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Global Collaboration Dynamics in Scientific Research: Why Does It Occur? Examining the Citation Economy

by Mark A. Tschopp

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14. ABSTRACT

This technical report delves into the dynamics of global scientific collaboration and its impact on citation outcomes, with a focus on the United States' international partnerships and the rising influence of China in the scientific landscape. By analyzing citation incentives for bilateral and multilateral collaborations between the United States and various global partners since 1990, this study provides new insights into the factors driving the growth of international collaboration. The research methodology leverages the OpenAlex database and employs novel approaches to quantify the relative and comparative citation incentives for collaborative articles. The findings reveal significant differences in how collaborations impact citation outcomes for the U.S., with countries like the United Kingdom, Canada, and Australia consistently providing high citation benefits, while others like Brazil, Russia, and India often show negative incentives. The study also explores the role of third countries in multilateral collaborations and highlights the complexities of aligning citation incentives with the broader goal of advancing scientific knowledge. Ultimately, this report aims to inform decisions on international partnerships and research strategies, shedding light on the motivations and outcomes driving global research efforts and their implications for the future of science.

15. SUBJECT TERMS

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1. Introduction

Citations have long been the lifeblood of scientific recognition, serving as markers of influence, quality, and the dissemination of knowledge across disciplines.[1–7] They act as the currency of the scientific enterprise, driving scientists' careers, securing funding, and shaping institutional prestige. In today's increasingly collaborative and globalized research landscape, understanding the dynamics of citations has never been more crucial. Not only are scientific publications and citations a sign of scientific prestige, but they are also used as a critical metric for assessing scientists for hiring, promotion, and tenure within academia, prompting what is defined as the "publish or perish" model. This report delves into the "citation economy"—the interplay between global collaboration patterns and the citation incentives they generate. Building on a prior analysis of collaboration frequencies,[8,9] this study shifts focus to the outcomes of these collaborations, exploring how partnerships between countries influence citation dynamics and illuminate the underlying incentives within the global collaboration landscape.

The exploration of citation dynamics falls within the growing transdisciplinary domain known as the Science of Science.[10,11] This emerging field leverages computational and data-driven approaches to uncover the mechanisms governing scientific discovery, production, and dissemination. Citation analysis, a field that has been studying the way articles are accessed and referenced by others for decades,[12] has evolved into a cornerstone of Science of Science, a more recent interdisciplinary field that leverages computational and data-driven approaches to understand the dynamics of scientific research. This powerful lens provides insights into how knowledge spreads, whose contributions gain recognition, and what factors drive scientific impact. By integrating insights from sociology, network science, and machine learning, researchers can reveal patterns of influence, collaboration, and innovation that shape the scientific enterprise. This study contributes to this expanding body of knowledge, focusing on the global citation economy to explore how bilateral and multilateral collaborations influence the reach and recognition of scientific work across borders.

While citations are widely used to evaluate scientific reputation and impact, it is essential to acknowledge that they are a flawed and imperfect measure of research quality and prestige of scientists, institutions, and nations. Citations and metrics such as the h-index[13] are widely used to evaluate scientific reputation and impact, but they are not without their limitations and biases.[14] The Matthew Effect, first described by Robert K. Merton in 1968, can lead to preferential attachment, where already prominent papers or authors receive disproportionate attention and citations.[3] Self-citations can artificially inflate citation counts of articles for scientists.[15] The increasing use of teams in science[16] is also associated with guest and honorary authors, whose presence (or lack as in the case of ghost authors) can obscure the true contributions of individual researchers.[17–19] The fact that citations can be influenced by factors such as journal prestige, author reputation, and social networks, can also lead to distorted views of scientific merit.[20] These biases and limitations can be exploited, either intentionally or unintentionally, by researchers seeking to increase their citation count and enhance their reputation within the scientific community. The existence of these biases creates a set of built-in citation incentives, where researchers can potentially game the system by engaging in practices such as excessive self-citation and citation farms,[*][21,22] or editors and peer reviewers can even coerce authors into citing their work or that of their journal.[23,24]

On a global scale, the incentives for researchers to boost their citation profiles can aggregate to create powerful incentives for institutions and even countries, which can be influenced by public research policy and other factors. For instance, some countries appear to be more prone to self-citation than others, with China being a notable example. In a recent Science article referring to several reports, China has been found to be the largest self-citer in the world, with a significant proportion of its citations coming from domestic sources.[25,26] This "home bias" in citations has been shown to boost China's global science ranking, highlighting the need for a better understanding of citation patterns and their relationship to scientific quality. Additional articles have noted other countries where self-citations are unusually high and where the tendency to self-cite is increasing as well, including countries such as Indonesia, Iran, Italy, Russia, and Ukraine.[27,28] Moreover, the increasing trend of global collaboration in research may be building upon these incentives, where researchers and institutions may be motivated to form international partnerships not only to advance scientific knowledge, but also to boost their citation profiles and reputation.[29] For instance, collaborations with prominent international researchers or institutions may be seen as a way to increase the visibility and citation potential

[*] Citation farms are defined as relatively small clusters of authors massively citing each other's papers.

of one's work, regardless of the actual scientific contribution. This raises important questions about the nature of global collaboration and its relationship to citation patterns, and whether the pursuit of citation incentives may be influencing the formation of international research partnerships and the dissemination of scientific knowledge.

Given the potential for biases and incentives to shape citation patterns, it is essential to examine the specific ways in which collaboration networks influence citation outcomes, and to identify the factors that drive citation impact in different research contexts. These considerations raise important questions about the relationship between collaboration and scientific recognition:

- How do bilateral (two-country) and multilateral (multi-country) collaborations compare in their ability to garner citations?
- Do certain country-pair collaborations exhibit disproportionate citation impact, and if so, why?
- Are citation trends consistent across research domains, or do they vary significantly depending on scientific fields?
- What role do the most prolific countries play in shaping these patterns?
- How do collaborative efforts influence the global flow of knowledge and scientific recognition?

This study contributes to our understanding of these issues by exploring bilateral and multilateral global collaboration, with a focus on the citation incentives underlying this collaboration. By examining the relationships between collaboration networks and citation outcomes, this study provides new insights into the citation economy and the role of global partnerships in shaping scientific recognition.

The global research ecosystem operates as a complex, interconnected network where ideas flow seamlessly across geographical boundaries. Citations, as markers of scientific influence, illuminate this flow, revealing patterns of recognition, competition, and knowledge dissemination among nations. While collaboration fuels the production of scientific work, citations trace its impact, shedding light on which contributions resonate most strongly within the research community. In this context, the global stage of citation dynamics reveals not only the influence of established scientific powers but also the emergence of new players, disparities across disciplines, and evolving patterns of global recognition.

To achieve a deeper understanding of these dynamics, this report leverages modern open-source tools and datasets to analyze the citation economy at scale. Central to this investigation is the OpenAlex dataset,[30–32] an open-source repository that captures millions of scientific works, citation relationships, authorship details, and institutional affiliations. By applying robust citation metrics, network analyses, and data-driven techniques, this study examines how collaboration structures—particularly those involving the United States—influence citation rewards and patterns.

This report serves as a natural complement to the preceding analysis of global collaboration patterns,[8,9] and offers insights into the tangible rewards of collaboration structures. Moving beyond the question of *how often global collaboration occurs* among leading countries, it explores the *outcomes* of these partnerships within the global citation economy. The report is organized as follows: Section 2 describes the datasets, citation metrics, and analytical tools used in this study. Section 3 presents the key findings, highlighting the relationships between collaboration structures and citation dynamics, with particular focus on the United States' partnerships. The discussion subsection goes beyond the data to explore the broader implications of these findings for the future of science. Finally, Section 4 summarizes the study and its contributions.

2. Methodology

2.1 A Brief Introduction to OpenAlex

OpenAlex is an openly accessible catalog of the global research system, unlike paywalled services like Elsevier's Scopus and Clarivate's Web of Science. The analysis of global collaboration in this study relies on the OpenAlex database. Tschopp[8] gives a general overview of the structure of the OpenAlex metadata and methods for extracting information through the OpenAlex API (https://api.openalex.org/).

As a brief overview, OpenAlex describes various entities in its metadata and their interconnected relationships, forming a network of scientific publications. This dataset includes entities such as works, authors, sources, institutions, concepts, publishers, and funders (try it through the dashboard at https://openalex.org/), creating a data representation of the global research landscape. Table 1 lists the various entities along with URL web links to both an example and the application programming interface (API). Each entity in OpenAlex is assigned a unique OpenAlex ID, allowing for stability and identification of specific resources within the database. The OpenAlex ID comprises two parts: the base, which is always https://openalex.org/, and the key, a unique primary identifier (first letter) corresponding to the entity's type (e.g., work, author, source, institution, concept, publisher, funder).

Table 1. The various accessible entities within OpenAlex along with a URL to an example record and to the API. The following examples were chosen: "The Limitations of Deep Learning in Adversarial Settings"[34] (works), Mark A. Tschopp (authors), DEVCOM Army Research Laboratory (institutions), Army Research Office (funders), Science (sources), American Association for the Advancement of Science (publisher), and Computer Science (concept).

Entity	URL for example entity	URL to access API
Works	https://openalex.org/W2180612164	https://api.openalex.org/works
Authors	https://openalex.org/A5073812740	https://api.openalex.org/authors
Institutions	https://openalex.org/I166416128	https://api.openalex.org/institutions
Funders	https://openalex.org/F4320338281	https://api.openalex.org/funders
Sources	https://openalex.org/S3880285	https://api.openalex.org/sources
Publishers	https://openalex.org/P4310315823	https://api.openalex.org/publishers
Concepts	https://openalex.org/C41008148	https://api.openalex.org/concepts

2.2 Using OpenAlex API Calls

This work focuses on citation incentives for global collaboration, specifically why countries collaborate in scientific research. To this end, several features associated with publications that involve multiple countries are being interrogated, including the year of publication, type of scientific work (article), language of work (English), countries involved (U.S., other countries), and the distinct number of countries (1, 2, and 3 or more). The primary objective is to capture the citation distribution for these publications, which will provide insights into the trends and patterns in global collaboration and the factors that influence citation rates. The methodology for capturing the citation distributions involves extracting metadata from the OpenAlex database, cleaning and preprocessing the data, and calculating the citation distributions for the specified features.

Navigating from a dataset of 261 million works requires leveraging the OpenAlex API. This allows users to tailor their queries by filtering, sorting, grouping, and conducting keyword searches within the dataset—explained within the technical documentation of OpenAlex.[36] To illustrate this, Table 2 provides a step-by-step example of constructing a URL for API access that is relevant to the current study.

The first step initiates with the API address and specifies the entity type that is to be accessed (works), bearing in mind that filters may vary depending on the entity type. Subsequent steps showcase how to progressively filter the dataset. For instance, the second step demonstrates filtering for a specific type of work, such as articles (inclusive of both journal articles and conference proceedings). The third step narrows down the dataset to records in English. Further refinements follow, such as filtering for works in the year 2023, works with authors associated with institutions in the U.S., works with authors associated with institutions in the China (CN), and lastly, limiting the dataset to publications featuring global collaboration with three or more countries. This curated query results in 19,104 publications just for this subset of conditions, showing the ability to gather a focused dataset for in-depth exploration across various dimensions on global collaboration.

Table 2. An example of accessing the OpenAlex API in successive steps: (1) initial URL, (2) only journal articles and conference proceedings, (3) only articles in English, (4) for publication year 2023, (5) only when U.S. is one of the author countries, (6) only when CN is one of the author countries, and (7) when there are three or more countries involved (accessed 2025-01-27)

Step	URL to access API	No. of records
1	https://api.openalex.org/works	263,370,998
2	https://api.openalex.org/works?filter=type:article	198,417,464
3	https://api.openalex.org/works?filter=type:article,language:languages/en	143,448,454
4	https://api.openalex.org/works?filter=type:article,language:languages/en,publication_year:2023	4,928,883
5	https://api.openalex.org/works?filter=type:article,language:languages/en,publication_year:2023,authorships.countries:countries/US	802,585
6	https://api.openalex.org/works?filter=type:article,language:languages/en,publication_year:2023,authorships.countries:countries/US,authorships.countries:countries/CN	54,104
7	https://api.openalex.org/works?filter=type:article,language:languages/en,publication_year:2023,authorships.countries:countries/US,authorships.countries:countries/CN,countries_distinct_count:3-	19,104

2.3 Understanding the JavaScript Object Notation (JSON) Format

Utilizing the OpenAlex API enables research and information retrieval from the dataset. It is essential to understand the nature of information provided by the API. To illustrate, focus on the entity `"works"` that encompasses articles, proceedings, books, datasets, and more. An excerpt from the JSON response of an API call is presented in Figure 1, specifically highlighting the `"meta"` key and its associated contents. Nested within this key is a dictionary comprising various keys and values. Noteworthy components include the total count of entities returned from the query (19,104 records), the response time in milliseconds (294 ms), the page number (pertinent for multiple pages), the count of records returned per page (25), and the count of groups returned (applicable when utilizing a group_by function). The `"page"` and `"per_page"` keys play a pivotal role in navigating through multiple JSON files, particularly when aggregating extensive records surpassing the 200-per-page limit.

JSON format for OpenAlex: `"meta"`

```
"meta": {
  "count": 19104,
  "db_response_time_ms": 294,
  "page": 1,
  "per_page": 25,
  "groups_count": null
      },
"results": [
      {
```

Figure 1. The JSON format for OpenAlex within the key `"meta"` that describes the total number of entities returned by the API (`"count"`), the response time (`"db_response_time_ms"`), and other information.

Direct your attention to the subsequent key presented in the JSON response—namely, `"results"`. In Figure 1, the `"results"` key, positioned at the bottom, houses a list of entries (25 in this instance, not shown). Each entry follows a dictionary format, featuring various keys that can be leveraged to extract pertinent information associated with each entry. Figure 2 provides an initial glimpse into the first entry within `"results"`. The default is to sort the entries by citation count, so this first entry is the Tlili et al.[35] 2023 journal article titled *What if the devil is my guardian angel: ChatGPT as a case study of using chatbots in education*, which was cited over 700 times. This entry furnishes details such as the OpenAlex ID (W4321499901), DOI (10.1186/s40561-023-00237-x), title, publication year, language, publication location, work type, and open-access status (`true`). Recognize that this overview only captures a fraction of the comprehensive information encapsulated within an entry. Additional data encompasses authorship details, countries

JSON format for OpenAlex: `"results"`


```
"id": "https://openalex.org/W4321499901",
"doi": "https://doi.org/10.1186/s40561-023-00237-x",
"title": "What if the devil is my guardian angel: ChatGPT as a case study of
   using chatbots in education",
"display_name": "What if the devil is my guardian angel: ChatGPT as a case study
   of using chatbots in education",
"publication_year": 2023,
"publication_date": "2023-02-22",
"ids": {
  "openalex": "https://openalex.org/W4321499901",
  "doi": "https://doi.org/10.1186/s40561-023-00237-x"
},
"language": "en",
"primary_location": {
  "is_oa": true,
  "landing_page_url": "https://doi.org/10.1186/s40561-023-00237-x",
  "pdf_url": "https://slejournal.springeropen.com/counter/pdf/10.1186/s40561
   -023-00237-x",
  "source": {
    "id": "https://openalex.org/S2494786546",
    "display_name": "Smart Learning Environments",
    "issn_l": "2196-7091",
    "issn": [
      "2196-7091"
    ],
    "is_oa": true,
    "is_in_doaj": true,
    "is_core": true,
    "host_organization": "https://openalex.org/P4310319965",
    "host_organization_name": "Springer Nature",
    "host_organization_lineage": [
      "https://openalex.org/P4310319965"
    ],
    "host_organization_lineage_names": [
      "Springer Nature"
    ],
    "type": "journal"
  },
  "license": "cc-by",
  "license_id": "https://openalex.org/licenses/cc-by",
  "version": "publishedVersion",
  "is_accepted": true,
  "is_published": true
},
"type": "article",
"type_crossref": "journal-article",
"indexed_in": [
  "crossref"
],
"open_access": {
  "is_oa": true,
  "oa_status": "diamond",
  "oa_url": "https://slejournal.springeropen.com/counter/pdf/10.1186/s40561
   -023-00237-x",
  "any_repository_has_fulltext": false
},
```


Figure 2. The JSON format for OpenAlex within the key `"results"` that contains information about OpenAlex ID, DOI, title, publication year, location of the published work, whether it is open access, etc.

involved, affiliated institutions, publishing charges, citation counts and rankings, associated concepts, work locations, optimal open-access repositories, alignment with sustainable development goals, references, abstract content, links to the list of citations, and citation counts per year (since 2012).

This study aims to capture the total number of citation counts and the distribution of citations, which can be readily accessed by appending "&group_by=cited_by_count" to the API URL above, i.e., https://api.openalex.org/works?filter=type:article,language:languages/en,publication_year:2023,authorships.countries:countries/US,authorships.countries:countries/CN,countries_distinct_count:3-&group_by=cited_by_count. Figure 3 shows the API call that now returns the number of articles with a distinct number of citations—there are 4,218 articles with 0 citations, 2,477 articles with 1 citation, 1,496 articles with 2 citations, etc. Extracting the list of distinct citation counts and their frequency for the conditions queried gives ample information to examine the incentive system for global collaboration.

In this study, articles are classified based on the number of countries involved, using the following terminology: "unilateral articles" to denote articles with authors from a single country, "bilateral articles" for those with authors from two countries, and "multilateral articles" for articles with authors from three or more countries. These terms will help streamline the analysis and ensure clarity when discussing the geographical scope of the studies reviewed.

JSON format for OpenAlex citations: `"group_by"`


```
"group_by": [
  {
    "key": "0",
    "key_display_name": "0",
    "count": 4218
  },
  {
    "key": "1",
    "key_display_name": "1",
    "count": 2477
  },
  {
    "key": "2",
    "key_display_name": "2",
    "count": 1907
  },
  {
    "key": "3",
    "key_display_name": "3",
    "count": 1496
  },
  {
    "key": "4",
    "key_display_name": "4",
    "count": 1236
  },
```


Figure 3. The JSON format for OpenAlex within the key `"group_by"` that contains the citation counts for the query, grouped by the number of citations.

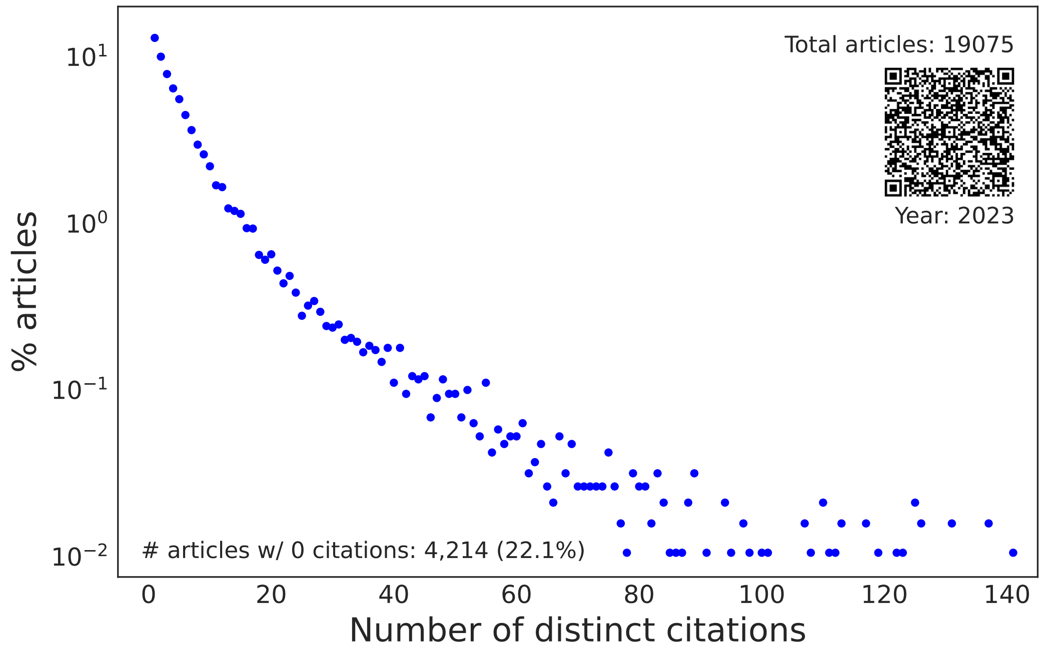
3. Results and Discussion

3.1 Citation Distribution for Global Collaboration

Figure 4 illustrates the citation distributions for multilateral English articles with at least one author from an institution in the United States and at least one author from an institution in China, published in 2019 and 2023. The x-axis represents the number of distinct citations, and the y-axis represents the percentage of articles with that many citations, plotted on a log scale. Figure 4a shows the citation distribution for articles published in 2023, while Figure 4b shows the distribution for articles published in 2019. Both plots exhibit a fat-tailed distribution, which is a distribution that has a long, slowly decaying tail that extends to extreme values. In this case, the tail represents a wide range of citations associated with the lower percentages of articles, often at orders of magnitude lower frequencies than those articles with relatively few citations. This is perhaps more obvious in 2023 because the scale limits were fixed to match between the two plots. The data also shows a zero-inflated distribution, whereby there is a higher percentage of works with zero citations than might be expected or predicted. This is more obvious in 2019, although the log scale makes it more difficult to visualize. Attempts to fit the distributions to simple models were met with varying success, and it was decided to use the mean and median number of citations to capture trends within the citation dynamics for global collaboration.

Table 3 presents a subset of the data collected in this study, focusing on citation distributions and collaboration patterns for a specific year and country criteria. The table includes headings for the year, total number of publications, total number of citations, and various percentiles, such as the median (50th percentile) and the 75th, 90th, 95th, and 99th percentiles. As can be observed, the median is often lower than the mean for the citation distribution, reflecting the large frequencies of publications with low numbers of citations. The table also includes a column for country-level criteria, which indicates the presence or absence of specific countries and the distinct number of countries for each publication. The data is organized into rows that capture publications with different numbers of countries involved, including those with just one country (unilateral), those with exactly two countries (bilateral—either the U.S. and any other country, or CN and any other country), and those with three or more countries (multilateral). This allows comparison of citation rates for publications with different levels of international collaboration, as well as

(a) Citation Distribution: US+CN, 3+ Countries, 2023



(b) Citation Distribution: US+CN, 3+ Countries, 2019

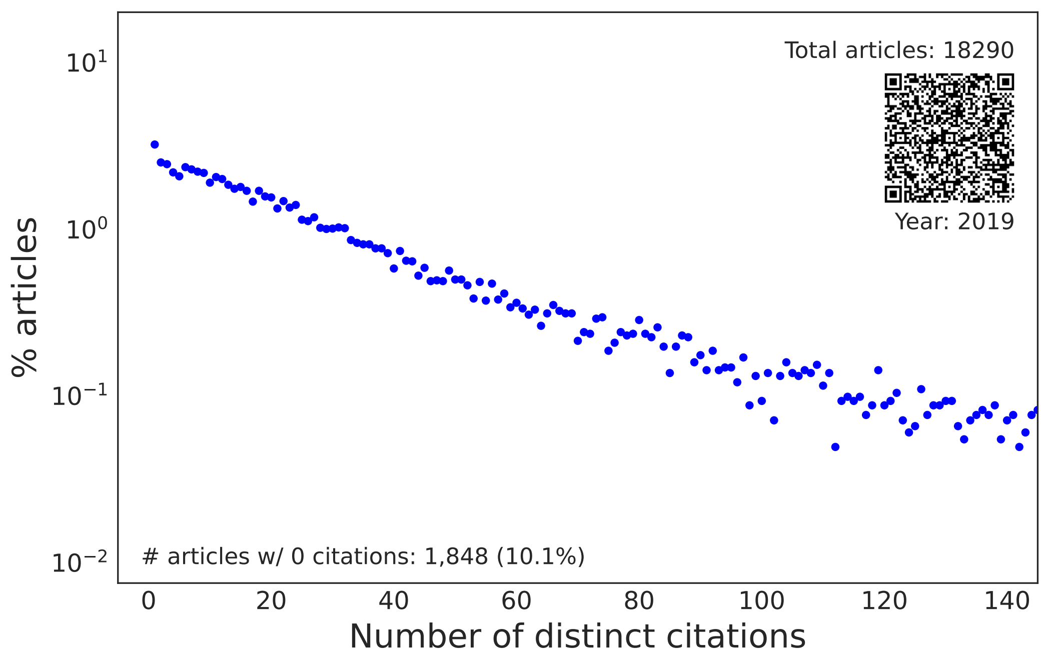


Figure 4. Citation distributions for multilateral English articles with authors from both U.S. and Chinese institutions published in a) 2023 and b) 2019. The x-axis shows the number of distinct citations, and the y-axis shows the percentage of articles with that many citations, plotted on a log scale.

comparisons of incentives for collaboration between specific countries. Overall, Table 3 provides a snapshot of citation patterns and collaboration trends for a specific year and country criteria, and when expanded to many different countries and many different years, it can serve as a foundation for further analysis and interpretation.

Table 3. Overview of publication data for U.S. and CN articles in 1990, including number of articles, number of citations, and citation distribution metrics such as mean, median, and percentiles.

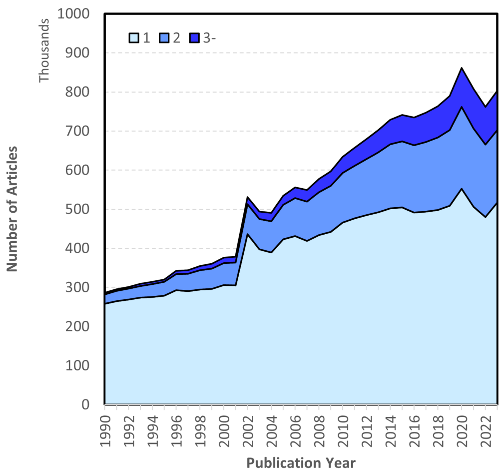
Country	Year	Publications	Citations	Mean	Median	75th	90th	95th	99th
US 1	1990	258544	10752780	41.6	10	36	91	154	442
CN 1	1990	9714	70056	7.2	1	6	19	32	80
US+!CN 2	1990	23164	1147438	49.5	16	44	105	174	515
!US+CN 2	1990	1825	34882	19.1	5	17	44	74	184
US+CN 2	1990	675	20095	29.8	10	29	78	130	254
US+!CN 3	1990	3429	181013	52.8	17	47	114	188	587
!US+CN 3	1990	250	6147	24.6	6.5	30	60	87	186
US+CN 3	1990	204	7772	38.1	13	38	93	123	370

3.2 Frequency and Citation Distribution for Global Collaboration

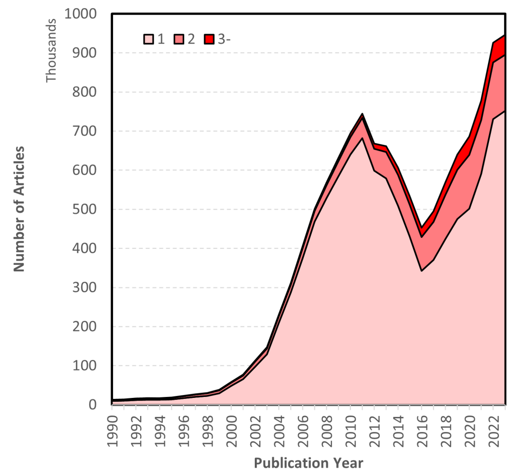
Figure 5 illustrates the frequency of articles over time for both the United States and China. The upper set of plots (Figures 5a and 5b) displays the number of articles as a function of the publication year. Different shades of colors represent unilateral, bilateral, and multilateral articles (bottom to top, respectively). This highlights the increase in articles involving more than one country, indicating a rise in global collaboration, particularly evident for the United States. China's growth in the number of articles is notable, with a rapid increase in publications per year until 2011, followed by a sharp decrease, and then another rapid increase.

The lower set of plots (Figures 5c and 5d) shows the number of articles as a percentage of the total number for each year. For the United States, this clearly demonstrates an increase in the percentage of bilateral and multilateral articles over time, rising from approximately 10% in 1990 to over 30% in recent years. For China, there is not a clear trend except for the observation that during the first peak, there was an increase in the percentage of articles published solely by Chinese institutions. After 2016, the percentage of bilateral and multilateral articles has remained approximately between 20%–25%.

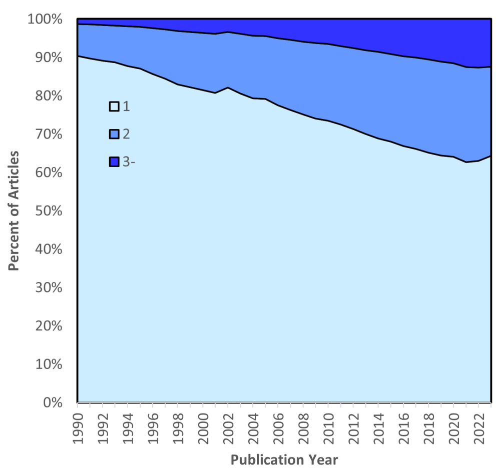
Figure 6 illustrates the number of citations accrued each year for unilateral, bilateral, and multilateral articles within the United States and China. Similar to Fig-



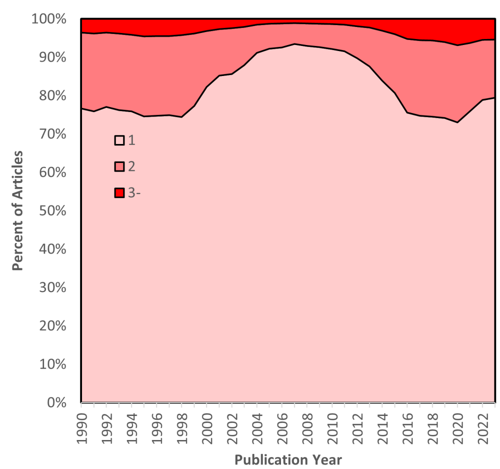
(a) U.S.



(b) CN



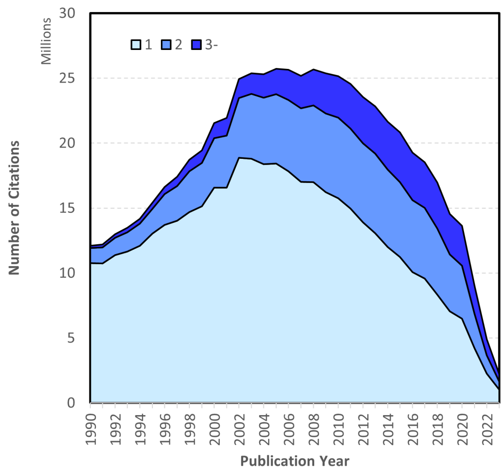
(c) U.S.



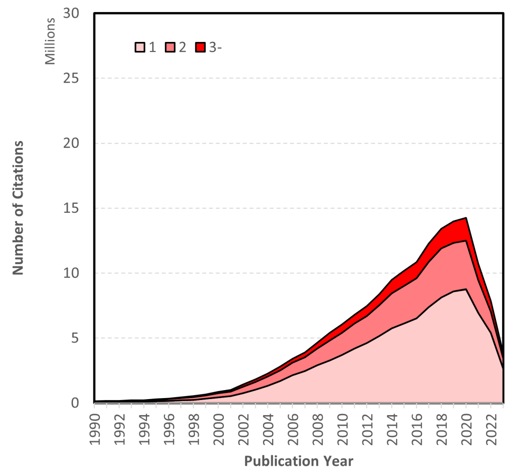
(d) CN

Figure 5. Number and percentage of unilateral, bilateral, and multilateral articles published over time for the United States and China. The upper plots (a, b) display total article counts of articles by publication year, while the lower plots (c, d) show the corresponding percentages each year.

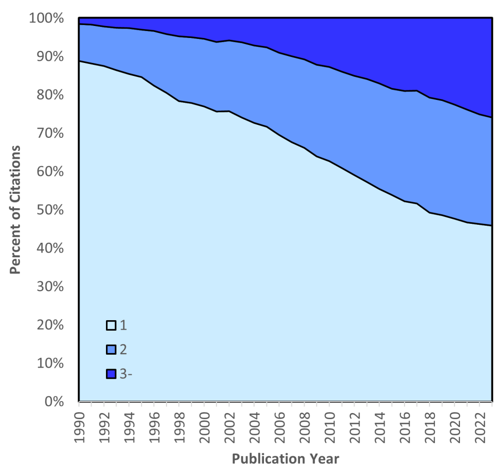
ure 6, different shades of colors represent unilateral, bilateral, and multilateral articles. The top two plots display the number of citations accrued over time, while the bottom two plots show the percent of citations as a function of the publication year.



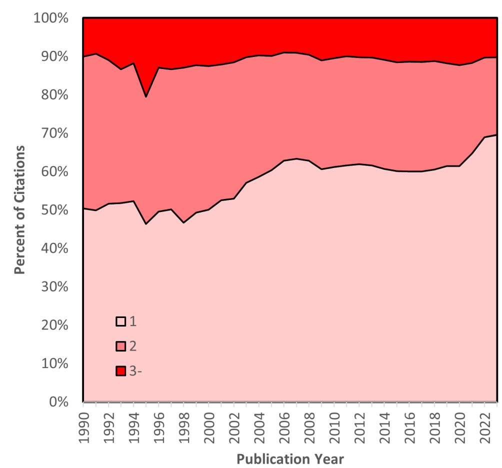
(a) U.S.



(b) CN



(c) U.S.



(d) CN

Figure 6. Number and percentage of citations of unilateral, bilateral, and multilateral articles published over time for the United States and China. The upper plots (a, b) display total citation counts of single/multi-country articles by publication year, while the lower plots (c, d) show the corresponding percentage of citations each year.

For the United States, the number of citations increases until around 2002 and remains steady until approximately 2010, after which there is a marked decrease in the total number of citations. In contrast, China shows an increasing number of citations until around 2019, followed by a marked decrease. This decrease can be partly attributed to the time required for articles to accrue citations, which may take multiple years.

In terms of the percent of citations per publication year, the United States demonstrates an increase from approximately 10% of their citations being from bilateral and multilateral collaborative articles in 1990 to over 50% in recent years. In contrast, China shows a nearly decreasing percentage of citations coming from bilateral and multilateral articles.

Interestingly, the period with a higher percentage of unilateral articles in China also corresponds to a median citation count of zero citations per article. While the total number of citations accrued increased steadily during this period, this growth was primarily driven by the large volume of articles, with a small number of articles contributing disproportionately to the total citations. Given that the median citation count is zero, the mean citation is heavily influenced by the upper end of the distribution. Despite the decrease in the percentage of bilateral and multilateral articles over this time, these articles still accounted for a substantial percentage ($\tilde{4}0\%$) of the citations for China's articles during these years. This indicates that the increase in unilateral articles did not result in a corresponding proportional increase in the percentage of citations for those articles.

This phenomenon may reflect a citation penalty for countries that do not collaborate as much globally. Countries focusing on unilateral articles may struggle to attract citations from the global research community, resulting in limited international visibility. From a network perspective, this can create a "small world" effect, where the research is primarily cited within a narrow network of local or regional scholars, without broader global attention. For most countries, this would likely lead to very low citation counts. However, for China, which now produces a significant share of global research, this is less of an issue. China's extensive publication output, combined with its high self-citation rate—the highest of any country from 2020 to 2022[25,26]—allows it to maintain citation visibility even without widespread international collaboration. In essence, China has created its own reinforcing network of citations, mitigating any lack of global engagement.

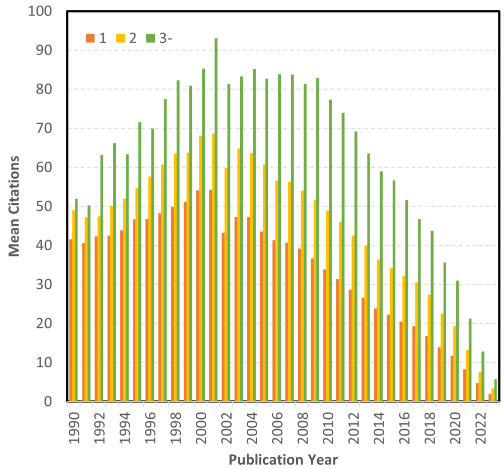
3.3 Evolution of Citation Distribution

Figure 7 illustrates the evolution of the publication and citation landscape by plotting the mean citations per article against the publication year. The top two plots display the mean citations for articles with authors from unilateral, bilateral, and multilateral collaborations for the U.S. (left) and China (right). A key observation is that bilateral/multilateral articles consistently receive more citations than unilateral articles, with multilateral collaborations yielding higher mean citations than bilateral collaborations.

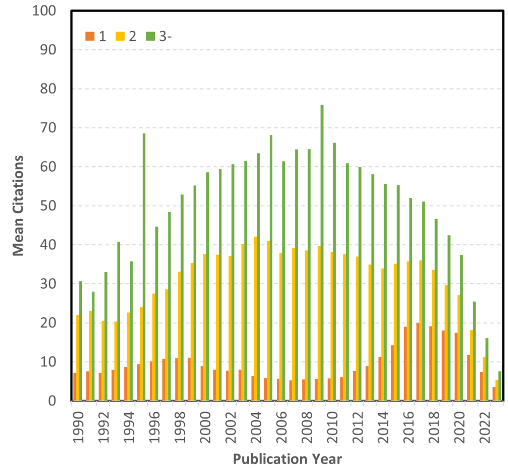
The bottom two plots show the percentage increase in mean citations for bilateral and multilateral articles compared to unilateral articles. To facilitate direct comparison between the U.S. and China, the Y-axes for each pair of plots are scaled equivalently. The most striking trend is the significant percentage increase in citations for bilateral and multilateral articles in China, where the increase can exceed 1000%. This dramatic rise is partly due to the initially low mean citations for unilateral articles authored by Chinese institutions (often under 10 citations), which amplifies the percentage change. To highlight the upward trend in citation increases for the U.S., an inset plot is included, revealing a gradual rise over time in the percent increase in mean citations for bilateral and multilateral articles.

The median citation for each publication year provides an alternative way to examine the central tendency of citation distributions, reducing the influence of outliers (e.g., articles with exceptionally high citations or many zero-citation articles). Figure 8 presents similar plots to Figure 7, but uses the median citation instead of the mean. For the U.S., the trends for median and mean citations are generally consistent. However, for China, the median citation for unilateral articles was zero for over a decade in the early 2000s, making it impossible to calculate a meaningful percent increase for bilateral and multilateral articles during this period.

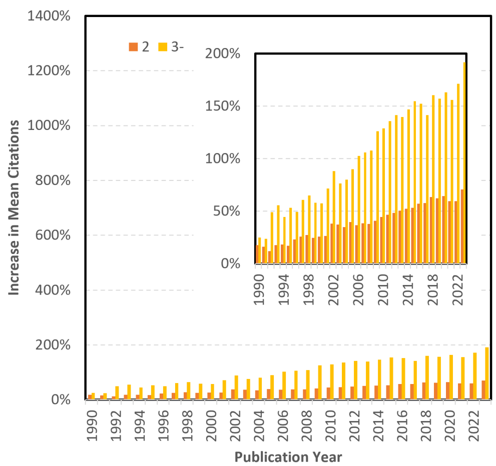
In the years before and after this period, China shows an extraordinary rise in the percent increase in median citations for bilateral and multilateral articles, reaching increases of over 2000%. However, in the last decade, this increase has slowed and even dipped below the U.S. levels, partly due to a rise in median citations for unilateral articles in China. This shift is likely influenced by the growing role of self-citations within China during this period.



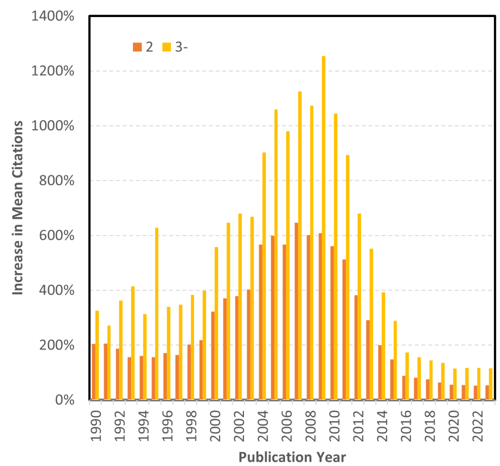
(a) U.S.



(b) CN

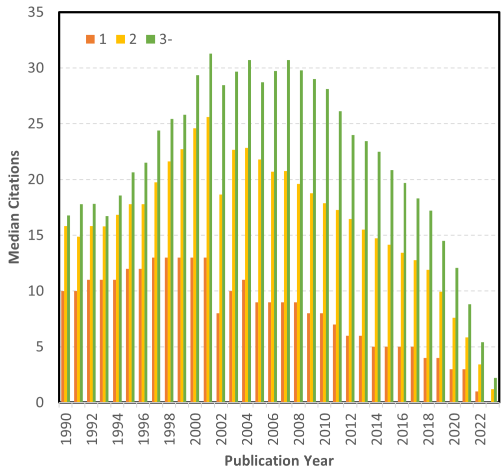


(c) U.S.

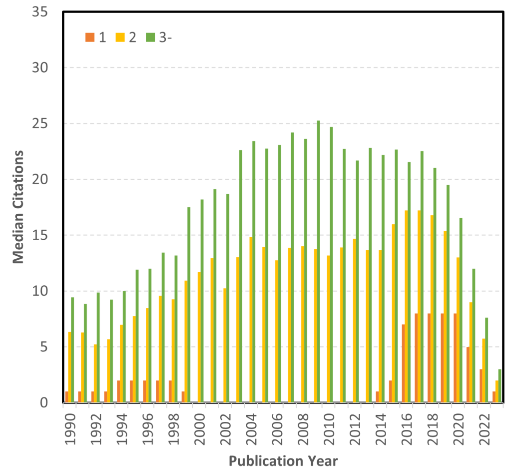


(d) CN

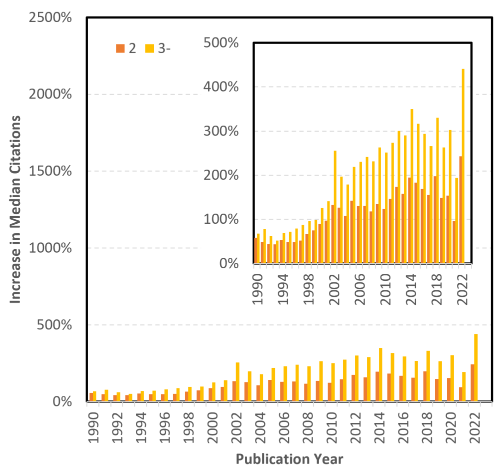
Figure 7. Mean citations per article by publication year for unilateral, bilateral, and multilateral collaborations. The top two plots show the mean citations for articles from the United States (left) and China (right). The bottom two plots display the percentage increase in mean citations for bilateral and multilateral articles relative to unilateral articles. The Y-axes for the plots are scaled equivalently for direct comparison between the U.S. and China. An inset plot for the U.S. highlights the trend in the percent increase over time.



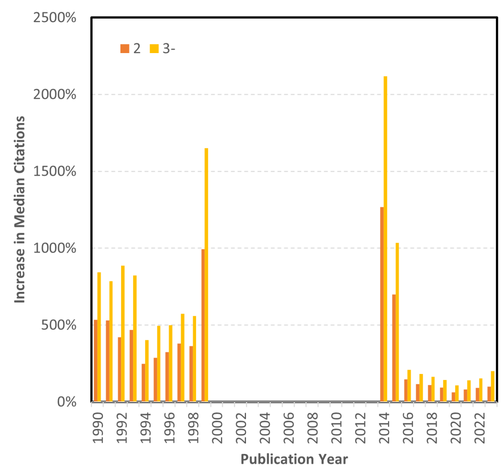
(a) U.S.



(b) CN



(c) U.S.



(d) CN

Figure 8. Median citations per article by publication year for unilateral, bilateral, and multi-lateral collaborations. The top two plots show the median citations for articles from the U.S. (left) and China (right). The bottom two plots display the percentage increase in median citations forbilateral and multilateral articles relative to unilateral articles. The Y-axes for the plots are scaled equivalently for direct comparison between the U.S. and China. An inset plot for the U.S. highlights the trend in the percent increase over time.

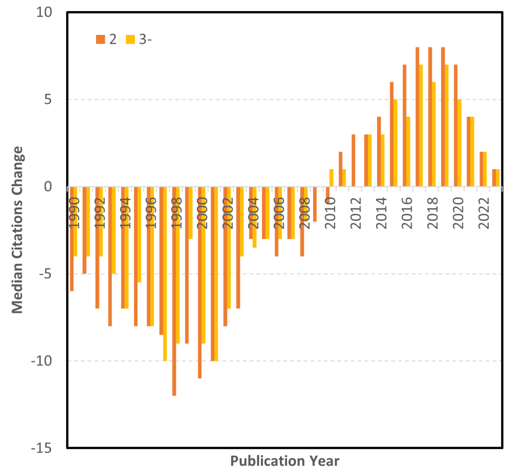
3.4 Relative Citation Incentive for Collaboration: CN

Up to this point, the analysis has not considered the role of collaboration between specific countries. Now, bilateral collaborative articles are categorized into three groups: the U.S. with China, the U.S. without China, and China without the U.S. Similarly, multilateral articles can be divided into these same categories. This breakdown explores the incentives for collaboration between the U.S. and China, as well as the reverse.

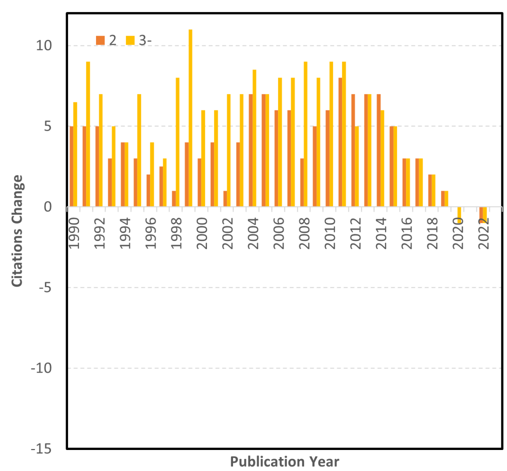
To better understand the dynamics of international research collaborations, this report examines two distinct measures of citation incentives: the “Relative Citation Incentive” and the “Comparative Citation Incentive.” The Relative Citation Incentive captures the citation advantage of bilateral or multilateral articles relative to unilateral articles produced by a given country. This metric provides insight into the added value of collaboration compared to publishing independently. On the other hand, the Comparative Citation Incentive evaluates the difference in citation increases when a country collaborates with one partner versus all other potential partners, whether bilaterally or multilaterally. This measure highlights how collaboration with specific partners impacts citation performance relative to other possible partnerships. Together, these metrics offer a comprehensive view of the benefits and dynamics of scientific collaborations across countries, enabling a deeper understanding of their relative and comparative advantages. The Relative Citation Incentive will be explored first.

Figure 9 shows the change in median citations for U.S. articles coauthored with China, and for Chinese articles coauthored with the U.S. Both bilateral and multilateral collaborations are included, and the trends are generally consistent in terms of magnitude and direction (positive or negative) over time. For the United States, collaborations with China prior to 2010 resulted in lower citations compared to collaborations with other countries. However, after 2010, there is a clear positive shift, with U.S.–China collaborations receiving higher citations. In contrast, China has experienced a positive citation increase (positive relative citation incentive) when collaborating with the U.S., although this trend has weakened in recent years.

Now that the relative citation incentive has been computed from both the U.S. and China perspectives over the period from 1990 to 2023, these values can be plotted within a two-dimensional space, as shown in Figure 10 for bilateral articles. In this



(a) U.S.



(b) CN

Figure 9. Median citation change as a function of publication year for (a) U.S. articles coauthored with China and (b) Chinese articles coauthored with the U.S. Trends are shown for both bilateral and multilateral collaborations, with changes in citation counts for each group over time.

plot, the horizontal axis represents the incentive for the U.S. to collaborate with CN relative to publishing independently (U.S. unilateral article), while the vertical axis represents the incentive for China to collaborate with the U.S. relative to publishing independently (CN unilateral article).

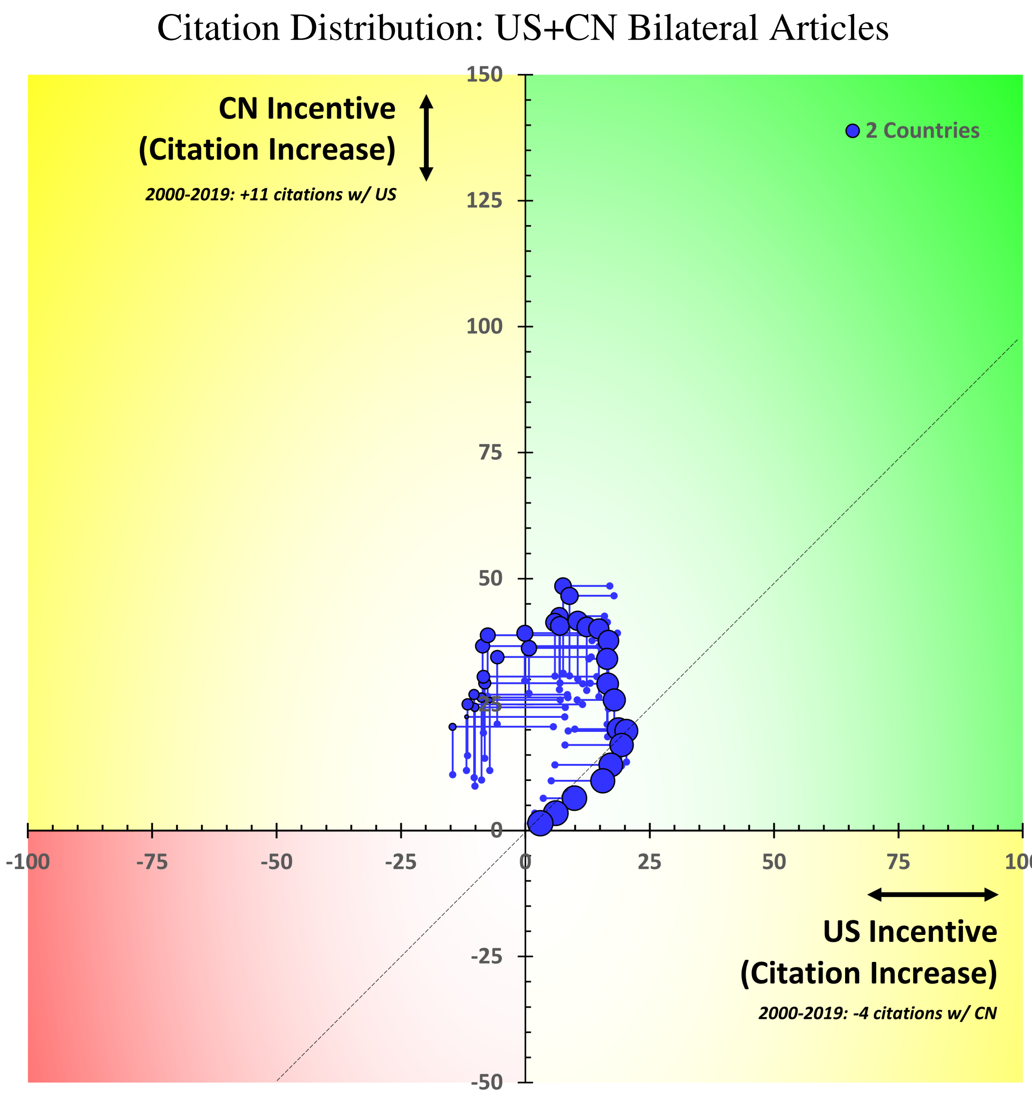


Figure 10. Relative citation incentives for bilateral articles co-authored by the U.S. and China (1990–2023). The horizontal axis represents the incentive for the U.S. to collaborate with China relative to U.S. unilateral articles, while the vertical axis represents the incentive for China to collaborate with the U.S. relative to CN unilateral articles. Colors indicate regions of mutual incentive (green), one-sided incentive (yellow), and mutual disincentive (red), and the 45° dotted line denotes symmetry in incentives between the two countries. Data points represent single publication years, with circle size increasing for more recent years. Vertical and horizontal lines show the incentive for each country to collaborate with partners other than the other country.

The plot is divided into quadrants, with the colors providing additional context: the green region indicates mutual incentive for collaboration (positive for both countries or win–win scenario), the yellow regions represent a one-sided incentive (positive for only one country or win–lose scenario), and the red region indicates a disincentive for both countries (lose–lose scenario). The dotted 45° line is a symmetrical boundary for equal relative citation incentive, showing points where the incentives (or disincentives) are equal for both countries. Points shifted away from this line indicate an asymmetry in incentives, where one country benefits more from collaboration than the other.

Notably, from 2000 to 2019, articles co-authored with the U.S. contributed to an average increase of 11 citations for China. Conversely, U.S. articles co-authored with China experienced an average decrease of four citations, demonstrating an imbalance in relative citation incentives between the two countries.

Each data point in the plot represents articles from a single publication year between 1990 and 2023, with the size of the circles increasing to indicate more recent publication years. The comparative citation incentives for bilateral articles without the other country are shown as smaller data points connected to the main points (relative citation incentives) by vertical and horizontal lines. The direction and magnitude of these lines denote the comparative citation incentive, i.e., citation incentive compared to other countries.

Vertical lines extending in the positive direction (upward) from a data point indicate that there is an incentive for China to collaborate with partners other than the United States in bilateral articles—this is not observed over the 30 years shown here. Similarly, horizontal lines extending in the positive direction (right) indicate an incentive for the U.S. to collaborate with partners other than China in bilateral articles—this is observed for some years. These connections provide additional insight into the relative benefits of collaboration and highlight asymmetries in the citation incentives for the two countries over time.

Interpreting the plot reveals a notable shift in the relative citation incentive for the United States, moving from negative to positive over time. In fact, the trajectory could be described as a quadratic-like arc or, in more colloquial terms, horseshoe-like. Notably, one edge of this horseshoe aligns closely with the 45° line, indicating a balance in citation gains between the two countries during the latter years of this dataset. In the early years of the dataset (the 1990s), bilateral collaborations with China resulted in fewer citations for the U.S. compared to publishing independently, as indicated by the points in the negative relative citation incentive quadrant (yellow). Additionally, the comparative citation incentives extend in the positive direction (to the right of the data points), indicating that bilateral articles with other countries garnered more citations than those with China. However, in more recent years, the comparative citation incentives extend in the negative direction (to the left) showing that collaborating with China on bilateral articles has garnered more citations for the U.S. than articles with all other countries.

From China's perspective, the comparative citation incentives pointing in the negative direction (down) throughout the dataset indicate a consistent incentive for China to collaborate with the U.S. on bilateral articles. However, in recent years, the length of these lines suggests that the incentive for the U.S. to collaborate with China has grown larger than the incentive for China to collaborate with the U.S., in part due to the large number of self-citations within CN for their unilateral articles.

The convergence of data points toward the dotted 45° line for more recent publication years indicates a near-equal increase in relative citation incentives for both countries in these collaborations, suggesting a more symmetric relationship. However, as these articles continue to accrue citations, the data points may shift further, potentially reflecting greater asymmetry in the citation benefits from each country's perspective.

Building on the analysis presented in Figure 10, Figure 11 extends the comparison to multilateral articles. While the structure of the plot remains the same, key differences emerge in the dynamics of citation incentives. For the period 2000–2019, China experienced a significant average increase of 23 citations when collaborating with the U.S., whereas the U.S. saw no net change in citations (0 citations gained or lost). As with the bilateral collaborations, the comparative citation incentive lines extending in the negative direction indicate a consistent incentive for China to collaborate with the U.S., but in multilateral collaborations, the longer length of these lines suggests an even greater benefit for China. Comparative citation incentive lines extending in the negative direction reveal that in more recent years, the U.S. sees a relative citation incentive to collaborate with China on multilateral articles compared to multilateral articles without China. However, the shorter length of these comparative citation incentive lines (horizontal) compared to Figure 10 suggests that the incentive for the U.S. is less pronounced in multilateral collaborations. Notably, data points for more recent publication years continue to converge toward the 45° line, indicating a trend toward increasing symmetry in the citation benefits for both countries in multilateral collaborations. This highlights the evolving nature of international research dynamics as the scope of collaborations expands.

3.5 Relative Citation Incentive for Collaboration: Top Countries

This subsection extends the analysis to the top six publishing countries from 2010 to 2019. Figure 12 presents a clipped region of interest from bilateral collaboration incentive plots, similar to Figure 10, for these six countries. The clipped regions are identical in dimensions across countries to facilitate direct comparison. The countries are ordered by their number of unilateral articles during this time period: China (CN), Great Britain (GB), Germany (DE), Japan (JP), France (FR), and India (IN).

China's trajectory over this 30-year span is notably distinct from the other countries. Great Britain, Germany, and France exhibit similar trajectories along the 45° line of equal relative citation incentive, with a slight tilt toward their own incentive axis, indicating marginally higher citation incentives for these countries compared to the U.S. This deviation, however, is far less pronounced than that observed for Japan and India, whose trajectories diverge substantially from the 45° line. India's trajectory, in particular, reveals significant asymmetry: the citation incentive for the U.S. is minimal compared to the incentive for India. The horizontal lines indicating the comparative citation incentive predominantly point to the right, suggesting that bilateral articles between the U.S. and other countries yield considerably higher citation incentives than those involving India or Japan.

Figure 13 presents a similar plot with regions of interest derived from the multilateral article trajectories over time for the top publishing countries. Similar trends are observed, though China's trajectory again stands out as somewhat distinct in its pattern, showing the quadratic horseshoe-like arc. Interestingly, while the horseshoe pattern is visible for other countries, it appears more compressed—maintaining a similar length along the trajectory but with a noticeably narrower width. For most countries, the relative citation incentives generally align with the 45° line, though some deviations are apparent in the earlier years of the dataset, favoring the coun-

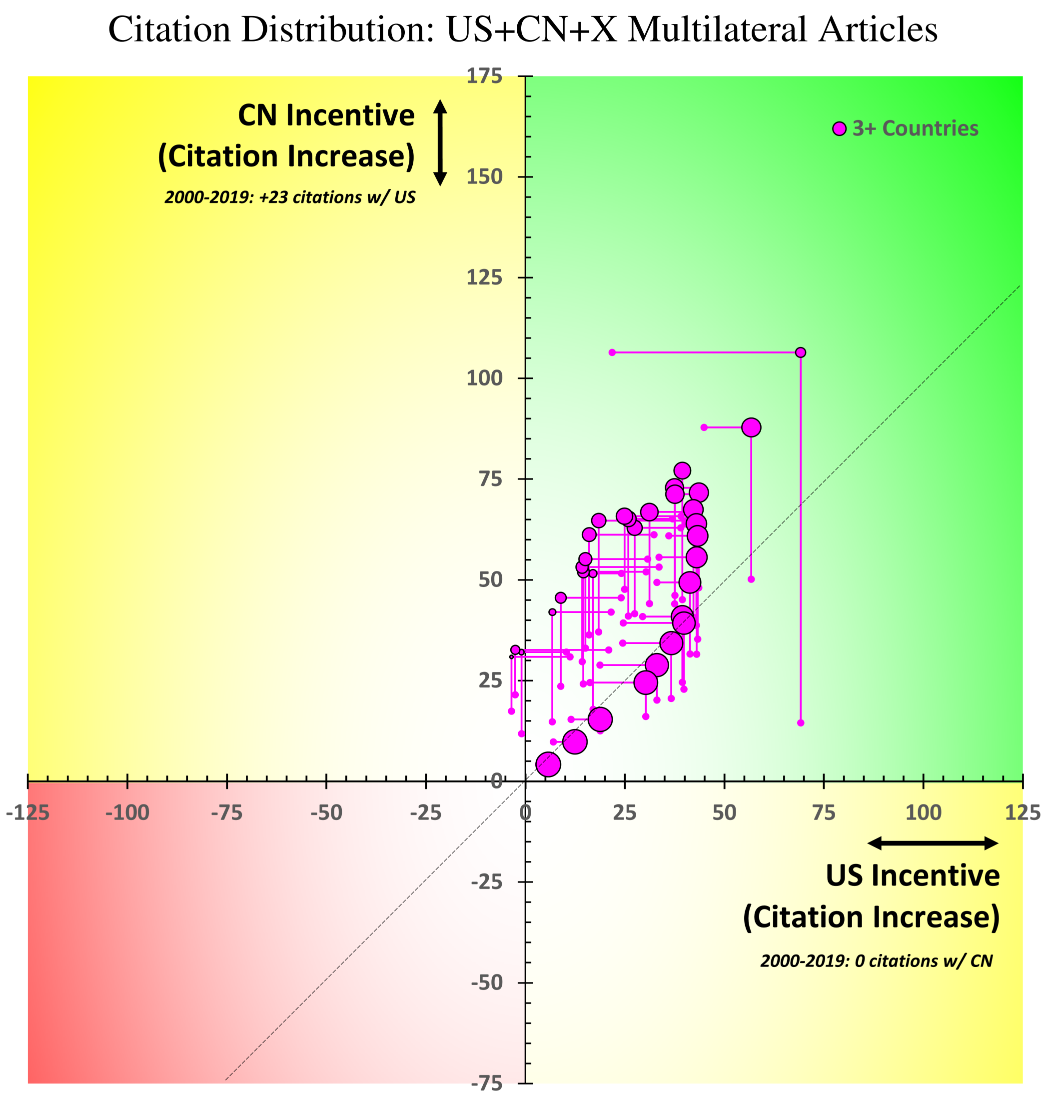


Figure 11. Citation incentives for multilateral articles co-authored by the U.S. and China (1990–2023). The horizontal axis represents the incentive for the U.S. to collaborate with China compared to other countries, while the vertical axis represents the incentive for China to collaborate with the U.S., consistent with definitions in Figure 10. Colors indicate regions of mutual incentive (green), one-sided incentive (yellow), and mutual disincentive (red), and the 45° dotted line denotes symmetry in incentives between the two countries. Data points represent single publication years, with circle size increasing for more recent years. Vertical and horizontal lines show the incentive for each country to collaborate with partners other than the other country.

U.S. Bilateral Collaboration Incentives

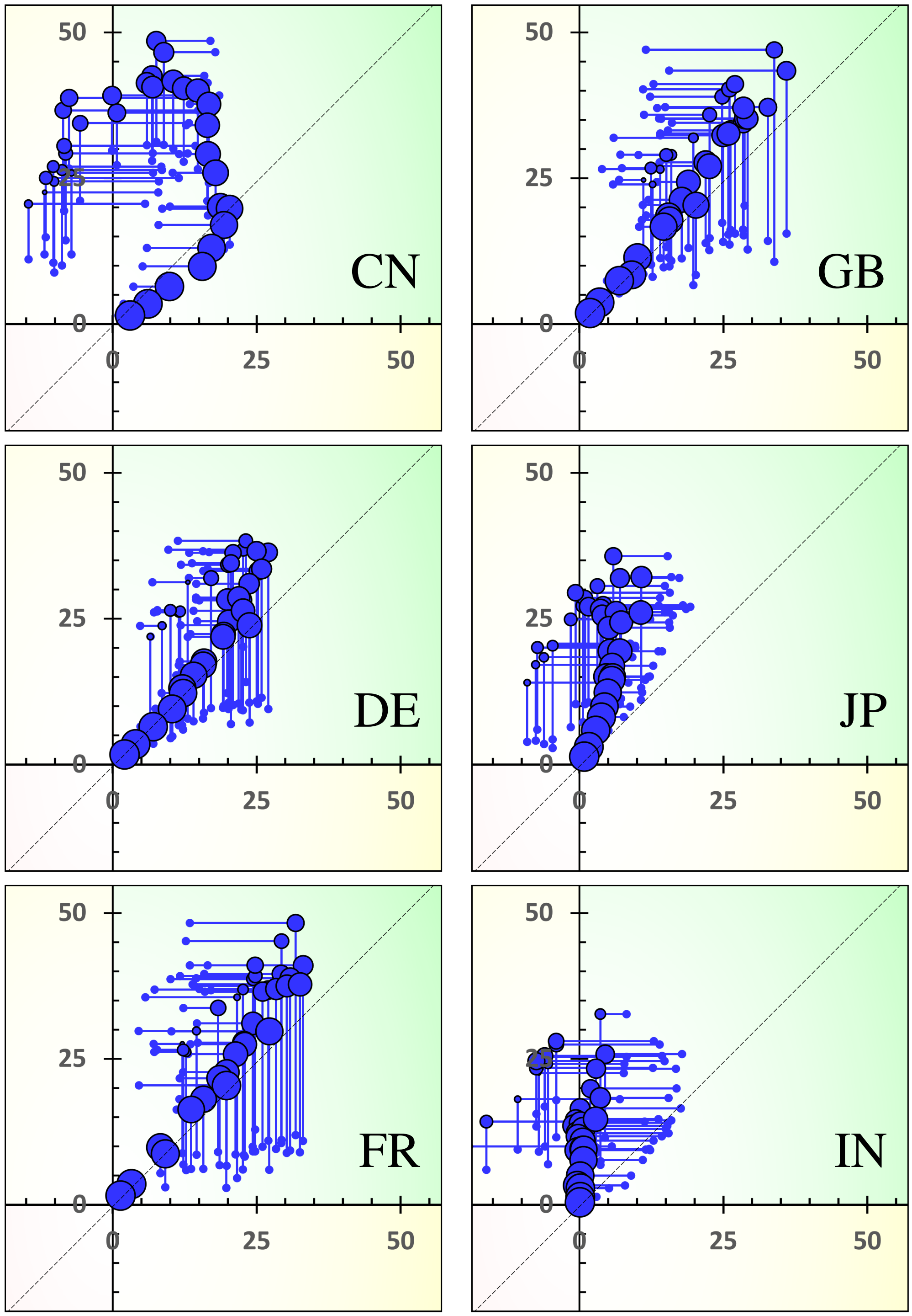


Figure 12. Bilateral article citation incentives for the top six countries (after U.S.) with the highest number of English articles (2010–2019), i.e., CN, GB, DE, JP, FR, IN (order of decreasing articles). The clipping shows the region of interest from Figure 10, zooming in on the citation data for these countries. The horizontal axis represents the incentive for the U.S., while the vertical axis shows the incentive for each country.

tries collaborating with the United States.

When compared with the bilateral article citation incentives shown in Figure 12, many of the trajectories appear similar, with most clustering closer to the 45° equal relative citation incentive line. Notably, this clustering suggests a gradual balancing of citation incentives across countries in multilateral articles. The relative citation incentive for the U.S. in collaborations with Japan and India is shifted toward the 45° equal relative citation incentive line, indicating that including these countries in multilateral articles with the U.S. often results in nearly equal incentives compared to unilateral articles. The shift in the direction of the comparative citation incentives indicates that their inclusion in multilateral articles with the U.S. garners higher citation counts than those multilateral articles that exclude them.

The significance of this plot lies in demonstrating the strong incentives for top publishing countries to collaborate with the U.S. (and each other) in multilateral articles. Since the citation incentives for multilateral articles are more evenly distributed across countries, fostering a cooperative environment where no single country gains a disproportionate advantage over the others. This balanced distribution reduces the competitive dynamic that often exists in bilateral collaborations, where one country may dominate the incentive structure. By collaborating with multiple partners, countries are incentivized to contribute to a collective effort, rather than pursuing individual advantages. This balance creates a powerful incentive for cooperation, as all parties involved benefit more equally, aligning their interests toward shared scientific goals and reducing the risks of imbalanced competition in citation rewards.

3.6 Comparative Citation Incentive for Collaboration: CN

The previous plots measured relative citation incentive comparing with a country's unilateral articles, i.e., Figures 10–13 in Sections 3.4 and 3.5 address this by illustrating the increase in citations for the U.S. and other countries from unilateral articles published by each nation. For example, when the U.S. collaborates with China on bilateral articles, there is a corresponding increase in citations compared to articles that either country publishes independently. However, this approach does not fully capture how bilateral and multilateral collaborations compare to similar articles involving other countries. To better understand the impact of such collaborations, it is useful to compare whether the citation increase from collaborations

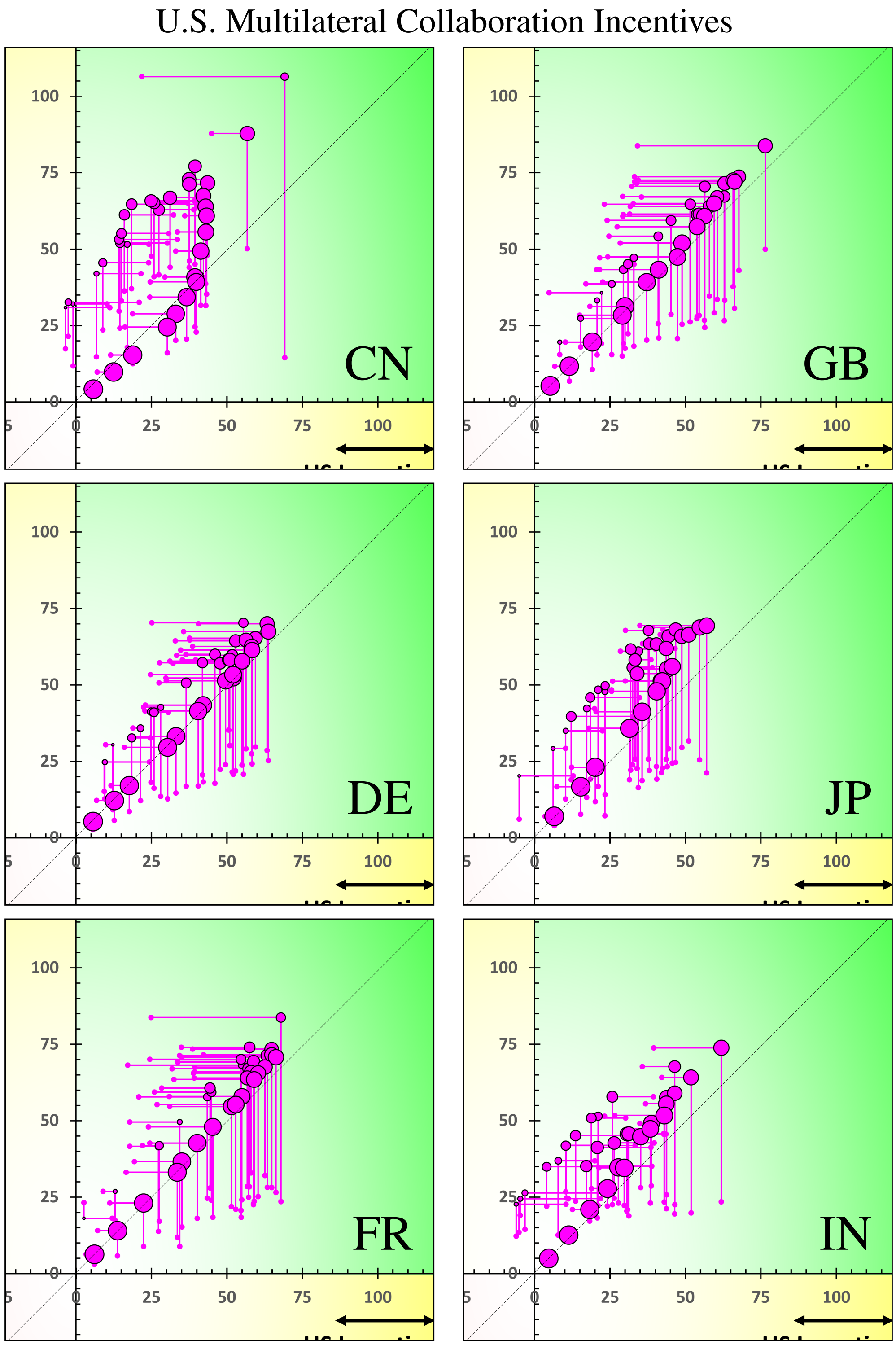


Figure 13. Multilateral article citation incentives for the top six countries (after U.S.) with the highest number of English articles (2010–2019), i.e., CN, GB, DE, JP, FR, IN (order of decreasing articles). The clipping shows the region of interest from Figure 11, zooming in on the citation data for these countries. The horizontal axis represents the incentive for the U.S., while the vertical axis shows the incentive for each country.

with China exceeds or falls short of the increase from collaborations with other countries.

The following introduces a comparative citation incentive analysis that focuses on the difference in citation increases between a particular country and all other countries for bilateral or multilateral articles. By exploring this comparative citation incentive for several top publishing countries over three decades (1990–2019), these figures provide deeper insight into the relative benefits of collaboration and reveal patterns in the global collaboration citation economy. This metric is important because it highlights trends in the evolving landscape of global scientific collaboration, offering a framework to understand the drivers behind increased international partnerships, particularly with certain countries.

Figure 14 is a spider (radar) plot that depicts the citation incentive for the U.S. to collaborate with various countries from 2010 to 2019, measured by the net citation impact of these collaborations over similar bi-/multilateral collaborations without that country. Each axis corresponds to a specific partner country, with the radial scale indicating the total number of articles in decreasing order over this time span (clockwise: CN is highest, NL is lowest). Positive values represent a net citation gain for the U.S. through collaboration (shaded in green), while negative values indicate a citation loss (shaded in red). The figure distinguishes between two types of collaborations: bilateral collaborations, shown with a blue line (representing articles involving the U.S. and one other country), and multilateral collaborations, shown with a red line (representing articles involving the U.S. and at least two other countries).

Countries closer to the center of the plot (with negative or smaller values) reflect a citation disincentive for the U.S. to collaborate with those partners, whereas countries further outward demonstrate higher citation incentives. The European countries (GB, DE, IT, ES, FR, NL), Canada (CA), and Australia (AU) stand out as providing the most significant citation benefit for the U.S. across both bilateral and multilateral collaborations, highlighting their key role as collaborators during this time period. China (CN) has a positive incentive for both bilateral and multilateral articles, although the net citation impact in multilateral articles in not as high as with other countries (allies). In contrast, countries such as Brazil (BR), Indonesia (ID), Russia (RU), Japan (JP), and India (IN) display negative citation incentives for bi-

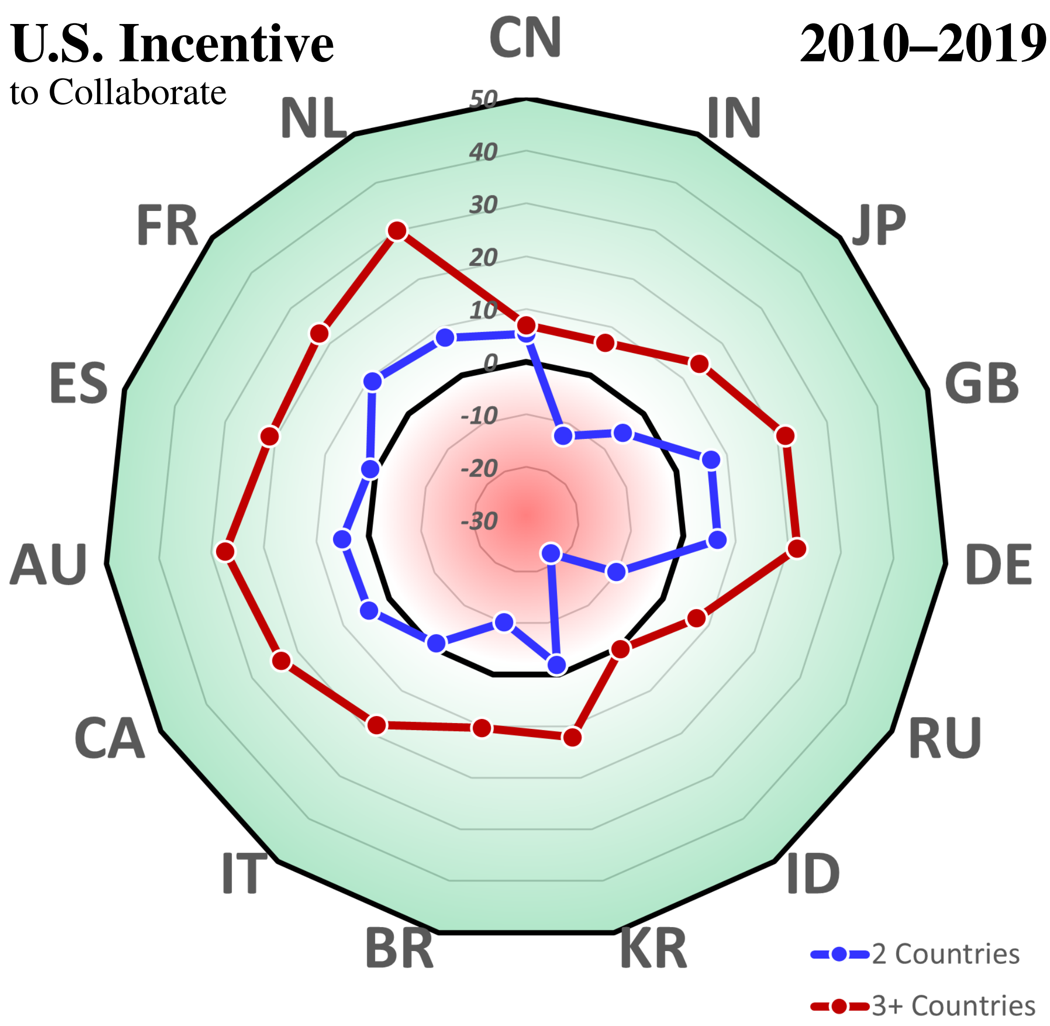


Figure 14. Radar plot showing the citation incentive for the U.S. to collaborate with various countries from 2010 to 2019. Each axis represents a partner country, with positive values indicating a citation gain and negative values indicating a citation loss for the U.S. The blue line denotes bilateral collaborations (two-country articles), while the red line represents multilateral collaborations (articles involving three or more countries).

lateral articles, and lower incentives for multilateral articles. The differences in the blue and red lines emphasize how the scale of collaboration—whether bilateral or multilateral—affects the citation outcomes for the U.S. with different international partners. This figure offers a large-scale perspective of specific international scientific collaborations from the U.S.'s standpoint.

The significant variation in citation incentives across different countries raises questions about the factors driving these disparities. For bilateral articles, this could potentially be explained by the researchers within the collaborating country and their ability to garner citations. However, for multilateral articles, one might expect that adding more countries would reduce the inequities in citation incentives by balancing contributions and impact. Interestingly, the data reveals that this is not necessarily the case; in fact, the diversity in citation incentives appears to be equal to or even greater for articles involving three or more countries.

A potential explanation lies in the identity of the additional countries involved. Analyzing the most frequent third country for each U.S.-country pair in multilateral articles reveals that the United Kingdom of Great Britain and Northern Ireland (GB) commonly plays this role, with a few notable exceptions. For instance, when the U.S. collaborates with South Korea (KR), China (CN) is the most frequent third country; for U.S. collaborations with Russia (RU), Germany (DE) is most often the third country; for U.S. and Indonesia (ID), Australia (AU) frequently joins as the third partner; and in the U.S.–United Kingdom partnership, Germany (DE) is the most frequent third country. These variations suggest that the composition of the multilateral collaboration network can vary, but the recurring presence of certain countries like the United Kingdom indicates that the third partner may not always be fundamentally different in their ability to influence citations. This observation points to the possibility that additional factors, beyond the identity of the third country, are driving the observed differences in citation incentives. These could include differences in research focus, institutional prestige, or even geopolitical and historical collaboration patterns.

Another important question is how the recent surge in publications from China between 2020 and 2024 has influenced the landscape of multilateral articles. From the U.S. perspective, the impact appears to be minimal. Across all the U.S.-country pairs analyzed in Figure 14, only one exhibited a shift in the most frequent third country. Specifically, for U.S. collaborations with Indonesia (ID) on multilateral articles, the most common third partner is now the United Kingdom, replacing Australia (AU). Notably, this shift was not to China, despite its rising publication dominance during this period, indicating that the dynamics of partner changes in multilateral partnerships involving the U.S. occurs rather slowly.

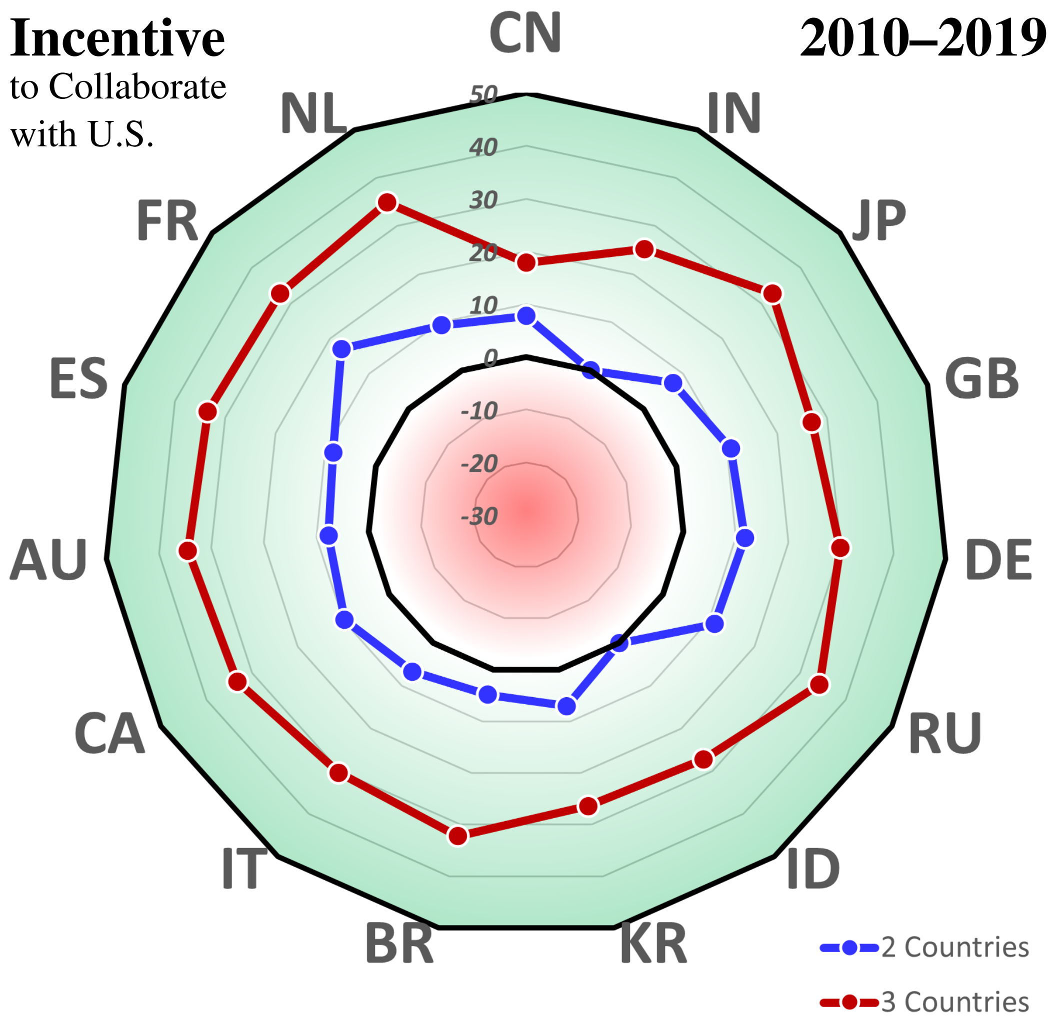


Figure 15. Radar plot showing the citation incentive for various countries to collaborate with the U.S. from 2010 to 2019. Each axis represents a partner country, with positive values indicating a citation gain and negative values indicating a citation loss for that country. The blue line denotes bilateral collaborations (two-country articles), while the red line represents multilateral collaborations (articles involving three or more countries).

3.7 Comparative Citation Incentive for Collaboration: Multiple Countries

Figure 15 presents a spider plot illustrating the citation incentive for various countries to collaborate with the U.S. from 2010 to 2019. This incentive is measured by the net citation impact of collaborations involving the U.S., compared to similar bilateral and multilateral collaborations without the U.S. Each axis represents a different country, with the radial scale showing the total number of articles produced over this time period, as described in Figure 14. All other aspects of this plot are consistent with those in Figure 14. Notably, the plot reveals that all countries show a positive citation incentive, meaning that both bilateral and multilateral collaborations involving the U.S. tend to result in higher citation rates. The countries with the lowest incentives for bilateral collaborations are Indonesia (ID) and India (IN), while China exhibits the lowest incentive for multilateral collaborations.

Countries closer to the center of the plot (with negative or smaller values) reflect a citation disincentive for the U.S. to collaborate with those partners, whereas countries further outward demonstrate higher citation incentives. The European countries (GB, DE, IT, ES, FR, NL), Canada (CA), and Australia (AU) stand out as providing the most significant citation benefit for the U.S. across both bilateral and multilateral collaborations, highlighting their key role as a collaborator during this time period. China (CN) has a positive incentive for both bilateral and multilateral articles, although the net citation impact in multilateral articles in not as high as with other countries (allies). In contrast, countries such as Brazil (BR), Indonesia (ID), Russia (RU), Japan (JP), and India (IN) display negative citation incentives for bilateral articles, and lower incentives for multilateral articles. The differences in the blue and red lines emphasize how the scale of collaboration—whether bilateral or multilateral—affects the citation outcomes for the U.S. with different international partners. This figure offers a broad perspective of specific international scientific collaborations from the U.S.'s standpoint.

Combining the insights from the previous plots and examining trends over time, Figure 16 shows the evolution of these spider plots across three decades: 1990–1999, 2000–2009, and 2010–2019 (top to bottom, respectively). On the left, the U.S. citation incentive is shown, while the right side displays the citation incentive for various countries to collaborate with the U.S. The countries are ordered around the spider plot based on their publication count during the 2010–2019 period, as

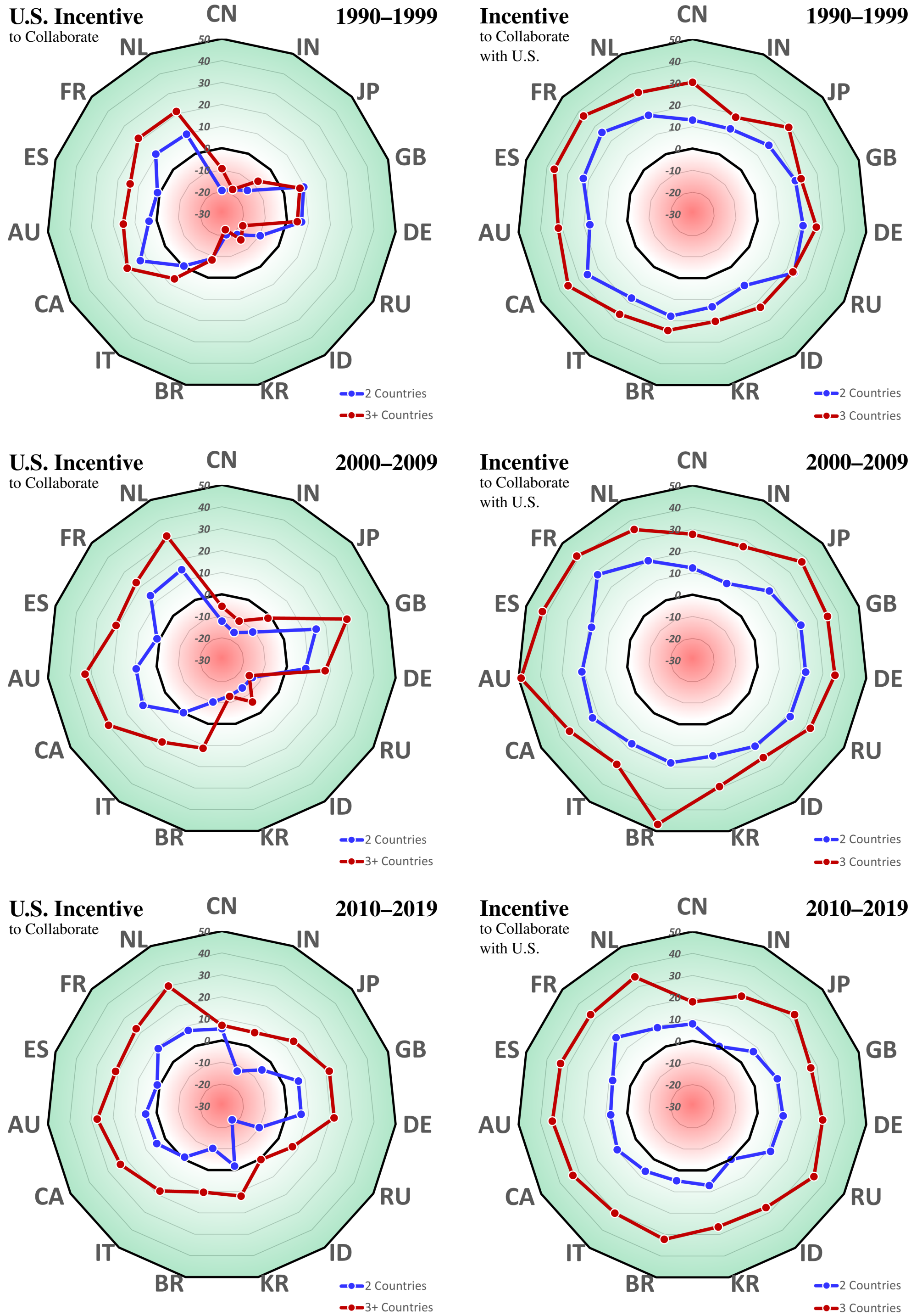


Figure 16. Radar plots showing the citation incentives for the U.S. to collaborate with various countries (left column) and for various countries to collaborate with the U.S. (right column) over a three-decade time span: 1990–1999 (top row), 2000–2009 (middle row), and 2010–2019 (bottom row). Both bilateral collaboration and multilateral collaboration incentives are shown within the plots (blue and red, respectively).

with prior figures, and this order is maintained across the earlier decades for ease of comparison.

A key takeaway is that, over the past three decades, all countries have exhibited a positive citation incentive to collaborate with the U.S., both in bilateral and multilateral collaborations (right-hand plots). Notably, the left-hand plots highlight a shift in multilateral collaboration incentives: from 1990 to 2009, it was generally not advantageous for the U.S. to collaborate with multiple countries, regardless of the collaboration type. Countries like China, India, Japan, Russia, Indonesia, and Korea stood out in this regard. In contrast, collaborations with European countries, Canada, and Australia were advantageous for the U.S., a trend that continued into the 2010–2019 period. The plot also illustrates asymmetry between the U.S.'s perspective and that of other countries, as the right-side plots generally show higher citation incentives for these countries than the U.S.'s own incentive to collaborate with them.

3.8 Discussion: Beyond the Data

Are Citations Really an Incentive?

The use of the terms "incentive" and "disincentive" in the context of citations warrants closer scrutiny. When an article is published, there are no immediate citation incentives or disincentives because citations accrue only over time. It is unlikely that authors consciously weigh future citation counts when deciding on collaborators or research directions. However, data reveals a persistent pattern: articles involving authors from multiple countries tend to accrue more citations than those without international collaborations. While this trend is not instantaneous, it gradually unfolds, potentially shaping perceptions of the benefits associated with cross-border partnerships.

Although direct citation incentives may not be top of mind for researchers, underlying factors likely contribute to the observed trends. Collaborating with authors from different countries broadens an article's visibility, distributing it across diverse research networks. These networks often differ significantly by region, with international authors bringing unique local connections and access points to otherwise inaccessible resources. By working with collaborators from distant parts of the global research network, authors may gain exposure to audiences and opportunities beyond their immediate academic circles. This "network diversification" could indirectly amplify the article's reach and impact, reinforcing the citation trends observed in the data.

Moreover, the real incentive for international collaboration may not lie in citations at all but rather in the broader opportunities such partnerships offer. Collaborators from different countries can contribute access to distinct funding sources, datasets, infrastructure and equipment, or specialized expertise. These advantages extend beyond the immediate research project, offering long-term benefits to participating researchers. Over time, these repeated interactions may create an unconscious association between international collaboration and success—manifested as increased visibility, academic reach, and eventually, citations. Even if citations themselves are not the primary motivator, the cumulative advantages of global partnerships may subtly guide researchers toward such collaborations.

Are Citations a Reliable Metric for Research Impact?

Citations are often regarded as a direct measure of an article's impact and quality, with high citation counts interpreted as evidence of significant contributions to a field. Similarly, an author's total citations are frequently used as a proxy for their professional prestige, and citation-based metrics influence assessments of journals, institutions, and even national research output. This emphasis has positioned citations at the heart of scientific evaluation, particularly within the open science community, where they are seen as a cornerstone of research success.

However, the reliance on citations as a primary metric raises important questions about their validity and potential unintended consequences. As Goodhart's Law warns, when a metric becomes a target, it risks losing its utility. The increasing focus on citations may encourage researchers to prioritize work that is more likely to be cited over exploratory or innovative research that could take longer to gain recognition. For instance, a recent study analyzing 45 million papers and 3.9 million patents found that papers and patents are becoming less disruptive over time, with a decline in work that breaks with the past and pushes science and technology in new directions.[37] Journals and institutions, driven by impact factors and similar metrics, might also shift their focus toward popular topics, sidelining less mainstream or interdisciplinary research that might otherwise have transformative potential.

Citations are also inherently context-dependent, varying significantly across disciplines, regions, and time scales. Highly innovative work that challenges prevailing paradigms may accrue citations slowly, whereas less transformative work might rapidly gain attention if it aligns with current trends or popular topics. This variability underscores the limitations of a one-size-fits-all approach to measuring research impact. Fields with lower publication volumes or emerging disciplines may struggle to achieve citation counts comparable to well-established or fast-moving areas, risking undervaluation.

The tendency for global collaborations to form larger teams may also be contributing to a shift towards more developmental research, rather than disruptive or innovative work. As Wu et al. have shown, smaller teams are more likely to disrupt science and technology with new ideas and opportunities, whereas larger teams tend to develop existing science.[38] This suggests that the increasing prevalence of large teams in global collaborations may be leading to a greater emphasis on building on existing knowledge, rather than challenging prevailing paradigms or exploring new ideas.

Moreover, citations alone fail to capture other critical dimensions of research impact, such as societal relevance and long-term influence. However, research has shown that for highly impactful papers, there is a surprising alignment between their citation counts and their public use and consumption. A study by Yin et al. found that the top 1% of papers, as measured by citations, are also highly aligned with public use and consumption, suggesting that these papers are not only widely cited by scientists, but also widely used and valued by the public.[39] This finding highlights the importance of considering multiple metrics of research impact, including both citation counts and public use, in order to gain a more complete understanding of a study's significance and influence. By examining both the scientific and public impact of research, we can gain a more nuanced understanding of how science contributes to society and how it can be supported and funded in ways that maximize its benefits.

While citations are undoubtedly a valuable tool for tracing knowledge dissemination and scholarly influence, they represent only a partial picture of a work's impact. To better reflect the true value of scientific contributions, it is essential to integrate citation metrics with qualitative assessments that consider broader dimensions, such as societal relevance, collaborative reach, and enduring significance. Such a balanced approach would help ensure that research evaluation aligns more closely with the diverse goals of science and its potential to advance society.

The Limits of Citation Metrics and the Recognition of Quality

While citation metrics are a widely used tool for assessing research impact, they are far from infallible. Concerns about the misuse and manipulation of citation counts are valid, but it is equally important to recognize that for much of the scientific community, the quality of a researcher's work transcends numerical measures. Scientists often evaluate one another based on expertise, creativity, and contributions, which are apparent through direct interactions, collaborations, and participation in professional societies. This recognition exists independently of citation counts, particularly for researchers working in fields where open publication is restricted, such as classified or proprietary domains. In these cases, reputations are built on demonstrated expertise and problem-solving capabilities, reinforcing the idea that impact is not solely tied to citation numbers.

Nonetheless, instances of citation manipulation—such as excessive self-citation[22] or the inclusion of "guest authors" who did not contribute meaningfully to the work[17–19]—pose challenges to the integrity of the system. As mentioned throughout this report, China is the largest self-citer of its articles in the world, with 62% of citations to China's top 10% of papers coming from within their borders, compared to U.S. at 24%, Italy at 13%, and CA at 6%.[26] One explanation could be the growing quality of articles, while others could be a strategy known as citation stacking, where scientists cite colleagues' works to boost their citations and expect the favor to be returned. These citation manipulation practices are generally recognized and highlighted/criticized by the scientific community. Fortunately, scientists are often adept at identifying and discounting such tactics when assessing a colleague's work.

Importantly, while manipulation might temporarily inflate citation counts, it has clear limitations. Truly impactful research garners attention because it advances knowledge, addresses critical challenges, or opens new avenues for exploration. Articles that accumulate hundreds or thousands of citations generally achieve this through genuine contributions to their fields. While the Matthew effect[3]—where well-cited articles or prominent authors attract additional citations preferentially[*]—may amplify visibility, it cannot manufacture lasting impact from inconsequential work.

[*] Hence the term "preferential attachment" is often used within the network science community.

Ultimately, citation metrics, despite their imperfections, provide a useful lens for identifying influential research. When combined with qualitative assessments, they offer a more nuanced view of a researcher's contributions. By recognizing both the measurable and intangible aspects of scholarly achievement, the scientific community can better appreciate the depth and breadth of impactful work, beyond the limits of citation-based evaluations.

Revisiting Global Collaboration: Individual Incentives and National Concerns

This analysis of citation incentives in bilateral and multilateral collaborations highlights the complexities of international partnerships in research. While the data suggest that such collaborations often lead to higher citation counts, this is just one facet of a multifaceted issue. The incentives that drive individual researchers to seek global collaboration can sometimes be at odds with broader national interests, particularly in areas with strategic or economic implications.

For individual scientists, international collaboration often enhances visibility, prestige, and access to diverse networks, which can lead to increased citations and career advancement. Articles involving multiple countries may receive broader attention and dissemination, boosting the perceived impact of the work. For academic institutions and researchers, this can translate into greater recognition, funding opportunities, and influence within the global scientific community. These incentives naturally encourage collaboration across borders, particularly in disciplines where research thrives on diverse perspectives and expertise.

However, from a national perspective, this openness is not always viewed as an unequivocal good. In fields such as military technology, advanced manufacturing, and economic policy, the unrestricted flow of knowledge across borders can raise concerns about intellectual property protection, national security, and technological competition. Countries may worry that openness accelerates the global dissemination of disruptive or innovative findings, leading to a race to commercialize or weaponize these advancements, potentially disadvantaging the very nations that funded or initiated the research.

This tension between individual incentives and national concerns reflects a broader challenge in balancing the global nature of science with the priorities of sovereign states. While scientists may be incentivized to pursue international collaboration for its career benefits, nations must grapple with the implications of such openness on strategic interests. These competing perspectives highlight the need for careful consideration of the policies and frameworks governing international research partnerships, ensuring that they support scientific progress while addressing legitimate concerns about national interests.

Ultimately, this study does not seek to advocate for or against global collaboration, but rather to provide insights into the incentives and behaviors shaping researchers' decisions. As science becomes increasingly interconnected, it is crucial to navigate these complexities with strategies that respect both the aspirations of individual scientists and the broader priorities of the nations they represent.

4. Conclusion

This study explores the relative and comparative citation incentives for collaboration between the United States and various global partners since 1990, offering new insights into how bilateral and multilateral collaborations affect citation outcomes. Two citation incentives were explored: a) the relative citation incentive refers to the citation increase (or decrease) for bilateral or multilateral collaborative articles *relative to* to unilateral articles, and b) the comparative citation incentive refers to the citation increase (or decrease) for bilateral and multilateral collaborative articles with a specific country *compared to* those bilateral and multilateral collaborative articles, respectively, without that country. Key findings from the analysis are summarized as follows:

1. **Impact of China's Rise on Citation Dynamics:** The growing number of articles published by authors from China is increasing at a rate higher than any other country (e.g., Figure 5b), although its percentage of bilateral and multilateral articles are not increasing (e.g., Figure 5d). With this growing output, the number of citations accrued by articles with author(s) from China has also markedly increased (Figure 6). Since around 2010, the relative citation incentive for U.S. to collaborate with China on articles has turned positive (the incentive for China to collaborate with U.S. has always been positive, i.e., Figure 9). This change to positive relative citation incentive means that it is a win–win scenario for collaborative articles from both the U.S. and China's perspective. The comparative citation incentives are also positive, meaning

that this is not just an effect of bilateral or multilateral articles but is also positive with respect to any other partner on bilateral or multilateral articles. Per the discussion, this effect may have many reasons, such as the high rate of self-citation within China coupled with their growing number of publications means that collaborative articles with China accesses a high number of future citations which is biased towards publications including authors from China.

2. **Global Citation Incentives and Collaboration Patterns:** This analysis was expanded to other top publishing countries. The analysis of citation incentives across multiple countries revealed significant differences in how collaborations impact citation outcomes for the U.S. The evolution of the relative citation incentives for CN, GB, DE, JP, FR, IN (top publishing countries) shows a shift toward positive incentives for both countries in bilateral and multilateral articles (Figures 12 and 13). These incentives were expanded to encompass a larger list of the top publishing countries over a three decade span, plotting these on a radar plot to compare the comparative citation incentives for bilateral and multilateral articles (Figure 16). From the U.S.'s perspective, countries like the United Kingdom, Canada, Australia, and other European partners consistently provide high citation benefits for both bilateral and multilateral collaborations, while countries like Brazil, Russia, and India often show negative citation incentives, particularly in bilateral collaborations. However, in nearly all cases examined, these countries benefit from collaborating with the U.S., with bilateral and multilateral articles receiving additional citations for those that included authors/institutions from the U.S.

3. **Role of Third Countries in Multilateral Articles:** The vast differences in comparative citation incentives for multilateral articles (as high as 20 citation difference, see Figure 14) raises the question "Why is this so vastly different for different countries?" The composition of the third country in multilateral collaborations was explored to examine who the most frequent partner was. While the United Kingdom is frequently involved as a third country, variations in other partnerships (i.e., with China, South Korea, and Indonesia) reveal that the identity of the third country does not always correlate with citation success, indicating other influencing factors. Collecting data from many factors and analyzing the statistical significance may shed light on what factors are truly driving these large citation incentive differences.

In conclusion, this study provides a detailed look at how global scientific collaborations shape citation dynamics, focusing particularly on the role of the U.S. in international partnerships with some focus on China, given its recent increase in publications. The findings highlight factors that may be influencing the increase in global collaboration. Understanding the various factors that influence citation incentives is important for the advancement of science, given that the goal of increasing citation counts for researchers, institutions, and countries may not always align with the broader goal of advancing scientific knowledge. These findings offer valuable insight into the incentives driving international collaboration and the complexities of international scientific collaboration in an era of rapidly expanding global research efforts.

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Appendix. Global Collaboration Frequency Map

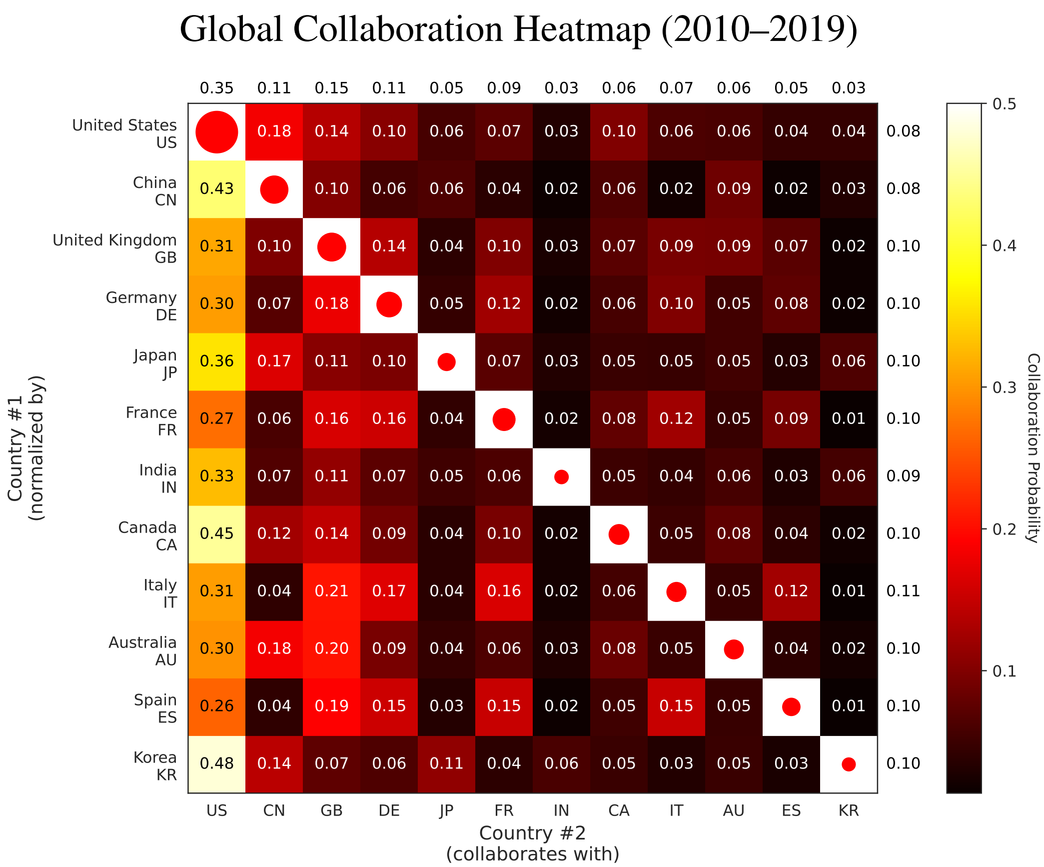

Figure A-1. A heat map illustrating global collaboration among the top 12 most prolific countries in the 2010s. Countries are arranged based on their scientific article productivity, with the y-axis representing the top-down order and the x-axis depicting the left-to-right order. The circular regions (highlighted in red) along the diagonal are proportional to the number of articles featuring multiple countries for Country 1. Each row is normalized by this count, converting each element within the heat map into a probability indicating how often a multi-country article for Country 1 (left) also contains Country 2 (below).

List of Symbols, Abbreviations, and Acronyms

ACRONYMS:

ARL	Army Research Laboratory
API	application programming interface
DEVCOM	U.S. Army Combat Capabilities Development Command
ID	identifier
URL	uniform resource locator (web address)

COUNTRY ACRONYMS:

Country designations in this report follow the ISO 3166-1 alpha-2 standard, as used in the OpenAlex dataset. For example, "GB" refers to the United Kingdom of Great Britain and Northern Ireland (shortened to United Kingdom within this report), following its official ISO code, even though "UK" is also commonly used. This convention is retained throughout to ensure consistency with the dataset.

AU	Australia
BR	Brazil
CA	Canada
CN	China
DE	Germany
ES	Spain
FR	France
GB	United Kingdom of Great Britain and Northern Ireland
ID	Indonesia
IN	India

IT	Italy
JP	Japan
KR	Korea, Republic of
NL	Netherlands, Kingdom of the
RU	Russian Federation
UK	United Kingdom of Great Britain and Northern Ireland
US	United States of America