GENDER ISSUES IN SCIENTIFIC COLLABORATION AND WORKFORCE DEVELOPMENT

Implications for a Federal Policy Research Agenda

Connie L. McNeely and Laurie Schintler
School of Public Policy
George Mason University

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Scientific collaboration is fundamental to how science is conducted and how scientific knowledge is diffused and applied within and across countries in the world today. Accordingly, as concerns about deficits in the United States (U.S.) science, technology, engineering, and mathematics (STEM) workforce have grown, increasing attention has been directed to research on collaboration in studies of scientific productivity. Moreover, the participation of women in STEM fields has emerged as a major political, economic, and social issue in related workforce development questions, with calls for research addressing gender dynamics as a critical consideration. In fact, it is clear that gender-specified metrics and more inclusive analytical perspectives must be engaged in order to assess the overall science and technology workforce situation and to inform related federal policy decisions and investments in human capital.

While there is a rich and burgeoning literature addressing women in science and technology, a great deal of work remains to be done in delineating related processes and linking key indicators of scientific productivity and workforce development to concrete outcomes and broader contexts. Accordingly, we provide an overview and assessment of relevant theoretical and methodological issues to help identify areas for policy development and resource investment, and to provide insights for furthering research on scientific knowledge creation and diffusion in general. In undertaking this task, we include gender as a central analytical consideration for exploring related research on the key issues and problem areas addressing STEM collaboration and workforce development at individual, national, and international levels of analysis.

Theoretical Issues

Documented since the 1920s, gender differences in scientific productivity have raised important questions in the face of calls for increasing the U.S. scientific workforce. Various studies have found that, in general, women tend to have lower levels of productivity than men.[1] This "productivity puzzle," as framed by Cole and Zucker in 1984, is a fundamental concern for STEM workforce development. It is in this regard that collaboration is cited as a key aspect of the creation and transfer of scientific knowledge in gender-specified terms.

[1] E.g., see references in Hill 2008;Tuner and Mairesse 2003; NAS 2007.

Collaboration occurs when two or more scientists work together to pursue scientific activities, principally conducting research and other related activities, e.g., data collection, conferences, technical support, and so on (Wagner 1997).[2] As such, collaboration can itself be viewed as a resource, offering access to skills, knowledge, techniques, and intellectual diversity and companionship (Katz and Martin 1997). However, viewing collaboration through the wider lens of occupational structure, mobility, and access, differentially available opportunities based on related societal constraints and needs become increasingly apparent as determinant factors. For example, although there have been gains in advanced degree attainment in some fields, the "leaky pipeline" is still the dominant image (Hill et al. 2010; Bell 2010); i.e., women still tend to be underrepresented and to occupy less than favorable positions in science in general (NAS 2007; Xie and Schaumann 2003).

In practice, publications have been used as the primary indicator of productivity, leading to the fundamental question of why male scientists might have higher publication rates than their female counterparts. Thus, note that, while various factors have been posited as increasing scientific cooperation and productivity, collaborations among scientists have been operationalized primarily as co-authored publications. That is, focused on outcomes, co-authored publications have provided the chief means for measuring scientific collaboration and productivity. Indeed, co-authorship analysis has been the most widely used approach in related research, to the extent that co-authorship has been treated as synonymous with collaboration.[3]

Collaboration as Productivity

Collaboration arguably can increase productivity, and can help combat the rising costs of doing research. Moreover, it is motivated in response to technological facilitation, growing scientific professionalization, increasing scientific specialization, and the expanded importance of interdisciplinary research. However, collaboration also can mean expanded financial burdens, extended time requirements, increased administrative needs, and problems with reconciling institutional financial, management, and property rights (Katz and Martin 1997), as well as strategic and political ends (Wagner 1997). All in all, we can say that increased scientific capacity translates into increased participation in the scientific community, and participation in expanded scientific networks can boost scientific intellectual, social, and cultural capital. The factors influencing collaborations have been delineated along dimensions that are internal and/or external to science. Each has different policy implications with respect to the diffusion of scientific capacity and/or to the interconnectedness of scientists (cf. Wagner and Leydesdorff 2006).

Why might a scientist collaborate? What determines when one might collaborate? What are the motivations for building, maintaining, or dissolving collaborative network relations? What determines with whom one collaborates? Collaboration is an iterative process reflecting various activities, stages, and contextual features (Sargent and Waters 2004; Sonnenwald 2007). It is dependent on the ways in which research is organized, conducted, and located, i.e., on the culture and organization of science (Fox and Mohapatra 2007; Wagner 2008; Drori et al. 2003). Understanding the collaboration process requires attention to work groups, practices, and climates that might stimulate or depress collaboration and productivity. Indeed, the social and

[2] See discussion on different definitions of collaboration in Bukvova (2010).

[3] Smith (1958) was one of the first advocates for the use of co-authored papers to measure scientific collaborations, and de Solla Price (1963) was one of the first to produce and establish direct bibliometrics measurement as the standard for that purpose.

organizational features of work are critical influences on research performance and, as such, represent important areas for studying scientists' productivity (Fox and Mohapatra 2007).

Research collaborations can be framed in terms of a variety of analytical dimensions, including collaborator role or skills, institutional affiliation, organizational level, discipline, and geographical focus (cf. Amabile et al. 2001; Sonnenwald 2007). The collaborative relationship is shaped by the resources that any individual scientist brings to the process. For example, intellectual capital includes both codified and tacit knowledge (Zucker et al. 2007). Codified knowledge – typically operationalized as publications – provides the means by which collaborative productivity has largely been measured. Tacit knowledge, however, refers to individual skills and experience, and the way in which it is engaged is through collaborations (Zucker et al. 2007; Hicks and Narin 2001). Moreover, in general, collaborations can be informal, without any formal agreement among scientists or institutions (or countries), or formal, involving contractual obligations to undertake specific research activities, which can make a difference to observed outcomes and perceptions of collaborative activity (Oldham 2005).

It has long been understood that factors internal to the conduct of science in and of themselves are responsible for increased collaboration (Merton 1973; Ben-David 1990). Internal factors involve, for example, quality, credit, resources, coordination, preparation, communication, awareness, backgrounds and perspectives, disciplinary cultures, familiarity, leadership, and personal characteristics (Bukvova 2010). The culture of scientific practice encourages cooperation and collaboration, but it is not necessarily equal collaboration – nor does it mean that the individual collaborative partners receive equal recognition and value for their role and the resources they bring to the relationship. Although problems can exist regarding variable assignment of credit to individual collaborators (Wray 2006; Heinze and Kuhlmann 2008), the hierarchy of scientific productivity also is encompassed in notions of preferential attachment – or the "Matthew effect" (Merton 1968) – in which collaborative attractiveness is directly proportional to a scientist's professional recognition and reputation, resulting in a process by which the more scientists collaborate, the greater their recognition, and the greater their recognition, the more they are sought after as collaborative partners (Price and Gursey 1976; Zucker et al. 2007). In turn, in the ideal situation, collaboration with a preferred partner then leads to greater professional visibility and reputation by association. In short, this collaborative spiral can lead to greater status, more promotions, increased funding, and greater productivity by definition (cf. Drori et al 2003). The questions here are who, in relative gender terms, is able to make and benefit from such preferential attachments and what are the factors determining such relationships.

Related workforce development largely depends on the formation of communities of learning and practice that have been identified and operationalized in research through analyses of collaboration patterns and participation. As is apparent, the role of networks is a crucial theme in defining collaboration and determining productivity in this regard, with particular reference to collegial circles and broader scientific communities (cf. Schott 1993). Collegial circles are constituted by personal webs of contacts, influenced by institutional arrangements that can enable or constrain the availability and selection of collaboration partners (e.g., professors bringing their students into their circles). In addition to internal institutional features, these arrangements encompass educational systems, professional associations and meetings, funding organizations and policies, and the like. Such conditions also affect participation and the size, specialization, centrality, reach, and autarky of broader scientific communities, which are constituted by networks that enable or constrain collaboration and productivity (cf. Centola 2010). Also, both collegial circles and the broader communities can be marked, to varying degrees, by a division of labor, hierarchical positions, and contextual relations. In this instance, the division of labor reflects individual and disciplinary specialization, with disciplines often evincing considerable difference in co-authorship tendencies among disciplines (Cronin et al. 2004; Newman 2004). Hierarchy is manifested in dominant-subordinate structural relations and positions, as in the preferential attachments discussed above. Contextual relations encompass spatial, cultural, and political links..

Viewing science as a public good, both internal and external social, political, and economic factors concern influences of particular interest to decision makers regarding mobilizing and supporting collaborations (Katz and Martin 1997; Callon et al. 1986; Latour and Woolgar 1986). Such factors include, among others, societal and institutional cultures, funding, research team size, institutional support and structure, and location (Bukvova 2010). Thus, for example, national and institutional politics can affect scientist's behavior; the development of intellectual capital and productivity often results from collaboration among scientists in different institutions and countries. Indeed, international co-authorships have been increasing with globalization (Glänzel and Schubert 2004; Wagner and Leydesdorff 2005), enabled by technological and communications advances (Stokols et al. 2008). The Internet and email have lowered communication costs, thereby facilitating collaboration, with recent evidence suggesting disproportionately positive affects on female co-authorship rates relative to those of males (cf. Butler and Butler, forthcoming). In the end, this point also raises questions about the extent to which productivity is reliant upon spatial correspondence.

Spatial considerations appear relatively dependent on the institutions and sectors with which selected researchers are associated (McNeely and Schintler 2010). While, arguably, “most scientific knowledge and expertise are located in relatively few advanced countries” (Oldham 2005), collaboration among scientists from developed and developing countries provides access to knowledge and expertise, to the extent that international scientific collaboration has been framed as a means for capacity building and has even been noted as a form of foreign aid (Oldham 2005; Chung 2002).[4] There is some indication that geographical distance is a significant factor in collaborations between academic and private sector scientists and that shorter distance collaborations result in positive spillover effects, particularly when the research is for quick-to-market projects (Bröstrom 2010). Further, spatial factors appear less important in collaborations between academic and government scientists, and are only a minor consideration for scientists in academic settings (who tend also to have more international collaborative relationships). However, "geographical proximity especially seems to matter for collaboration in the case of institutional differences" and, more to the point, "is more important in an indirect way by overcoming institutional differences than in directly stimulating interaction" (Ponds et al. 2007, p. 425). For analytical purposes, the typical way that research is conducted and located can be characterized as either centralized or distributed (Schintler et al. 2010). Centralized research generally occurs in one location associated with particular resources or facilities; distributed research can take place in disparate locations with teams performing tasks independently to be later integrated. Both of these collaborative productivity issues are matters of scientific capacity and infrastructure.

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[4] However, political gains of formal collaborations may have been lessened by globalization dynamics that have made international collaboration more commonplace (Skolnikoff 2001).

Various factors, such as political and policy motivations, including government fostering of interdisciplinary research, historical considerations, and the globalization of science and technology, compel not only individual scientists but the scientific community to respond to social and political mobilizations for collaboration (cf. Drori et al. 2003; Hwang 2008). Note too that increases in international collaborations are heavily correlated with notions of social justice, human rights, and women's rights (Drori et al. 2003). It is in this context that gender was initially framed as a critical consideration for STEM workforce development.

Interdisciplinary research also has been framed as particularly amenable to collaboration by its very nature (Pfirman et al. 2005). Moreover, with an emphasis on developing social capital and maintaining connections to obtain access to knowledge generated by other scientists, interdisciplinary collaboration has been extolled as a means to increased productivity for female scientists (Pfirman et al. 2008). Collaboration means combining resources which, for women, is an especially relevant point given the explicit and implicit challenges and barriers to professional advancement and productivity that they often face – e.g., exclusion from information networks, exclusion from grant writing opportunities, marginalization of their research areas, smaller and less well-equipped offices and laboratories, and general denial of voice in institutional decision making (MIT 1999, 2002; Roos and Gatta 2006). Scientific research typically involves working with others to pool intellectual resources, and “collaborative projects provide women with expertise in associated disciplines, a collegial vetting and support network, a sense of community, and an opportunity to relate to others” (Pfirman and Balsam 2004). Importantly, this conception of scientist relations also encompasses assertions of the need to collaborate in the typical atmosphere of “insecurity in highly competitive environments” and of “uncertainty of scientific findings” (Hwang 2008).

Gender Dynamics

Although it appears that education and skills contribute more or less equally to male and female publication levels, female publication productivity also is strongly influenced by both structural and individual factors (cf. Prpić 2002). Of these, situational issues, such as the *gender imbalance* itself in some STEM fields resulting from the low presence of women, are arguably crucial considerations for understanding the observed unequal outcomes. For example, citing the ratio of men to women in particular science and technology fields, some psychological research suggests that, rather than being inherent to women, the (subtle or not so subtle) experience of "identity threat" can be attributed to gender imbalance and that male-dominated disciplinary cultures and the organization of some fields contribute largely to a lag in expectations and performance by women (Murphy et al. 2007). Of course, such situational features also make for a circular pattern in which gender imbalance leads to gender imbalance.

Additionally, some researchers posit *fewer professional and collegial networks* as the reason for lower female publication rates; others point to the tendency for *same sex co-authorship* (Bentley 2003) – which, of course is confounded by the STEM gender imbalance in the first place. Furthermore, publication productivity has been linked to early career *mentoring*, which research shows is relatively lacking for most women scientists, and also to availability of *time* to conduct one's work, which research shows is relatively lacking for most women scientists, with particular reference to family responsibilities that most men do not incur (NAS 2007; Xie and Schaumann 2003; Symonds 2007; Francl 2005; Bentley 2003).[5] Moreover, mentoring can affect early access to professional networks and legitimation. It is also possible that, reflecting the growing complexity of STEM disciplines, *research specialization* may be an important intervening variable that negatively affects productivity. There is some evidence that women specialize more than men, yet the most productive scholars are those with more broadly diversified research programs (cf. Leahey 2005). Note too that specificity rather than breadth can be related to available time. Also, broader *disciplinary cultures* represent another factor that must be considered, given that some fields have been referenced as relatively more "female friendly" (e.g., biology).

Gender disparities in academic publishing have been attributed to the greater likelihood for females to work in non-tenure track and contingent positions, to work at teaching (rather than research) institutions, to lack access to institutional support, resources, and time; to participate in service activities that detract from research; to be excluded from broader professional networks; and to have family responsibilities that encroach on time for research (Matthews and Andersen 2001; Suitor et al. 2001; Robinson 2006; NAS 2007; Fox and Mohapatra 2007). Such points become particularly salient in recognition of the fact that women tend to (and are expected to) devote more time to teaching and service than men, which are relatively undervalued activities. Women also have fewer opportunities for attaining positions at research universities where the availability of related resources and support facilitate increased faculty productivity (Dundar and Lewis 1998). In general, the decreased female productivity reflects the increased unpredictability of their careers. As noted by Symonds (2007, p. 49), if women's productivity falls behind early in their careers, "even if they subsequently increase publication rates (which they do) they will, at any time, appear less productive than men of equal experience. Because assessing the ability of a scientist focuses so greatly on quantity of publications, this 'catch-up' scenario has all sorts of vicious-circle implications. Once you start to fall behind, it is harder to get funding, and more difficult to produce research, and so on. While this quantity-based focus persists, women are bound to struggle, to publish less, and to be under-represented at the top levels."

It seems clear that, rather than focusing principally on beginning assumptions and end results, the *process* that leads to collaboration and productivity outcomes must be conscientiously incorporated into related models and analyses. Scientific collaboration in general is a highly complex process and, when gender is explicitly recognized and engaged as a critical influence on observed outcomes, it adds another layer of complexity to that process to the extent that further study is demanded in order to gain insight and understanding of the institutional, cultural, political, and economic dynamics that shape today's science and technology workforce. In other words, gender identity alone hardly explains or is responsible for STEM pipeline issues or related differences in collaboration and productivity outcomes. Rather, as shown in Figure 1, *gender must be considered as a critical determinant within a complex web of relational dynamics and processes*. Only by capturing those interactive dynamics can we develop the kind of understanding and evidence on which to formulate effective policies and interventions for building an inclusive and diversified — and ultimately world-class and strengthened — science and technology workforce.

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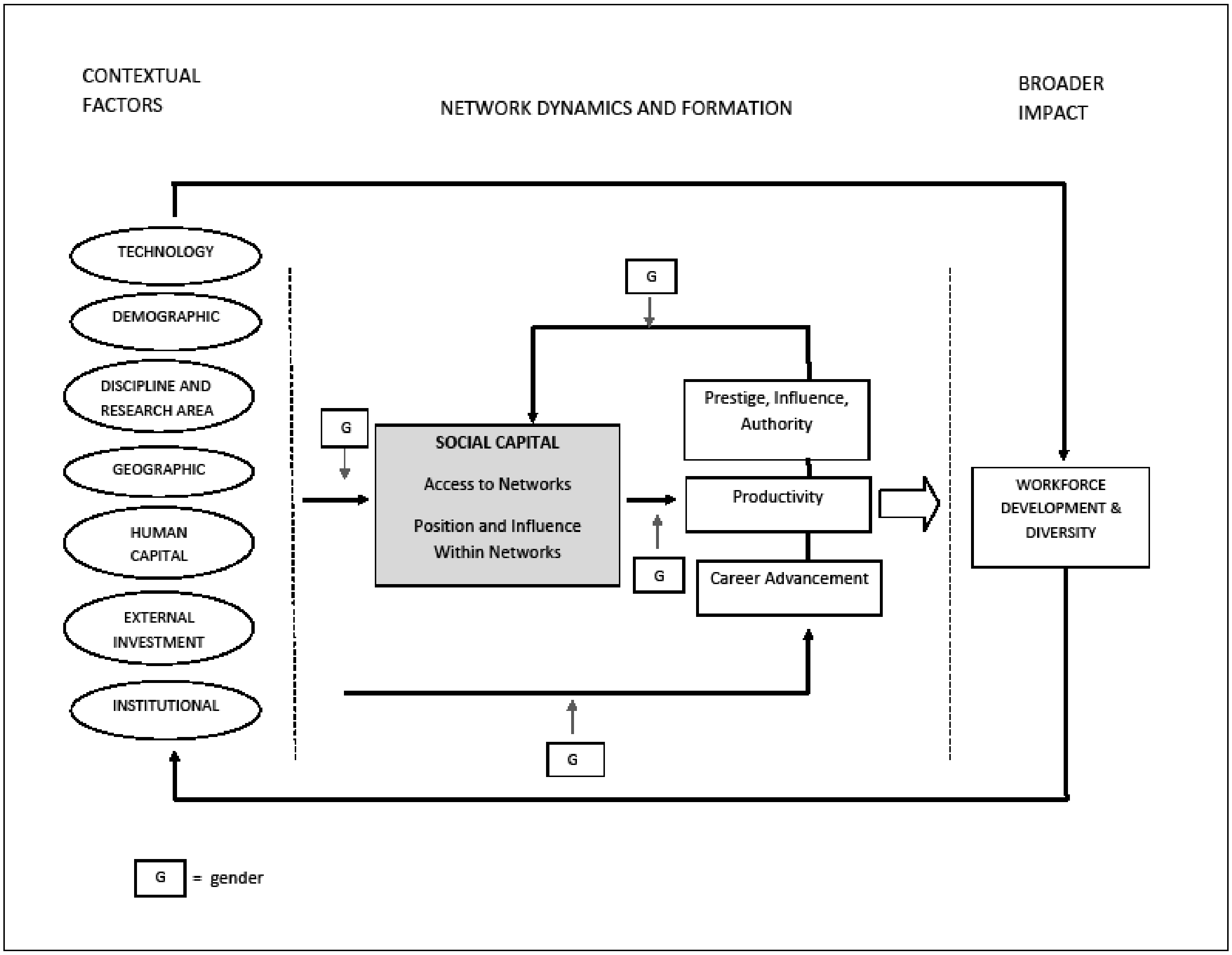
[5] This certainly is the perception, but empirical evidence is mixed regarding arguments crediting increased family responsibilities for women as the cause of lower publication rates (Sax et al. 2002). However, it is also the case that this may be due to specification issues.

Figure1. Collaborative Processes and Productivity



Methodological Issues

Measuring collaboration is itself no small task, and the construction of detailed measures aimed at capturing the role of gender and society in scientific collaboration and productivity is a critical topic on scholarly and public agendas, especially as regard issues of science and technology workforce development. Although the operationalization of productivity as number of publications is a widely accepted and relatively easy means for measuring collaboration, publication counts do not indicate quality or relevance. Indeed, as Hicks and Narin (2001) argue, using publication counts to study knowledge creation and dissemination does not require that they effectively convey knowledge; it is enough that the processes that transfer knowledge also tend to produce the publication. Although peer-reviewed publications in high-prestige journals or proceedings tend to carry more weight, this type of measure says little about actual quality or whether they encompass new insights, applications, or significant discoveries. To some extent, attempts to address such problems have been made by considering number of citations. Employing citation rates to examine co-authorship relative to productivity, some research considers the value of collaborations for further productivity at national and international levels, using citations to provide some kind of weight to the importance of collaboration (e.g., Glänzel 2005; Moed 2005; Leydesdorff and Wagner 2008).

Interestingly, citation analysis also points to another side of the productivity puzzle: the "impact enigma" in which, in some fields (e.g., biochemistry and biology), women's papers, although fewer, have been found to be more frequently cited than those of their male counterparts. Moreover, their research was more highly cited even when they occupied more "marginal" professional positions (Long 1992; Symonds 2007). While such findings have yet to be explained, they do lead to challenges and questions about the analytical reliance on sheer mass of publications as the measure of productivity (Francl 2005).

However, the fact is that citations too might occur for a variety of positive or negative reasons and still do not necessarily indicate content quality or relevance. In fact, relying on publication and citation counts might belie the research collaboration and productivity process itself, in which time for conducting research and making breakthroughs and discoveries can be highly variable. Defining productivity through its operationalization can prove problematic in the first place and might require a re-conceptualization and re-orientation to the process. Critical productivity issues such as knowledge integration, grant awards, and time invested in research and the research process itself – in addition to teaching and service – are not captured in number of publications or citations. Moreover, these can vary dramatically by field and subfield and by the nature and substance of the research itself. In addition, number of publications – which are highly correlated to opportunity and to time commitment – does not indicate quality or creativity (Fox 1985, 1992). More encompassing content techniques and also qualitative approaches might be needed to capture the more nuanced nature of knowledge creation and value in these instances, especially as they relate to female collaboration and productivity.

Other methodological issues also arise in regard to measuring association. The causal relationship (or endogeneity) between collaboration and productivity is sometimes misspecified, affecting the reliability of research findings. Models in which collaboration is an instrumental (or endogenous) variable would be more appropriate (e.g., Lee and Bozeman 2005). Related to this issue, however, is the question of how to effectively introduce gender into a model as either a contextual factor or, perhaps more importantly, as an intervening factor in a correlational or causal relationship.[6] To truly measure how the rate at which productivity increases with more collaboration differs for women and men, interaction must be explicitly included as a crucial aspect of the model, as suggested in Figure 1 above.[7]

Data and Measures

Co-authorship as a measure of scientific interaction has also been criticized for being an incomplete and inaccurate characterization of collaboration. For example, it does not reflect the degree or way in which each individual author might actually contribute to a publication. In fact, authors may be listed on an article, not for their contribution to the research, but rather for social or political reasons (Katz and Martin 1997), which also can reflect preferential attachment considerations. Moreover, listed authors (or even acknowledgements) do not necessarily reflect all of the individuals involved at various steps in the research process (Sonnenwald et al. 2009).

Beginning with earlier work defining network properties as appropriate measures of collaboration at different levels of analysis (Schott 1993), social network analysis has been used

[6] The former would be done through the use of a dummy variable for gender, introduced as a separate independent variable.
[7] Although such action would necessitate more sophisticated regression analyses to avoid violating key assumptions.

increasingly over time examine collaboration within and across disciplines. Network connections arguably can contribute to interpersonal influence (Brass 1984) and career opportunities (Burt 1992); the structure of collaboration networks and relative positions within them influence access to resources of all types (Lin 2002). For collegial circles, network diversity has been of particular analytical concern, reflecting measures of homophily, homogeneity, and multiplexity. Network composition too has been foremost in related analyses, looking to circle range and density of connections. Moreover, various measures have been used to gauge the dominance (or lack thereof) of external connections over those defined as internal in order to examine the effect of, for example, global versus local network links.[8] Important considerations in determining such measures are sensitivity to network boundaries and awareness of bias introduced by individual perceptions of network positions. (In fact, gender might be a differentiating factor in such perceptions.)

Data on co-authorships and citations is readily and amply available via online bibliographic archives, allowing for large-scale sampling.[9] Moreover, since many of the large co-authorship analyses rely on the same databases, possibilities for research reconstruction and comparison are enhanced. Thus, while not obviating conceptual and operationalization issues, this provides an advantage for research validation and assessment. The basic analytical features engaged in collaboration studies using co-authorships are author, institution, and country (Gauffriau et al. 2007).[10] Some other advantages of bibliometric co-authorship analysis are that the measures are invariant and verifiable, it is a relatively inexpensive and practical means for quantifying collaborations, the sample size is typically large thus facilitating tests for significance, and it is an unobtrusive and non-reactive measure.

However, problems also have been identified. For example, because some authors claim multiple addresses (institutional affiliations and/or countries), the number of authors gives lower limits to the number of institutions represented through collaboration (Wagner and Leydesdorff 2005; Leydesdorff and Wagner 2008). In addition, coding of institutions and locations may be inconsistent within and across databases, and counting approaches too may differ for determining number of authors, institutions, and/or countries, ranging from whole counting to fractional counting to rank dependent counting (Gauffiau et al. 2007).[11] Furthermore, disciplinary coverage varies in available databases, and the ways in which scientific disciplines are categorized, differences in disciplinary publication outlets, and types of literature also present important considerations in co-authorship analysis (Moed 2005). Part of this issue rests on whether or not the scientific disciplinary communication is mainly through peer-review journals, non-peer-reviewed journals, the so-called "gray literature" (e.g., conference proceedings), or even books. Moreover, again addressing issues of access, there is a heavy bias towards English in most available databases and, although English is the lingua franca in many sciences, this is not necessarily the case in all fields (Stefaniak 2001).

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[8] E.g., the E-I index (see discussion in Hill 2008) or the "cosmopolitan scale" (see discussion in Lee and Bozeman 2005).

[9] While there are some smaller specialized databases, the most used databases for co-authorship and citation analyses include Thompson Scientific's large database of journal article, comprised of SCI (Science Citation Index), SSCI (Social Science Citation Index), and AHCI (Arts & Humanities Citation Index); ISI's Web of Knowledge; and Elsevier's Scopus. Google Scholar also has started indexing peer-reviewed literature and gray literature, but it supplies only citation counts and author names, and not address information.

[10] Other measures of collaboration that have been suggested include research and development budgets devoted to collaboration and conference participation and support (Wagner et al. 2001), although reliable access to such data for measuring these activities can prove problematic.

[11] Such issues can provide significant hurdles for automating co-authorship coding.

In any case, another more fundamental problem exists for conducting research on gender differentials relative to epistemic networks and broader scientific communities using such samples: author gender designation. Author gender designation is a daunting task not only because of the sheer number of records that would need to be processed, but also because of difficulties in many cases of delineating gender based solely on author name, especially in light of linguistic and cultural variations (McNeely and Schintler 2010; Schintler et al. 2010). This problem explains, at least in part, why related research has not been performed at this level.

In light of some of the problems associated with using citations and co-authorships for measuring collaboration and productivity, not to mention problems of determining collaborator gender, some researchers have administered surveys and questionnaires and performed content analyses of curricula vitae to obtain productivity data (Kiopa and Melkers 2009; Lee and Bozeman 2005; Gaughan and Ponomariov 2008; Hill 2008). Such work begins to explore more detailed characteristics and other dimensions of the issues discussed above, as permitted within the limits of the data. Some caveats include the costs (time and money) associated with survey administration, which often prohibits the collection of large numbers of records based on respondents. Also, depending on the format and length of the survey, along with various other determining factors, even when overall response rates are acceptable, they may also result in lower sample sizes and potential problems related to representativeness within categories, such as institution, discipline, or gender. Mindful of such conditions when conducting analyses and interpreting findings, researchers call for future work to extend and supplement the data for more comprehensive and in-depth analyses.

In addition, in regard to collaborative networks, this data has been employed in egocentric network designs that stand as a complement to the abovementioned analyses of extended networks. Framed in terms of collegial circles and broader scientific communities, some of this work has shown distinct differences in the scientific collaboration networks of men and women relative to size or number of perceived collaborative partners (Welch and Melkers 2008). However, still, while the importance of identifying network structure and position – e.g., in terms of betweeness and centrality – has been identified as critical determinants of collaboration possibilities (Hill 2008; Lin 2002), few if any studies contrast network structure and position by gender using formation on the topology of collaboration networks at different levels (especially global) of analysis, leaving this a fertile area for exploration.

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Conclusions and Implications

Our overall goal here has been to offer a general overview and understanding of the role of gender and society in scientific collaboration and workforce participation and productivity. While providing a discussion of related research, we also have endeavored to identify areas for federal policy development and resource investment. We posit that recognition and inclusion of gender dynamics and relations in analyses of scientific productivity will provide a more detailed depiction and greater insight into the processes affecting science and technology workforce issues in society today. Moreover, they also can provide "lessons learned" that can be applied in other areas and to other groups, further informing and providing direction for future inquiry and policy development. We have taken a first step in addressing data needs and limitations and identifying strengths and gaps in the current research to lead us to important questions that remain to be asked in the first place and will allow us to indicate fruitful research areas and analytical approaches. Taking these points together, we offer here a few straightforward "action items" for considering gender inequality as an integral component in the complex causal relations reflected in collaboration processes.

- Identify potential measures to better reflect STEM collaboration and productivity. Explore varieties of indicators that allow for measuring inequity, conditioned on some categorical variable (e.g., gender differences in productivity conditioned by discipline) for a more accurate picture of the effect of gender on collaboration and productivity. Parametric and non-parametric testing can be used to assess distributional inequalities and gender differences across institutions, sectors, and countries.
- Develop a general set of indicators for assessing collaborative work. Construct a set of detailed metrics reflecting the dynamic interactive properties of gender relations to provide a common platform at all levels of analysis on which to develop or assess the consequences of various STEM-related policies and interventions.
- Establish programs that will encourage researchers to develop comprehensive theoretical and conceptual models that capture relative interactions at greater levels of detail, and that address their broader implications for policy development and social impact.
- Develop longitudinal datasets for characterizing network dynamics. Emphasize the use of longitudinal data and methods in order to effectively portray the dynamics of the relevant relationships.
- Establish citation databases that explicitly include author gender information linked to publication records to enable related research.
- Delineate and map key spatial indicators and measures to illuminate areas in which scholar's tend to have more or less prominence in terms of collaboration and if there is gender variation. Spatial approaches can be used to control for the underlying geographic distribution of collaboration relationships by including comparative analyses of the measures or through the development of related measures conditioned by gender and location.
- Determine measures that capture the content or impact of the published research (e.g., through text mining of selected publications). Such measures could be used to integrate and supplement other network analysis techniques to better understand collaboration dynamics and the role of gender in related processes.

Growing attention to research on collaboration as a key aspect of scientific productivity – not only as an outcome, but as a process – has led to a broader recognition that it must be understood within the context of larger social, cultural, political, and economic factors. Moreover, gender dynamics play a central role in determining related developments in the scientific workforce which, in turn, affect national capabilities. Gender is one of those issues that so permeates social interaction that its effects cannot be rightly captured by characterizing it simply as a separate factor to consider in related analyses. The complex nature of the embedded gender dynamics in the collaboration process requires the explicit recognition of its critical interactive nature and influence. Moreover, in-depth analyses of changing network patterns over time and place are needed in order to better understand the role of gender relative to other determinant factors affecting the role of collaborative relationships in the development of the STEM workforce.

References

Allison, P.D., and Stewart, J. A. (1974). Productivity Differences Among Scientists: Evidence for Accumulative Advantage, *American Sociological Review,* 39: 596-606.

Amabile, T.M., Patterson, C., Mueller, J., Wojcik, T., Odomirok, P.W., and Marsh, M. (2001). Academic-Practitioner Collaboration in Management Research: A Case of Cross-Profession Collaboration, *The Academy of Management Journal*, 44(2): 418-431.

Astin, H.S. (1984). Academic Scholarship and its Rewards. In M.W. Steinkamp and M. L. Maehr (Eds.), *Advances in Motivation and Achievement* (pp. 259–279), vol. 2. Greenwish, CO: JAI Press.

Bell, N. (2010). *Graduate Enrollment and Degrees: 1999 to 2009.* Washington, DC: Council of Graduate Schools.

Ben-David, J. (1990). *Scientific Growth*. Berkeley: University of California Press.

Bentley, J. T. (2003). *Gender Differences in the Careers of Academic Scientists and Engineers: A Literature Review*. Arlington, VA: National Science Foundation.

Bozeman, B., and Corley, E. (2004). Scientists' Collaboration Strategies: Implications for Scientific and Technical Human Capital, *Research Policy,* 33: 599-616.

Bozeman, B., and Gaughan, M. (2007). Impacts of Grants and Contracts on a Academic Researchers' Interactions with Industry, *Research Policy*, 36: 694-707.

Brass, D.J. (1984). Being in the Right Place: A Structural Analysis of Individual Influence in Organization, *Administrative Science Quarterly,* 29: 518-539.

Broström, A. (2010). Working with Distant Researchers – Distance and Content in University-Industry Interaction, *Research Policy*, 39: 1311-1320.

Bukvova, H. (2010). Studying Research Collaboration: A Literature Review, *Sprouts: Working Papers on Information Systems,* 10 (3). [http://sprouts.aisnet.org/10-3]

Burt, R. (1992). *Structural Holes*. Campbridge, MA: Harvard University Press.

Butler, D.M., and R.J. Butler. (Forthcoming). Is the Internet Bridging the Gender Gap? The Case of Political Science. *Economics of Education Review*.

Callon, M., Law, J. and Rip. A. (1986). *Mapping the Dynamics of Science and Technology: Sociology of Science in the Read World*. Houndmills, UK: Macmillan.

Centola, D. (2010, 3 September). The Spread of Behavior in an Online Social Network Experiment. *Science* 329 (5996): 1194-1197.

Chung, S. (2002). Catching Up Through International Linkages: Science, Technology, and the Korean Experience, *Science and Public Policy,* 29 (6): 431–437.

Cole, J.R., and Zuckerman, H. (1984). The Productivity Puzzle: Persistence and Change in Patterns of Publication of Men and Women Scientists." Pp. 217-258 in *Advances in Motivation and Achievement*, vol. 2, edited by M.W. Steinkamp and M. L. Maehr. Greenwich, CO: JAI Press.

Cronin, B. Shaw, D. and La Barre, K. (2004). Visible, Less Visible, and Invisible Work: Patterns of Collaboration in 20^{th} Century Chemistry, *Journal of the American Society for Information Science and Technology*, 55(2): 160-168.

Drori, G.S., Meyer, J.W., Ramirez, F.O., and Schofer, E. (2003). *Science in the Modern World Polity: Institutionalization and Globalization*. Stanford, CA: Stanford University Press.

Dundar, H., and Lewis, D.R. (1998). Determinants of Research Productivity in Higher Education, *Research in Higher Education,* 39 (6): 607-631.

Fox, M.F. (1985). Publication, Performance, and Reward in Science and Scholarship. In J.C. Smart (Ed.), *Higher Education: Handbook of Theory and Research*, vol. 1. New York: Agathon.

Fox, M.F. (1992). Research, Teaching, and Publication Productivity: Mutuality versus Competition in Academia, *Sociology of Education,* 65 (4): 293-305.

Fox, M.F., and S. Mohapatra. (2007). Social-Organizational Characteristics of Work and Publication Productivity Among Academic Scientists in Doctoral-Granting Departments. *Journal of Higher Education* 78 (5): 543-571.

Francl, M.M. (2005, 21 June). The 'Productivity Puzzle' and the 'Impact Enigma,' The Culture of Chemistry. [http://cultureofchemistry.blogspot.com/2005/06/productivity-puzzle-and-impact-enigma.html]

Gaughan, M., and B. Ponomariov. (2008). Using quasi-experimental design and the curriculum vitae to evaluate impacts of earmarked center funding on faculty productivity, collaboration, and grant activity. *Research Evaluation* 17: 103-110.

Gauffiau, M., Larsen, P.O., Maye, I., Roulin-Perriard, A. and von Ins., M. (2007). Publication, Cooperation and Productivity Measures in Scientific Research, *Scientometrics,* 73 (2): 175–214.
Glänzel, W., and Schubert, A. (2004). Analyzing Scientific Networks Through Co-Authorship. In H.F. Moed, et al. Kluwer (Eds.) *Handbook of Quantitative Science and Technology Research* (pp. 257-276).
Heinze, T., and Kuhlmann, S. (2008 June). Across Institutional Boundaries? – Research Collaboration in German Public Sector Nanoscience, *Research Policy*, 37(5): 888-899.
Hill, C., C. Corbett, and A. St. Rose. (2010). *Why So Few? Women in Science, Technology, Engineering, and Mathematics.* Washington, DC: American Association of University Women.
Hill, V. (2008, 14 July). Collaboration in an Academic Setting: Does the Network Structure Matter? CMU-ISR-08-128. Technical report.
Hwang, K. (2008). International Collaboration in Multilayered Center-Periphery in the Globalization of Science and Technology, *Science, Technology, Human Values,* 33 (1): 101-133.
Hicks, D., and Narin, F. (2001). Strategic Research Alliances and 360 Degree Bibliometrics Indicators, Proceedings of NSF Workshop: Strategic Research Partnerships. [http://www.nsf.gov/statistics/nsf01336/p1s6.htm]
Katz, J.S., and Martin, B. R. (1997). What is Research Collaboration? *Research Policy*, 26(1), 1–18.
Kiopa, A., and Melkers, J. (2009). Industry Ties of Academic Scientists: Access to Human and Social Capital through Collaborative Networks, Paper prepared for presentation at the Workshop on Original Policy Research.
Lee, S., and Bozeman, B. (2005). The Impact of Research Collaboration on Scientific Productivity, *Social Studies of Science,* 35: 673-702.
Latour, B., and S. Woolgar. (1986). *Laboratory Life: The Construction of Social Facts*. Princeton, NJ: Princeton University Press.
Leahey, E. (2005). Solving the Productivity Puzzle: Research Specialization as a Missing Link. Presented at the annual meeting of the American Sociological Association, Philadelphia.
Leydesdorff, L., and Wagner, C. (2008, October). International Collaboration in Science and the Formation of a Core Group. *Journal of Informetrics*, 2(4): 317-325.
Lin, N. (2002). Social Capital: A Theory of Social Capital and Action. Cambridge: Cambridge University Press.
Long, J. S. (1992). Measures of Sex Differences in Scientific Productivity. *Social Forces,* 7 (1): 159-178.
Massachusetts Institute of Technology (MIT). (1999/2002). "A Study on the Status of Women Faculty in Science at MIT," Report of the School of Science, Committees on the Status of Women Faculty. Cambridge: MIT.
Mathews, A.L., and Andersen, K. (2001). A Gender Gap in Publishing? Women's Representation in Edited Political Science Books, *Political Science and Politics, 34* (1): 143-147.
McNeely, C.L., and Schintler, L. (2010). Exploring Epistemic Communities: A Gendered Perspective on Scientific Collaboration, *ERN Public Policy Institutes Research Paper Series,* 2 (3). http://ssrn.com/abstract=1596134
Merton, R.K. (1968). The Matthew Effect in Science: The Reward and Communication Systems of Science are Considered**,** *Science.*
Merton, R.K. (1973). The Sociology of Science: Theoretical and Empirical Investigations (University of Chicago Press, Chicago).
Moed, H.F. (2005). *Citation Analysis in Research Evaluation.* Dordrecht, the Netherlands: Springer.
Murphy, M. C., Steele, C. M., and Gross, J. J. (2007). Signaling Threat: How Situational Cues Affect Women in Math, Science, and Engineering Settings, *Psychological Science,* 18 (10): 879-885.
National Academy of Sciences (NAS). (2007). *Beyond Bias and Barriers: Fulfilling the Potential of Women in Academic Science and Engineering.* Committee on Maximizing the Potential of Women in Academic Science and Engineering/Committee on Science, Engineering, and Public Policy (National Academy of Sciences/National Academy of Engineering/ Institute of Medicine). Washington, DC: National Academies Press.
Newman, M.E.J (2004, 6 April). Coathorship Networks and Patterns of Scientific Collaboration. Proceedings of the National Sciences of the United States of America, 101(Suppl 1): 5200-5205.
Oldham, G. (2005, 19 April). International Scientific Collaboration: a Quick Guide. Science and Development Network, Policy Brief. http://www.scidev.net/en/policy-briefs/international-scientific-collaboration-a-quick-gui.html
Pfirman, S., and P. Balsam. (2004, 9-10 December). “Women and Interdisciplinary Science: Promise and Peril.” *Women, Work, and the Academy*, Barnard Center for Research on Women. [http://www.barnard.edu/bcrw/womenandwork/pfirman.htm]

Pfirman, S., P. Balsam, R.E. Bell, P. Culligan, and J.D. Laird. (2008, 1 February). "Maximizing Productivity and Recognition, Part 2: Collaboration and Networking." *Science* 319 (5863). [http://sciencecareers.sciencemag.org/career_magazine/previous_issues/articles/2008_02_01/caredit.a0800016]
Pfirman, S., J.P. Collins, S. Lowes, and A.F. Michaels. (2005, 11 February). "Collaborative Efforts: Promoting Interdisciplinary Scholars." *The Chronicle of Higher Education* 51 (23): B15.
Ponds, R., van Oort, F., and Frenken, K. (2007). The Geographical and Institutional Proximity of Research Collaboration, *Papers in Regional Science,* 86 (3): 423-443.
Price, D., and Gürsey, S. (1976). Studies in Scientometrics. Part 1. Transience and Continuance in Scientific Authorship, *International Forum on Information and Documentation*, 17–24.
Prpić, K. (2002). Gender and Productivity Differentials in Science, *Scientometrics,* 55 (1): 27-58.
Robinson, D. (2006). *The status of higher education teaching personnel in Australia, Canada, New Zealand, the United Kingdom, and the United States*. Education International.
Roos, P., and M. Gatta. (2009). "Gender (In)Equity in the Academy: Subtle Mechanisms and the Production of Inequality." *Research in Social Stratification and Mobility* 27 (3): 177-200 .
Sargent, L. and Waters, L.E. (2004, April). Centers and Academic Research Collaborations: An Inductive Process Framework for Understanding Successful Collaborations, *Journal of Vocational Behavior*, 64(2): 308-319.
Sax, L.J., Hagedorn, S., Arredondo, M. and Dicrisi, F. A. (2002). Faculty Research Productivity: Exploring the Role of Gender and Family-Related Factors, *Research in Higher Education,* 43 (4): 423-446.
Schaumann, K.A., and Xie, Y. (2003). Explaining Sex Differences in Publication Productivity among Postsecondary Faculty. In L.S. Hornig (Ed.), *Equal Rights, Unequal Outcomes: Women in American Research Universities* (pp. 175-210) New York: Kluwer.
Schintler, L., Galiazzo, G., and McNeely, C.L. (2010). Geography and Scientific Colloboration: A Gendered Perspective, Conference Paper P1903. Presented at the Annual North American Meeting of the Regional Science Association International, Denver.
Schott, T. (1993). World Science: Globalization of Institutions and Participation, *Science, Technology, and Human Values,* 18: 196–208.
Skolnikoff, E.B. (2001). The Political Role of Scientific Cooperation, *Technology in Society*, 23: 461-471.
Smith, M. (1958). The Trend Toward Multiple Authorship in Psychology, *American Psychologist,* 13: 596-599.
de Solla Price, D.J. (1963). *Little Science, Big Science* (Columbia University Press, New York).
Sonnenwald, D.H. (2007). Scientific Collaboration. *Annual Review of Information Science and Technology*, 41: 643-681.
Stefaniak, B. (2001). International Co-operation in Science and in Social Sciences as Reflected in Multinational Papers Indexed in SCI and SSCI, *Scientometrics,* 52(2): 193–210.
Suitor, J.J., Mecom, D., and Feld, I.S. (2001). Gender, Household Labor, and Scholarly Productivity among University Professors, *Gender Issues, 19* (4): 50-67.
Symonds, M. (2007). Quantity, Quality, and Equality, *New Scientist,* 194 (2611): 48-49.
Valian, V. (1998). *Why So Slow? The Advancement of Women*. Cambridge: MIT Press.
Wagner, C.S. (1997) *International Cooperation in Research and Development: An Inventory of U.S. Government Spending and a Framework for Measuring Benefits*, Santa Monica, CA: Rand.
Wagner, C.S. (2008). *The New Invisible College: Science for Development*. Brookings Institution Press: DC.
Wagner C.S., and Leydesdorff, L. (2005). Network Structure, Self-organization, and the Growth of International Collaboration in Science, *Research Policy,* 34 (10): 1608-1618.
Welch, E. and J. Melkers (2008, September). Effects of Network Size and Gender on Research Grant Awards to Scientists and Engineers: An Analysis from a National Survey of Six Fields. Paper presented at the 2008 Meeting of PRIME, Mexico City, Mexico.
Wray, K.B. (2006, September). Scientific Authorship in the Age of Collaborative Research, *Studies in History and Philosophy of Science Part A*, 37(3): 505-514.
Xie, Y., and Schaumann, K.A. (2003). *Women in Science: Career Processes and Outcomes*. Cambridge: Harvard University Press.
Zucker, L.G., Darby, M.R., Furner, J., Liu, R.C., and Ma, H. (2007). Minerva Unbound: Knowledge Stocks, Knowledge Flows and New Knowledge Production. *Research Policy,* 36 (6): 850-863.