

The Productivity Puzzle in Invasion Science: Declining but Persisting Gender Imbalances in Research Performance

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We analyzed 27,234 publications published since the rise of the field of invasion science in 1980 to evaluate the presence of gender differences in research productivity, the extent of collaboration, and the research impact of those differences. Our analysis revealed significantly fewer female than male authored publications, both per capita and as a group, and the underrepresentation of women as first and single authors persists despite improvements in the gender gap. At the current rate of increase, gender parity in first authorship will not be achieved until 2100, and men will continue to constitute the principal voice of first or single authors in invasion science. Women collaborate with fewer coauthors and are cited less frequently than men, on average, which may influence recruitment and retention to more senior academic positions. These gender disparities in this aspect of research performance suggest that, although the gender gap is lessening, women experience barriers in invasion science.

Keywords: bibliometrics, authorship, gender disparities, women in science, citations

Although the representation of women in academia has increased (West et al. 2013), studies continue to document disparities between genders in publishing, hiring or promotions, funding or awards, and many other features of an academic career (Grogan 2019). Women are less likely to work in elite research groups, experience longer time to promotion, and are more likely to leave the academic workforce (Shaw and Stanton 2012, Sheltzer and Smith 2014, Grogan 2019). These disparities can interact synergistically to reinforce gender inequities and contribute to the leaky pipeline, a phenomenon by which women, as well as other marginalized groups, do not progress at the same rate as men and are passively lost at each academic career stage (Pell 1996, Grogan 2019).

Disparities between genders vary greatly over time and across specific fields (Kanny et al. 2014). Invasion science forms a distinct discipline examining the causes, consequences, and management of species introduced to areas outside of their native range. It covers research in fields beyond ecology and biology, including but not limited to economics, human history, philosophy, and politics (Richardson and Ricciardi 2011, Richardson et al. 2011, Vaz et al. 2017). The transdisciplinary and highly collaborative nature of invasion science is driven by the complexity,

urgency, and global scale of biological invasions. The field of invasion science is relatively young, and publications concerning biological invasions began to rapidly increase only in the 1990s (Richardson and Pyšek 2008, Campbell and Simberloff 2022) after the Scientific Committee on Problems of the Environment project on biological invasions in the early 1980s (Simberloff 2011a, 2011b). Because the rise of the field coincided with increased gender equity (Tourkoushian 1999) and as the percentage of women earning doctorates approached 50% in the life sciences (NCSES 2021a), invasion science should have lower gender imbalances than more established fields, such as ecology. To our knowledge, our analysis in the present article is the first to examine literature in invasion science comprehensively from the rise of the field in the early 1980s to the present day for gender imbalances in measures of research performance.

A vast body of literature has examined the underlying mechanisms structuring or reinforcing disparities between genders, particularly gender differences in the quantity of publications, because this is the principal measure of research productivity and performance in academia (Ioannidis 2014), the primary method by which scientific research is communicated (Lortie et al. 2007), and greatly influences hiring decisions (Van Dijk et al. 2014), tenure and

promotion decisions (Fox 2004), and the ability to acquire funding or awards (Lerchenmueller and Sorenson 2018). Previous work (e.g., Larivière et al. 2013, West et al. 2013, Aguinis et al. 2018, Bendels et al. 2018, Bhagat 2018, Huang et al. 2020, Giakoumi et al. 2021) has shown that, on average, men publish more than women over their careers, a pattern known as the *productivity puzzle* (Cole and Zuckerman 1984). Although there are no universal practices in authorship roles (Helgesson and Eriksson 2018), the first author typically completes most of the research, whereas the last author is often the supervisor or senior academic (Hundley et al. 2013). Gender disparities in publication productivity have decreased in most scientific fields, but women remain underrepresented in the literature relative to their numbers as scientists (West et al. 2013, Whelan and Schimel 2019, Dworkin et al. 2020), especially in the key authorship roles of first, last, corresponding, and solo authors (Martin 2012, Larivière et al. 2013, West et al. 2013, Bendels et al. 2018, Fox et al. 2018, Holman et al. 2018, Frances et al. 2020, Giakoumi et al. 2021). In ecology and evolutionary biology, the proportions of female authorships in key roles still fall below that of women receiving doctorates in biology (Frances et al. 2020), although some research has shown gender disparities to be decreasing among early career scientists in other fields (e.g., Addessi et al. 2012). Furthermore, although the proportion of female authorships has increased in general in ecology and evolutionary biology, the representation of women in last author position has increased the least, suggesting that, despite improving equity in recruitment of women to science, retention remains a challenge (Frances et al. 2020). This is also true of science, technology, engineering, and mathematics (STEM) fields in general, and the lower retention of women than men partially accounts for the productivity puzzle (Huang et al. 2020). The historical overrepresentation of men in academia may also influence the productivity puzzle. As a group, women may be as productive as men; however, if men are more numerous than women, men would account for a higher proportion of the publications produced (Astegiano et al. 2019).

Many studies across various fields have demonstrated an increase in the proportion of publications that are multiauthored and in the average number of authors per paper (e.g., Nabout et al. 2015, Kuld and O'Hagan 2017, Verleysen and Ossenblok 2017, Barlow et al. 2018). Coauthorship is often used as a proxy for research collaboration (Katz and Martin 1997, Franceschet and Costantini 2010). Collaboration can affect a researcher's career by leading to higher publication productivity and increased citations, and it often influences funding, hiring, and promotion decisions (Katz and Martin 1997, Glänzel 2002, Hsu and Huang 2011, Nabout et al. 2015). On average, men establish research networks with collaborators more frequently than women do (Abramo et al. 2013, Smith 2014, Collins and Steffen 2019). Men are more likely to collaborate with other men (Araújo et al. 2017) and to collaborate internationally (Abramo et al. 2013), whereas women have collaboration networks

that are less cosmopolitan and prestigious (Abramo et al. 2019). The relationship between the number of coauthors and gender has been mixed, with studies showing that men have numbers of coauthors higher than (Elsevier Research Intelligence 2020), lower than (Bozeman and Gaughan 2011, Fox et al. 2018, Dworkin et al. 2020), or similar to (Abramo et al. 2013) those of women. The patterns of collaboration can affect the social capital of women in academia and, therefore, potentially partially explain gender differences in productivity (Abramo et al. 2019).

Citation metrics are widely used to measure research quality, success, and impact (Lawani 1986, Hamilton 1990), and, like research productivity, they can influence hiring, tenure and promotion decisions, obtaining funding, speaker invitations, and recognition (Faria and Mixon 2021, Llorens et al. 2021). Although many studies have demonstrated that, on average, women publish fewer papers than men over their careers, it has been hypothesized that women focus on quality over quantity and produce more highly cited publications in higher-impact journals (Mauleón and Bordons 2006, Duch et al. 2012). Other studies have shown that women publish in less-prominent journals with lower impact factors, with increasing underrepresentation of women as the impact factor increases (Brooks et al. 2014, Bendels et al. 2018). In some cases, women have fewer citations or lower citation rates than men in the same key authorship positions do (Larivière et al. 2013, Sugimoto et al. 2013, King et al. 2017, Bendels et al. 2018, Lerchenmüller et al. 2018), which likely negatively affects their academic careers.

The number of accumulated citations and citation rates can be biased or influenced by other factors (Leimu and Koricheva 2005, Borsuk et al. 2009). Differential citation practices between genders, whereby men are more likely to self-cite and to undercite female scientists (King et al. 2017, Dworkin et al. 2020), may be a contributing factor in those studies that have documented higher citation rates among papers authored by men (e.g., Larivière et al. 2013, King et al. 2017, Bendels et al. 2018). Furthermore, the smaller, less cosmopolitan, and less prestigious research networks that women have in some cases (e.g., Abramo et al. 2019) may affect citation rates, because a larger network potentially disseminates research more widely, increases visibility, and may result in increased citations by that network. Likewise, many studies have found factors other than gender to be more important or have shown no gender differences in the number of citations or citation rates (e.g., Leimu and Koricheva 2005, Borsuk et al. 2009, Prozesky and Boshoff 2012, Cameron et al. 2016). Gender imbalances in the number or rate of citations likely depend on the discipline (Huang et al. 2020), and the presence of imbalances may have important implications for the retention of women in STEM, given the importance of productivity and impact metrics to career advancement.

In the present article, we examine gender differences in research output, collaboration, and impact in invasion science literature published between 1980 and 2020. More

specifically, we examine the patterns in the proportion of papers published by each gender in invasion science, whether these patterns have changed, and patterns in the per capita publication records of each gender (research output); whether the proportion of single and first authorship differs between genders and, for multiauthored publications, whether the number of coauthors differs on the basis of the gender of the first author (extent of collaboration); and whether the gender of first authors influences citation rates and the prevalence of self-citations (research impact). We expect that the proportion of publications authored by women has increased as the representation of women in STEM across all career stages has increased (NCSES 2021a, 2021b). Any differences in research output will be lower than that of other fields because the invasion science discipline is relatively young, and the rise of the field occurred as approximately 50% of doctorates in life sciences were earned by women (NCSES 2021a). Although evidence is mixed across studies, in ecology or invasion ecology, previous work has demonstrated that women generally collaborate with more coauthors (Fox et al. 2018) and show no or very small differences in citations or citation rates (e.g., Leimu and Koricheva 2005, Borsuk et al. 2009, Prozesky and Boshoff 2012, Cameron et al. 2016, Fox et al. 2018), and we predict a similar trend in the invasion science literature. Understanding whether gender imbalances exist within invasion science and documenting baseline patterns provide the opportunity to assess the success of current and future initiatives that promote gender equity in invasion science research and academia in general.

Supporting data and statistical approach

To examine the representation of each gender among first authors in invasion science literature and how the gender of first author is related to citations, we queried Clarivate Analytics Web of Science Core Collections topics between May and October 2021 for papers published between 1980 and 2020, as was described by Campbell and Simberloff (2022). Briefly, Campbell and Simberloff (2022) examined the rise of multiauthored papers in invasion science and used (“non-native” OR “nonnative” OR “exotic speci*” OR “alien” OR “invas* speci*” OR “biolog* invas*”) as search terms to screen publications in invasion science by refining by publication year (1980–2020), excluding irrelevant Web of Science categories (e.g., dermatology), and systematically screening remaining results using a predetermined set of rules for inclusion (see the supplemental material for more information on screening protocols). A total of 27,234 publications met the criteria for inclusion; although a further 301 publications also met the criteria for inclusion, they were either outside of the focal time period (i.e., early view 2021 or 2022 publications) or were retracted and, therefore, were excluded from analyses. Bibliographic information for each publication (e.g., names of the authors, publication title, total times cited, publication date) was exported via Web of Science Fast 5k. The total number of authors for

each publication was also tallied, and the annual citation rate (*sensu* Leimu and Koricheva 2005) for each publication was calculated as the number of citations divided by the number of years since publication (Campbell and Simberloff 2022).

To examine the relationships among gender, first authorship, and impact as measured by citations, we inferred binary gender for the first author of each publication in our data set. We acknowledge that this does not capture the full diversity of the gender spectrum, and, therefore, authors who identify as a nonbinary gender are unrepresented in our study. In addition, inferring a binary form of gender without author input may have resulted in an incorrect gender assignment. Despite these limitations, our analysis aims to identify differences between genders in research output, the extent of collaboration, and research impact, if those differences are present.

We assigned gender for all full names using the genderize method in the gender package in R (Mullen 2021). The genderize.io database contains over 250,000 unique names and assigns a probability that a name is male or female on the basis of publicly available social network data sources (<https://gender-api.com>). For authors publishing using first initials, we completed an Internet search (via Google, Google Scholar, ResearchGate, Twitter, LinkedIn, etc.) to find full names or news stories or biographies with gendered pronouns. When gender was clear (e.g., pictures or gendered pronouns were available), and in cases of personal acquaintances, we manually assigned gender to these names. When gender was unclear, we added full names to the list containing all records in which the first author's full name was provided to be assigned gender by genderize. Approximately 90% of the names submitted to genderize had a probability equal to or greater than 90%. When genderize could not assign gender, we used the same search method as that for authors publishing using first initials to attempt to assign gender manually. If an author's name had a probability less than 60% for the assigned gender, we confirmed whether the assigned gender was correct using the same search method as that for authors publishing using first initials. Of these, a total of 150 authors were correctly assigned gender, 81 authors could not be confirmed, and 122 authors had a different gender than genderize assigned, which we manually changed for analyses. We assigned gender as “unknown” (less than 0.9% of all the first authors) in cases in which full names or gendered pronouns could not be found, gender could not be determined, or genderize could not assign a gender.

After assigning gender to each first author, we calculated the percentage of publications authored by each gender for each year from 1980 to 2020. We also calculated the percentage of single-authored papers published by each gender for each year from 1980 to 2020. We used chi square statistics to determine whether the distribution of authors of single-authored papers and first authors of multiauthored papers significantly varied by gender, excluding records for which the first author was assigned unknown gender. As

a complementary approach, we compared the productivity between genders using authors as the sampling unit rather than papers. Most authors (67.5%) contribute only one publication to the field of invasion science (Campbell and Simberloff 2022), and to ensure the analyzed authors represented scientists active in the field of invasion science, we selected authors who published at least five papers in our data set. We inferred gender using the methods described above for each author who first published in invasion science in 1995, 2000, 2005, or 2010 to examine the gender gap in productivity and whether it changed over time. We compared the median number of papers published by individuals between genders across authors using Mood's median test. We used an Internet search (via Google Scholar, ResearchGate, etc.) to record the total number of papers each author published across all fields; genetic sequences and supplemental files were excluded from the ResearchGate publication counts.

The number of authors has been shown to influence citation rates in invasion science literature (Campbell and Simberloff 2022); therefore, to control for the number of authors, we calculated fractional citation rates for each publication as the annual citation rate divided by the number of authors (*sensu* Prozesky and Boshoff 2012). To determine how gender may influence citation rates, we completed Mood's median test comparing fractional annual citation rates between genders. To explore how the rate of self-citation is related to gender, we randomly sampled 250 papers first authored by each gender. We recorded the total number of citations and the number of citations excluding self-citations up to 15 July 2022 for each randomly sampled paper using data available on the Web of Science. We also completed a generalized linear mixed model (GLMM) examining differences in the number of coauthors between genders using number of coauthors as a response variable, gender, and an interaction between gender and the time since publication, which tests for changes in the effect of gender of first author over time, as fixed effects, and the time since publication as a random effect. Authors with an unknown gender were excluded from the citation and from the GLMM analyses. All of the analyses were completed in R statistical software, version 4.0.5 (R Core Team 2021) using the *dplyr* (Wickham et al. 2021), *emmeans* (Lenth 2021), *gender* (Mullen 2021), *ggplot2* (Wickham 2016), *ggpubr* (Kassambara 2020), *lme4* (Bates et al. 2015), *MuMIn* (Bartoń 2020), and *RVAideMemoire* (Hervé 2022) packages. The data used for our analyses will be available via the Dryad Digital Repository.

Disparities persist

A total of 27,234 records were published between 1980 and 2020, and, of these, 10,205 (37.5%) were first or single authored by women, 16,787 (61.6%) were first or single authored by men, and 242 (less than 0.9%) had a first or single author of unknown gender. The average fractional rate of increase between each year and the previous year

in the percentage of female first or single authors was 3.1% from 1990 to 2020 but only 0.3% from 2010 to 2020. The percentage of female first or single authors has more than doubled, from approximately 15.0% in the early 1990s to approximately 38.9% in 2020 (figure 1). Among only multi-authored papers, the patterns are very similar to the pooled data patterns, with the percentage of publications first authored by women increasing from approximately 20.0% in the early 1990s to approximately 39.5% in 2020. Of the 25,045 multiauthored publications, 9678 (38.6%) were first authored by women, 15,199 (60.7%) were first authored by men, and 168 (0.7%) had a first author of unknown gender; there were more male first-authored than female first-authored papers ($\chi^2 = 1225.3$, $p < .0001$). In contrast to multiauthored publications, the percentage of single-authored papers published by women has increased only modestly, from approximately 20.0% in the early 1990s to approximately 23.2% in 2020 (figure 2). Of the 2189 single-authored papers, 527 (24.1%) were authored by women, 1588 (72.5%) were authored by men, and 74 (3.4%) authors had unknown gender; more such papers were authored by male authors than by female authors ($\chi^2 = 532.26$, $p < .0001$). Comparisons of the per capita productivity between genders showed similar patterns. For pooled data across all authors, we found significant differences in the median number of publications produced by each gender; the male authors had a higher median number of publications (129 papers) than the female authors (88 papers) across all fields of study ($\chi^2 = 13.37$, $p < .001$). However, the gender gap in the per capita number of publications declined; the difference in the median number of papers between genders decreased from 59.5 papers in 1995 to 11.5 in 2010 (figure 3).

Examining the influence of gender on the fractional annual citation rates, we found that male first- or single-authored publications had higher median citation rates and a larger distribution of citation rates than did female first- or single-authored publications ($\chi^2 = 5.44$, $p = .02$; figure 4). The rate of self-citation was similar between randomly sampled male (17.0%) and female (16.5%) first-authored papers, despite male first-authored papers accumulating a higher number of citations (table 1). Among the multiauthored publications, men had a larger distribution of coauthors and collaborated with more coauthors than women did ($p < .0001$; figure 5). The time since publication also predicted the number of coauthors ($p < .0001$); however, the effect of gender of first or single author on the number of coauthors did not change over time ($p > .05$). The marginal coefficient of determination was less than .04, indicating a low fraction of variation explained by gender and the time since publication.

Gender imbalances in measures of research performance in invasion science

This study analyzed gender differences in research output, collaboration, and impact across 40 years of invasion science literature. We found significantly fewer female than

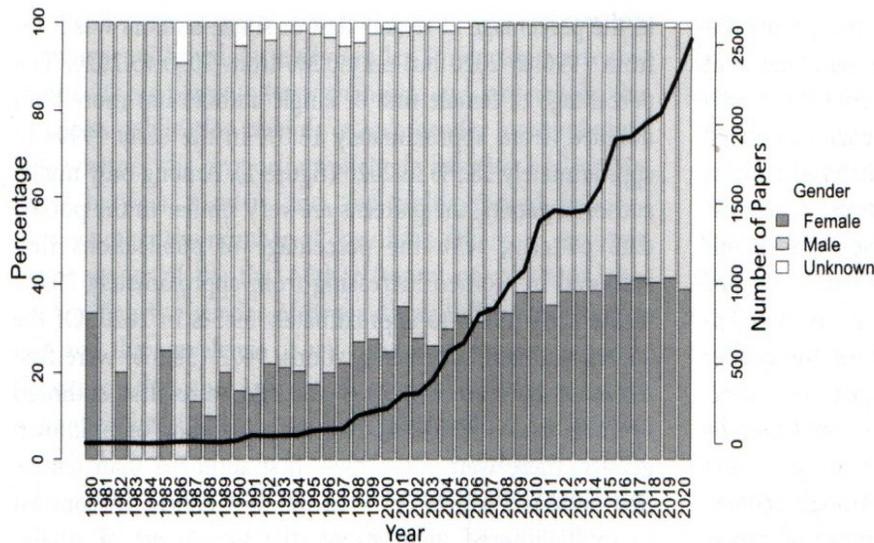


Figure 1. The percentage of publications ($N = 27,234$) in invasion science published between 1980 and 2020 and registered in the Clarivate Analytics Web of Science Core Collections (see the text for the screening criteria) first or single authored by a female author, male author, or author with unknown gender. The black line and the corresponding right axis display the total number of publications each year.

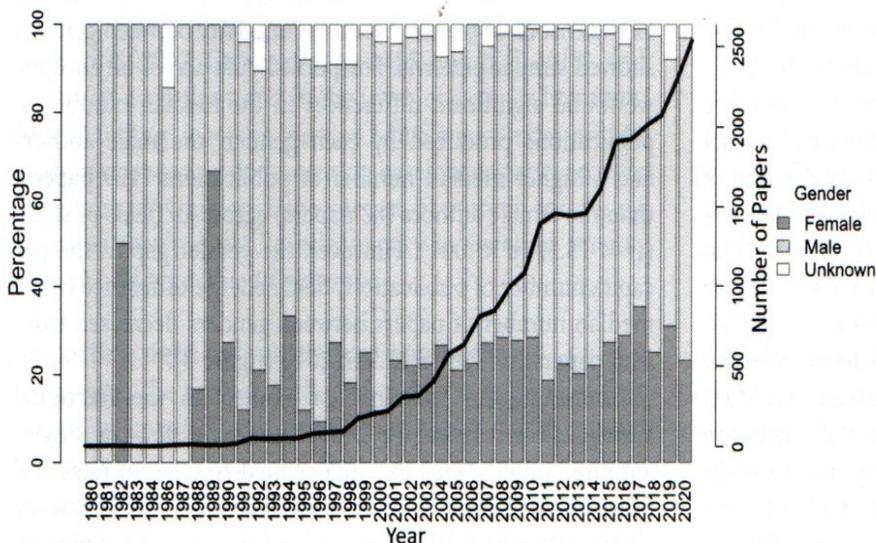


Figure 2. The percentage of single-authored publications ($N = 2189$) in invasion science published between 1980 and 2020 and registered in the Clarivate Analytics Web of Science Core Collections (see the text for the screening criteria) authored by a female author, male author, or author with unknown gender. No single-authored papers were published in 1985. The black line and the corresponding right axis display the total number of publications each year.

male first- and single-authored publications across all papers published between 1980 and 2020. For publication records of individuals, women have a lower median number of publications than men, but the gender gap has decreased. Although the percentage of female first and single authored publications has increased, the rate of increase has been low over the past 10 years, women collaborate with fewer coauthors, and women have lower fractional annual citation rates, indicating barriers continue to affect the research performance of female invasion scientists. Although our results demonstrate women are increasingly represented in invasion science as authors, female first authors remain

underrepresented each year relative to the proportion of women earning their doctorates in biology and in ecology and evolutionary biology. These disparities in research output, collaboration, and impact may partially contribute to an underrepresentation of women in more senior academic positions.

The research productivity of women in invasion science has increased since the rise of the field in the early 1980s, but women are still underrepresented as authors and may remain so at least in the near future. As in previous research in ecology (e.g., Fox et al. 2016, 2018, Whelan and Schimel 2019) and other scientific fields (e.g., West et al. 2013, Holman et al. 2018, Astegiano et al. 2019, Walker 2019, Rock et al. 2021), we found that women are particularly underrepresented as sole authors, with only 24.1% of all publications single authored by women. Between 1990 and 2000, only 25.5% of multiauthored publications were first authored by women, compared with 40.4% for multiauthored papers published between 2010 and 2020. First authors are often graduate students, a career stage in which women are in the majority (NCSES 2021a), or postdoctoral fellows; that women currently constitute 40.4% of first authors suggests the representation of women in other authorship roles (e.g., last author) will likely increase as these early career researchers progress to more senior positions. The patterns in invasion science publication productivity manifest better representation compared with statistics for certain other scientific fields (e.g., West et al. 2013, Bendels et al. 2018) and resemble trends documented in studies examining gender differences in ecology (e.g., West et al. 2013, Fox et al. 2016, 2018,

Salerno et al. 2019, Whelan and Schimel 2019, Frances et al. 2020), which estimate between 23% to 43% of publications first authored by women for time periods between the early 1990s and late 2010s. Our analysis revealed that men, both as a group and per capita, produce more publications than women. Although a significant gender gap exists in the total number of publications between genders, as they were measured by publication records, this gap is smaller for authors whose first publication appeared in 2010 than for those whose first publication appeared in 1995. Our results indicate that, although gender imbalances persist, the gender gap has lessened since the rise of the field, contrary to

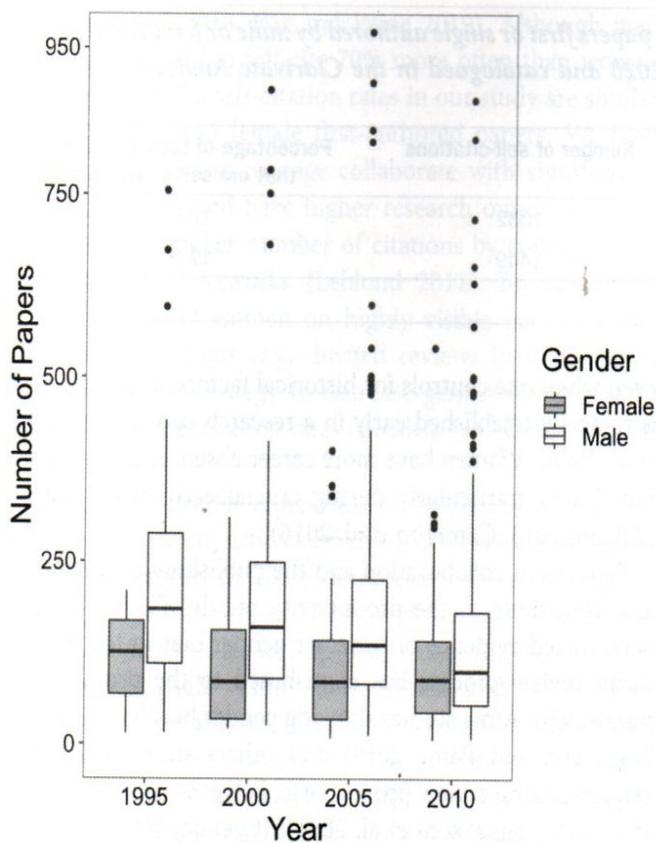


Figure 3. The total number of publications across all fields as a function of gender for individual authors whose first publication registered in the Clarivate Analytics Web of Science Core Collections in invasion science literature appeared in 1995, 2000, 2005, or 2010. The boxplot displays the median (central line), interquartile range (box), interdecile range (bars), and outliers (circles).

a recent meta-analysis that showed that the gender gap in science fields had not significantly changed with the implementation of gender equity policies (Astegiano et al. 2019). Our results suggest that there are fewer women in the field and that women publish less because of other factors or time constraints (e.g., increased childcare, service, or teaching duties).

Currently, for every publication first authored by a woman, approximately 1.5 articles are first authored by men. Despite steadily increasing, the proportion of publications first or single authored by women has stagnated over the past decade. The average fractional rate of increase from 1990–2020 in the percentage of publications first or single authored by women in invasion science is approximately 3.1% and at this rate, gender parity would be reached by 2030. However, the average fractional rate of increase for the past 10 years is approximately 0.3% and, at this rate, gender parity for first or single authorship positions will not be achieved until around 2100. Recent estimates in the biological sciences suggest that it will take an estimated 25–50 years before women are equally represented in other key authorship positions (Holman et al. 2018). The increased representation of women as first authors and the declining gender gap manifested by individual publication records is promising; however, women are 20% less likely than men

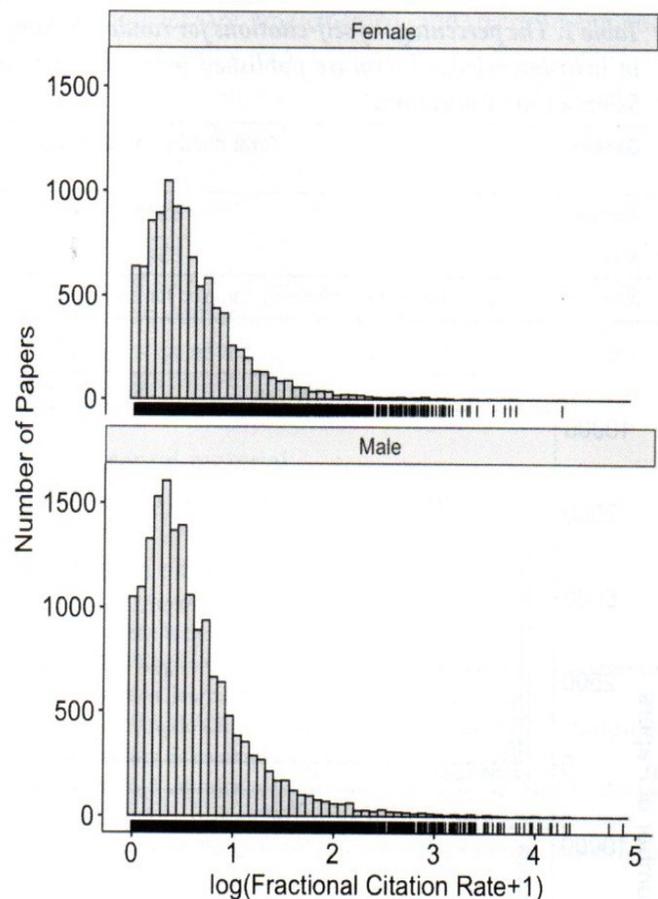


Figure 4. The distribution of log-transformed fractional annual citation rates for publications ($N = 26,992$) first or single authored by women ($n = 10,205$) and men ($n = 16,787$) in invasion science literature published between 1980 and 2020 and registered in the Clarivate Analytics Web of Science Core Collections.

to become a principal investigator, and publication records account for 60% of this disparity (Lerchenmueller and Sorenson 2018). Furthermore, recent research indicates that gender disparities in research productivity and impact have increased as the representation of women in science has increased, mostly because of the leaky pipeline and career length differences (Huang et al. 2020). Most recently, the COVID-19 pandemic has disproportionately influenced the working conditions and productivity of women (Myers et al. 2020, Collins et al. 2021, Yildirim and Eslan-Zyia 2021), and we observed a 6.2% fractional decrease in the percentage of publications first or single authored by women between 2019 and the beginning of the pandemic (i.e., 2020) compared with the 0.06% fractional decline in the percentage of publications first or single authored by men. In light of the impact that publication and research productivity have on research careers, any factors influencing the representation of female authorships have important implications for addressing gender equity.

Although our analysis does not identify causal mechanisms for gender disparities in publication productivity, many complex factors may contribute to this pattern. On average, women spend less time than men completing research (Aldercotte et al. 2017) and spend more time

Table 1. The percentage of self-citations for randomly sampled papers first or single authored by male or female authors in invasion science literature published between 1980 and 2020 and catalogued in the Clarivate Analytics Web of Science Core Collections.

Gender	Total number of citations	Number of self-citations	Percentage of total citations that are self-citations
Female	6246	1032	16.5
Male	8544	1449	17.0

Note: A total of 250 papers were randomly sampled for each gender.

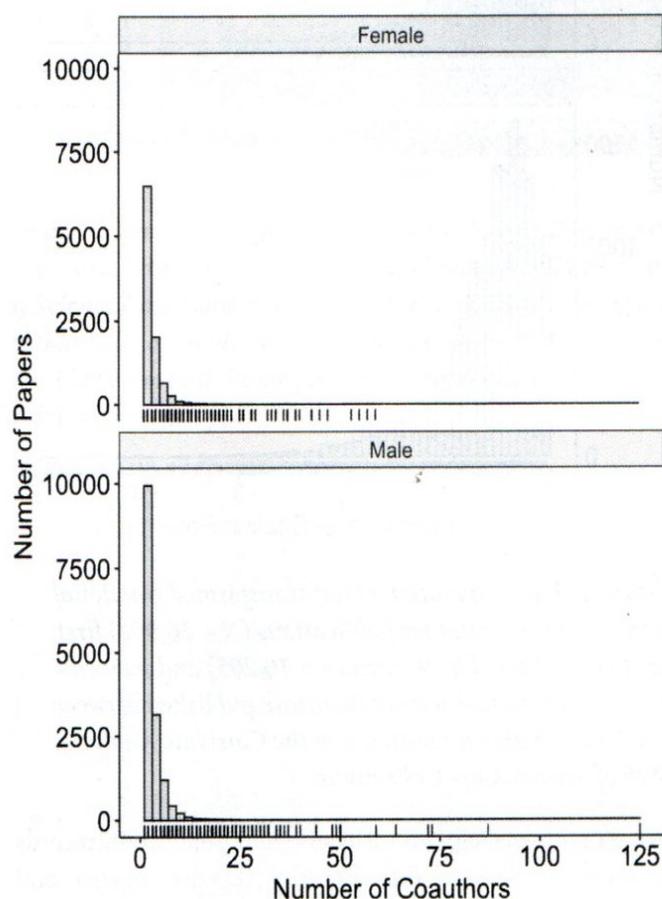


Figure 5 The distribution of number of coauthors for multi-authored publications ($N = 24,876$) first authored by women ($n = 9,677$) and men ($n = 15,199$) in invasion science literature published between 1980 and 2020 and registered in the Clarivate Analytics Web of Science Core Collections. One outlier for the number of authors ($n = 1$, with 642 authors) was excluded.

engaging in nonpromotable tasks (Babcock et al. 2017) and service work (Babcock et al. 2017, Britton 2017, Guarino and Borden 2017, O'Meara et al. 2017), which are valued less in tenure and promotion decisions (Misra et al. 2012). The publication productivity of women may be lower partly because women perform more household work or have greater childcare responsibilities (Sax et al. 2002, Craig and Mullan 2011, McGuire et al. 2012, O'Brien and Hapgood 2012), although some studies have found the latter factor depends on the age of children (e.g., Stack 2004, Fox 2005). This tradeoff between research and other work may contribute to the productivity puzzle; in ecology, women continue to publish fewer papers than men throughout their career

even when one controls for historical factors, and this trend is typically established early in a research career (Cameron et al. 2016). Women have more career absences (e.g., maternity leave), particularly during crucial early career stages (Adamo 2013, Cameron et al. 2016).

Patterns in collaboration and the publishing process may also contribute to the productivity puzzle. There has also been mixed evidence on whether gender bias in the manuscript review process has contributed to the productivity puzzle, with some studies showing gender bias (e.g., Chawla 2018, Fox and Paine 2019) and others showing a fairly gender-neutral review process (e.g., Fox et al. 2016, Edwards et al. 2019, Squazzoni et al. 2021). If gender bias is present during the review process, women would be more likely to be underrepresented in journals that do not have a double-blind peer review process (West et al. 2013). Alternatively, it is also possible that the higher representation of women in early career positions (e.g., graduate students) who often publish as first authors does not compensate for the historical legacy of the leaky pipeline, paucity of representation throughout the 1900s, and underrepresentation of women in later career stages. Women often have lower social capital (e.g., support or social networks) and fewer collaborators than men (Zeng et al. 2016). In the present article, we have found that women have significantly fewer coauthors on average in invasion science, which may contribute to the observed authorship trends, given that collaboration has been shown to influence productivity (Abramo et al. 2009, 2019), although a more rigorous test of this hypothesis is necessary in this case.

In contrast to previous research that revealed no significant differences in fractional citation rates between genders in a more restricted portion of the invasion ecology literature (Prozesky and Boshoff 2012), we have shown that publications first or single authored by men have significantly higher fractional annual citation rates than publications first or single authored by women in invasion science. Prozesky and Boshoff (2012) examined invasion ecology literature published between 1990 and 2002 with at least one author of South African affiliation, and the increased scope of our analysis in temporal breadth and criteria for inclusion may account for this incongruity. Our findings also contradict several studies in ecology that have demonstrated no significant gender differences in citations or citation rates (Leimu and Koricheva 2005, Borsuk et al. 2009, Cameron et al. 2016) but are consistent with more recent empirical analyses

(Bendels et al. 2018, Fox and Paine 2019). Although men have been shown to self-cite 70% more often than women (King et al. 2017), self-citation rates in our study are similar between male and female first-authored papers. We have shown that men on average collaborate with significantly more coauthors and have higher research output, and this may confer a higher number of citations by colleagues via larger research networks (Leblond 2012). Increasing the representation of women on highly visible papers in key authorship positions (e.g., invited reviews in high-impact journals) is one strategy to decrease gender differences in fractional annual citation rates (Bendels et al. 2018, Holman et al. 2018).

Progress in gender representation has been documented both in the present article and in other studies. Addressing gender disparities in research productivity, collaboration, and impact will require a multifaceted approach. Institutions and individuals in leadership positions must work toward measurable goals using data-driven and transparent approaches that address disparities (Grogan 2019, Colwell et al. 2020). Recent research has shown that early and mid-career female researchers may also be disproportionately affected (Herman et al. 2021), with fewer manuscript submissions than women in more senior positions and men (Vincent-Lamarre et al. 2020, Pinho-Gomes et al. 2020). The lower productivity of caregivers in general, particularly female caregivers, as well as women in earlier career stages should be considered in hiring, promotion, and tenure decisions in light of the important influence publication productivity can have on career progression. The criteria used for funding and grants, awards, recruitment, hiring, promotion, and tenure should be examined for any potential bias. Transparent and standardized criteria could be established for authorship, and senior authors should recruit diverse, multigendered author teams, which have been shown to be cited more frequently and result in more impactful research (Campbell et al. 2013, Frances et al. 2020). Any initiatives that increase representation and minimize bias should be regularly examined for effectiveness.

Conclusions

This study reveals important gender differences in research output, collaboration, and impact in the literature of invasion science, a relatively young field. Although the representation of female authors has increased, both as a group and per capita, the proportion of publications first authored by women has remained relatively unchanged for the last decade and is still below parity; the proportion of publications single authored by women has increased only slightly since the initial rise of the field. Women still have lower median per capita publication rates. Women also collaborate with fewer coauthors and have significantly lower fractionalized annual citation rates than men, on average. Although our analysis does not test causal factors, our results nevertheless suggest barriers to women in invasion science, although these may recede as gender

equity policies are implemented and recruitment and retention of women into more senior positions improves. Gender bias disproportionately affects individuals whose gender also intersects with other marginalized identities (e.g., race, ethnicity, disabilities, sexual orientation, gender identity), and research is needed to fill the knowledge gap on these disparities. Our results underscore the continued importance of evaluating gender disparities in scientific research and demonstrate that, although the gender gap is declining, it is nevertheless still present in modern invasion science.

Supplemental material

Supplemental data are available at *BIOSCI* online.

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