were not necessarily correlated. Interdisciplinary author teams did not necessarily produce publications that referenced multiple disciplines or were cited by multiple disciplines. Our findings reinforce the importance of analytically distinguishing between different forms of interdisciplinarity in order to gain a comprehensive understanding of the complete dynamics involved in integrating knowledge. This distinction, and the analytic framework provided here, enables scholars to identify and assess policies that can effectively promote specific forms of interdisciplinarity.

Third, while the ADVANCE program successfully promoted the integration of social science knowledge into STEM fields, the reverse was not true: social science publications did not reference STEM publications at a measurably higher rate. This may suggest that, paradoxically, the epistemic (or perhaps institutional) distance from STEM fields to social science fields may be less than from social science to STEM fields. Future research could explore this potential, examining how to successfully promote social science to STEM integration (the growing fields of computational social science and computational humanities, for example, may be an example of this directional integration).

Fourth, our linear model suggests that reference diversity has a much larger effect on long-term impact compared to any other observable variables, including author team diversity. Given that problem-oriented scholarship is historically underrewarded in academia, and that women and nonwhite scholars are more likely to both do this research and to be underrepresented in the higher ranks of academia, producing

work with traditional impact could make or break the careers of engaged scholars. Interestingly, then, foundations can potentially address one challenge (producing problem-oriented scholarship with academic impact) with another challenge (producing interdisciplinary knowledge). But our findings suggest that, if traditional academic impact is important, scholars might focus on integrating knowledge within a publication, not necessarily on collaborating across disciplines.

Interdisciplinary and translational scholars should be encouraged by our findings. Programs can promote this type of work, and it can be done in a way that maintains traditional academic impact. Yet our findings not only raise more questions but also challenge the very answers they offer. In particular, if disciplinary author teams are drawing on publications from outside their own discipline, might they be doing so in a way that does not take full advantage of that other discipline's knowledge, given disciplinary training structures? Can we expect disciplinary authors to fully understand fields far away from their own? And if not, how might we structure knowledge production so that interdisciplinary author teams are rewarded with citations? Future research could address these questions and more, comparing across programs to better understand the cross-field dynamics of interdisciplinary *and* translational ideals within disciplinary structures.

ACKNOWLEDGMENTS

The authors wish to thank Jessie Dearo for helpful conversations about the impact of the ADVANCE program. We would also like to thank the many undergraduate and graduate research assistants who assisted in data collection and wrangling. In particular, Sushant Kumar, Miranda Melson, Allison Deese, Jaini Gala, Alexia Rios, Joselyn Gil, Isabel Silva, Mireya Dorado, and the entire team of undergraduate students in the Fall of 2020. The link to the document is: https://docs.google.com/document/d/10UhShm8Clm3svHRJILDnrqZqhLCXoW5RFCKx5WWNQ_8/

This material is based upon work supported by the National Science Foundation under Grants No. 1836671 and 2000713. 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. The research has been approved by Northeastern's IRB board (#18-6-01).

CONFLICTS OF INTEREST STATEMENT

All authors declare no conflicts of interest.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Gates, Alexander J., Jessica R. Gold, Laura K. Nelson, and Kathrin Zippel. 2024. "Translating interdisciplinary knowledge for gender equity: Quantifying the impact of NSF ADVANCE." *Social Science Quarterly* 105: 342–58. https://doi.org/10.1111/ssqu.13339