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Interpreting CNCIs on a country-scale: The effect of domestic and international collaboration type

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A R T I C L E I N F O

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A B S T R A C T

Greater collaboration generally produces higher category normalised citation impact (CNCI) and more influential science. Citation differences between domestic and international collaborative articles are known, but obscured in analyses of countries' CNCIs, compromising evaluation insights. Here, we address this problem by deconstructing and distinguishing domestic and international collaboration types to explore differences in article citation rates between collaboration type and countries. Using *Web of Science* article data covering 2009–2018, we find that individual country citation and CNCI profiles vary significantly between collaboration types (e.g., domestic single institution and international bilateral) and credit counting methods (full and fractional). The 'boosting' effect of international collaboration is greatest where total research capacity is smallest, which could mislead interpretation of performance for policy and management purposes. By incorporating collaboration type into the CNCI calculation, we define a new metric labelled Collab-CNCI. This can account for collaboration effects without presuming credit (as fractional counting does). We recommend that analysts should: (1) partition all article datasets so that citation counts can be normalised by collaboration type (Collab-CNCI) to enable improved interpretation for research policy and management; and (2) consider filtering out smaller entities from multinational and multi-institutional analyses where their inclusion is likely to obscure interpretation.

1. Introduction

Citations are widely seen as an indicator of the impact, significance and influence of academic publications (Cole & Cole, 1973; Garfield, 1955). Though reasons for citing are numerous (Garfield, 1977; Small, 1982), it is generally held that publications receiving a greater number of citations - and recognised through other means (e.g., peer review) - contribute significantly to academic knowledge (Moed, 2005, 2017).

If we wish to compare the citation counts of any two publications, or to compare a specific publication with some reference point, then we also need to consider factors other than quality that can influence citation accumulation. First, we note that citation counts vary temporally and with field: they increase over time at a rate that is discipline dependent (Garfield, 1979; Hurt, 1987; Leydesdorff, Bornmann, Mutz, & Opthof, 2011; Waltman & van Eck, 2013; and see Fig. 1). For this reason, it is obligatory to index the citation count for each publication in a sample against an appropriate average for the year in which it

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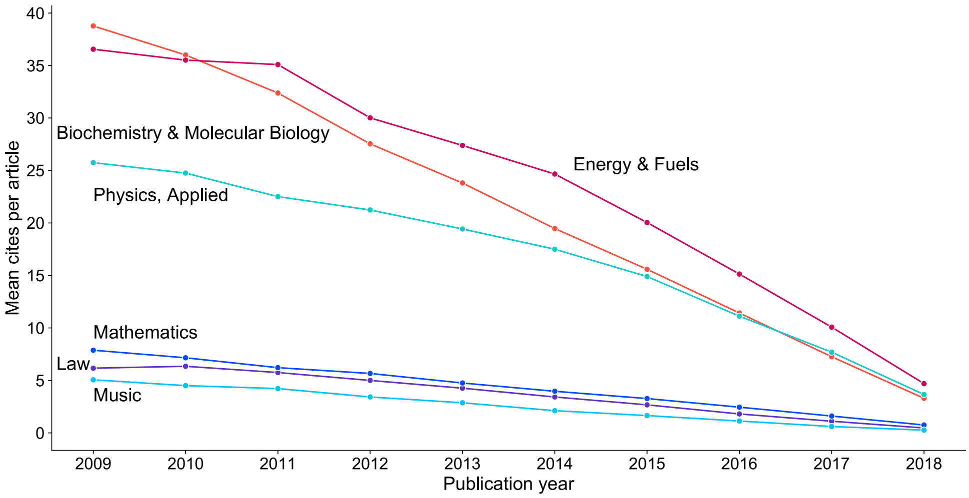

Fig. 1. Average cites per article for articles from six *Web of Science* journal subject categories for the publication years 2009–2018.

was published and its category (typically the publication set for a group of cognate journals). This is called normalisation and is essential for any cross-field or multi-year comparisons (Batista, Campiteli, & Kinouchi, 2006; Kaur, Radicchi, & Menczer, 2013; Radicchi, Fortunato, & Castellano, 2008; Waltman, 2016).

The standard normalisation approach for researchers drawing on data in the *Web of Science* is to use the category normalised citation impact (CNCI). This normalises citations based on journal publication year, document type (e.g., article, review) and *Web of Science* journal subject category (WoScat). The world average cites per paper within the year is taken as a benchmark and the ratio of any specific paper to this indicates its performance relative to that average (i.e., where world average = 1.0 then CNCI = 1.2 indicates a document for which the normalised citation impact is above the world average whereas a CNCI of 0.8 would be beneath the world average). Taking portfolios of publications, an average CNCI can then be calculated for individual entities (researchers, institutions or countries) and used for comparative purposes or as part of an Impact Profile (Adams, Gurney, & Marshall, 2007; Adams, McVeigh, Pendlebury, & Szomszor, 2019). It is now the case that such CNCI comparisons are widely used, for example, to inform government policy (country level: BIS, 2009), to allocate resources (institution level: Carlsson, 2009) and to promote and hire staff (author level: Holden, Rosenberg, & Barker, 2005).

Time and WoScat are not, however, the only factors that affect citation accumulation. There are, for example, national cultural influences (Adams, 2018) which may accelerate or slow the rate of growth. It is also well documented, across many fields, that citation counts increase with collaboration whether in relation to an increasing number of contributing authors, institutions or countries (Herbertz, 1995; Jones, Wuchty, & Uzzi, 2007; Katz & Hicks, 1997; Larivière, Gingras, Sugimoto, & Tsou, 2015; Waltman & van Eck, 2015; Wuchty, Jones, & Uzzi, 2007).

In citation analysis, collaboration has historically been a noteworthy but marginal factor. In the 1980s, when bibliometrics were evolving, international collaboration rarely accounted for more than a few percent of a country's or an institution's publication output. There has, however, been a signal change in international collaboration as research has moved into the 'fourth age' (Adams, 2013), with many more internationally collaborative articles being published (Adams & Gurney, 2018; Ribeiro, Rapini, Silva, & Albuquerque, 2018). For countries in western Europe, international co-authorship now accounts for more than one half and as much as two thirds of annual publication output. More frequent collaboration has two effects. First, it blends the research activity and performance of collaborating entities, making analytical comparisons more challenging and debatable. Second, it is associated with a general increase in mean CNCI in terms of both authors and countries (Adams, Pendlebury, Potter, & Szomszor, 2019; Thelwall, 2020; Waltman & van Eck, 2015). Fig. 2 visualises this effect, which is greater for one additional country than one additional author. The important consequence is that greater collaboration can obfuscate any analysis of the specific effort and contribution of individual entities (authors, institutions or countries) making bibliometric analysis less transparent.

Can the credit for collaborative work be attributed appropriately, given the evidence that significant research management decisions are based, rightly or wrongly, on indicators such as CNCI? Various credit defining methods exist (e.g., full counting, fractional counting, first-author counting) and have been discussed in detail (e.g., Van Hooydonk, 1997; Egghe, Rousseau, & van Hooydonk, 2000; Gauffriau & Larsen, 2005; Huang, Lin, & Chen, 2011; Aksnes, Schneider, & Gunnarsson, 2012; Waltman & van Eck, 2015). No strong preference has emerged in favour of any particular method, possibly because continuing problems are evident for all. For example:

Full counting provides each individual entity with a full production credit and the full CNCI value for each article. Though this covers participation, it does not reflect contribution. It is also argued that it results in the multiple counting of articles, but this only happens in that an article counts once for each contributing entity, not multiple times for any one entity.

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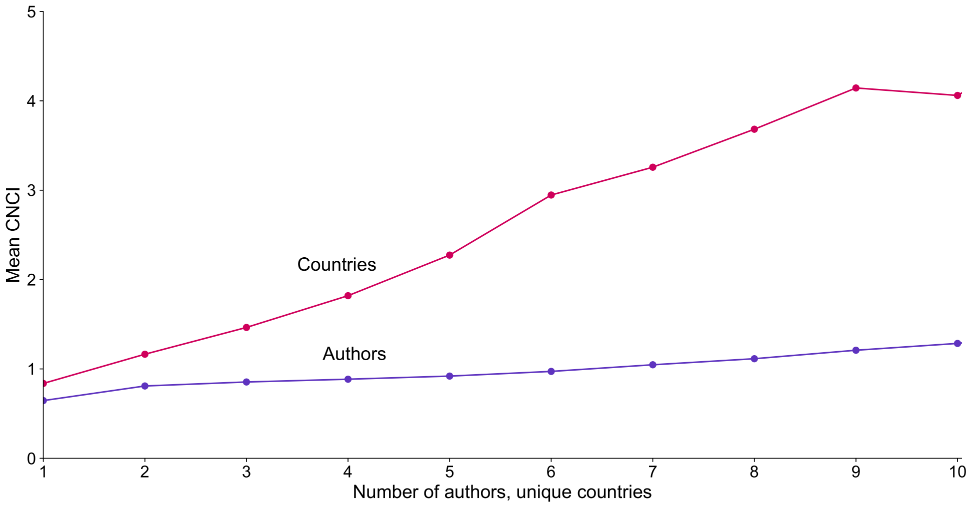

Fig. 2. Mean category normalised citation impact (CNCI) as a function of number of authors and unique countries. Data cover 2009–2018 articles indexed in the *Web of Science*. Reproduced from Adams, Pendlebury et al. (2019: Fig. 3).

Fractional counting assumes that credit and CNCI value can be distributed equitably. An even fraction may accurately reflect credit for some small groups (e.g., two to four individual entities), but this will likely disproportionately allocate credit among larger groups where major and minor contributors must be present.

First-author counting assumes that the first named author is the main contributor and is assigned either full or a higher weighted credit and CNCI value (zero credit or a fraction of the residual is given to any other entity). However, author order is highly field dependent, e.g., alphabetical (Frandsen & Nicolaisen, 2010; Waltman, 2012) or placing group leaders last, limiting its usefulness. The corresponding author may also be used as the 'main contributor'.

Citations are clearly affected by authorship patterns (Fig. 2) and there is a demonstrable difference in citation performance between domestic and internationally collaborative papers (Adams, 2013). But does this compromise quantitative evaluation through CNCI or other bibliometrics and, if so, by how much? Can we identify and describe a typology of authorship that can be used to inform and improve current evaluation approaches and avoids making assumptions about the balance and apportionment of author credit?

Here, we address this problem by deconstructing internationally collaborative authorship and describing a domestic and international typology in order to elucidate the pattern of associated differences in article citation rates between both collaboration type and countries. Our collaboration types are exclusive and comparisons are made only between articles of the same type. This allows articles to be wholly counted (i.e., not fractionated), as all entities within a type have the same, equal share of credit.

Further, we incorporate collaboration type into the normalisation calculation to define a new metric – Collab-CNCI – which also accounts for the level of collaboration without presuming credit (i.e., fractional counting). We then compare results derived from the collaboration typology and Collab-CNCI with those from full and fractional counting methods using the same dataset. We discuss the advantages and disadvantages of these different approaches.

2. Methods

2.1. Time period

The data source is the journal set indexed in the *Web of Science* Core Collection, covering the main citation indices also reported in the Journal Citation Report, over a ten-year period from 2009 to 2018.

2.2. Document type

The document set was reduced to include only documents identified as articles. Reviews, though primary academic research publications, were not included as their citation characteristics differ from those of articles and thus should not be directly compared (Ketcham & Crawford, 2007; Miranda & Garcia-Carpintero, 2018). The final dataset included 15,650,080 articles.

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2.3. Normalisation

The CNCI of each article was calculated by the standard method, using the ratio between the article's citation count and the average citation count in the year of publication for all articles in the WoScat to which the article's journal is assigned.

Some journals indexed in *Web of Science* are assigned to more than one WoScat. In such instances, all CNCI values were calculated for the article for each of its relevant WoScats. The article's reference CNCI for the purposes of the analysis was then calculated by taking the average of the individual WoScat CNCIs.

For full counting, each country on a given article was allocated full credit. Thus, if an article with two countries had a CNCI of 1.3, each country was awarded an article count of 1.0 and a CNCI value of 1.3. A country's mean CNCI was then calculated by summing the CNCI of all the articles on which the country was recorded in an author address and dividing this by the number of such articles, over the entire dataset.

Fractional counting was implemented at the author level, based on arguments presented within Waltman & van Eck (2015) (e.g., fewer complications than organisation level; similar results between different levels). An author's credit share for an article was calculated as the reciprocal of the number of unique authors (e.g., for an article with four authors, each had a credit share of 0.25). The number of unique countries per author was then determined. This was multiplied by their author share to get the country share per author (e.g., if an author has an author share of 0.25, and is affiliated with two countries, each country would receive a credit of (0.25 × 0.5) = 0.125). These shares were then summed per country to find each country's overall share of an article. This was then multiplied by the article's CNCI. A country's mean CNCI was then calculated by summing its CNCIs on which the country was recorded in an author address and dividing this by the sum of its total fractional credit share.

An example of author level fractional counting (following Waltman & van Eck, 2015):

- A two-author paper has a CNCI of 2; author A is affiliated with country X and author B is affiliated with country X and country Y.
- Each author receives 1/2 (0.5) credit.
- This credit is then multiplied by the number of countries associated with each author.
- Author A, Country X: 0.5 × 1 = 0.5. Author B, country X: 0.5 × 0.5 = 0.25; Author B, country Y: 0.5 × 0.5 = 0.25.
- These credits are then summed per country (country X = 0.5 (from Author A) + 0.25 (Author B) = 0.75; country Y = 0.25 (Author B).
- Country A's CNCI value is then 2 × 0.75 = 1.5; Country B's CNCI value is 2 × 0.25 = 0.5).

Not all articles had complete address data, so not all authors could be assigned to an organisation and, therefore, to a country. Consequently, when analysing data at the author level, approximately 4 % of articles were not included (when considering the top 20 countries by article count). For example, the USA was assigned to 3,964,964 articles at the article level, but 3,733,803 articles (~94 %) at the author level. However, given the size of the dataset, there is no reason to expect that outcomes for any one country would be consistently affected by this.

2.4. Country assignment

In order to implement a primary in-depth analysis and comparison across the 215 countries and territories listed in articles' addresses, a global spread of comparator countries was selected for analysis taking into account relevant issues such as population size and research maturity. These included:

Five countries with large and well-established research economies: Australia, China (including Macau and Hong Kong), Russia, United Kingdom and USA.

Five countries with smaller and relatively emergent research economies: Chile, Ethiopia, Georgia, Indonesia and Sri Lanka.

These are henceforth referred to as large research economies and smaller research economies, respectively.

2.5. Collaboration typology

For collaboration-type counting, address data was used to classify an article into one of five categorical types (representing components of an overall national portfolio):

- Domestic single (authored by a single institution);
- Domestic multi (authored by two or more institutions from the same country);
- International bilateral (authored by two countries, regardless of the number of authors or institutions);
- International trilateral (authored by three counties, regardless of the number of authors or institutions);
- International quadrilateral-plus (authored by four or more countries, regardless of the number of authors or institutions).

These categorical types were chosen to represent the diversity of collaborations. The more intensively collaborative group (international quadrilateral-plus) accounted for ~1.7 % of all articles in the dataset. Additional collaboration groups to take into account, for example, hyper-authorship (30+ countries; Adams, Pendlebury et al., 2019), were considered but only

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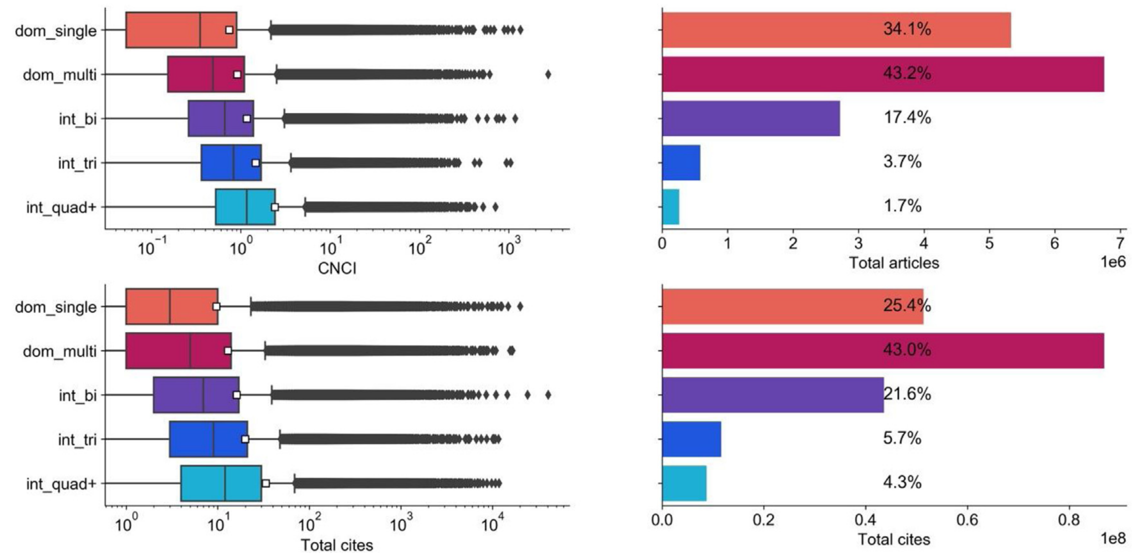

Fig. 3. Article and citation distribution for all articles. Articles are divided into five types: domestic single (dom_single) and multi (dom_multi), and international bilateral (int_bi), trilateral (int_tri) and quadrilateral-plus (int_quad+). White squares on boxplots represent the mean.

accounted for trivial numbers of papers (30+ country papers accounted for ~0.01 %). Authorship numbers, and therefore the definition of multi-authorship, can vary between research fields and we direct the reader to Adams, Pendlebury et al. (2019) for a discussion of multi-authorship at the research field level.

Each country on each article was assigned the appropriate collaboration type. As with full counting, a country was given full credit and the full CNCI value for an article, though the mean CNCI was calculated considering each collaboration-type separately (e.g., only a country's international bilateral articles were considered when calculating the country's CNCI for international bilateral). Total cites for each country were also calculated.

Note that an article with a single author could theoretically fall within any of these collaboration types, depending on affiliations. Additionally, due to organisational enhancement, articles by a single institution may be listed as 'domestic multi' if an institution falls under an umbrella organisation. For example, a University College London publication may also have a University of London affiliation; a University of California Los Angeles publication may also have a University of California System affiliation. However, such articles were still correctly identified as domestic.

2.6. Normalisation by collaboration type

Following our examination of the collaboration types, and the development of a preliminary typology as described here, we will show (in Section 3) that the variation in mean CNCI associated with the degree of international collaboration is clearly confirmed. This consequently affects the mean CNCI for a complete country portfolio. The overall impact calculated from a data sample will be dependent on the balance between collaboration types, with relatively more frequent internationally collaborative papers tending to boost mean CNCI compared to domestic activity.

To determine and understand these effects, a complete normalisation was carried out within each of the collaboration types - citation count for every article was normalised against the average for publication year, article type, WoScat and collaboration type. The indicator created via this procedure is named Collab-CNCI.

3. Results

3.1. Dataset

Of the 15,650,080 articles, 16.8 % are currently uncited. The frequency of uncited articles varies from 10 % of articles published in 2009, 2010 and 2011 to 40 % of articles published in 2018. The dataset has received 202,250,239 citations. The 2009 publications have received 29,077,898 citations while the 2018 publications have received 4,221,639.

The overall article and citation distribution between the five collaborative types (domestic single, domestic multi, international bilateral, international trilateral, international quadrilateral-plus) is summarised in Fig. 3. Domestic output accounts for ~77 % of all articles (34.1 % single and 43.2 % multi). Note that article share does not always follow citation share. Although ~34 % of all articles are domestic-single, only ~25 % of all citations are drawn from these articles. By contrast, the larger internationally collaborative articles, while fewer in number, account for a greater citation share relative to their article share: trilateral collaborations make up 3.7 % of articles but 5.7 % of all citations; quadrilateral-plus collaborations account

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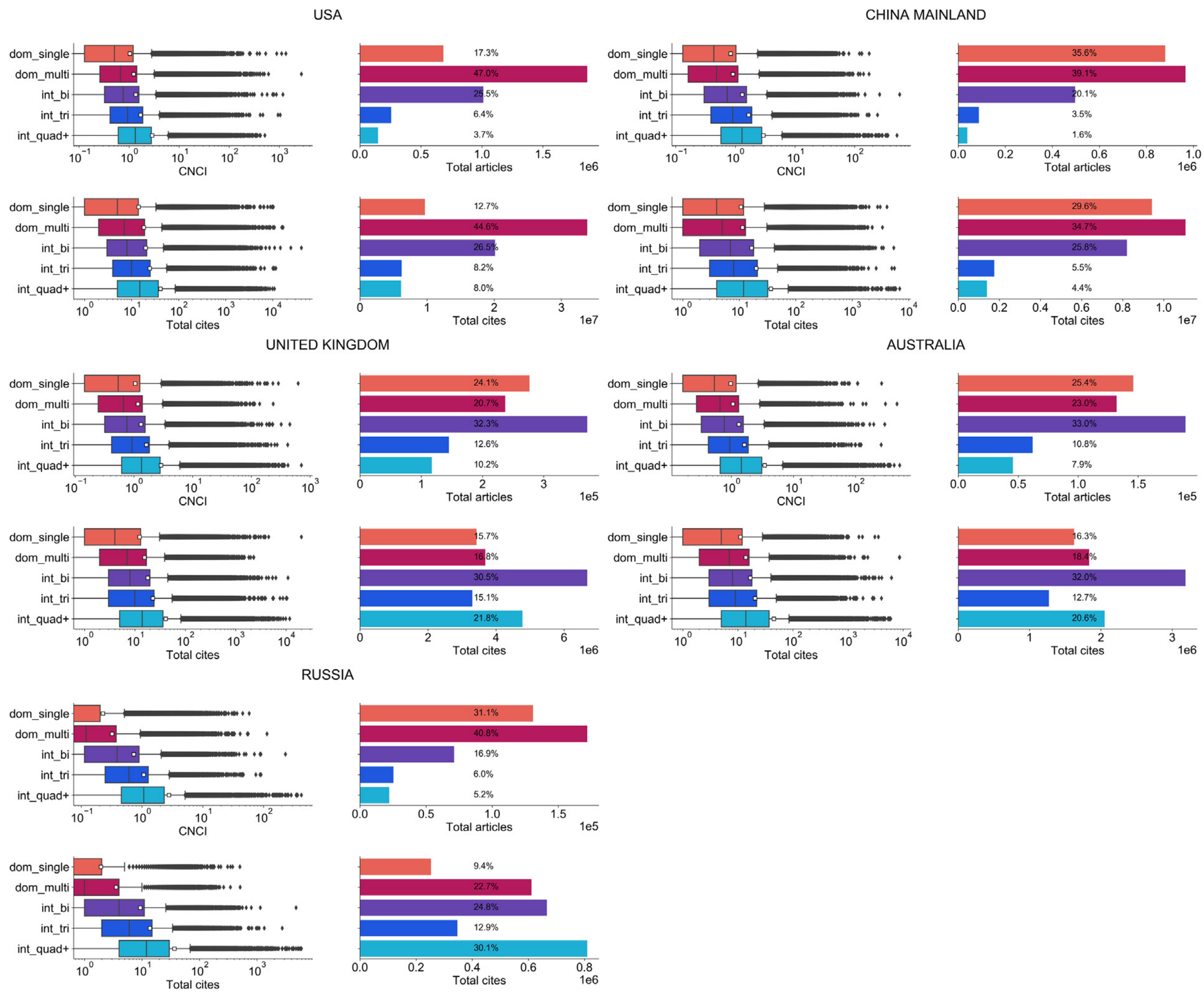

Fig. 4. Article and CNCI values for five large research economies.

for 1.7 % of articles but 4.3 % of all citations. It is a necessary property of a collaborative paper that it is a component not only of the dataset as a whole but also of each national sub-set for the relevant collaborators. However, the total sample for each country is smaller than the whole dataset. It is therefore not an anomaly that the frequency of quadrilateral-plus papers is greater in every national sample than it is over the full dataset.

There is a gradual and progressive increase in CNCI (mean and median) as collaboration increases from domestic single (mean CNCI 0.74) to international quadrilateral-plus (mean CNCI 2.40) in line with previous studies (e.g., Adams, 2013; Adams, Pendlebury et al., 2019).

3.2. Countries

The citation and CNCI distributions for the five large research economies (Australia, China, Russia, United Kingdom and USA) are illustrated in Fig. 4. Across the 15,650,080 articles, researchers from the USA are (co)authors on 25 % of all articles (3,964,964); China is an author on 16 % (2,469,444); United Kingdom (1,147,927) and Germany (1,044,111) on 7%; and Japan (810,683) and France (730,572) on 5%. The other large research economies in our selected group are Australia (575,227 articles, rank 11th) and Russia (421,457 articles, rank 14th).

USA: 64.3 % of output is domestic, with domestic multi accounting for 47 %; 25.5 % of articles are international bilateral. International trilateral and quadrilateral-plus each account for ~8% of citations, despite their article share being 6.4 % and 3.7 %, respectively.

China: 74.7 % of output is domestic, the highest of the large research economy set, and accounts for 64.3 % of all citations; 20.1 % of articles are international bilateral. International trilateral and quadrilateral-plus account for lower shares of articles and citations, relative to the USA.

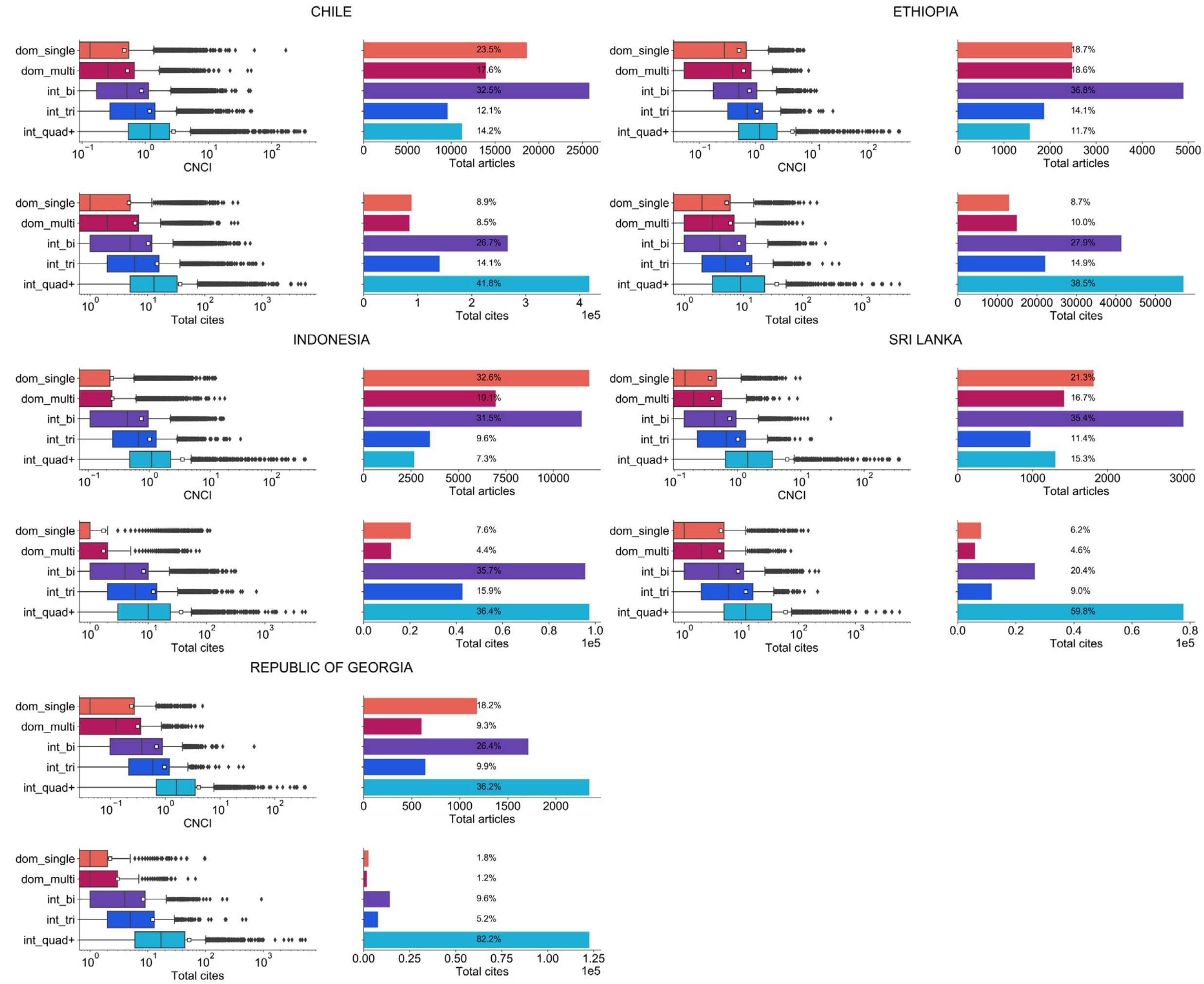

Fig. 5. Article and CNCI values for five smaller research economies.

United Kingdom: 44.8 % of output is domestic; however, international bilateral is the largest individual group (32.3 %). International quadrilateral-plus account for 10.2 % of articles, but 21.8 % of cites - second only to international bilateral (30.5 %).

Australia: 48.4 % of output is domestic, though the largest single group is international bilateral (33 %). International quadrilateral-plus accounts for 7.9 % of all articles, but 20.6 % of all citations - second only to international bilateral (32 %).

Russia: 71.9 % of output is domestic. While domestic single accounts for 31.1 % of all articles, this type accounts for only 9.4 % of all cites. International quadrilateral-plus accounts for 5.2 % of all articles, but 30.1 % of all citations - the largest national share.

The increase in mean and median CNCI as collaboration increases for the large research economies is broadly similar, though Russia has greater variation (particularly domestic single through to international bilateral). There is significant overlap in the interquartile ranges of CNCIs for each collaboration type and country (less so for Russia), and outlier range is similar.

The citation and CNCI distribution results for the five smaller research economies (Chile, Ethiopia, Georgia, Indonesia and Sri Lanka) are illustrated in Fig. 5. By article count these ranked globally as: Chile – 42nd with 79,253 articles; Indonesia – 53rd with 36,518; Ethiopia – 71st with 13,287; Sri Lanka – 85th with 8519 and Georgia – 91st with 6485 articles.

Chile: 41.1 % of output is domestic, but this accounts for only 17.4 % of citations. The largest individual group is international bilateral (32.5 %). International quadrilateral-plus accounts for 14.2 % of articles but a significant 41.8 % of cites. CNCI steadily increases between collaboration types, though there is a marked increase in the mean CNCI between international trilateral (1.18) and quadrilateral-plus (2.80).

Ethiopia: Output volumes are roughly equal for domestic (37.3 %) and international bilateral (36.8 %). International trilateral and quadrilateral-plus account for 14.1 % and 11.7 % of articles, respectively. Despite the volume output, international

Table 1
Top five of 215 countries and territories indexed globally in *Web of Science*, ranked by mean category normalised citation impact (CNCI) for a range of alternative methods for assigning citation credit. Each cell contains (from top to bottom) country name, article count (for that method or type) and mean CNCI.

Rank	Parameter	Full count	Fractional count	Domestic single	Domestic multi	International bilateral	International trilateral	International quadrilateral-plus
	Country	Micronesia	French Polynesia	Marshall Islands	Monaco	Marshall Islands	Marshall Islands	Micronesia
1	Articles	153	264.8	2	11	24	6	51
	Mean CNCI	14.06	1.85	2.31	2.47	1.52	3.98	40.53
	Country	St. Lucia	Singapore	French Polynesia	French Polynesia	Singapore	French Polynesia	St. Lucia
2	Articles	56	71,882.5	57	34	49,777	191	16
	Mean CNCI	8.79	1.34	1.55	2.12	1.43	2.20	29.14
	Country	Belize	Switzerland	Guinea Bissau	New Caledonia	Netherlands	USA	Belize
3	Articles	213	140,963.6	2	60	117,465	255,689	65
	Mean CNCI	6.07	1.33	1.16	1.32	1.37	1.69	17.57
	Country	Tonga	Netherlands	Netherlands	Singapore	USA	Singapore	Afghanistan
4	Articles	72	218,142.8	65,215	26,724	1,012,022	16,643	114
	Mean CNCI	4.68	1.30	1.14	1.25	1.36	1.69	13.37
	Country	Liberia	USA	Tonga	Switzerland	Switzerland	China	Bahrain
5	Articles	334	2,884307.8	2	48,360	100,869	87,522	32
	Mean CNCI	2.96	1.29	1.09	1.23	1.34	1.67	9.53

bilateral accounts for only 27.9 % of all cites, while international quadrilateral-plus has a far greater share (38.5 %) compared to its articles. There is notable increase in mean CNCI between international trilateral (1.06) and quadrilateral-plus (4.54).

Indonesia: 51.7 % of output is domestic. International bilateral accounts for 31.5 % of articles and 35.7 % of citations. International quadrilateral-plus accounts for 7.3 % of articles but 36.4 % of cites. Mean CNCI increases significantly from domestic multi (0.25) to international bilateral (0.74), and again from international trilateral (1.02) to international quadrilateral-plus (3.50).

Sri Lanka: 38 % of output is domestic, though international bilateral has the largest individual group share (35.4 %). However, domestic and international bilateral only account for 10.6 % and 20.4 % of citations, respectively. International quadrilateral-plus accounts for 59.8 % of all citations. Mean CNCI increases almost six-fold between international trilateral and international quadrilateral plus (from 1.01 to 6.08).

Georgia: 27.5 % of output is domestic; international bilateral accounts for 26.4 % of articles and international quadrilateral-plus accounts for 36.2 %. This most collaborative group also accounts for 82.2 % of all citations; no other type accounts for more than 10 % of citations. Mean CNCI increases almost four-fold between international trilateral and international quadrilateral-plus (from 0.97 to 4.10).

Mirroring the larger research economies, the mean and median CNCI increases as collaboration increases for the smaller research economies. However, the steps between collaboration types are not as consistent (Fig. 5) as the large research economies (Fig. 4). Furthermore, overlap between the CNCI interquartile ranges has greater inconsistencies: Chile has a similar pattern to the large research economies; Indonesia has no overlap in interquartile ranges between domestic and international trilateral and quadrilateral-plus. The smaller research economies also have a less consistent outlier distribution than the large research economies: international quadrilateral-plus outliers have a greater range than the other collaborative types.

3.3. Comparison of counting methods and collaboration types

Table 1 compares the top five countries by rank for each of the counting methodologies and collaboration types. This table is dominated by smaller research economies, particularly island nations in the Pacific and the Caribbean. However, some large research economies (Netherlands, USA, China, Switzerland and Singapore) are present, particularly for fractional counting and international trilateral. For full counting, the CNCI of Micronesia (14.06) is not only exceptionally high but 1.75 times that of the second ranked nation (St. Lucia, 8.79).

Many of the high-ranking countries have only a small number of articles within each category: St. Lucia has 56 in full counting; Monaco 11 in domestic multi. Within the domestic single category, three of the top five ranked countries (Marshall Islands, Guinea Bissau and Tonga) have just two articles. For comparison, the Netherlands has over 65,000 articles in this category. Similarly, the Marshall Islands has six articles in international trilateral whereas the USA has over 250,000. Full count rank closely follows the international quadrilateral-plus rank. Data for all 215 countries and territories present in addresses are given in the Supplementary Table for additional comparisons.

The absolute mean CNCI difference between the top two ranked countries is <1 for the fractional count and the domestic and international bilateral collaborative types. This difference increases to ~2 for international trilateral and ~11 for international quadrilateral-plus collaboration types.

Table 2 ranks the five large and five smaller research economies shown in Figs. 4 and 5, respectively, by mean CNCI for each counting method. Using a full counting methodology, Georgia and Sri Lanka rank higher than the large research

Table 2
Mean CNCI for five large and five smaller research economies across different credit counting methods. Data are ordered by full count mean CNCI. Cells contain rank (among these ten countries and, in brackets, globally) within method or type, mean CNCI and coverage (the percentage of a country's total articles that are included in this method or type). The highest ranked country in each column is in **bold**.

Country	Parameter	Full count	Fractional count	Domestic single	Domestic multi	International bilateral	International trilateral	International quadrilateral plus
Georgia	Rank (global)	**1 (25)**	8 (171)	9 (156)	9 (126)	10 (129)	10 (128)	3 (49)
	Mean CNCI (coverage)	**1.84 (100 %)**	0.46 (100 %)	0.24 (18 %)	0.32 (9%)	0.70 (26 %)	0.97 (10 %)	4.10 (36 %)
Sri Lanka	Rank (global)	2 (52)	7 (151)	7 (109)	7 (104)	7 (108)	9 (113)	**1 (21)**
	Mean CNCI (coverage)	1.46 (100 %)	0.53 (100 %)	0.37 (21 %)	0.40 (17 %)	0.75 (35 %)	1.01 (11 %)	**6.08 (15 %)**
United Kingdom	Rank (global)	3 (58)	2 (6)	**1 (8)**	2 (8)	3 (9)	3 (9)	7 (120)
	Mean CNCI (coverage)	1.42 (100 %)	1.25 (100 %)	**1.05 (24 %)**	1.16 (21 %)	1.32 (32 %)	1.63 (13 %)	2.90 (10 %)
Australia	Rank (global)	4 (65)	3 (11)	3 (10)	3 (10)	2 (8)	4 (10)	5 (77)
	Mean CNCI (coverage)	1.37 (100 %)	1.15 (100 %)	0.97 (25 %)	1.06 (23 %)	1.32 (33 %)	1.61 (11 %)	3.43 (8%)
USA	Rank (global)	5 (69)	**1 (5)**	2 (9)	**1 (6)**	**1 (4)**	**1 (3)**	8 (121)
	Mean CNCI (coverage)	1.32 (100 %)	**1.29 (100 %)**	1.04 (17 %)	**1.23** (47 %)	**1.36 (26 %)**	**1.69 (6%)**	2.89 (4%)
Ethiopia	Rank (global)	6 (91)	5 (86)	5 (67)	5 (52)	6 (102)	7 (86)	2 (37)
	Mean CNCI (coverage)	1.18 (100 %)	0.71 (100 %)	0.51 (19 %)	0.61 (19 %)	0.78 (37 %)	1.06 (14 %)	4.54 (12 %)
Chile	Rank (global)	7 (119)	6 (99)	6 (82)	6 (73)	5 (72)	5 (63)	9 (127)
	Mean CNCI (coverage)	1.03 (100 %)	0.66 (100 %)	0.47 (24 %)	0.52 (18 %)	0.87 (33 %)	1.18 (12 %)	2.80 (14 %)
China	Rank (global)	8 (120)	4 (41)	4 (22)	4 (19)	4 (10)	2 (5)	6 (114)
	Mean CNCI (coverage)	1.02 (100 %)	0.95 (100 %)	0.84 (36 %)	0.91 (39 %)	1.31 (20 %)	1.67 (4%)	2.96 (2%)
Indonesia	Rank (global)	9 (185)	9 (187)	8 (154)	10 (147)	8 (112)	8 (109)	4 (72)
	Mean CNCI (coverage)	0.71 (100 %)	0.37 (100 %)	0.24 (33 %)	0.25 (19 %)	0.74 (31 %)	1.02 (10 %)	3.50 (7%)
Russia	Rank (global)	10 (205)	10 (188)	10 (162)	8 (125)	9 (116)	6 (85)	10 (135)
	Mean CNCI (coverage)	0.53 (100 %)	0.36 (100 %)	0.23 (31 %)	0.32 (41 %)	0.73 (17 %)	1.06 (6%)	2.77 (5%)

economies. This is also the case for international quadrilateral-plus articles. However, the same two countries rank low for fractional and other collaborative type counts.

United Kingdom, USA, Australia and China all achieve a high ranking mean CNCI for fractional counting and collaborative type, apart from international quadrilateral-plus. Indonesia achieves a noticeable increase in rank if only the international quadrilateral-plus articles are considered. The CNCI of Russia ranks low for all methods.

There is an evident and clear increase in CNCI for groups of articles that are more collaborative, particularly between international trilateral and international quadrilateral-plus: the mean CNCI for Sri Lanka increases six-fold; Georgia and Ethiopia increase four-fold. However, for the same indicator comparison, the mean CNCI of the large research economies (other than Russia) only doubles for Australia and increases less than two-fold for the United Kingdom, USA and China.

3.4. Collaboration type normalisation

Sections 3.1–3.3 confirm that collaboration type has a clear influence on CNCI which suggests that a country's mean CNCI will be affected by the balance of activity across collaboration types. However, the results in Tables 1 and 2 do not use CNCI values that are normalised by collaboration type: they only segregate those types. To better integrate these collaboration types with CNCI values, collaboration type was used as an additional normalisation parameter in article CNCI calculations (i.e., normalising by collaboration type, in addition to document type, publication year and WoScat) in a metric which we denote as Collab-CNCI.

The top five ranking countries for each counting method using Collab-CNCI are shown in Table 3 (all countries are listed in the Supplementary Table). The highest-ranking countries across the different categories are similar to those in Table 1; the smaller research economies rank highest in each method, with some large research economies also present (Singapore, Netherlands, China and USA).

Because of the additional normalisation parameter, all mean CNCI values have decreased relative to those for the same country in Table 1. The full count Collab-CNCI ranking is still heavily influenced by the number of articles (small counts are associated with high CNCI) and the five highest ranked are relatively small countries: St. Lucia (3.46 CNCI, 56 articles), Micronesia (3.38, 153), Belize (2.42, 213), Afghanistan (1.29, 660) and Marshall Islands (1.26, 48).

For the more complex collaborative group (international quadrilateral-plus), overall ranking again closely matches the full counting method, reaffirming the influence of multi-national articles on full counting mean (Collab) CNCI. This is particularly true where they account for a significant fraction of a country's articles as they do for St. Lucia (29 % of articles are quadrilateral-plus) and Micronesia (33 % quadrilateral-plus).

Mean Collab-CNCI results for the five large and five smaller research economies are presented in Table 4 (alongside the full count values from Table 2), ranked by full count mean Collab-CNCI. Using full count Collab-CNCI, the USA now ranks highest (having overtaken fellow large research economies United Kingdom and Australia). Georgia and Sri Lanka, which previously ranked first and second, drop to fifth and sixth, respectively. The relative decrease in mean CNCI for the full count method with and without collaboration-type normalisation is greater for the smaller research economies: Georgia's mean CNCI falls from 1.84 to 0.95 and Sri Lanka from 1.46 to 0.80, approximately halving. By contrast, the larger countries experience a much smaller adjustment: the USA decreases from 1.32 to 1.23; China from 1.02 to 1.01.

3.5. Filtering for total output

Finally, we note that the introduction of filtering by article volume noticeably changes ranking. For example, filtering by a minimum of 1000, 10,000 and 100,000 articles for full counting (Table 5) results in different countries being ranking highest: Gambia (2.57 CNCI; 1202 articles), Iceland (1.97; 10,557) and Switzerland (CNCI 1.63; 279,089 articles), respectively. Considering only countries that (co)authored at least 10,000 articles over the ten-year period (an average of 1000 articles per year), then larger and more established research economies (e.g., USA, Netherlands, Denmark, Switzerland) rank as the top five for full (standard CNCI and Collab-CNCI) and fractional counting methods.

4. Discussion and conclusions

In our analysis of citation impact and collaborative authorship across 15,650,080 journal articles indexed in the *Web of Science* between 2009 and 2018, we have shown that individual country citation and CNCI profiles can vary significantly between collaboration types (e.g., domestic single and international quadrilateral-plus) and credit counting methods. The relative numbers of domestic and internationally collaborative papers therefore influence citation analysis outcomes. The 'boosting' effect of international collaboration is greatest where the total research capacity is smallest, which can be misleading for policy and management purposes. Fractional counting does not sufficiently account for these factors. We recommend that:

- Analysts should partition all article datasets with citation counts normalised by collaboration type (named Collab-CNCI) to enable improved interpretation for research policy and management.

Table 3
Top ranked countries by mean Collab-CNCI for each credit counting method, where an article's CNCI was additionally normalised by collaborative type. Each row contains (from top to bottom) the country's name, number of articles (for that method), and mean Collab-CNCI.

Rank	Parameter	Full counting	Fractional counting	Domestic single	Domestic multi	International bilateral	International trilateral	International quadrilateral plus
	Country	St. Lucia	French Polynesia	Marshall Islands	Monaco	Marshall Islands	Marshall Islands	St. Lucia
1	Articles	56	264.8	2	11	24	6	16
	Mean Collab-CNCI	3.46	1.60	2.91	2.54	1.30	2.79	10.92
	Country	Micronesia	USA	French Polynesia	French Polynesia	Bermuda	French Polynesia	Micronesia
2	Articles	153	2,884307.8	57	34	218	191	51
	Mean Collab-CNCI	3.38	1.27	2.11	2.30	1.18	1.44	8.81
	Country	Belize	Singapore	Netherlands	New Caledonia	Singapore	Singapore	Belize
3	Articles	213	71,882.5	65,215	60	49,777	16,643	65
	Mean Collab-CNCI	2.42	1.25	1.44	1.40	1.17	1.13	6.11
	Country	Afghanistan	Netherlands	Denmark	Switzerland	USA	China Mainland	Afghanistan
4	Articles	660	218,142.8	34,108	48,360	1,012,022	87,522	114
	Mean Collab-CNCI	1.29	1.22	1.34	1.29	1.12	1.12	5.04
	Country	Marshall Islands	Switzerland	Guinea Bissau	Singapore	Netherlands	USA	Barbados
5	Articles	48	140,963.6	2	26,724	117,465	255,689	169
	Mean Collab-CNCI	1.26	1.19	1.32	1.29	1.12	1.12	3.25

Table 4
Mean Collab-CNCI for five large and five smaller research economies across different credit counting methods, where an article's CNCI was normalised by collaborative type. Data are ordered by full count normalised mean CNCI. Cells contain ranking within group (global ranking), mean CNCI and coverage (percentage of a country's articles covered by method or type). The highest ranked country in each column is in **bold**.

Country	Parameter	Full count	Full count (Collab-CNCI)	Domestic single (Collab-CNCI)	Domestic multi (Collab-CNCI)	International bilateral (Collab-CNCI)	International trilateral (Collab-CNCI)	International quadrilateral plus (Collab-CNCI)
USA	Rank (global)	5 (69)	**1 (8)**	**1 (2)**	**1 (6)**	**1 (6)**	**1= (4=)**	8 (114)
	Mean CNCI (coverage)	1.32 (100 %)	**1.23 (100 %)**	**1.32 (17 %)**	**1.27 (47 %)**	**1.12 (26 %)**	**1.12 (6%)**	1.19 (4%)
United Kingdom	Rank (global)	3 (58)	2 (16)	2 (7)	2 (9)	2= (8=)	3= (8=)	9 (117)
	Mean CNCI (coverage)	1.42 (100 %)	1.17 (100 %)	1.31 (24 %)	1.19 (21 %)	1.08 (32 %)	1.08 (13 %)	1.18 (10 %)
Australia	Rank (global)	4 (65)	3 (19)	3 (10)	3 (10)	2= (8=)	3= (8=)	4 (67)
	Mean CNCI (coverage)	1.37 (100 %)	1.14 (100 %)	1.21 (25 %)	1.09 (23 %)	1.08 (33 %)	1.08 (11 %)	1.36 (8%)
China	Rank (global)	8 (120)	4 (36)	4 (24)	4 (19)	2= (8=)	**1= (4=)**	5 (89)
	Mean CNCI (coverage)	1.02 (100 %)	1.01 (100 %)	1.01 (36 %)	0.96 (39 %)	1.08 (20 %)	**1.12 (4%)**	1.27 (2%)
Georgia	Rank (global)	**1 (25)**	5 (46)	9 (158)	9 (126)	10 (133)	10 (128)	2 (23)
	Mean CNCI (coverage)	**1.84 (100 %)**	0.95 (100 %)	0.30 (18 %)	0.33 (9%)	0.58 (26 %)	0.67 (10 %)	1.78 (36 %)
Sri Lanka	Rank (global)	2 (52)	6 (76)	7 (106)	7 (104)	7 (110)	9 (115)	**1 (10)**
	Mean CNCI (coverage)	1.46 (100 %)	0.80 (100 %)	0.47 (21 %)	0.42 (17 %)	0.62 (35 %)	0.69 (11 %)	**2.14 (15 %)**
Ethiopia	Rank (global)	6 (91)	7 (88)	5 (60)	5 (51)	6 (97)	7 (90)	3 (40)
	Mean CNCI (coverage)	1.18 (100 %)	0.77 (100 %)	0.69 (19 %)	0.64 (19 %)	0.66 (37 %)	0.73 (14 %)	1.52 (12 %)
Chile	Rank (global)	7 (119)	8 (96)	6 (86)	6 (72)	5 (69)	5 (56)	7 (101)
	Mean CNCI (coverage)	1.03 (100 %)	0.74 (100 %)	0.58 (24 %)	0.55 (18 %)	0.73 (33 %)	0.82 (12 %)	1.22 (14 %)
Indonesia	Rank (global)	9 (185)	9 (185)	8 (156)	8 (149)	8= (112=)	8 (104)	6 (96)
	Mean CNCI (coverage)	0.71 (100 %)	0.50 (100 %)	0.31 (33 %)	0.26 (19 %)	0.61 (31 %)	0.70 (10 %)	1.26 (7%)
Russia	Rank (global)	10 (205)	10 (194)	10 (165)	10 (123)	8= (112=)	6 (83)	10 (119)
	Mean CNCI (coverage)	0.53 (100 %)	0.43 (100 %)	0.28 (31 %)	0.34 (41 %)	0.61 (17 %)	0.74 (6%)	1.17 (5%)

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Table 5
Top ranked countries by mean CNCI for full count, mean Collab-CNCI for full count and mean CNCI for fractional count methods filtered by countries authoring at least 1000, 10,000 and 100,000 articles. Each row contains (from top to bottom) the country's name, number of articles (for that method), and mean CNCI.

Rank	Parameter	Full count (≥1000)	Full count (≥10,000)	Full count (≥100,000)	Full count (Collab-CNCI; ≥1000)	Full count (Collab-CNCI; ≥10,000)	Full count (Collab-CNCI; ≥100,000)	Fractional count (≥1000)	Fractional count (≥10,000)	Fractional count (≥100,000)
	Country	Gambia	Iceland	Switzerland	USA	USA	USA	Singapore	Singapore	Switzerland
1	Articles	1,202	10,557	279,089	3,964,964	3,964,964	3,964,964	71,914.3	71,914.3	140,981.6
	Mean CNCI	2.57	1.97	1.63	1.23	1.23	1.23	1.34	1.34	1.33
	Country	New Caledonia	Switzerland	Denmark	Singapore	Singapore	Singapore	Switzerland	Switzerland	Netherlands
2	Articles	1,665	279,089	164,189	120,605	120,605	120,605	140,981.6	140,981.6	218,164.9
	Mean CNCI	2.39	1.63	1.60	1.22	1.22	1.22	1.33	1.33	1.30
	Country	Rwanda	Denmark	Netherlands	Netherlands	Netherlands	Netherlands	Netherlands	Netherlands	USA
3	Articles	1,965	164,189	370,884	370,884	370,884	370,884	218,164.9	218,164.9	2,885,185.7
	Mean CNCI	2.36	1.60	1.59	1.21	1.21	1.21	1.30	1.30	1.29
	Country	Panama	Netherlands	Singapore	Gambia	Denmark	Denmark	USA	USA	United Kingdom
4	Articles	3,939	370,884	120,605	1,202	164,189	164,189	2,885,185.7	2,885,185.7	673,017.4
	Mean CNCI	2.31	1.59	1.52	1.21	1.19	1.19	1.29	1.29	1.25
	Country	Papua New Guinea	Estonia	Belgium	Denmark	Switzerland	Switzerland	United Kingdom	United Kingdom	Australia
5	Articles	1,291	18,914	208,202	164,189	279,089	279,089	673,017.4	673,017.4	366145.6
	Mean CNCI	2.27	1.59	1.47	1.19	1.18	1.18	1.25	1.25	1.15

- Analysts should consider filtering out smaller entities from multinational and multi-institutional analyses where their inclusion is likely to obscure interpretation.

Greater collaboration (more researchers, institutions, countries) generally produces more impactful science (i.e., a higher CNCI). There is a known difference between domestic and international collaborative articles (Adams, 2013) but methods for comparing CNCIs for each entity (researchers, institutions, countries) can obscure important details about their research portfolio, possibly compromising quantitative evaluation through CNCI or other indicators.

In this paper we presented a typology of authorship that can be used to inform and improve current approaches to evaluation. Articles were divided into five categories representing domestic (single and multi-institution) and international (bilateral, trilateral and quadrilateral-plus) to gain insight into the distribution and driving factors behind CNCI values.

Large and established research economies (e.g., USA, China, United Kingdom) produce a large absolute volume of international collaborative articles, but this represents a lower relative share of their total articles compared to other countries. Mean CNCI rankings for a selected group of five large and five smaller economies were consistent through the collaboration types of domestic single to international trilateral and agreed with those using a fractional counting method (Table 2). However, there was a more significant increase in mean CNCI between international trilateral and quadrilateral-plus collaboration which produced less familiar outcomes, confirming the significance of these article types on a country's mean CNCI (Tables 1 and 2).

To extend the implementation of collaboration typology into citation analysis, we introduced the Collab-CNCI, where the CNCI of each article in the dataset was additionally normalised by collaboration type. This reduced the impact of large collaborative articles on a country's mean CNCI when using the full count method, providing a more balanced view than the standard mean CNCI (Table 4).

By dividing articles into collaborative types, article distribution can be analysed intra- and inter-nationally. This allows us to recognise, understand and describe multi-author effects and, therefore, interpret single metric values obtained through fractional or full counting methods. As all articles in each collaboration type are of the same nature, fractional counting and, therefore, credit estimation, is not required.

Context is critical. The number of articles must be considered when comparing entities, because significant differences in output volume result in significant effects on average citation impact. The interpretation of collaboration type is a further argument in favour of profiling publication portfolios rather than relying on a single, summary metric for CNCI values. A profiling method could be applied at an individual author, institution, or country level to help better understand research activity and inform and drive policy.

4.1. Large and smaller research economy differences

In the context of collaborative research analysis, the size of large research economies is a dominant characteristic: greater capacity means more research activity and output; activity also creates the opportunity to be involved in more projects, including collaborative ones. Additionally, the collaborative output volume is itself significant. For example, the USA published 148,323 quadrilateral-plus articles in ten years compared with Georgia's 6485 total articles in the same period.

Critically, USA and China, whose size and capacity allow them to be the two largest research-producing countries and have a network of large, research-intensive institutions, also have a very substantial domestic output. Though large research economies are involved in more projects at all collaboration scales (Fig. 4), international collaboration with four or more countries remains relatively scarce (Adams & Gurney, 2018; only 1.7 % of all articles analysed here). The consequence of a large domestic capacity is that international quadrilateral-plus articles generally have a lower share of total output (3.7 % for the USA, 7.9 % for Australia) than the smaller research economies (Indonesia 7.3 %, Chile 14.2 %, Sri Lanka 15.3 %, Georgia 36.2 %).

Among the ten sample countries, the smaller research economies garner the majority (>50 %) of citations from their international collaborative articles (Fig. 5). International collaboration for smaller research economies can be focused on pertinent national issues (i.e., public, environmental and occupational health) that require large cooperative projects. For example, Indonesia, Ethiopia, Sri Lanka and Georgia, are all participants on a high CNCI (364.32) longitudinal study on obesity (Ng et al., 2014); the USA, United Kingdom, China, Australia and Russia are also among the 40 co-authoring countries. Micronesia was also involved in a similar study (GBD 2015 Mortality & Causes of Death Collaborators, 2016).

Collaboration can also be driven by international emergencies. Following several large outbreaks, beginning in 2007, the Zika virus became a focus for assorted smaller research economies in the Tropics, spawning many highly cited articles. This work included Micronesia (Duffy et al., 2009), Marshall Islands (Shapiro-Mendoza et al., 2017) and French Polynesia (Dejnirattisai et al., 2016; Hamel et al., 2015). This was an exceptional share of their total research output or CNCI credit and explains their high-ranking positions in terms of mean CNCI (Table 1).

International collaboration for smaller research economies may also be highly specialised. For example, Chile is involved in large-scale astronomy and astrophysics projects (Planck telescope: Planck Collaboration & Ade et al., 2014; Planck Collaboration & Ade et al., 2016) and particle physics (CERN: CMS Collaboration, 2012a); Georgia is also involved in CERN projects (CMS Collaboration, 2012b). Sri Lanka benefits from its involvement in both public, environmental and occupational health (e.g., Lozano et al., 2012) and particle physics (Aad & (ATLAS Collaboration, CMS Collaboration), 2015).

The large international collaborations for smaller research economies (e.g., Sri Lanka, Georgia) produced a greater range of CNCI values than other collaborative types (Fig. 5). These high-value CNCI outliers dictate the mean CNCI for this category and, consequently, the overall mean CNCI, boosting their ranking (Table 2).

Large research economies are also involved in specialised projects, such as CERN, and large clinical medicine studies which garner many citations. However, as noted, these countries also produce significant output across all other collaboration types and have well cited domestic output. Unlike the smaller economies, their CNCI range is similar for all collaboration types (Fig. 4), limiting the influence of high mean CNCI for large international collaborations on their overall mean CNCI (Table 2).

4.2. Credit counting methods

When comparing mean CNCIs across countries, the rankings under different counting methods are heavily influenced by sample sizes. This becomes most apparent for the smallest research economies, which have fewest articles over the ten-year period, so that outliers become most influential (Table 1). Micronesia (153 articles), Marshall Islands (48), St. Lucia (56) and other smaller research economies (mainly Pacific or Caribbean islands) benefit across the counting methods from co-authorship of a relatively small number of articles which have a relatively high CNCI. Filtering by a given number of articles (Table 5) presents a more comparative view of countries with similar article output.

Fractional counting generally benefits large research economies, improving their ranking relative to smaller economies: Switzerland, Netherlands and USA rank in the top five of all countries analysed by fractional counting (Table 1); the large research economies rank highest in Table 2. Comparing fractional credit count to full credit count also highlights the level of international collaboration (i.e., countries with lower levels of collaboration will have a fractional credit count closer to their full credit count). For example, Marshall Islands (fractional credit to full credit ratio of 0.24), Micronesia (0.24), Belize (0.25), St. Lucia (0.31), Liberia (0.31) and French Polynesia (0.34) have far lower ratios than Switzerland (0.51), Netherlands (0.59), United Kingdom (0.59), Singapore (0.6), USA (0.73) and China (0.86). This is also highlighted in the Table 2 results: Georgia and Sri Lanka, which rank, respectively, first and second for full counting and third and first for international quadrilateral-plus, are ranked only seventh and eighth by fractional counting. This may suggest that their participation in the highly collaborative articles is marginal, but this would require expert review. However, the fractional credit arithmetically assigned to any one country based on author affiliations must generally be subject to reinterpretation on peer review or (better) author agreement.

Counting via a collaborative typology allows a more detailed analysis of a country's research output, without potentially assigning inaccurate fractional credit, as each category is self-contained. Ranking results between collaborative type and fractional counting are comparable (Table 2), except for international quadrilateral-plus where ranking is closer to that for full counting. Again, this highlights the influence of highly collaborative research on a country's mean CNCI index.

In Table 3, where CNCI has been normalised by collaboration type (Collab-CNCI), rankings are similar to those in Table 2. Our select smaller research economies still rank the highest for international quadrilateral-plus articles: Sri Lanka, Georgia and then Ethiopia. However, this ranking no longer follows that of the full count. The effect of normalising by collaborative type has significantly altered the full count ranking (relative to international quadrilateral-plus).

An evaluation of the fractional counting method using Collab-CNCI is not presented in Table 4. This was to avoid inaccurately assigning country credit to articles and because collaboration type was now included in the CNCI calculation. However, the calculation was done, with the unpublished results closely matching all collaborative types, bar quadrilateral-plus, in line with the previous calculation.

Author contributions

Ross W. K. Potter: Conceived and designed the analysis, Collected the data, Performed the analysis, Wrote the paper.
Martin Szomszor: Conceived and designed the analysis, Wrote the paper.
Jonathan Adams: Conceived and designed the analysis, Wrote the paper.

Declaration of Competing Interest

The authors are all employees of the Institute for Scientific Information which is part of Clarivate Analytics, the owner of the *Web of Science*.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.joi.2020.101075.

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