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Perspective

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Collaboration between women helps close the gender gap in ice core science

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Within ice core science, woman-led studies contain 20% more women co-authors than man-led studies, and exceed the estimated proportion of women within the community by nearly 10%. We conclude that collaboration with other women is a key factor in closing gender gaps in science.

Publications serve as currency in academic science, determining in part the attainment of academic positions, as well as professional recognition such as invited talks, fellowships and awards. While the prevalent focus on publication records as a measure of scientific contributions has been critiqued for perpetuating sexist and racist value systems[1], publishing papers remains critical to individuals' success and longevity in the sciences[2]. Women publish at lower rates than men both within the Earth sciences[3] and more broadly[4], including in high-impact journals[5]. And, despite progress towards gender parity (defined hereafter as 50%:50% men:women) at the PhD level within the Earth sciences over the past several decades (1973 to 2016, ref. 6), women continue to be substantially under-represented at the Assistant Professor rank and above, at least in the United States[7,8]. In addition, they receive disproportionately fewer opportunities for recognition, such as invited talks at major conferences[9] and nominations for research awards[10]. While the exact causes of the gender gap in Earth science publishing are not known[3], common structural barriers and biases probably contribute both to lower retention of women in the academic workforce, and to fewer women authorships[7,11–13]. Because the strategies that enhance women's publication rates and impact, often measured as citation rates or journal impact factors, will also probably contribute to the success of women in academic science (for example, through hiring, fellowships, awards, and other forms of recognition), it is essential to understand patterns related to women's authorship and to identify mechanisms to support women's publication rates and impacts. Here we examine relationships among author gender, career stage, publication rate and impact, and co-authorship networks within the ice core sciences over the past 50 years.

Collaboration can contribute to a sense of community and belonging, and can enhance productivity, both of which promote the retention of women in science and engineering[14,15]. While difficult to measure directly, collaboration can be assessed implicitly through co-authorship[4], allowing the evaluation of relationships among publications, gender and career stage, as well as other variables. To explore the impact of women in co-author networks, we analysed a set of >3,400 abstracts of peer-reviewed published papers by leveraging the Smithsonian Astrophysical Observatory/NASA (National Aeronautics and Space Administration) Astrophysics Data System bibliographic archive to extract all 'ice core(s)'-related science contributions spanning back to 1969 AD (the publication year of the original deep ice core climate record from Camp Century, Greenland[16]). Of these, we were able to infer gender ratios on $n = 3{,}141$ abstracts using the application programming interface genderize.io (Demografix ApS) tool, which is based on a database of >250,000 names spanning 80 languages, and built using name–pronoun gender associations from public online text entries generated across >240 countries and dependent territories. Critically, it permits name-specific probabilistic 'man-vs-woman' estimates from which we were able to further propagate and assess community-wide gender uncertainties (Methods). The genderize.io tool has been used to assess gender gaps in publishing in the Earth sciences[3]; however, we recognize many important limitations of its use. For example, it cannot account for transgender, non-binary and gender nonconforming identities, nor is it likely to assign gender accurately to people from countries with non-gendered given names[3] (Methods). It may also incorrectly assign gender in cases where the author is of the less typical gender for a given name, and it cannot reveal gender where authors have used only their initials. While an imperfect tool, it nevertheless provides a useful proxy-metric for assessing a half-century's worth of gender-related differences in publishing, citation rates and the size and make-up of co-author networks in the absence of self-reported demographic data, all of which are critical for helping to close the gender gaps in publishing and workforce retention.

Gendered patterns in publications

As with many areas of science, including the Earth sciences[3,4], ice core science suffers from a gender gap in publications. In the early days of

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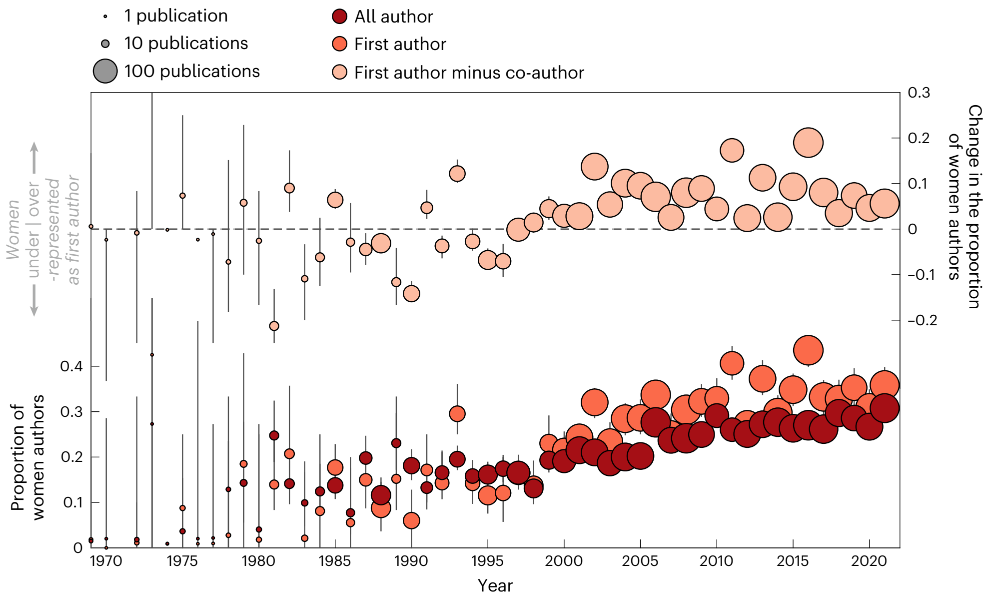

Fig. 1 | Trends in women authorship in ice core science. The changing proportions of women first authors versus all authors (bottom) through time. The difference between first and co-author proportions (providing an 'out-of-sample' comparison) is shown above; positive (negative) values indicate that women are over- (under)represented as first authors. Beginning in the late 1990s, the proportion of woman first-authored studies exceeds the total woman co-author proportion. Bubble sizes indicate the number of publications per year, and vertical lines indicate the gender proportion 95% confidence interval based on Monte Carlo resampling of genderize.io-derived probabilities (Methods).

the field, considered here to be 1969–1979, women represented <10% of contributing authors (Fig. 1). In the wake of a significant jump in woman-led studies between the 1990s and early 2000s, this gap has since narrowed to ~30%:70% women:men, with women's first-authored studies exceeding the estimated proportion of women within the community by ~8% during the most recent decade (2012–2021; upper panel of Fig. 1). Similar citation rates for man- and woman-led studies indicate comparable scientific quality and impact on a broad scale (Extended Data Fig. 1).

Women's first-authored studies continue to be most strongly under-represented in the four highest-ranking journals by impact factor (as of January 2023) where ice core research is commonly published: *Nature*, *Science*, *Nature Geoscience*, and *Proceedings of the National Academy of Sciences of the USA* (*PNAS*) (Fig. 2; see also Extended Data Fig. 2). Collectively, man first-authored papers have been published at roughly five times (3.1–7.4, 95% confidence) the rate of woman first-authored papers in these journals during the past five decades. This contrasts with man:woman-led publishing rates found across all other leading journals during the past decade (~1.8:1), despite men outnumbering women in ice core science during this period by a greater ~2.6:1 ratio (Fig. 3a). Indeed, *Nature* and *Science* are the only leading journals whose first-author gender ratios have not yet reached the ice core community's estimated gender balance within 95% certainty (Extended Data Fig. 2). While the so-called 'prestige gap' is not unique to ice core science[5], these results highlight pervasive gender-related differences with potential long-term negative impacts on women's careers[2]. Although our data are unable to identify the underlying causes, recent research shows that social factors[17] and a systematic lack of attribution[18] play a role in determining authorship inclusion and ordering within large collaborative projects, which may be more likely to be published in high-impact journals. In addition, gender bias in peer review may influence where men's and women's research ultimately is published[19].

The impact of women in co-author networks

While the number of co-authors per study has increased for both men and women, the size of co-author networks has remained strikingly similar between men and women over time (Fig. 2b). Likewise, the number of nations per study has increased through time but has not differed by gender; women are just as likely to lead studies that include international representation (estimated on the basis of affiliation at time of publication), despite accounting for a smaller number of overall publications (Extended Data Fig. 1). As the collection and analysis of new ice cores requires individuals with a broad range of expertise, often spanning multiple countries, this may explain why the number of co-authors and international collaborators does not show a strong relationship to first-author gender, in contrast to broader observations across the Earth and space sciences[4,20].

Where we see a notable difference between men's and women's co-author networks is in the proportion of women co-authors. Women-led studies contain, on average, 20% more women co-authors than those led by men (1.8 vs 1.5 women co-authors per study for the period 2012–2021, Extended Data Fig. 1). Similar differences are reflected in estimates of women co-author proportionality for woman- vs man-led studies spanning the past five decades (Fig. 2b). Considering that the difference in the numbers of co-authors is nearly indistinguishable between man- and woman-led studies, but that women co-author ratios on man-led studies fall well below the estimated community-wide proportion of women for both periods (0.20 and 0.27 for 1969–2011 and 2012–2021, respectively; Fig. 2b), these findings point towards systemic gender biases in man- vs woman-led co-author networks in ice core science.

This raises interesting questions about the role of women in supporting other women in publishing; namely, do senior women scientists play a critical role in supporting junior women in ice core science co-author networks? By tracking the publication occurrence for each author in the database, we designated 'junior' scientists as those within 10 years of their first publication (that is, typically comprising PhD, postdoc and early-career faculty or research positions) and 'senior' scientists as those beyond 10 years. We included all authors who had contributed two or more papers, to avoid overestimation of junior scientists and to give a more robust estimate of ongoing involvement in the field, and we trimmed the first and last 10 years of the dataset to avoid biases in career stage designation. While men make up the

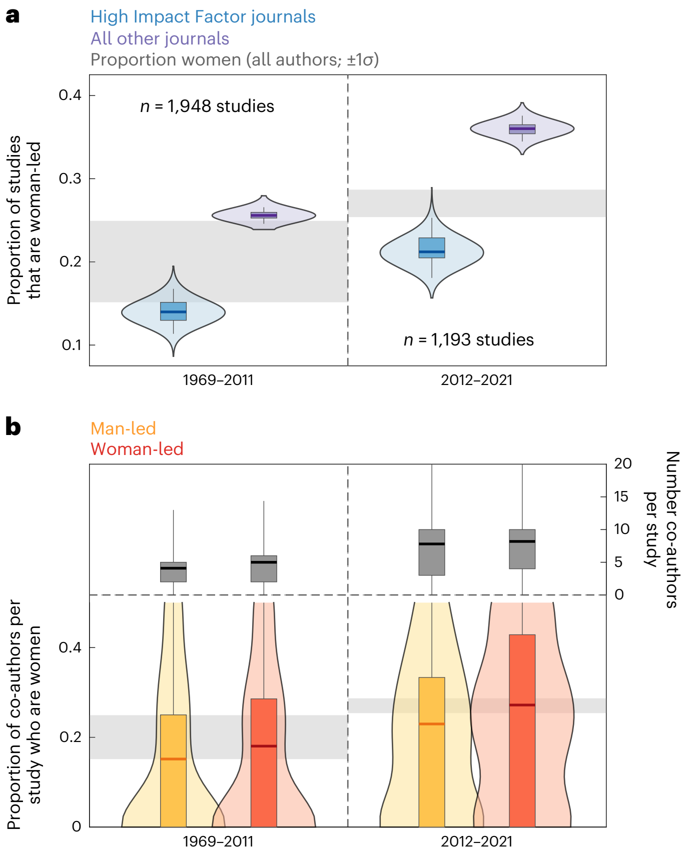

Fig. 2 | Divergences across woman- versus man-led ice core studies. a, The proportions of woman-led studies in the four leading (that is, with an impact factor (IF) > 12) journals where ice core science is regularly published (blue; *Nature*, *Science*, *PNAS* and *Nature Geoscience*) relative to all other journals (purple), comparing the first four decades of ice core science (left) relative to the most recent (right). **b**, Distributions of the proportion of women co-authors on man-led (yellow) versus woman-led (red) studies (bottom), as well as the total number of co-authors (top), for the same time intervals shown in **a**. The grey shading represents the proportion of women authors (all authors; ±1σ). Violin plots show the shapes of the probability density functions of each dataset, with the vertical line showing the 95% range, the box heights giving the interquartile range and the solid horizontal line indicating the average.

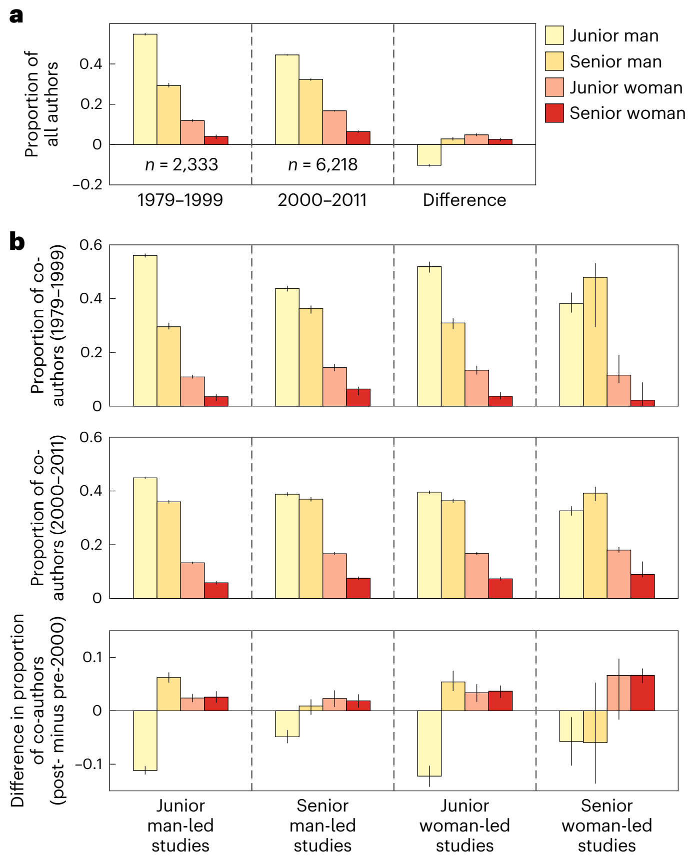

Fig. 3 | Shifting co-author networks of junior versus senior men and women in ice core science. a, Proportion of authors contributing to ice core science publications pre- and post-2000 CE, partitioned by estimated gender and career stage. Authors are considered 'junior' if they are within the first 10 years of their first ice core publication, and senior thereafter. **b**, The proportion of co-authors for all junior man-, senior man-, junior woman- and senior woman-led studies during the pre- (top, 1979–1999) and post-2000 CE (middle, 2000–2011) time periods, and the difference between them (bottom). The bottom panel of **b** shows that the ongoing shift towards gender parity has benefitted from senior woman-led co-author networks. Vertical lines show interquartile ranges based on Monte Carlo resampling (Methods).

majority of all co-authors, we found that co-author associations have changed with time as women's representation has increased (Fig. 3). Post-2000, we see a shift towards a greater proportion of junior women, senior women and senior men co-authors, and a decrease in junior men authors (Fig. 3a). We find strong proportional gains for women co-authors on woman-led papers, particularly senior woman-led studies (Fig. 3b), suggesting that senior women, more than senior men, are especially important in fostering the success of both junior and senior women.

Polar science has a reputation for being an 'old boys' club; for instance, women were not permitted to work on the Antarctic continent through the US National Science Foundation until 1969 (ref. 21), and the British Antarctic Survey did not lift all restrictions on women's participation in Antarctic research until 1996 (ref. 22). Although clearly this dynamic has changed substantially, our results show that more work is needed for our field to achieve gender parity. Importantly, previous research showed that observed patterns in co-author networks become established early on—that is, "old boys clubs begin as 'young boys clubs'"[20]. This suggests that implicit bias early in scientists' careers leads to persistent, structural imbalances[20]. If men want to continue dismantling historical patterns of gender disparity in publishing, concerted efforts will be needed to broaden their co-author networks early in their careers, as the longitudinal structures of male-dominated co-author networks are self-perpetuating. Continued change will require structural barriers to women's participation to be demolished (whether specific to ice core science or more broadly within academia[7,13]), recognition of women's contributions[17,18] and intentional work to build new and inclusive collaborative networks, helping in turn to retain the best minds within ice core science.

Perspectives from the past offer lessons for the future

Earth's climate, as documented by ice cores, demonstrates intervals of both linear and nonlinear change, as well as abrupt shifts and tipping points. The representation of women in ice core science, measured using first-author studies, has been climbing at a pace of ~5% per decade. At this rate, it will take 30–40 years to reach gender parity. But what if, instead of assuming our community is capable only of linear changes, we imagine a nonlinear shift towards inclusivity? Might there be a tipping point past which the proportion of women, and associated changes in structural barriers[7], sustains in perpetuity a shift towards gender parity? As ice core science matures into its second half-century, let this be a moment to pause and reflect on how to make our scientific community even stronger. One thing is clear: women play a pivotal role in co-author networks, catalysing increased participation of other women in the field.

Online content

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41561-023-01315-y.

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Methods

Historical ice core science metadata collection

To evaluate the progression of ice core sciences during the past half-century, we took advantage of meta-analytical data included in published scientific contributions by compiling a large, representative body of peer-reviewed abstracts. Rather than attempting to web-scrape (for example, ref. 3) across a subset of academic journals, we leveraged the Smithsonian Astrophysical Observatory/NASA Astrophysics Data System (ADS)—an online public bibliographic portal that houses abstract metadata information spanning the astronomical and physical sciences, more broadly[23]—to first isolate a preliminary body of ice core science-related contributions. This was done by extracting all abstracts containing the phrasing "ice core(s)" in either the abstract's text or title-text over the reference interval of 1969–2021 AD, representing the (1) publication year of the original deep ice core record from Camp Century, Greenland by Dansgaard and colleagues[16] through to (2) the most recent completed calendar year at the time of data collection (that is, summer 2022), respectively.

ADS filtering yielded a total of 5,180 abstracts spanning >200 academic journals worldwide, which needed further refinement. In particular, given the vast thematic scope of peer-reviewed scientific contributions incorporating ice core data, one specific challenge is defining a set of criteria for isolating 'true' ice core abstracts from this preliminary database. Although a hands-off approach may be warranted in some special cases, a broad survey of "ice core(s)"-related ADS submissions revealed that not all abstracts were equally suited to our central aim of assessing the progression of ice core science across the past half-century. Thus, to refine this database to better reflect contributions that primarily focus on the (for example) exploration, interpretation or application of novel ice core data, we applied a secondary filtering approach by manually vetting each $i = 1, 2, \ldots, 5{,}180$ abstract across multiple (2) workers. Here, an abstract was flagged as a candidate for removal if the ice core data were quoted as being used solely for:

(1) Comparative purposes in, for example, validating independent indices, measurements or climate proxies (such as sedimentary, tree ring, speleothem, moraine);
(2) Defining non-interactive model boundary conditions (for example, CO_2);
(3) Didactic or educational purposes;
(4) Supporting journal-published comments, author responses, opinion pieces and (or) media/press releases (for example, Nature News & Views).

In addition, we removed any ADS-identified abstracts that were, in fact, non-peer-reviewed conference proceedings or otherwise. This secondary filtering approach succeeded in refining our ADS ice core abstract database to a finer $n = 3{,}423$ subset of abstracts. While we acknowledge the introduction of possible user subjectivity in our manual vetting procedure, we stress that our aim was not scientific 'completeness', but communal 'representativeness'. As all auxiliary "ice core science" metadata including author names, affiliations, venue (that is, journal) and citation information were kept independent of these manual vetting procedures, we maintain the veracity of these metadata as being broadly representative of the ice core science community make-up (notwithstanding the possibility of underlying, unknown gender–scientific covariation).

Name-based gender inference

Following previous studies (for example, refs. 3,24), we inferred the gender of authors' reported names by leveraging the genderize.io application programming interface (Demografix ApS) locally routed using a MATLAB script. Genderize.io is based on a database of >250,000 names (at time of calculation) spanning 80 languages and built using name–pronoun gender associations from public online text entries generated from >240 countries and dependent territories. Using the number of assigned gender associations, each name is given a male vs female probability score that represents the occurrence frequency of the assigned name–gender association. If no name–gender association exists, the name is denoted 'unknown'. To infer ice core science gender parity, we parsed given names by extracting the first token of author names across all $n = 3{,}423$ studies. For authors who only provided initials (9,110 out of 21,004 total assessed authors), we followed the approach of Pico et al.[3] by conducting a post hoc inference of gender. This was done by truncating all authors' names down to first name initial and surname, then comparing the degree of co-author overlap of these truncated names (mandating at least 1 independent occurrence of co-author overlap) across all other studies where gender inferences (that is, first names) were available. In total, we were able to retrieve adequate (defined as >50% gender-inference completion) gender parity inferences for 3,141 studies. We note that the primary conclusions of this report seem to be broadly insensitive to our post hoc gender determination, and the per-study co-author threshold for gender-inference completion.

To propagate uncertainties related to community-wide gender balance, we leveraged genderize.io-derived probabilities to generate a large number ($m = 10{,}000$) of pseudo-random name-based gender assignments following a Monte Carlo approach. This was done by considering the gender assignment probability (p) on a per author basis (p_i), and thereafter redefining the assigned gender of that author for the subset of all $m_i = 1, 2, \ldots, 10{,}000$ uniform-randomly drawn values ($p_{m,i} \sim U(0{,}100)$) that exceed p_i. By considering all m independent and identically distributed gender assignment realizations (spanning all authors, studies and (or) years), we then generated concomitant probability distributions representing the propagated uncertainties associated with community-wide (or journal-specific) gender balance.

We stress that inferring gender based on given names only is an indirect, and thus imperfect, approach. For example, genderize.io will not work well for cultures or languages where given names are not readily transcribable to gender, or where gender is not typically represented by the first-listed name. Similarly, genderize.io is incapable of distinguishing between non-binary, transgender or gender nonconforming individuals (nor do we have an avenue to correct for such additional gender identities in the absence of self-reported data). Thus, we accept that considerable uncertainty exists across our gender inferences, and that we have not captured the full spectrum of gender identities that exist, but instead have assessed the most common binary. Nonetheless, in the absence of available, long-term and self-reported ice core science survey data, these data provide a useful proxy for relative changes in community gender balance spanning the past half-century. Similar to our inability to capture the full range of gender identities (and hence assess their trends and impacts), we are unable to assess long-term patterns in racial and ethnic diversity. We recognize that ice core science is a very non-diverse field and that recruiting and retaining persons historically excluded because of their ethnicity, race or other reasons needs to be a priority. While this Perspective focuses on gender, rather than other measures of diversity, we hope that drawing attention to co-author networks may inspire action within the ice core community to work towards building a field that is more inclusive of under-represented persons and groups[25,26]. To this end, funding agencies and journals may want to consider including anonymized questions on the identities of contributing authors on grant reports and/or submitted manuscripts to draw attention to this important issue.

Data availability

All underlying data are publicly available via GitHub at: https://github.com/mattosman/Ice-core-gender.

Code availability

All of the supporting code is publicly available via GitHub at: https://github.com/mattosman/Ice-core-gender.

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Author contributions

B.G.K., M.O. and A.C. conceptualized the project. All authors contributed to data curation. M.O. developed the software, conducted the data analysis and visualized the data with input from B.G.K. B.G.K. and M.O. wrote the original draft, and all authors contributed to reviewing and editing the final manuscript.

Competing interests

The authors declare no competing interests.

Additional information

Extended data is available for this paper at https://doi.org/10.1038/s41561-023-01315-y.

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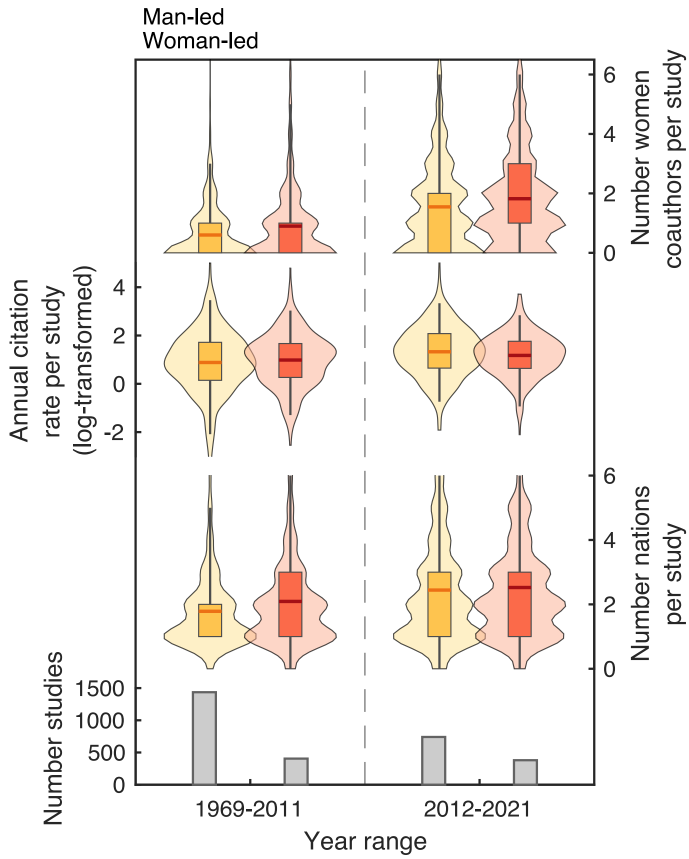
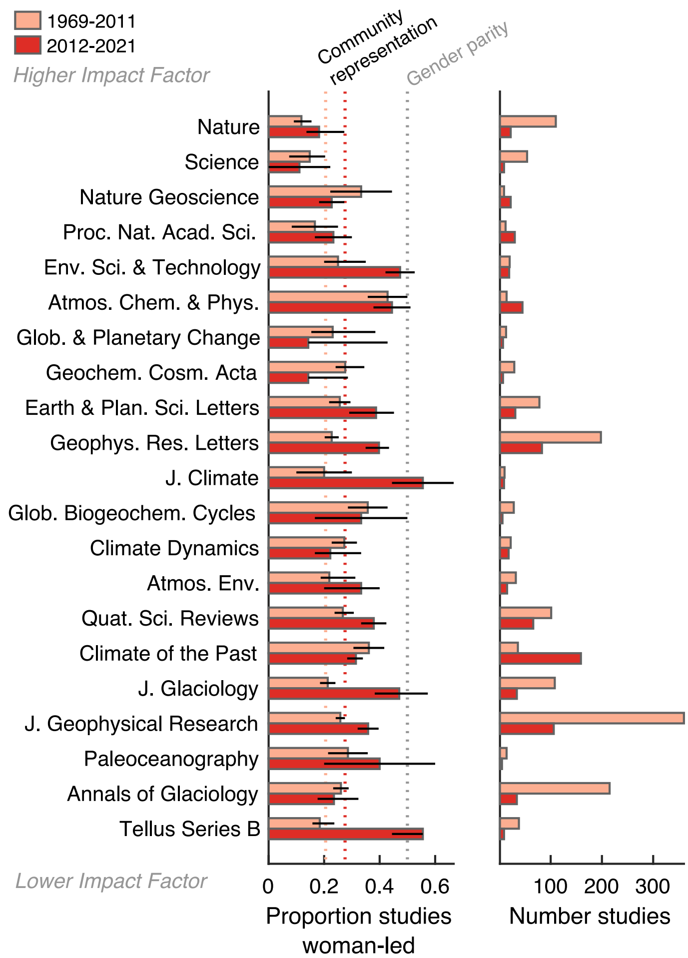


Extended Data Fig. 1 | Patterns in citation rate, coauthorship, and internationality by gender. Distributions of women coauthors per study (top panel), citation rate per study (top middle), and number of unique nations per study (bottom middle) for man vs. woman-led studies, comparing the most recent decade of data (2012–2021) to the preceding ~four decades (1969–2011). The total number of studies analyzed for each grouping is also displayed in the bottom panel. Violin plots are shown as described in Fig. 2.



Extended Data Fig. 2 | Proportion of studies led by women across leading ice core journals. Dashed lines at left indicate gender parity (gray), and the estimated average community proportion of women during 1969–2011 (salmon) and 2012–2021 (red). Error bars indicate 95% confidence ranges based on Monte Carlo resampling (Methods). The top 21 journals that publish ice core research (which encapsulate approximately 90% of ice core contributions each year) are shown, listed from highest Impact Factor (top) to lowest Impact Factor (bottom). In the past decade, the proportion of woman-led studies in all top-21 journals has met or exceeded the estimated proportion of women in ice core science within 95% confidence, except for *Science* and *Nature*.