FEATURE

The U.S. Academic Fisheries Co-Authorship Network Under the Lens of Diversity and Inclusion

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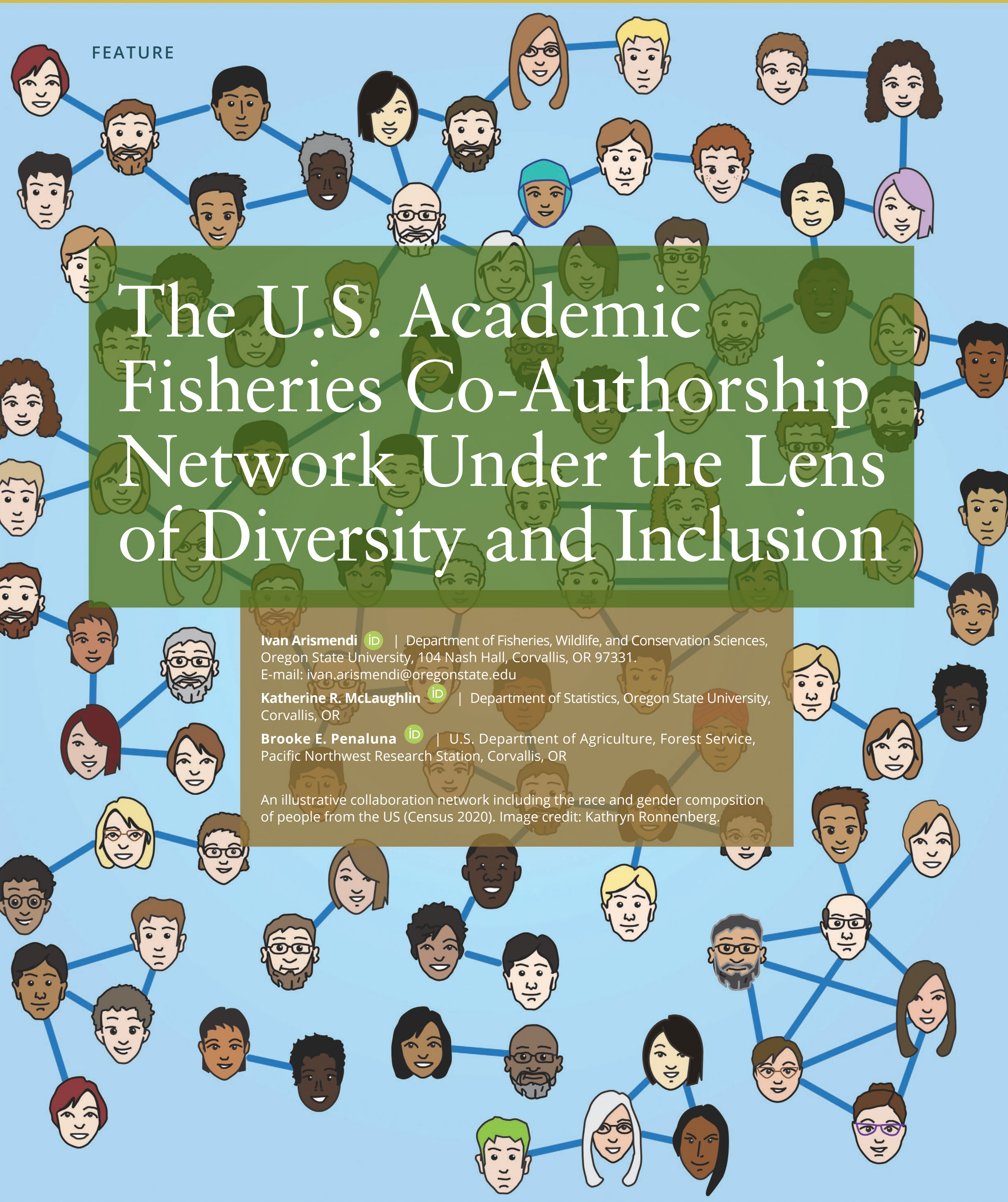

An illustrative collaboration network including the race and gender composition of people from the US (Census 2020). Image credit: Kathryn Ronnenberg.

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The inclusion of diverse individuals in ecological sciences has shown little progress over the past 2 decades for various reasons, including structural barriers in societies, organizations, and academia. Collaboration networks are important for productivity, promotion, and scientific impact, yet the extent to which the structure of these networks affects the inclusion of minoritized people remains unknown. Here, we evaluated trends in published research between 1965 and 2017 within the U.S. fisheries science academic co-authorship network and evaluated its structural composition, focused on gender and race/ethnicity. Although the number of publications, number of authors per article, and lead authorship by women and people of color have increased over time, white men still lead more than 70% of published articles. Network analysis demonstrates a shift in the structure of the network over time from an initial concentration of research among a few fragmented clusters to a nearly completely connected network by 2016. However, centrality metrics for women and people of color consistently showed lower scores, suggesting that their integration into the network remains incipient. Our findings illustrate that although progress has been made towards the inclusion of diverse talent in fisheries science over time, continued progress requires strategic, explicit efforts to overcome biases and barriers.

INTRODUCTION

High impact publications are one of the ultimate goals in science because they have a greater potential to create real change in management, policy, and society. In research, there is an emphasis on rewarding lead authorship positions in articles and publishing in high impact journals. Lead authors of published articles receive most of the recognition (Tscharntke et al. 2007). Indeed, the future success of early-career researchers is positively associated with the number of lead-author publications (von Bartheld et al. 2015). Articles that include multiple authors are both published in higher-impact journals and receive more citations than those by single authors (Wuchtyet al. 2007). As a result, authorship information is commonly used during many decision-making processes, including career advancement (Bornmann and Daniel 2006), promotion (Patrick O'Neill and Sachis 1994), and funding (Ginther et al. 2011). However, recent studies have documented a lower representation of women in lead authorship positions in scientific publications (Larivière et al. 2013; West et al. 2013). In addition, Freeman and Huang (2015) show that co-authors of similar ethnicity are most likely to publish together than co-authors of varying ethnicities. Hence, the structure of scientific co-authorship networks may affect the level of inclusion and retention of talented people from minoritized groups (i.e., groups that are different in race/ethnicity or gender and because of social constructs have less power or representation).

The participation of diverse scientific talent in social interactions, collaborations, and co-authorship is challenging, owing to the existing systemic biases and barriers in science and our broader society. Social interactions among scientists often play out as a reflection of cultural, social, and legal norms. They are fundamental to building collaborations that will eventually result in co-authorship (Liberman and Wolf 2013; Goring et al. 2014) and mentor–mentee relationships play an important role in facilitating research published in high-impact journals (Sekara et al. 2018). Systemic barriers are represented by multiple biases against minoritized groups in education (McCook 2011; Moss-Racusin et al. 2012), publishing opportunities (Pezzoni et al. 2016), hiring (Smith et al. 2015), peer review (Wennerås and Wold 1997; Handley et al. 2015; Helmer et al. 2017), grant funding (Ginther et al. 2011; Vernos 2013), and scientific prizes or awards (Ma and Uzzi 2018). Those aforementioned biases are in addition to socially constructed barriers, such as gendered expectations of parenting roles that can hinder the advancement of women in their careers. Consequently, a formal quantification of the degree of participation and inclusion of women and people of color in scientific co-authorship networks important for understanding continued barriers to inclusion and advancement.

Co-Authorship Networks

Network analysis can describe and quantify the structure of social interactions among scientists as collaboration networks, such as co-authorship networks of individuals connected by their co-publications. Co-authorship networks have been defined as "small worlds" or clusters, in which network members are often separated by a short path of intermediate colleagues (Newman 2001). The organization of these clusters not only reveals the structure of collaborations among members, but also can predict their future scientific performance (Guimerà et al. 2005; Abbasi et al. 2011; Ma and Uzzi 2018). Often, small clusters represent functional groups (Newman 2001), with disciplinary collaborations emerging as more important to career development than interdisciplinary collaborations (van Rijnsoever and Hessels 2011). Network members who are highly connected or repeatedly collaborate with other members show better citation-based performance than those with relatively fewer connections or collaborations (Abbasi et al. 2011). Conversely, isolated clusters might be indicative of people publishing in low-impact journals (Guimerà et al. 2005) or the seclusion of ideas outside of most influential research groups in the field (Horta 2013; Borrett et al. 2014; Ma and Uzzi 2018). Broadly, collaboration networks can also undergo changes over time from small network fragments growing in isolation during early stages, toward an expanded and more unified network(s) in later stages (Barnes et al. 2016; Anderson et al. 2017; Britt et al. 2018). Yet, the role that talented members from minoritized groups play in multidisciplinary and field-specific co-authorship networks is still unclear (Abbasi et al. 2011; Britt et al. 2018; Potvin et al. 2018).

Large-scale information on scientific careers can provide insights about the potential causes of inequalities in science and stimulate the development of models that can enlighten policy solutions (Fortunato et al. 2018). Here, we examine long-term trends in scientific publications (1965–2017) and perform a network analysis to evaluate potential diversity inequities in the U.S. fisheries science academic co-authorship network (Arismendi and Penaluna 2016). This network is composed by 389 tenure-track faculty from 56 U.S. institutions of higher education that offer minors, majors, or graduate studies in fisheries. To our knowledge, this is the first attempt for a detailed reconstruction of an extensive co-authorship network that includes information about gender and race/ethnic composition over more than 4 decades. This co-authorship network faces issues of diversity and inclusion that are similar to those in many other disciplines (Arismendi and Penaluna 2016; Fortunato et al. 2018) and thus, our findings can provide a baseline for comparisons with other co-authorship networks in science.

Our approach provides a dynamic understanding of the social underpinnings in collaborations and knowledge generation in fisheries science by digging into the U.S. fisheries academic co-authorship network. We aim to reveal characteristics and patterns within hidden subgroups in fisheries science recognized by Syed et al. (2019). We hypothesize that we will find increasing trends in the number of publications from women and people of color over time, but because of existing systemic barriers in society, science, and academia, we also anticipate inequities in leadership positions in the network. We anticipate that the co-authorship network may experience changes, with highly clustered groups increasing in size and connectivity over time. We expect a decrease in the participation of fisheries science academics, owing to the increase in authors from outside of the network, illustrating the importance of non-academic investigators to the field of fisheries science and an increasing importance of multidisciplinary work and partnerships over time (Fortunato et al. 2018). Collectively, a better understanding of these networks and how they have changed over time illustrates past and present disparities and biases in collaboration networks that can be deliberately addressed to move towards a more diverse and inclusive scientific community. Ultimately, diversifying these networks brings multiple perspectives to the table (Diamond 2019), keeping science relevant and allowing decision makers access to the best information so they can respond more broadly and deeply to challenges and new discoveries in fisheries science.

MATERIALS AND METHODS

Fisheries Science Academic Workforce

We extracted information from the U.S. Fisheries Academic database described by Arismendi and Penaluna (2016). This database contains faculty members from 56 U.S. institutions of higher education that offered minors, majors, or graduate studies in fisheries. The list of institutions was found at the website of the National Association of University Fisheries and Wildlife Programs (Available: https://bit.ly/3uBQ9DL). Some additional institutions that offered majors in marine biology or aquaculture were also included (see the complete list in Arismendi and Penaluna 2016). The faculty composition of these programs may not broadly include all disciplines related to fisheries science, but it represents the literature from individuals who hold academic fisheries positions in the USA. We recognize that U.S. fisheries academics do not fully represent the wider field of fisheries professionals (government, non-governmental organizations, private industry, other countries) publishing fisheries research, especially those related to social science and humanities. Indeed, fisheries science is a complex field that includes multiple disciplines such as limnology, oceanography, biology, ecology, statistics, management, economics, sociology, anthropology, psychology, and others. Here, we focused on a subset of the database described by Arismendi and Penaluna (2016) that included a binary gender (man or woman) and race/ethnicity (based on categories from the 2010 U.S. Census) information for tenure-track faculty (n = 389). We considered only tenure-track appointments because they represent permanent positions allowing us to track patterns of academic collaboration over the long-term. In this database, more than 70% of tenure-track faculty are men, and over 88% are white. We did not consider the examination of changes in patterns of collaboration based on race or the intersectionality of gender and race owing to the low sample sizes of these categories.

Publication Dataset

We created a publication list (1965–2016) by querying the Clarivate Analytics Web of Science (available: http://www.webofknowledge.com) Core Collection database, using the names of tenure-track faculty listed in the U.S. Fisheries Academic database (Arismendi and Penaluna 2016). We found more than 16,000 publications that were saved as .bib files and exported to the R programming language using the bibliometrix package (Aria and Cuccurullo 2017). The first 10 authors for each publication (representing 97% of all publications) were retained. We revised the list to remove duplicate publications and we attempted to confirm the identity of the authors. We suspect that the data quality is not perfect, because of common last names and records with metadata on only first initials rather than complete first names. However, the error introduced by authors having the same initials and surnames has been estimated to be less than 5% (Newman 2000). We ranked and listed the top 20 journals with most publications from the network for every decade from 1965 to 2016.

Trends in Publications over Time

We evaluated the significance of historical trends in number of publications and authorship using a non-parametric Mann–Kendall tau test for monotonic time series (Mann 1945). This rank-based test is robust for non-normal data series with outliers and non-linear trends. When trends were statistically significant ($P < 0.05$), we estimated the magnitude of trends using the non-parametric Sen slope (Sen 1968). We used a block–bootstrap method to account for potential serial correlation effects (Yue and Pilon 2004).

Network Analyses of Co-Authored Publications

The publication dataset was used to create the network by subsetting records containing at least two authors from the U.S. Fisheries Academic database. The edge list contained the IDs of the two authors and the year of publication. We restricted the years considered from 1972 (the earliest co-authorship by two members of the database) to 2016 (the last full year before the records were queried). Node covariates (properties of the node or person) for gender (male/female) and race (white/person of color) were acquired from the database. The network edges (connections between nodes) were weighted and aggregated such that for a given year the weight of an edge between two authors was the number of co-authored publications they had for that year and all preceding years. Thus, the edge weights only increased over time.

We calculated the bonding number for the U.S. fisheries science academic co-authorship network to understand the level of communication within that fisheries community (Liberman and Wolf 1998). The bonding number provides information about changes in patterns of collaboration within a particular discipline over time or to contrast among disciplines (Liberman and Wolf 1998). Overall, higher bonding numbers indicate more collaborative research. The bonding number for a particular period is the number of bonds per author in that time frame,

$$\sigma = \frac{\frac{1}{2}\sum_n n\,(n-1)\,A_n}{\sum_n A_n},$$

where $n = 1, 2, \ldots$ is the number of authors on an article and A_n is the number of articles with n authors published during that period. We calculated the overall bonding number (1965–2017), the bonding number for each decade from the 1960s to 2010s, and the bonding number from 1982–1994 to contrast with a previous study (Liberman and Wolf 1998).

We evaluated the relative importance of each member within the co-authorship network using network centrality metrics. Network centrality measures were calculated for each time point (Opsahl 2009; Opsahl et al. 2010). Because of the disconnected clusters, particularly at early timepoints, we omitted other network metrics, such as closeness, but calculated degree and betweenness. Degree and betweenness metrics quantified the number of co-authorships of each member (as an aspect of scientific productivity) and the frequency of times that a member acted as a bridge over the shortest path between two other members (co-authorship influence upon other members) respectively. These two metrics were calculated using the weighted edges. The network at year y can be expressed as a binary $N \times N$ adjacency matrix A^y, where N is the number of individuals in the U.S. Fisheries Academic database and entry a_{ij}^y is equal to 1 if an edge connects node i to node j at time y, and 0 otherwise. Note that owing to the cumulative way in which the networks are constructed, a_{ij}^y will be equal to 1 if nodes i and j have published together in any year $\leq y$. Further, let the edge weight w_{ij}^y be the number of co-authored publications by nodes i and j during years $\leq y$. The co-publication network is undirected and thus, $a_{ij}^y = a_{ji}^y$ and $w_{ij}^y = w_{ji}^y$ by definition. The weighted degree centrality of node i, also known as the strength of node i, at year y is $s_i^y = \sum_{j=1}^{N} a_{ij}^y w_{ij}^y$. This quantity measures the strength of nodes (individuals) in terms of the total weight of their connections (co-authored publications). Betweenness centrality quantifies the number of times a node acts as a bridge along the shortest path between two other nodes. The betweenness centrality of node i at year y is $b_i^y = \sum_{s \neq i \neq t} \sigma_{st}^y(i)/\sigma_{st}^y$, where s and t are a pair of nodes in the network not involving i, σ_{st}^y is the total number of shortest paths between nodes s and t at time y, and $\sigma_{st}^y(i)$ is the total number of shortest paths between nodes s and t at time y that pass through node i. In the case of weighted betweenness, σ_{st}^y and $\sigma_{st}^y(i)$ incorporate the edge weights into the calculation of number of paths. For example, an edge between nodes s and t with weight two counts as two paths.

To examine the pattern of co-authorship from most influential men and women members of the network, we contrasted ego networks of high-centrality individuals in 2016. A node that represents the individual member ("ego") and all other nodes (other members) directly connected to that member, including the number of interactions (publications) among them composed a co-authorship ego network. Thus, we used ego networks to examine the structure of "local networks" of influential members. We selected the top five men and the top five women in terms of weighted degree and weighted betweenness in 2016, restricting the set of eligible men and women to those who had at least one publication with another member of the network by year 2000. This restriction allows us to consider co-publication trajectories.

RESULTS

Trends in Published Research and Authorship

Trends in publishing research from the U.S. fisheries science academic network showed consistent growth over the past 50 years (Figure 1). Of the 387 authors that make up this network, only 13% did not publish with another member and 3% had no publications indexed in the Web of Science. Network members contributed to more than 16,000 published articles in 513 journals (counting journals with at least three articles) between 1965 and 2016. Forty-seven journals were among the top 20 most popular in terms of number of publications by network members over this time frame (Table S1).

Trends in the volume of articles published, number of authors per article, and the role of network members on publications illustrated shifts in patterns of collaboration over time. The research published by network members increased over time, from fewer than 10 articles in 1965 to more than 900 in 2016 (Figure 1A; Table S2). Similarly, the mean number of authors per article increased from 2.4 to 5.3, whereas the proportion of single authorship decreased from 67% in 1968 to 1.7% in 2015. When all articles published between 1965 and 1974 are considered, almost 50% of authors belonged to the network. This percentage gradually decreased over time (e.g., 24% between 2005 and 2016). Further, examining a time series of authorship position by article showed a gradual shift toward network members taking fewer leadership roles over time (Figure 1B). Until the middle 1990s, nearly half of the published articles had a lead author from the network, but this percentage decreased to approximately 15% in 2016. Similarly, the mean authorship position of members of the network shifted consistently toward less primary roles. The degree of collaboration among scientists in this network (expressed as the bonding number) also increased consistently every decade (1965–1969 = 0.89, 1970–1979 = 1.08, 1980–1989 = 1.11, 1990–1999 = 1.68, 2000–2009 = 3.06, and 2010–2017 = 4.47) with an overall value of 1.26 during the period between 1982 and 1994 increasing to 3.49 from 1965 to 2017.

Similarly, the participation of minoritized groups in published research has shifted over time. Specifically, women and people of color not only showed an increased participation in published research (Figure 2A), but they also increasingly took on the lead-author role over time (Figure 2B). Although the increase in participation of both minoritized groups as primary authors was consistent over time, men or white members still led more than two-thirds of the published articles from the network since 2010.

Co-Authorship Network Analysis

Our network analysis illustrated the trajectory of co-authorship among members showing an overall more cohesive network over time (Figure 3; Movie S1). The network was fragmented and disjointed, with several distinct clusters in 1980, 1990, and 1995 (Figure 3). However, increased collaboration over time resulted in more connected clusters toward a unified component that was visible beginning in the 2000s. By 2016, the whole network was almost completely connected, with only a few pairs of members in isolation.

Women and people of color did not occupy influential positions in the co-authorship network. Although trajectories of weighted network metrics of centrality (i.e., degree and betweenness) for women and people of color have consistently increased in the past 15–20 years, men and white members occupied the most influential network positions over time (Figure 4). Both weighted degree (as an aspect of scientific productivity) and weighted betweenness (co-authorship influence upon other members) showed men and white members consistently having the highest scores.

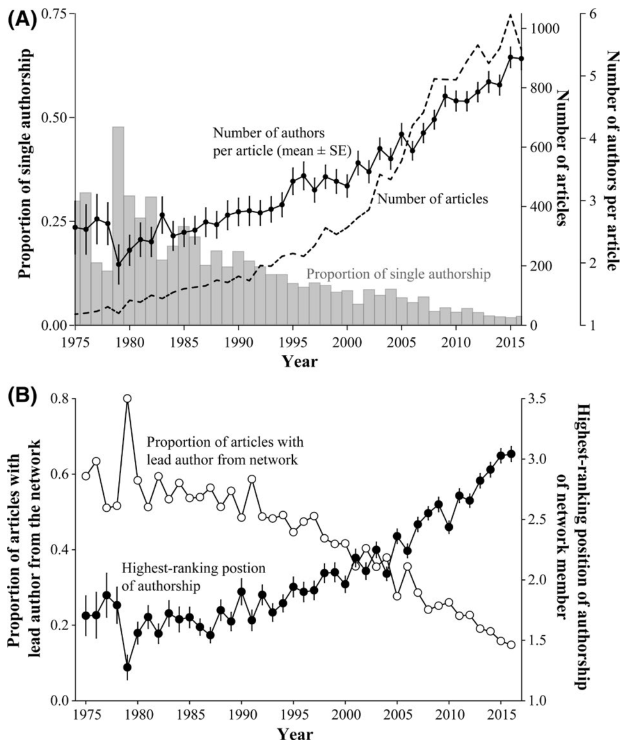

Figure 1. Publishing trends in the U.S. fisheries science academic network between 1975 and 2016. (A) Proportion of single authorship decreased over time (left *y*-axis; grey bars; slope = −0.1/decade, *P* < 0.001) whereas the number of articles published by the network have increased (primary right *Y*-axis; dotted line; slope = 231/decade, *P* < 0.001); number of authors per article has also increased over time (mean ± SE; secondary right *y*-axis; solid line; slope = 0.7/decade, *P* < 0.001). (B) Decreasing trends in the proportion of articles published with members of the network as lead author over time (left *Y*-axis; slope = −0.1/decade, *P* < 0.001). Highest-ranking position of authorship of network member has increased over time (mean ± SE; right *y*-axis; slope = 0.3/decade, *P* < 0.001). Data from 1965 to 1974 are not shown owing to the relatively small number of articles published during that timeframe (full dataset is available in Table S2).

Patterns of co-authorship of highly influential positions in the network showed marked differences by gender. The five top-ranked ego networks (or "local networks" of top-ranked members), based on the weighted degree, showed distinctive patterns for men compared to women (Figure 5A). Most members within top-ranked men's networks were also men. These top-ranked local networks showed strong and frequent collaborations with other highly productive men (i.e., generally the same members from other top-ranked networks). This contrasted with top-ranked women who did not collaborate with other top-ranked members, except for one example (i.e., Wd5). In this case, a substantial portion of the network for Wd5 included other top-ranked men (i.e., Md1 and Md3). However, the co-authorship relationship for Md1 and Md3 with Wd5 consisted of only a small portion of their network portfolio (Figure 5A). In general, top-ranked women had relatively simpler ego networks with a single main productive co-author.

Similarly, the five top-ranked ego networks based on the weighted betweenness metric differed by gender (Figure 5B). High betweenness highlighted members who hold the most influential positions in the network, where they act as a bridge between other members, and who are influential to the structure of network collaborations. Men connected more disparate clusters in the network of differing productivity levels. Women had fewer connections to potential collaborators and the connections they did have were to members with lower productivity relative to men. Lastly, only one man (i.e., Md3/Mb4) was in both the top-ranked weighted degree and betweenness, whereas three (i.e., Wd3/Wb5, Wd4/Wb3, and Wd5/Wb2) of the five women were the same individual for both weighted degree and betweenness top-ranked positions (Figure 5).

DISCUSSION

Here, we demonstrate that the U.S. fisheries science academic co-authorship network has experienced a profound transformation, becoming inherently more collaborative and larger over the past 5 decades. This expansion has been recognized in fisheries science collaborations around the globe since 2000 (Syed et al. 2019). The rapid growth we observe is consistent with the recent increases in the inclusion of talented people dedicated to developing creativity and innovation in science, technology, engineering, and mathematics (NSF 2017; Fortunato et al. 2018). The prediction of an exponential expansion over time in scientific collaboration (Price 1976) is supported by our data, with single authorship being almost phased out and co-authorship becoming increasingly more common (Regalado 1995; Duffy 2017; Milojević et al. 2018). Indeed, the observed growth in the number of authors per article is comparable to other natural resource sciences (Duffy 2017), but higher than observed in economics, psychology, astronomy, and mathematics (Guimerà et al. 2005; Mihaljevic-Brandt et al. 2016). It has been postulated that each scientific discipline has a characteristic bonding number over a given period (Liberman and Wolf 1998) with little change over time (Liberman and Wolf 2013). Higher bonding numbers indicate more collaborative disciplines. For a similar period, the bonding number in fisheries science is smaller than in physics and biotechnology, but greater than in mathematics and anthropology (Liberman and Wolf 1998). However, the bonding number in fisheries science has increased by almost a factor of four over the past decade, suggesting that connections are occurring among disparate groups at a faster rate.

We show that the fisheries co-authorship network has experienced a major change over time, shifting from a series of isolated fragments toward an expanded, unified, and collaborative unit, like other science disciplines (Barnes et al. 2016; Anderson et al. 2017; Britt et al. 2018). The increased number of articles published in non-traditional disciplinary-specific journals over time also echoes this expansion (Table S1). At early stages, network fragments might represent groups studying the same or different research topics in isolation (Barabâsi et al. 2002). Over time, more connected fragments might indicate awareness of each other's group working on similar research topics or research topics becoming more integrated as groups start to identify connections among research topics (Syed et al. 2019). More collaborations outside of this academic network not only indicates increased interdisciplinary work, but also mean that members of minoritized groups from outside the network could also be recruited. This might increase the actual representation of minoritized groups in the full co-publication network. Yet, the lack of inclusion of minoritized groups into this cohesive and unified co-authorship network is a challenge.

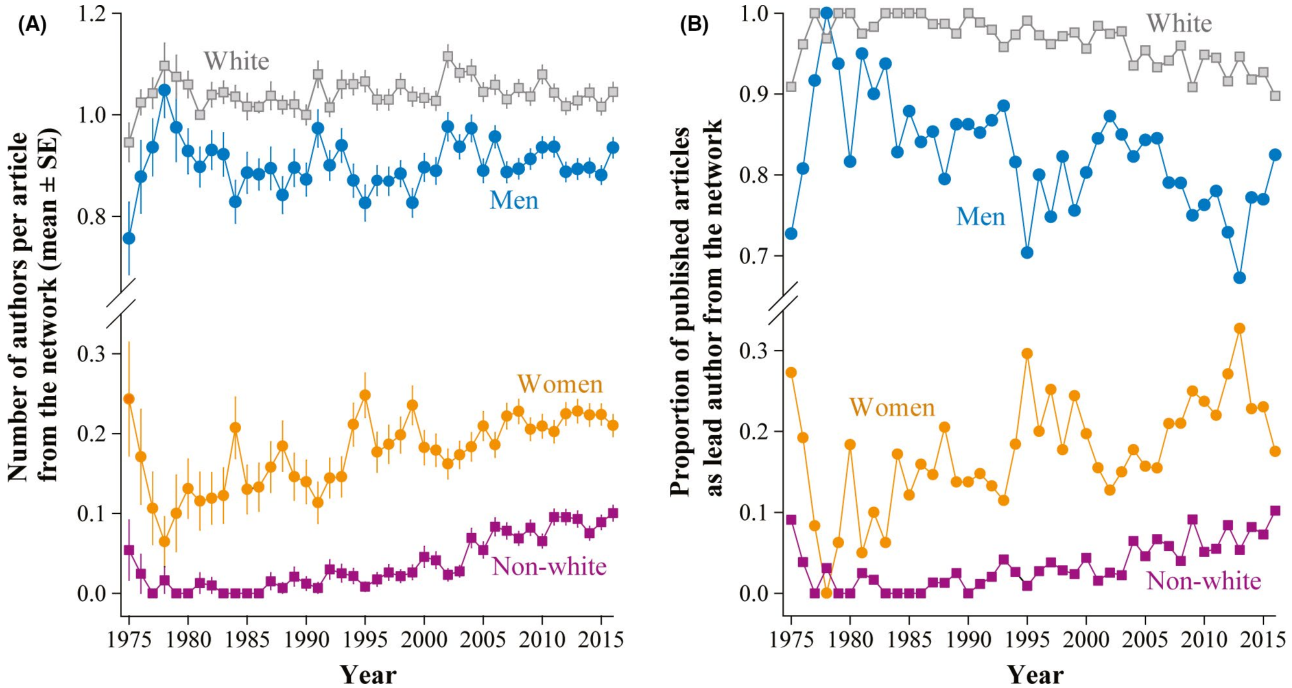

Figure 2. Authorship trends by gender and race/ethnicity in the U.S. fisheries science academic network between 1975 and 2016. (A) Number of men authors per article (mean ± SE) who are part of the network has not changed (slope men = 0.00/decade, $P = 0.70$) whereas it has increased for women over time (slope women = 0.03/decade, $P < 0.001$). Similarly, there is no increase in the number of white authors (slope white = 0.00/decade, $P = 0.41$), but there is an increase in the number of authors representing people of color over time (slope person of color = 0.02/decade, $P < 0.01$). (B) Proportion of published articles for which the lead author is part of the network has decreased for men (slope men = −0.04/decade, $P < 0.001$) and increased for women over time (slope women = 0.04/decade, $P < 0.001$). A decreasing trend is observed for white members (slope white = −0.02/decade, $P < 0.001$) whereas an increasing trend is also seen for people of color over time (slope person of color = 0.02/decade, $P < 0.001$). Data from 1965 to 1974 are not shown due to the small number of articles published during that timeframe.

The influence of the historical context in the social construction of race (Smedley and Smedley 2005) and gender (Lorber and Farrell 1991) in the United States helps to explain why a high network centrality of men and white members persists over time. The legacy of foundational ideas of slavery of Africans in the 18th century, followed by questioning their humanity in the 19th century persist to current day (Omi and Winant 1986; Smedley and Smedley 2005). Similarly, the social structure and individual identities in western societies deliberately have devaluated women, while benefiting men (Lorber 2004). Consequently, the persistence of socially constructed racism and sexism have left residues in science (Ong et al. 2011; Laurencin 2020). In our co-authorship network, the continued centrality of white men suggests these individuals may fulfill the role of intellectual gatekeepers by shaping both new links among topics within fisheries science, even as its structure is changing and existing links among previously disparate researchers. In any case, a better understanding of links between centrality and connectivity over time can provide insights about the underlying dynamics by which men and white members exercise and maintain most influential roles within the network.

Although science is most effective when more people are involved (Guimerà et al. 2005; Cook et al. 2015), we show that the rapid growth of the fisheries network contrasts with the ongoing inclusion of women and people of color. Indeed, there are consistent increases in lead authorship roles by women and people of color over time, but a gap still exists in this network and elsewhere related to publications and citations (Abramo et al. 2013; West et al. 2013; Branch and Linnell 2016; Mihaljevic-Brandt et al. 2016). Unfortunately, given the low sample size, we cannot examine our findings considering the intersectionality of gender and race/ethnicity. However, it is reasonable to argue that some network members experience intersectional marginalization (i.e., women of color). Overall, observed disparities for the inclusion of women and people of color in the fisheries network mirrors their low representation in the academic and federal workforce (Arismendi and Penaluna 2016) and in most of the highly cited publications in fisheries (Branch and Linnell 2016). Only 26% of federal fisheries scientist/manager positions and fewer than 30% of tenure-track professor positions are currently occupied by women, and fewer tenure-track (<12%) positions are held by people of color (Arismendi and Penaluna 2016). Systemic biases in science and academia still exist at multiple levels (Wennerås and Wold 1997; Vernos 2013; Reuben et al. 2014) and act cumulatively, affecting the retention and promotion of members from such minoritized groups (Perna 2005; Kaminski and Geisler 2012). Hence, the full inclusion of minoritized groups is challenging in both academic and publication networks, particularly if men and white members have both intellectual and personal gatekeeper roles.

Top local networks (or ego networks) based on centrality measures illustrate patterns of co-authorship from the most productive members, and these show that men occupy the most influential positions in research compared to women. Top-ranked men have more extensive and stronger co-authorship networks, and these networks are usually composed of other top-ranked men, whereas top-ranked women are more likely

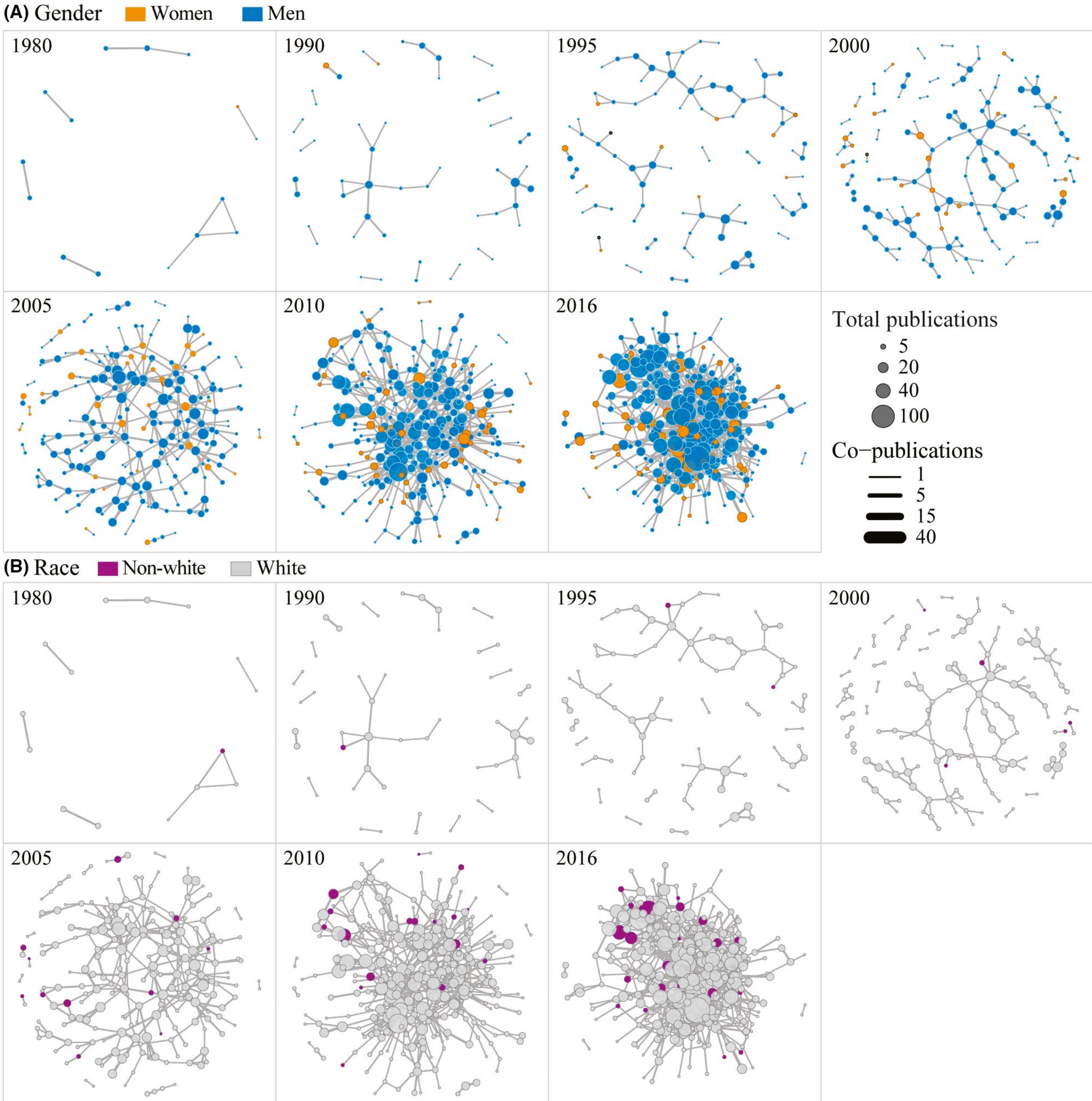

Figure 3. Structure of the U.S. fisheries science academic network on selected years. The figure illustrates the temporal trajectory from heavily clustered to a more cohesive network over time. Individual nodes represent network members by (A) gender (blue = men; orange = women) and (B) race (gray = white; purple = person of color). The size of the node is proportional to the total number of co-publications for a member, and the width of the edge is proportional to the number of co-publications between two members. Animation of the network dynamics by each year over the entire timeframe can be found in the Supplementary Material (Movie S1 and Movie S2).

to collaborate with less influential members. Both top-ranked men and women are mostly co-publishing with other men. This suggests an increase in the visibility of members that are already well positioned in the network (Fortunato et al. 2018). This phenomenon is often referred to as the Matthew effect (or accumulated advantage) where the eminent scientists get more credit than lesser-known scientists, even if they did not have a prominent position in the work (Merton 1968). In addition, the same women occupy top-ranked positions in both degree and betweenness relative to men, suggesting that to be successful in the network women must both publish and be influential to the rest of the network. This supports the idea that, for women, leadership success is more difficult under less inclusive social networks (Yang et al. 2019). Top-ranked network members who are highly connected or publish repeatedly with others have more publications, as seen in other disciplines (Guimerà et al. 2005; Fortunato et al. 2018). In other STEM fields, researchers with higher levels of betweenness also show higher performance scores, such as the g-index (Abbasi et al. 2012). This index is based on the author's publication records and the number of citations, balancing the importance of low-cited or non-cited articles while

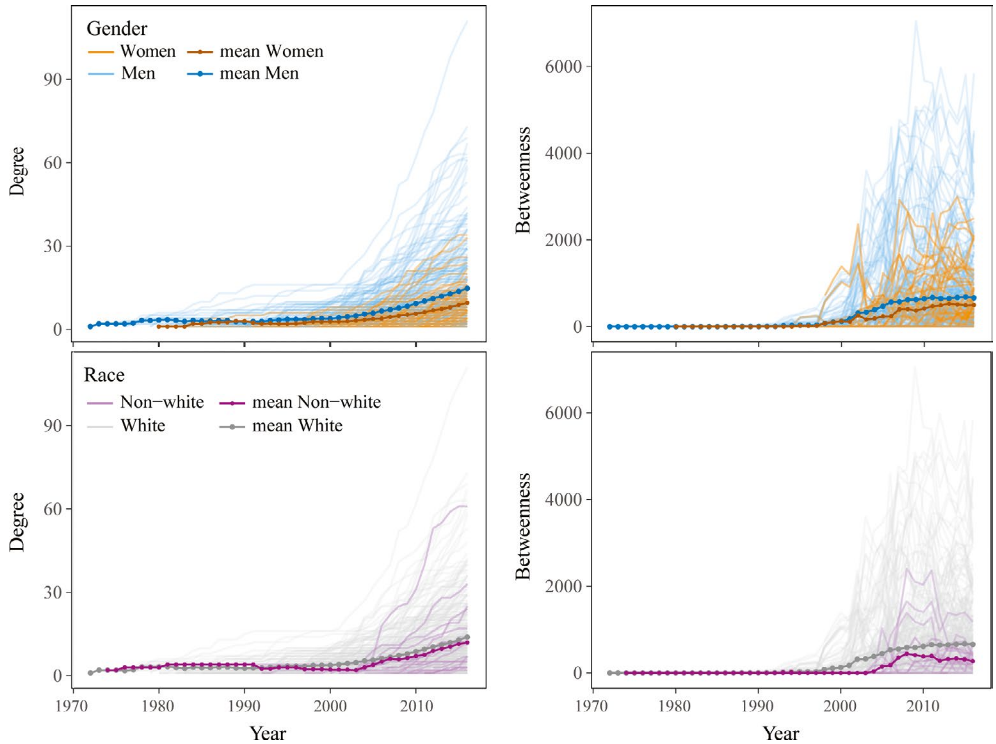

Figure 4. Trajectories in the U.S. fisheries science academic co-authorship weighted network metrics over time. The figure shows consistent lower scores for women (upper panel; blue = men, orange = women) and people of color (lower panel; gray = white, purple = person of color) illustrating co-authorship inequalities for both gender and race/ethnicity. Lines represent trajectories of individual network members. Whereas weighted degree represents the strength of co-authorship (as the total weight of their connections), weighted betweenness denotes the influence of a member upon other network members (as the number of times a member acts as a bridge along the shortest path between two other members).

imputing more weight to highly cited articles. The extensive use of citation metrics as indicator of scientific productivity, however, has been recently challenged due to the potential to perpetuate disadvantages of minoritized groups favoring citation elites (Nielsen and Andersen 2021). Although our current scientific reward system in science is based on quantity of publications and citations, which perpetuates sexist and racist "rewards" through narrowly prioritizing citations and impact factors, it has been suggested that we should shift our value system to broadly include metrics of justice, equity, diversity, and inclusion (Davies et al. 2021). This would help us to reimagine the science workforce as a collection of paths that change and adapt to the needs of the individual under a foundation of mentoring. If there was a shift in our scientific value systems, then scientists would be valued for contributions that influence aspects of mentorship, diversity, and wellbeing, as well as for the quality of their publications.

Traditional practices and cultural boundaries that persist within and among science disciplines play a role in helping or hindering the full inclusion of minoritized individuals into their corresponding network. Collaborations start at the individual level based on social interactions (Liberman and Wolf 2013; Goring et al. 2014) and trust, expressed as "motive-based trust" and "competence-based trust" (Siegrist et al. 2003; Twyman et al. 2008). However, competence impressions can be subjective and strongly biased against women (Moss-Racusin et al. 2012; Oh et al. 2019) and people of color (Parks and Kennedy 2007). Biases toward traditional practices within science disciplines can perpetuate barriers to the inclusion of minoritized groups (Kost-Smith et al. 2010; Riegle-Crumb and Humphries 2012; West et al. 2013; Ma and Uzzi 2018). For example, even though the gender-neutral term to describe people who fish is "fishers," their use in scientific publications has not yet been fully adopted (Branch and Kleiber 2017).

Deliberate actions to promote the inclusion of diverse talent and to break obstacles and biases starts at multiple levels including at the individual, group, or institutional. Mentoring can be an important component to include diverse talent in the workforce because it can be catered to the unique experiences and skills of the individuals (Penaluna et al. 2020). At the institutional level, inclusive practices can change the culture and tone of work environments (Smith et al. 2015) and scientific societies (Penaluna et al. 2017; Abernethy et al. 2020). The inclusion of minoritized groups in collaboration networks may also benefit from a double-blind peer review process and increased diversity of journal editors to decrease biases. Lastly, we can celebrate women in fisheries (Murphy et al. 2020; Zatkos et al. 2020) to increase their visibility leading to more as role models for future generations.

CONCLUSIONS

The explosive increase in the number of scientific publications during the last half of the 20th century (Regalado 1995; West et al. 2013; Barlow et al. 2018) is an unequivocal indication of the rapid growth and expansion of scientific knowledge. However, scientific collaboration is not a random process and thus, it represents an important barrier in the development of scientific communities. Here, we demonstrate that the fisheries co-authorship network has expanded and become more unified over time, yet women and people of color are not fully

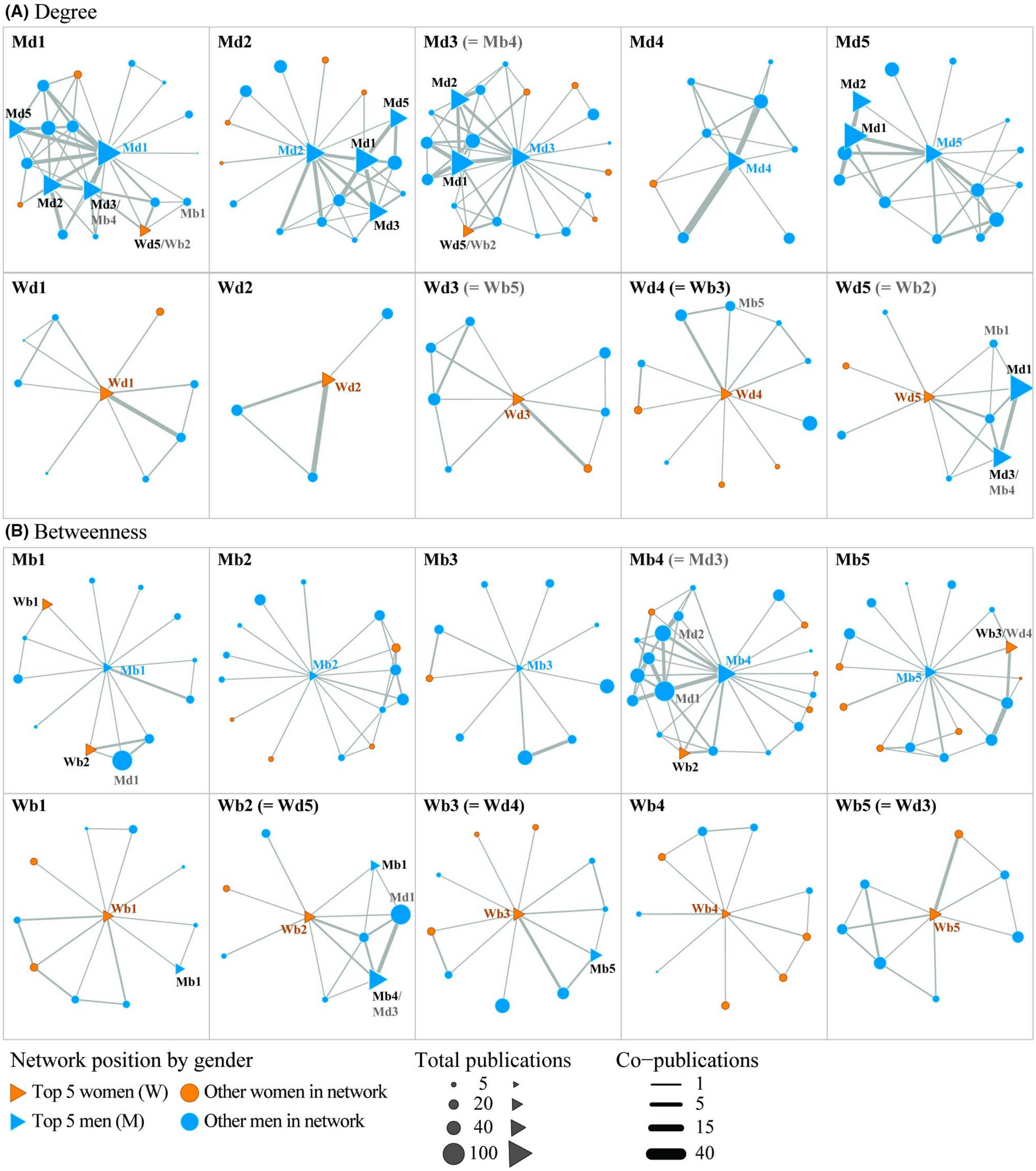

Figure 5. Structure of ego-networks of top-10 ranked members by gender. Ego-networks represent local networks of the top-five men (blue – M1 to M5) and top-five women (orange – W1 to W5) by weighted degree (A) and (B) betweenness in 2016. Node size is weighted by total number of publications and edges are weighted by total number of coauthored publications. The top-five men showed higher mean weighted degrees of co-authors (excluding themselves; mean of 17.4 ± 2.7 SD) compared to the top-five women (mean of 9.1 ± 3.1 SD). The weighted degrees of co-authors represent both how productive co-authors were overall and how clustered each ego-network was.

included and not in the most-influential positions, owing to the systemic sexism and racism found in society. Moreover, if talented people from diverse identities are left out of science, then dominant ideas remain unchallenged and the inclusion of new ideas are limited in ways that are difficult to identify and quantify (Britt et al. 2018; Diamond 2019). Critical evaluation of structures and practices are warranted to increase opportunities for women and people of color, especially into leadership roles. Changes from the bottom-up, starting at the personal level and at individual research groups as well as from the top-down at institutions, societies, and by leaders are necessary to move towards science that is more diverse, equitable, and inclusive.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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SUPPORTING INFORMATION

Additional supplemental material may be found online in the Supporting Information section at the end of the article.

Movie S1
Movie S2
Table S1
Table S2