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Forty years of invasion research: more papers, more collaboration...bigger impact?

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Abstract

Scientific research has become increasingly collaborative. We systematically reviewed invasion science literature published between 1980 and 2020 and catalogued in Clarivate Analytics Web of Science to examine patterns of authorship and the relationship between co-authorship and annual citation rates. This study analysed 27,234 publications across 1,218 journals and demonstrated that, as the number of publications in invasion science has exponentially increased, the number of authors publishing per year and the average number of authors per paper have also increased. The rising number of authors per paper coincides with a marked decline of single-authored publications; approximately 92% of publications in this dataset were multi-authored, with single-authored papers comprising less than 4% of all papers published in 2020. The increase in multi-authored papers is likely driven by multiple factors, including the widespread perception that collaboration increases scientific quality. The number of authors is positively correlated with perceived research impact; papers with two or more authors produce research that is more frequently cited compared to single-authored papers, and papers with five or more authors have annual citation rates almost double that of single-authored papers. The complexity, context-dependence and urgency of biological invasions contributed to the rise of the highly collaborative field of modern invasion science.

Keywords

Bibiometrics, biological invasions, citations, coauthorship, collaboration, scientific publication

Introduction

Charles Elton's 1958 monograph, "The Ecology of Invasions by Animals and Plants", documented the breakdown of Wallace's biogeographic realms and discussed the biology and impacts of invasive species on native communities, constituting one of the first works calling scientific attention to biological invasions. This monograph resulted in some, albeit insignificant, initial interest in biological invasions (Simberloff 2011a) but has since become the single most cited source in the field of invasion science (Richardson and Pyšek 2008) with > 8500 citations (via Google Scholar) at the time of writing. Invasion science encompasses research in multiple disciplines examining facets of the causes, consequences and management of non-native species (Richardson et al. 2011; Richardson and Ricciardi 2011). Though Elton (1958) is often cited as the foundation of invasion science as a distinct discipline, the field was catapulted into mainstream ecology in the 1980s (Simberloff 2011a, 2011b) after the Scientific Committee on Problems of the Environment (SCOPE) programme on biological invasions generated research on the causes, impacts and management of invasive species (Mooney and Drake 1986; Drake et al. 1989). Research on biological invasions subsequently grew at an exponential pace, beginning in the 1990s (Richardson and Pyšek 2008; Davis 2009; Simberloff 2011a), reflecting the need to address the management of the rapidly increasing number of non-native species spreading globally. The initiation of several journals solely dedicated to research on biological invasions (e.g. "Biological Invasions" in 1999 and "NeoBiota" in 2011) and journals relaunching with substantial focus on invasions (e.g. "Diversity and Distributions" in 1999) demonstrate the increased scientific interest in understanding and managing invasive species.

Price (1963) is often cited as the foundational paper predicting the demise of single-authored publications by 1980 after observing an increasing trend in multiple authorship in chemical science. Many studies have duplicated Price's observation of the rise of multi-authored publications in a wide variety of disciplines, including, but not limited to, economics (e.g. Hudson 1996; Kuld and O'Hagan 2017), the social sciences and humanities (e.g. Ossenblok et al. 2014; Henriksen 2016; Verleysen and Ossenblok 2017), medical sciences (e.g. Khan et al. 1999; King 2000) and natural sciences (e.g. Regalado 1995; Nabout et al. 2015). However, the decline in single authorship and rise of multiple authorship has not been consistent across fields. While social sciences manifested declines in single authorship of 72% to 38%, pharmacology manifested declines from 13% to 4% (Gorham and Kelly 2014). Research in the fields of ecology and environmental sciences shows a similar overall trend in the rise of multiple authorship (e.g. Weltzin et al. 2006; Gorham and Kelly 2014; Barlow et al. 2018), with a decline in single authorship from 35% to 5% between 1981 and 2012 (Gorham and Kelly 2014). Qiu and Chen (2009) examined some authorship patterns in the field of invasion science; however, their temporal scope was limited to research published between 1991 and 2007 and, although they calculated the average number of authors per publication for each year, they did not examine the proportions of single- and multi-authored papers. In light of the necessity of a transdisciplinary approach

to and the complexity and the global nature of biological invasions (Diagne et al. 2020), the field of invasion science as a distinct field selects for multi-authored papers.

The declining trend in the proportion of single-authored papers is probably driven by a complex interplay of multiple factors. Collaboration is likely, in part, a byproduct of advances in transportation (i.e. deregulation of the airline industry reducing travel costs) and technology (e.g. fax, long-distance phone calls, email, the internet, videoconferencing) that facilitate communication amongst collaborators (Rosenblat and Mobius 2004; Hamermesh 2013). The decline of single-authored papers also likely reflects the increasingly collaborative and interdisciplinary nature of science. This trend is often encouraged by funding sources (e.g. National Science Foundation, European Research Council) and promoted by working groups and institutions (e.g. National Center for Ecological Analysis and Synthesis, German Center for Integrative Biology Research) in the field of ecology (Weltzin et al. 2006; Barlow et al. 2018). Interdisciplinary teams with a wide range of skills (e.g. taxonomists, statisticians, ecological modellers, field assistants, technicians) are often required to conduct ecological studies. Additionally, the increased number of co-authors may also be driven by changes in the criteria for authorship. Technicians, data collectors, field assistants or research students who, in the past, may have been included in the acknowledgements, are now often co-authors (Weltzin et al. 2006; Gorham and Kelly 2014; Barlow et al. 2018). Moreover, the notion of 'publish or perish' and publications as a currency for productivity in science may play a large role in increasing collaboration (Nabout et al. 2015). Multiple authorship allows for a division of labour and costs, effectively decreasing the amount of time and funding each individual author contributes in comparison to a single-authored publication (Leimu and Koricheva 2005a), which may increase overall perceived productivity. Furthermore, funding, hiring and promotion decisions are all often influenced by collaborations (Katz and Martin 1997), and this fact may increase the participation of scientists in multi-authored papers. No single factor drives the decline of single-authored papers, but multiple factors act together to promote the rise of multi-authored papers.

Collaboration is often assumed to result in higher quality research and impact (Katz and Martin 1997; Franceschet and Costantini 2010). However, the evidence for this presumption is not always clear. Scholars have examined the impact of collaboration on the quality and impact of research by relating the number of authors to citations or citation rate. Citations are used as a proxy for scientific success, academic impact and the relative importance of a publication and/or its author (Hamilton 1990) despite studies (e.g. Leimu and Koricheva 2005b; Borsuk et al. 2009) demonstrating bias and influence by other unrelated factors. Some disciplines show a negative or no relationship between citations or citation rate and number of authors (e.g. Smart and Bayer 1986; Rousseau 2001; Leimu and Koricheva 2005a; Bornmann et al. 2012), while others show a positive relationship (e.g. Smart and Bayer 1986; Rousseau 2001; Hudson 2007), including the field of ecology (e.g. Leimu and Koricheva 2005a; Borsuk et al. 2009; Fox et al. 2016; Barlow et al. 2018). In the field of invasion science, Qiu and Chen (2009) examined patterns in citations per publication by journal, country,

institution and amongst the top ten most productive authors, while Pyšek et al. (2006) evaluated the most-cited publications for changes in citations over time, which journals published highly-cited papers and citation performance for specific sub-fields of study. To our knowledge, no work has examined the relationship between citation rate and number of authors in invasion science.

While some studies (e.g. Pyšek et al. 2006; Qiu and Chen 2009) have addressed authorship patterns and the impacts of collaboration on citation rate in invasion science, no systematic review to date covers publications published from the rise of modern invasion science (i.e. 1980s) to the present. Here, we systematically review literature in the field of invasion science published between 1980 and 2020 to determine how trends in co-authorship have changed over time and how patterns of authorship relate to citation rate. We expected that the mean number of authors and proportion of multi-authored publications will have increased over time and that there will be a positive relationship between the number of authors and citation rate.

Methods

We queried Clarivate Analytics Web of Science Core Collections topics, which examines the title, abstract, author keywords and keywords plus for all records in the database, between May and October 2021 for the following search terms: ("non-native" OR "nonnative" OR "exotic speci*" OR "alien" OR "invas* speci*" OR "biolog* invas*"). The results of this search (N = 76,239*) were further refined by publication year (1980–2020, inclusive) to coincide with the rise of modern invasion science and to exclude irrelevant Web of Science categories (e.g. 'Dermatology'; see Suppl. material 1: Appendix S1 for complete search query). We defined an invasion as a species introduced, deliberately or accidentally, to geographic areas outside of their historical native range (Simberloff 2011c). We systematically screened the remaining results (N = 42,695*) following a co-developed set of rules. A publication was retained if it discussed an invasion, range-expanding natives (Simberloff 2011c) while addressing the issue of analogy to an invasion and potential impacts, documented new records while discussing possible route of invasion and/or potential impacts, had a clear objective of quantifying the proportion of non-native species in an area, documented the spread of an established non-native species, examined the biology of a non-native species in its native or non-native range and clearly linked the reported biology to the invasion or managing it and/or was related to the management of non-native species. A publication was excluded if it contained species occurrences for an area and mentioned only that a species was introduced without further discussion regarding the invasion, examined the biology

* Clarivate Analytics Web of Science continually updates the database such that content is added or purged from the system and/or KeyWords Plus are recalculated which generates new sets of terms. These features resulted in minor fluctuations in the number of records produced by the query over the course of this systematic review as the most relevant results were continuously updated.

of a non-native species in its native or non-native range without discussion of how the biology related to the invasion or managing it, mentioned that the study organism was non-native in the study area and that the research could be used for management without any detail or obvious linkages between the research and management, indicated a new record of a non-native species without further discussion regarding potential route of invasion, impacts or control and any biocontrol publications that focused on non-invasion related aspects (e.g. treatment of the biocontrol agent during importation).

A total of 27,535 publications met the criteria for inclusion. These publications included three papers that have been retracted, 297 early view papers published in a volume in 2021 and one early view paper published in a volume in 2022, which were all excluded from further analyses. Bibliographic information for each publication was exported via Web of Science Fast 5K, including the name(s) of the author(s), publication type, publication title, journal or source title, total times cited, publication date, volume, issue, page number(s), early access date, digital object identifier and accession number (a unique Web of Science identification number) when available and where applicable.

For each record, we tallied the total number of authors to calculate the mean number of authors, maximum number of authors and the proportion of single-author publications each year from 1980 to 2020. We excluded a single outlier published in 2020 with 642 authors from mean and maximum calculations, as well as the analysis examining citations. We also summed the total number of papers each author co-authored. We assumed that papers with an anonymous author (N = 56) were single-authored and that authors with the same last name and first initial(s) were the same author. We searched each record via Google Scholar and matched institutional affiliations to the best of our ability in cases where multiple authors had the same last name and first initial(s). Annual citation rates for individual publications were calculated as the number of citations divided by the number of years since publication (sensu Leimu and Koricheva 2005b). We calculated mean annual citation rates as the sum of all citation rates across publications in a year divided by the number of publications published in that year. To explore how the number of authors is related to citation rate, we completed a generalised linear mixed model (GLMM) with the annual citation rate (plus one) log-transformed as a response variable, number of authors (one, two, three, four or more than four) as a fixed effect and age calculated as number of years since publication as a random effect. We also examined the relationship between the number of authors and the rate of self-citation. We randomly sampled 100 papers authored by one, two, three, four, five, six to ten and eleven or more authors, respectively. We accessed the entry for each randomly sampled paper on Web of Science, recorded the total number of citations up to 20 June 2022 and recorded the number of citations excluding papers authored by authors of the randomly sampled paper (i.e. we excluded self-citations). All 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), *ggplot2* (Wickham 2016), *ggpubr* (Kassambara 2020), *lme4* (Bates et al. 2015) and *MuMIn* (Bartoń 2020) packages.

Results

The total number of publications related to invasion science published each year and registered in Clarivate Analytics Web of Science Core Collections has exponentially increased (Fig. 1) from three publications in 1980 to 2,535 publications in 2020, with an average of 680.9 publications per year. The number of source titles (e.g. journals) publishing papers each year has also increased exponentially from three source titles in 1980 to 495 source titles in 2020 (Fig. 2). A total of 1,218 source titles have published invasion science literature between 1980 and 2020. The top five journals publishing papers in invasion science during this period were "Biological Invasions" (N = 2653), "PLoS ONE" (N = 723), "Diversity and Distributions" (N = 547), "Hydrobiologia" (N = 432) and "Aquatic Invasions" (N = 397) (Table 1). Approximately 29.5% of source titles have contributed only one publication between 1980 and 2020.

Patterns in authorship also changed over this period (Figs 3 and 4). A total of 53,685 authors contributed to 27,234 publications. Of these, 36,232 (67.5%) authors contributed a single paper, 14,293 (26.6%) contributed between 2 and 5 papers, 1,833 (3.4%) contributed between 6 and 9 papers and 1,327 (2.5%) contributed 10 or more papers. Amongst authors who have published a paper in any given year, the proportion of those who have published a single paper versus those who have published two or

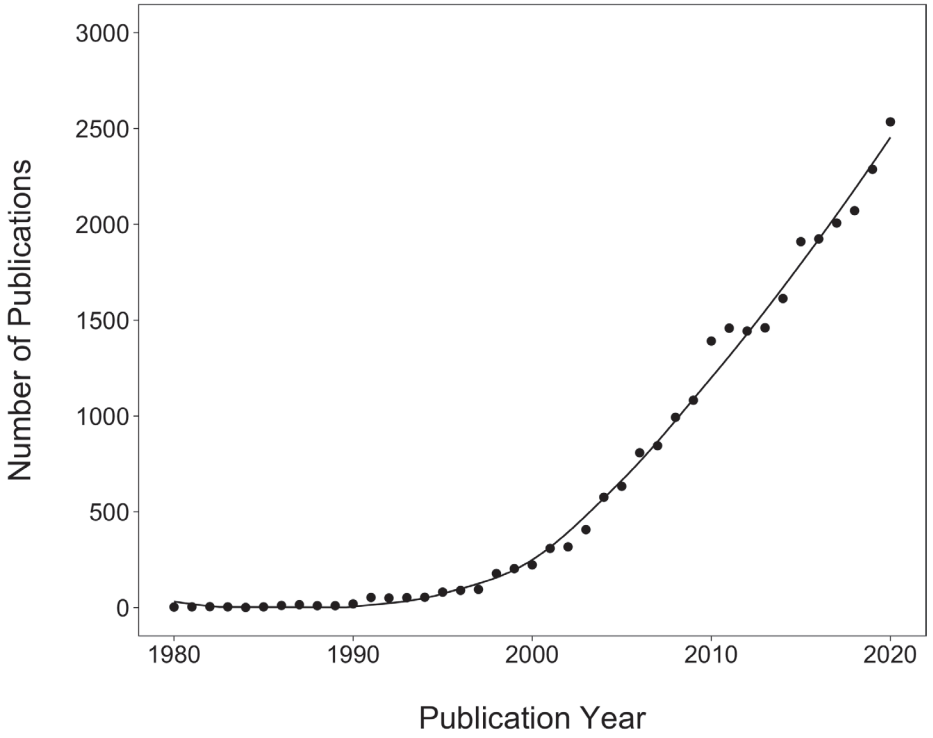

Figure 1. Total number of publications (N = 27,234) in invasion science published between 1980 and 2020 and registered in Clarivate Analytics Web of Science Core Collections (see methods for screening criteria).

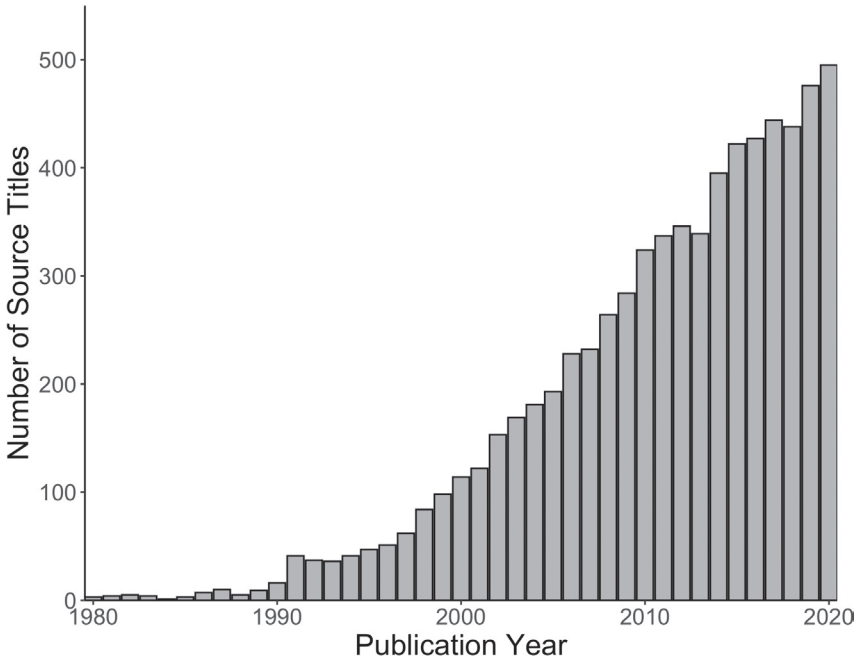

Figure 2. The total number of source titles (e.g. journals, N = 1,218) that have published at least one publication in invasion science literature (N = 27,234) between 1980 and 2020 that were also registered in Clarivate Analytics Web of Science Core Collections (see methods for screening criteria).

Table 1. The number of papers published by the 20 most productive source titles (e.g. journals) in invasion science literature published between 1980 and 2020 and registered in Clarivate Analytics Web of Science Core Collections (see methods for screening criteria).

Journal	Number of Publications				
	1980–1990	1991–2000	2001–2010	2011–2020	Total
Biological Invasions	0	0	757	1896	2653
PLoS ONE	0	0	33	690	723
Diversity and Distributions	0	0	255	292	547
Hydrobiologia	0	23	104	305	432
Aquatic Invasions	0	0	66	331	397
Biological Conservation	7	43	164	181	395
Ecology	3	35	144	181	363
Oecologia	3	29	123	180	335
Journal of Applied Ecology	2	17	109	194	322
Ecological Applications	0	30	149	138	317
Ecology and Evolution	0	0	0	313	313
Forest Ecology and Management	0	7	81	205	293
Invasive Plant Science and Management	0	0	64	202	266
Plant Ecology	0	8	94	160	262
Conservation Biology	3	47	126	84	260
Freshwater Biology	0	9	82	164	255
Marine Ecology Progress Series	0	5	102	128	235
Scientific Reports	0	0	0	231	231
Management of Biological Invasions	0	0	0	229	229
Journal of Ecology	0	8	79	139	226

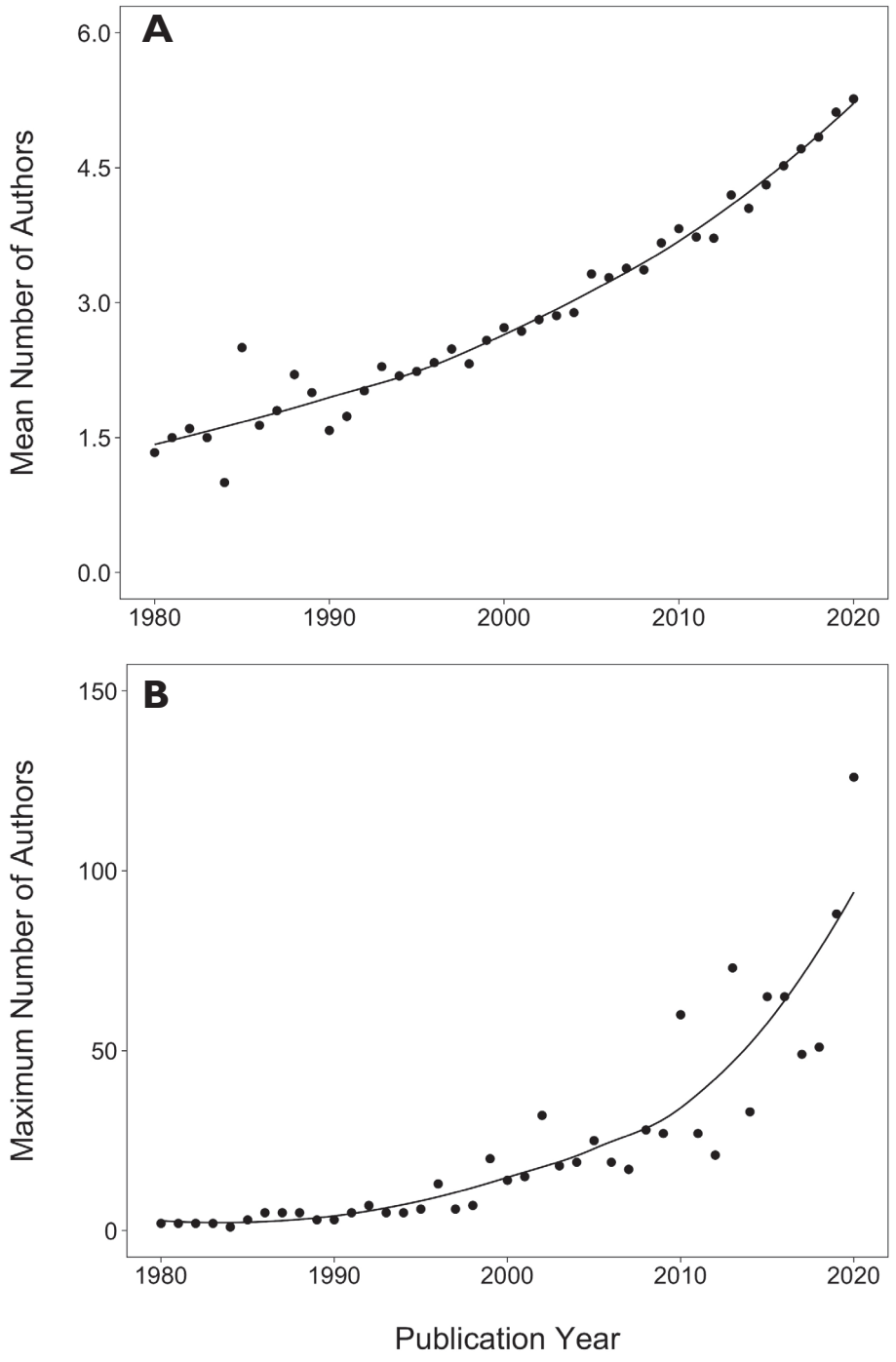

Figure 3. The mean (**A**) and maximum (**B**) number of authors on publications in invasion science (N = 27,233) published between 1980 and 2020. A single outlier (with 642 authors) published in 2020 was removed.

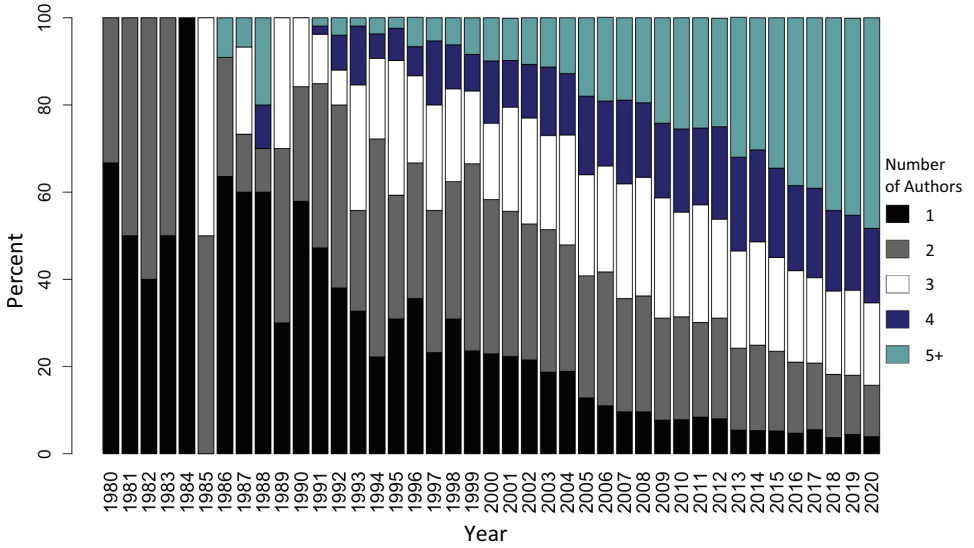

Figure 4. The proportions of single- and multi-authored publications (N = 27,234) in invasion science published between 1980 and 2020 and registered in Clarivate Analytics Web of Science Core Collections (see methods for screening criteria).

more papers between 1980 and 2020 has remained relatively stable (Fig. 5). The mean number of authors has steadily increased between 1980 and 2020 from ~ 1.3 to ~ 5.3. Likewise, the maximum number of authors has increased from 2 in 1980 to 126 in 2020, not counting the outlier. Approximately 92.0% of publications (N = 25,045), published in the invasion science literature between 1980 and 2020 were multi-authored (Fig. 4; Table 2). The proportion of single-authored publications has decreased from ~ 66.7% in 1980 to ~ 3.9% in 2020 and has fluctuated around 5% or less since 2013 (Fig. 4; Table 2). Conversely, the proportion of publications with five or more authors has increased from 0% in 1980 to 48.3% in 2020 (Fig. 4; Table 2).

The mean annual citation rate across publications has increased from ~ 0.6 citations per year in 1980 to ~ 3.6 citations per year in 2020 (Fig. 6). Approximately 28.7% of publications accounted for 80% of total citations; these publications had a mean of 4.2 authors, while the remaining 71.3% of publications had a mean of 4.1 authors. A positive relationship exists between annual citation rates and number of authors. While the number of authors predicted the annual citation rate ($p < 0.001$), the marginal coefficient of determination (i.e. considering only fixed effects) was 0.04, indicating high variability in the data and a low fraction of variation explained by number of authors alone. Examining the influence of number of authors on annual citation rate, we found that multi-authored papers had significantly higher citation rates than did single-authored papers ($p < 0.0001$; Fig. 7). Papers with four or more authors had significantly higher citation rates than did papers with one, two, or three authors ($p < 0.0001$; Fig. 7); however, no significant differences existed in citation rates between papers with two authors

Table 2. The proportion of single- and multi- authored publications (N = 27,234) in invasion science published between 1980 and 2020 and registered in Clarivate Analytics Web of Science Core Collections (see methods for screening criteria).

Year	Percentage of publications by number of authors				
	1	2	3	4	5+
1980	66.7	33.3	0	0	0
1981	50.0	50.0	0	0	0
1982	40.0	60.0	0	0	0
1983	50.0	50.0	0	0	0
1984	100.0	0	0	0	0
1985	0	50.0	50.0	0	0
1986	63.6	27.3	0	0	9.1
1987	60.0	13.3	20.0	0	6.7
1988	60.0	10.0	0	10.0	20.0
1989	30.0	40.0	30.0	0	0
1990	57.9	26.3	15.8	0	0
1991	47.2	37.7	11.3	1.9	1.9
1992	38.0	42.0	8.0	8.0	4.0
1993	32.7	23.1	28.8	13.5	1.9
1994	22.2	50.0	18.5	5.6	3.7
1995	30.9	28.4	30.9	7.4	2.5
1996	35.6	31.1	20.0	6.7	6.7
1997	23.2	32.6	24.2	14.7	5.3
1998	30.9	31.5	21.3	10.1	6.2
1999	23.6	42.9	16.7	8.4	8.4
2000	22.9	35.4	17.5	14.3	9.9
2001	22.3	33.3	23.9	10.7	9.7
2002	21.5	31.2	24.3	12.3	10.7
2003	18.7	32.7	21.6	15.7	11.3
2004	18.9	29.0	25.2	14.1	12.8
2005	12.8	28.0	23.2	18.0	18.0
2006	11.0	30.7	24.3	14.9	19.2
2007	9.6	26.0	26.3	19.2	18.9
2008	9.6	26.6	27.2	17.1	19.5
2009	7.7	23.4	27.6	17.1	24.2
2010	7.8	23.6	24.0	19.1	25.5
2011	8.4	21.7	27.0	17.6	25.3
2012	8.0	23.1	22.7	21.2	24.9
2013	5.4	18.8	22.3	21.5	32.1
2014	5.3	19.6	23.7	21.1	30.3
2015	5.2	18.3	21.5	20.5	34.5
2016	4.7	16.3	21.0	19.5	38.5
2017	5.5	15.3	19.6	20.5	39.1
2018	3.7	14.5	19.1	18.5	44.2
2019	4.4	13.6	19.5	17.2	45.2
2020	3.9	11.8	18.9	17.1	48.3

and papers with three authors ($p = 0.1078$; Fig. 7). The average rate of self-citation across all randomly sampled papers was 15.9% and was positively correlated with the number of authors (Table 3). Papers with three or more authors had self-citation rates three to four times higher than single-authored papers (Table 3) and papers with eleven or more authors had the highest self-citation rate at 23.7%.

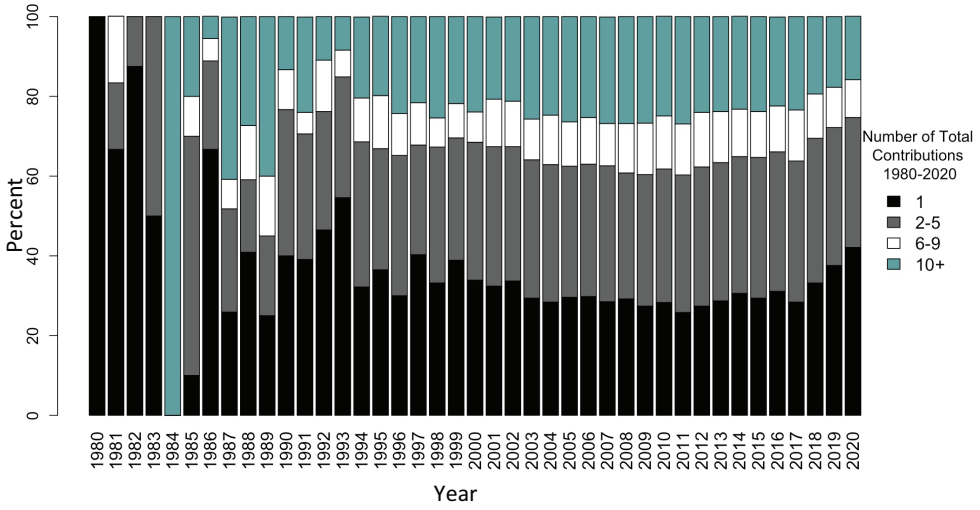

Figure 5. The proportions of authors publishing a paper in invasion science each year who have contributed one, two to five, six to nine or ten or more papers between 1980–2020.

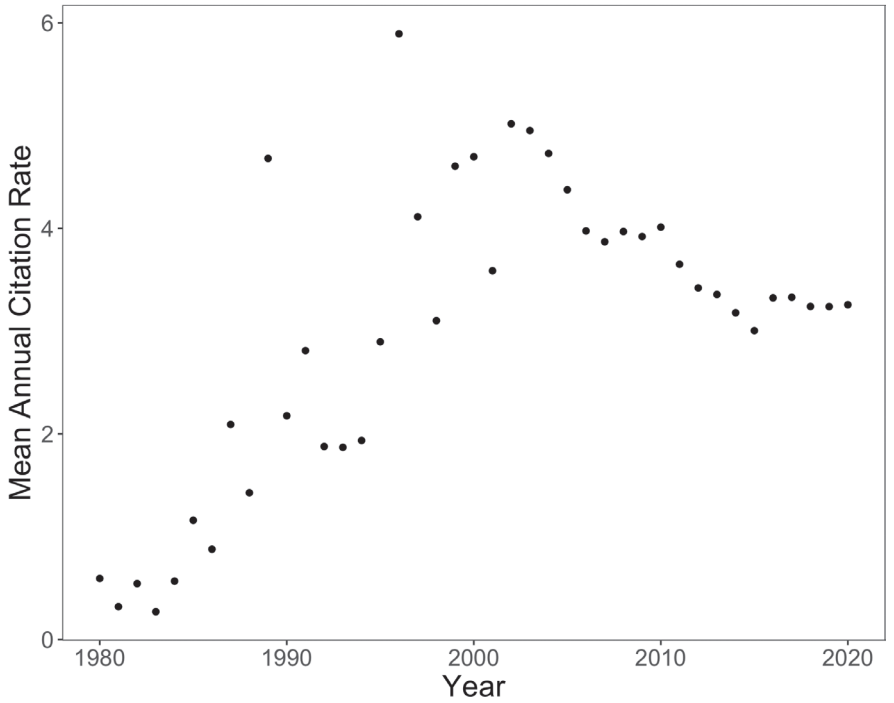

Figure 6. The mean annual citation rate for publications (27,225) in invasion science published between 1980 and 2020 and registered in Clarivate Analytics Web of Science Core Collections (see methods for screening criteria). Mean annual citation rate was calculated as the sum of citation rates across publications published in a year divided by the number of papers published that year. Outliers for number of authors (N = 1; 642 authors) and number of citations (N = 8; > 1900 citations) were excluded.

Table 3. The percentage of total citations that are self-citations for randomly sampled papers authored by one, two, three, four, five, six to ten and eleven or more authors, respectively, in invasion science literature published between 1980 and 2020 and registered in Clarivate Analytics Web of Science Core Collections. A total of 700 papers were randomly sampled evenly across author number groups.

Number of Authors	Total Number of Citations	Number of Citations Excluding Self-Citations	Percentage of Total Citations that are Self-Citations	Average Age of Sampled Papers (Years)
One	5029	4763	5.3	13.4
Two	3862	3512	9.1	11.4
Three	2237	1775	20.7	10.4
Four	2931	2489	15.1	8.8
Five	3052	2359	22.7	8.2
Six to Ten	2595	2040	21.4	6.5
Eleven or More	4658	3552	23.7	5.6

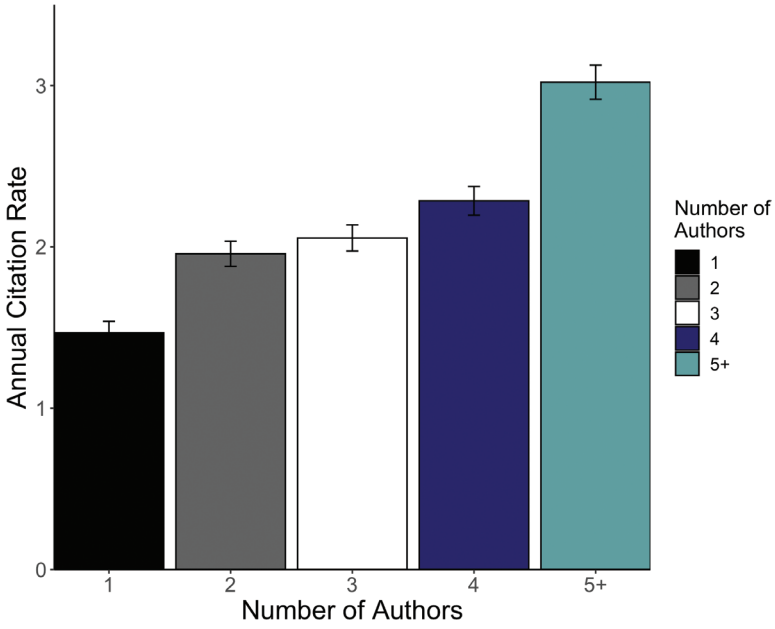

Figure 7. The back-transformed least square mean annual citation rate and standard error for publications (N = 27,225) with one (N = 2,188), two (N = 5,523), three (N = 6,032), four (N = 4,949) and five or more (N = 8,533) authors in invasion science published between 1980 and 2020 and registered in Clarivate Analytics Web of Science Core Collections (see methods for screening criteria). Annual citation rate was calculated as the number of citations divided by the number of years since initial publication. Outliers for number of authors (N = 1; 642 authors) and number of citations (N = 8; > 1900 citations) were excluded.

Discussion

This study examined patterns of authorship and how these relate to citations in the field of invasion science. Our analysis indicates research activity has exponentially increased since the rise of modern invasion science in the 1980s and the rate of increase

in the number of papers published is almost 50 times higher than that recorded for the biological sciences between 1990 and 2016 (Boltovskoy et al. 2018). Invasion science is highly collaborative, with a very small proportion of single-authored publications and two-thirds of authors publishing only a single paper between 1980 and 2020. The proportion of multi-authored papers surpassed that of single-authored papers in the early 1990s, coinciding with a sharply increased rate of publication. The steady increase in the mean number of authors could signal the maturation (Clarke 1964) of the field of invasion science, which is also supported by the growth of journals publishing invasion science literature. Collaboration has a positive relationship with research impact as measured by annual citation rate. Publications with four or more authors have a significantly higher citation rates than those with one, two or three authors. The higher citation rates amongst multi-authored papers in comparison to single-authored papers may reflect benefits and higher quality of collaborative research, increased visibility owing to a larger network for dissemination or other factors.

Invasion science has become increasingly collaborative over the past 40 years. The number of publications has exponentially increased and the increase in the mean number of authors per publication indicates the growth of the number of scientists working in the field. Over 53,000 authors have contributed at least one publication in invasion science, with only one-third contributing multiple publications between 1980 and 2020. Although Qiu and Chen (2009) documented an average of 3.2 authors per publication between 1991 and 2007, the fact that our data for the same time period show a lower number is likely due to the increased scope of this analysis with additional search terms, temporal breadth and, thus, sample size. Regardless, the increase in the number of authors reveals the theoretical, analytical, temporal, spatial and financial scale of biological invasions that requires multiple skillsets, expertise and division of labour or cost. Similarly, as data on biological invasions have accumulated globally, collaborative authors benefit from sharing data. Although it is nearly impossible to parse out the frequency of data-sharing in collaborative papers, the increase in data publications may provide some indication of this collaborative benefit. Our dataset included 27 publications categorised as data papers that were published between 2016 and 2020 (see Suppl. material 1: Appendix S2) with an average of 14.6 authors, while only two were single-authored. Two of these publications accounted for the highest number of authors in our dataset, with 126 and 642 authors. Sharing data, amongst other factors, has likely played an important role in the rise of multi-authored papers.

Collaboration plays an important role in the invasion science literature. Fewer than 10% of publications published between 1980 and 2020 were single-authored, a trend comparable to patterns of multiple authorship in the biological sciences generally (Franceschet and Costantini 2010) and the field of ecology (Paine 2005; Gorham and Kelly 2014; Barlow et al. 2018). The frequency of multi-authored publications increased rapidly, with the first publication containing five or more authors appearing in 1986, indicating the early contribution of multiple authorship to the rise of the field. By 1991, publications with two or more authors exceeded the proportion of single-authored publications and, in 2020, close to half of all publications had five or more

authors. The proportion of publications with two authors has decreased since 2007, with three authors has decreased since 2012, with four authors has decreased since 2015 and with five or more authors has steadily increased. This pattern may reflect the widespread notion that collaborative research results in higher quality science, particularly in light of the finding that manuscripts with four or more authors were more likely to be accepted for publication (Tregenza 2002; Barlow et al. 2018).

The increasing complexity in the challenges and types of questions studied in invasion science, ecology and science in general, increasingly requires synthesis of information. The rise of synthesis in ecology is demonstrated by the establishment of synthesis centres around the world beginning in the 1990s (Lynch et al. 2015) where researchers assemble in working groups for intensive, collaborative research on a key topic or question in the field. These groups often include individuals at different career stages with different specialities, expertise, and skills (Baron et al. 2017). Although examining the proportion of publications produced by working groups was outside the scope of our analysis, working groups have, nonetheless, played an important role in research on biological invasions, with SCOPE working groups initiating the rise of the field. Collaboration on SCOPE projects set an early precedent for synthesis and the necessity of biologists, statisticians, modellers and managers to work together to address the growing concern regarding biological invasions and their management (Simberloff 2011b). This rise in synthesis is further demonstrated by the establishment of institutions like the Centre for Invasion Biology in South Africa, which has produced 1,745 peer-reviewed publications between 2004 and 2018; this work involved 4,237 authors from 110 countries across 1,729 of these publications (Richardson et al. 2020). Working groups and institutions will likely continue to contribute to an ongoing decline in the proportion of publications that are single-authored; examples in invasion science include, but are not limited to, the European Information and Research Network on Aquatic Invasive Species (ERNAIS), Global Invader Impact Network (GIIN), Global Invasions Research Coordination Network, Global Naturalized Alien Flora database (GloNAF), Mountain Invasive Research Network (MIREN), Phragmites Network (PhragNet), Pacific Invasives Partnership and Southern Hemisphere Network on Conifer Invasions.

The increase in the number of source titles publishing invasion science literature signals the growth of the discipline. During the rise of modern invasion science, general journals like "Ecology" published increasing numbers of papers on invasions and the specialised journal "Biological Invasions" began in 1999. Another specialised journal, "NeoBiota", began in 2002 as conference proceedings and became a standard journal in 2011. Although "NeoBiota" ranks below the top 20 journals publishing invasion science literature, this is likely an artifact of the scope of Clarivate Analytics Web of Science, as the earliest record in our dataset was published in 2015; similarly, the first volume of "Biological Invasions" is also absent on Web of Science. Pyšek (1995) found that nine journals published 28% of plant invasion literature and 20 journals accounted for almost 50% of plant invasion literature between 1974 and 1993. Although our study examines literature across taxa from 1980 to 2020, we similarly found that the top nine journals accounted for 22.6% of invasion science literature. However, the top

20 journals published only 33.2% of papers and this pattern, coupled with the large number of journals contributing only one paper to invasion science literature, indicates the growth of the field beyond popular generalised journals like "Ecology", as well as specialised journals like "Biological Invasions" or "NeoBiota". Qiu and Chen (2009) examined the journals publishing invasion research from 1991 to 2007 and our analysis documented more than twice the number of source titles. The ten most productive journals identified by Qiu and Chen (2009) were similar to the top ten in our study and all were amongst the top twenty source titles identified by our analysis. The slight departure in our analysis compared to Qiu and Chen (2009) probably stems from increased search terms, a longer time series, the growth of the discipline and the launch of new scientific journals. Despite the challenges associated with records registered in Web of Science, the sheer number of journals publishing invasion science literature in 2020 indicates the impact biological invasions have across ecosystems, taxa and sub-fields of study globally.

Analysis of citations and citation rates reveals important information on the maturity of the field, citation density and the potential role of collaboration in the impact of research. Here, we have shown that the mean annual citation rate steadily increased as the field has matured, a pattern Pyšek et al. (2006) also noted amongst highly-cited publications in invasion ecology. As the number of publications and scientists working in the field has increased, the body of work available for citation has also grown. Garfield (2006) termed a pattern of 20% of articles accounting for 80% of publications the "80/20 phenomenon," with the majority of publications receiving few or no citations. We found that approximately 28.7% of publications accounted for 80% of total citations in the field between 1980 and 2020. The number of highly-cited papers depends on the size of the field, and the relative youth of modern invasion science as a distinct discipline may explain the slight departure of our results from the 80/20 indicator. We also found a positive relationship between collaboration and impact as measured by annual citation rates. Previous research on the ecological literature has demonstrated that publications with four or more authors (Leimu and Koricheva 2005b; Barlow et al. 2018) were cited more and our analysis found multi-authored publications have a higher annual citation rate than do single-authored publications. The positive association between collaboration and annual citation rate could indicate a net benefit of collaboration on the quality of a publication or, alternatively, researchers may perceive greater merit or credibility in multi-authored publications and are more likely to cite them rather than a single-authored paper.

Multiple factors could account for a positive relationship between citations and number of authors. Characteristics of the author(s) could influence the number of citations a publication accumulates. Rather than a reflection of collaborative benefits, multi-authored publications may accumulate more citations via self-citation (Herbertz 1995; Aksnes 2003; Leimu and Koricheva 2005a; Glänzel et al. 2006), even if self-citations do not solely account for the positive relationship between citations and the number of authors (Larivière et al. 2015). Previous work has shown that citations by others increases in parallel with self-citations (Leimu and Koricheva 2005a), and our analysis of randomly sampled papers also demonstrates a positive relationship between the number of authors and rate of self-citations. A potentially important factor might

be citations by colleagues of authors who may be more familiar with the work; an increased number of authors equates to a larger network and, potentially, citations by that network. The positive relationship between citations and number of authors could also reflect the common scientific practice of citing recent publications, which are more likely to be multi-authored as the proportion of single-authored publications declines. Citation rates may not necessarily always reflect research quality or real impact (American Society for Cell Biology 2012; Pulverer 2015; Schmid 2017).

The positive association between annual citation rate and number of authors may also be a by-product of technological advancements facilitating collaboration of scientists amongst different countries and institutions, both of which have been shown to be associated with increased citation rates (Narin et al. 1991; Katz and Hicks 1997; Goldfinch et al. 2003; Leimu and Koricheva 2005a). Larger collaborative teams could also promote the visibility of research, thus increasing citations; as the number of authors increases, the number of research networks and individual researchers introduced to the publication also increases (Franceschet and Costantini 2010). The emergence of 'citation farms,' whereby groups of scientists preferentially cite one another's work (Van Noorden and Chawla 2019), may also play a role in the relationship between collaboration, number of authors and citation rates. Although there have been calls for increasing interdisciplinarity in invasion science to advance the field (e.g. Vaz et al. 2017; Heger et al. 2021), socio-ecological research began in the 1990s and early 2000s (Vaz et al. 2017), and some advances in interdisciplinary collaboration have occurred in research on historical, economic and management aspects of biological invasions. As interdisciplinary collaboration has been associated with increased citation rates in some instances in ecology (Leimu and Koricheva 2005a), such a relationship could also play a role in the effect of number of authors on citation rates in invasion science. Despite the potential role other factors – including, but not limited to, authors' stages of career, previous contributions to the field, open access status and type of contribution (e.g. primary research, review, data paper) – may play in the annual citation rate of a publication, we have demonstrated here a positive association with number of authors.

Conclusions

Price (1963) predicted the extinction of single-authored publications by 1980 and, although this prediction coincided with the beginning of modern invasion science, the field, nonetheless, shifted towards increasing multiple authorship almost immediately. The field of modern invasion science responded to the complexity, idiosyncrasy and urgency of biological invasions through increased collaborative research. The rise of multiple authorship likely reflects a combination of multiple factors including perceived scientific quality, division of labour and costs, technological advances in communication and transportation and increasingly interdisciplinary teams. Collaboration has a positive impact on the accumulation of citations, effectively conferring a higher likelihood of increased research impact as measured by annual citation rates.

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Supplementary material 1

Appendices S1, S2

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Data type: Search Query (docx. file)

Explanation note: Appendix S1. Clarivate analytics Web of Science core collections topics search query. Appendix S2. List of publications published in invasion science between 1980 and 2020, registered in Clarivate Web of Science Core Collections, and categorized as data papers.

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