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Research Paper

Global trends in international research collaboration, 1980-2021①

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Citation: Aksnes, D. W., Sivertsen, G.. (2023). Global trends in international research collaboration, 1980-2021. *Journal of Data and Information Science*, 8(2), 26–42. https://doi.org/10.2478/jdis-2023-0015

Received: Feb. 14, 2023
Revised: May 16, 2023
Accepted: May 19, 2023

Abstract

Purpose: The aim of this study is to analyze the evolution of international research collaboration from 1980 to 2021. The study examines the main global patterns as well as those specific to individual countries, country groups, and different areas of research.

Design/methodology/approach: The study is based on the Web of Science Core collection database. More than 50 million publications are analyzed using co-authorship data. International collaboration is defined as publications having authors affiliated with institutions located in more than one country.

Findings: At the global level, the share of publications representing international collaboration has gradually increased from 4.7% in 1980 to 25.7% in 2021. The proportion of such publications within each country is higher and, in 2021, varied from less than 30% to more than 90%. There are notable disparities in the temporal trends, indicating that the process of internationalization has impacted countries in different ways. Several factors such as country size, income level, and geopolitics may explain the variance.

Research limitations: Not all international research collaboration results in joint co-authored scientific publications. International co-authorship is a partial indicator of such collaboration. Another limitation is that the applied full counting method does not take into account the number of authors representing in each country in the publication.

Practical implications: The study provides global averages, indicators, and concepts that can provide a useful framework of reference for further comparative studies of international research collaboration.

Originality/value: Long-term macro-level studies of international collaboration are rare, and as a novelty, this study includes an analysis by the World Bank's division of countries into four income groups.

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① A shorter and preliminary version of this paper was presented as a poster at the 26th International Conference on Science and Technology Indicators, STI 2022 (Aksnes & Sivertsen, 2022)

Keywords: International collaboration; Research collaboration; Team science; Co-authorship; Internationalization; Globalization

1 Introduction

International research collaboration is an important aspect of modern science. According to Adams (2013), such co-operation represents the fourth age of research, following the individual, the institutional, and the national ages. However, collaborative partnerships across borders have a long historical precedent, and Beaver and Rosen (1978) noted their emergence in the 19th century.

Already in 1958, Smith observed a rise in the number of publications authored by multiple individuals, suggesting that this reflected an increasing role of collaboration in science. Since then, utilizing information on the number of authors and their institutional affiliations has been a common way for studying the extent of collaboration bibliometrically (Katz & Martin 1997; Newman, 2001; 2004). Although not without limitations, co-authorship remains the most useful and empirically robust indicator for measuring and evaluating patterns of research collaboration (Cugmas et al., 2016).

International research collaboration in a global context has been analyzed in Science Citation Index (Web of Science (WoS)) for more than four decades. Early examples include Frame & Carpenter (1979) and later studies have confirmed the trends towards increased international collaboration and networks in science (see e.g., Adams 2012; 2013). Studies of international collaboration have also moved forward with conceptual clarifications (e.g., Katz & Martin, 1997), new indicators, e.g., of collaboration intensity (Coccia, & Bozeman 2016; Fuchs et al., 2021; Luukkonen et al., 1992), new visualization technologies (e.g., Van Eck & Waltman, 2014) and utilizing additional databases such as Scopus (Fu et al. 2022) Also, international collaboration (or collaboration more generally) has been addressed from a citation impact perspective, showing that such papers tend to be cited more than other articles (see e.g., Thelwall et al. 2023a).

Most studies of international collaboration have focused on specific periods, fields of research, countries, or geographic areas. The most recent global overviews of main patterns and trends in country-level collaboration are Coccia & Wang (2016), covering the period 1973-2012, Wagner et al. (2015), covering the period 1990-2011, and Lariviére et al. (2015), covering the period 1900-2011. These overviews have at the same time focused on specific aspects such as basic versus applied science, the relation to politics and economy, and team size.

The purpose of this study is to describe the main patterns and trends in international research collaboration over four decades, 1980-2021. We analyze the articles with

international collaboration as part of the whole database that is now named the Web of Science (WoS) Core Collection. Global patterns and trends in more than 50 million publications and more than a billion citations are analyzed. Although there is an extensive body of previous literature on international research collaboration, updated analyses are needed to demonstrate developments on a global level, particularly in recent years. Specifically, this paper addresses the following research questions:

- How has the extent of international research collaboration developed globally over the four decades, and what is the trend when analyzing citations?
- How does the degree of international research collaboration vary over time, across countries and across groups of countries? Here specific attention is given to the economic status of the countries.
- How has international collaboration evolved across fields? Here, we analyze sixteen main areas of research as aggregations of all subfields in WoS.

Our aim is to inspire new studies of international research collaboration by demonstrating how basic factors related to publications and citations have developed over four decades. Science and scientific publishing have grown tremendously since 1980, and so have the global configurations of country-level scientific production, collaboration, and citation impact.

2 Data and methods

2.1 Data

The study is based on the Web of Science (WoS) Core collection database, coverings Science Citation Index Expanded, Social Sciences Citation Index, Arts & Humanities Citation Index, Emerging Sources Citation Index, Conference Proceedings citation indexes, and the Book Citation Index. We have applied a local replication database of WoS maintained by the Norwegian Agency for Shared Services in Education and Research in collaboration with NIFU, our research institute.

In one analysis we apply the World Bank's classification of countries into income groups (i.e., high, upper middle, lower middle, and low income), based on the 2020 gross national income (GNI) per capita (data source: https://data.worldbank.org/), see World Bank (2022a and 2022b).

2.2 Measure/ indicator applied

International collaboration is defined as scientific articles with affiliations of

authors in at least two countries. That is, an article is considered to be internationally co-authored when authors are affiliated with institutions located in different countries. This principle is commonly applied in bibliometric studies of scientific collaboration based on co-authorship data (Katz & Martin, 1997). Data in the address field of the publications are used to identify the country of the institutions and authors.

There is a special case where a paper has only one foreign address, but this is because one of the authors has both a domestic and international affiliation. In such cases, these papers are considered as internationally co-authored. We believe this is reasonable because publications authored by researchers with both domestic and international affiliations have an institutional international collaborative dimension.

In cases where two different countries are listed in the address field, the publication is considered as involving bilateral collaboration. Similarly, trilateral collaboration applies to cases where three different countries are present and multilateral collaboration to papers involving four or more different countries.

2.3 Analysis procedure

The analyses are carried out at a global level. The study covers the period 1980-2021 and is based on 51.7 million publications and 1.1 billion citations received by these publications. Included are publications of the following main types: article, review, proceedings paper, book, and book chapter. Minor contributions such as editorials, letters and abstracts are excluded.

The analysis of research subfields is based on the approximately 250 field categories of the WoS-database. These have further been aggregated in 16 main areas of research based on a classification method developed by the Nordic NORIA-network (for details, see Piro et al., 2017).

3 Results

3.1 Global developments

There has been a very strong growth in the annual number of indexed scientific publications in the last 41 years. In 1980, 406,000 papers were indexed, compared with 2,880,000 in 2021. Thus, the annual production as measured within the data source has increased by more than 600%. The increase is probably related to at least four factors, the expansion of the global research system itself within the economies and as an expression of economic growth, the integration of local research activities in a global research communication and publishing system, increased collaboration and mobility among researchers, and an increased journal coverage in the Web of

Science (Aksnes & Sivertsen, 2019). The addition of new WoS indexes contributed to this, in particular the Proceedings citation index starting at the beginning of the 1990s and the Emerging source citation index from 2005 and onwards.

Figure 1 shows the development of publication numbers by collaboration type. In Figure 2, the corresponding proportions are displayed. In 1980, 4.7% of the publications involved international collaboration. This proportion increased to 25.7% in 2021. Although the number of publications involving such collaboration has grown at a rapid rate, domestic research still dominates, as three out of four publications in 2021 were authored by researchers in one country only.

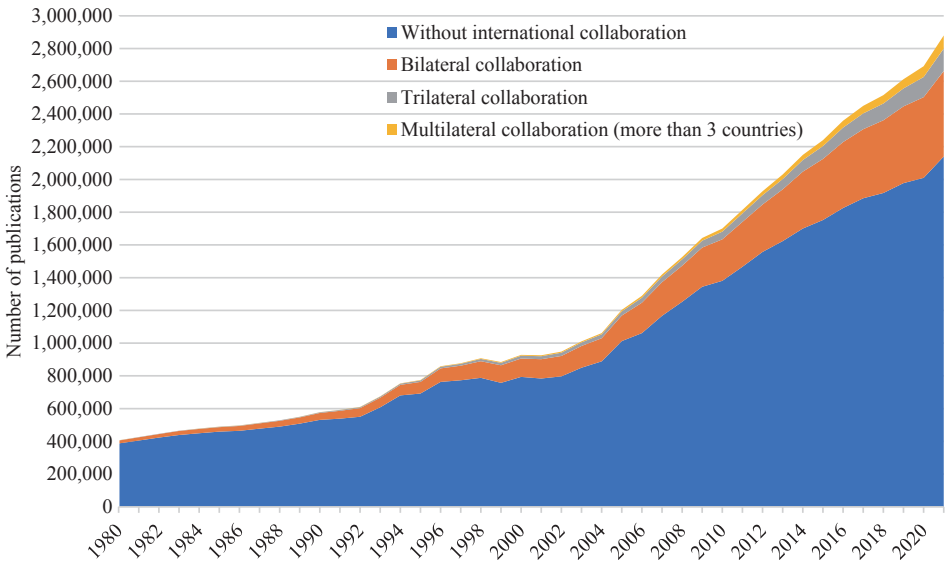

Figure 1. Number of publications by types of international collaboration, 1980-2021.

Bilateral collaboration is by far the most common type of international collaboration. In 2021, 18% of all articles published globally involved collaboration between researchers located in two different countries. The proportion was only 4.4% in 1980 and has increased steadily during the four decades, with some annual fluctuations. One notable exception is a reduction of 0.4 percentage points in 2005, likely related to the major expansion of the database this year with the addition of the Emerging source index.

Trilateral and multilateral collaboration was extremely rare in 1980, accounting for 0.3% and 0.06% of the publications, respectively. In 2021, these figures were 4.8% and 2.8%. In relative terms, the growth has been exceptional, as multilateral collaboration was 50 times more common in 2020. At the same time, bilateral

cooperation still dominates in terms of volume. This point was also noted by Adams (2013), who observed that much of the growth in international collaboration can be attributed to bilateral partnerships rather than multinational programs.

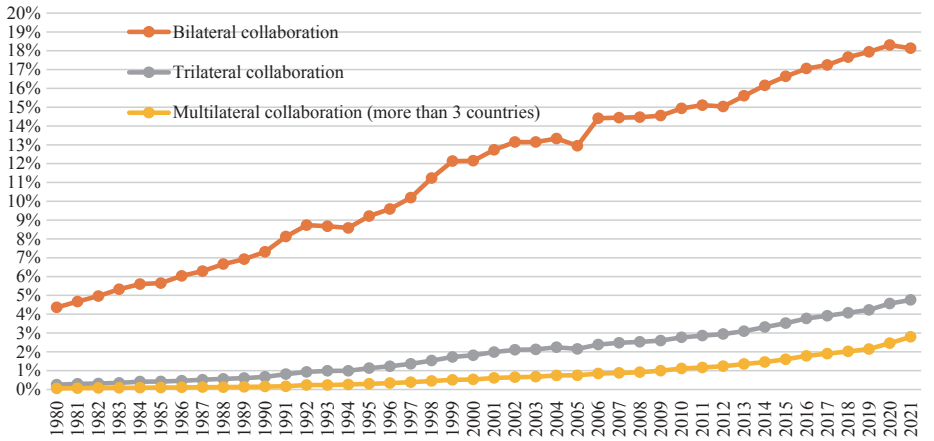

Figure 2. Proportions of the world production of articles involving international co-authorship, 1980-2021, in three groups: multilateral, trilateral, bilateral collaboration.

It has been known for a long time that articles involving international collaboration are more cited on average than other papers (Narin et al., 1991). In Figure 3 this is shown at a global level. Here, it is calculated as the proportion of all citations received by the internationally co-authored publications. For example, the papers

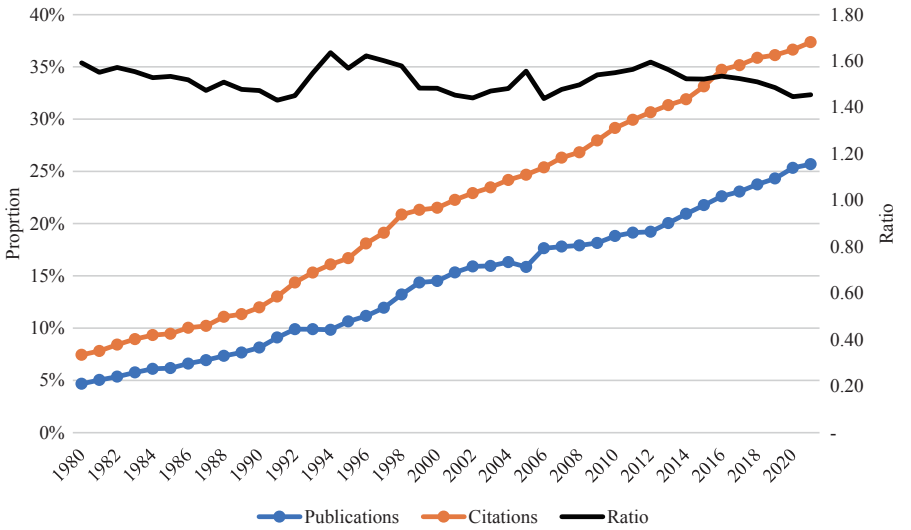

Figure 3. Proportion of internationally co-authored publications and their share of all citations.

published in 1980 have in total received 10 mill citations. Of these, 748,000 were to the 1980-papers involving international collaboration. This corresponds to a proportion of 7.4%, which is 1.6 times higher than the publication share (4.7%). Over time, the proportion of the citations has increased at a similar rate as the publications (shown by the black line in Figure 3) and passed 35% in 2016. This analysis shows that in terms of impact, the internationally co-authored publications have a more important role in the global research system than suggested by the publication numbers.

4 Country level developments

The proportion of articles with international collaboration is necessarily higher when studied at country level. The reason is that articles with international collaboration are deduplicated when counted at the global level (the whole database) while they are counted once for each contributing country when specified for individual countries.[②] The most recent figures, covering 2020 and 2021 combined, show that there are only three countries with an international collaboration rate of less than 30%: China, India, and Turkey (all with 26%). On the other hand, there are several nations where the international collaboration rate is as high as 90% or more, for example, Sudan, Malawi, and Mongolia. From the perspective of each country, international research collaboration is much more prevalent and important than suggested by overall global average figures. Indeed, many of the European countries have collaboration rates of 60% or more.

The country proportions are visualized in the world map presented in Figure 4. The collaboration rate tends to be particularly high in many African countries, as well as in some countries in South America and Asia. These tend to be low-income countries with a higher degree of dependency on investments in research in collaborating countries (Boshoff, 2010). However, cross-national collaboration is also very frequent in many high-income countries, e.g., within the European Union,

[②] The table below illustrates this point. Here 1 of 3 articles (33 percent) are internationally co-authored, but the proportions for each country are 50 and 100 percent.

Article	Country A	Country B	Country C
Article 1	X	X	X
Article 2		X	
Article 3			X
Total number of articles	1	2	2
Number of internationally co-authored articles	1	1	1
Proportion of internationally co-authored articles	100%	50%	50%

where collaboration is stimulated by the funding sources (Hoekman et al., 2013; Kwiek, 2021; Leydesdorff, 2000). Another important factor explaining high rates of collaboration among high-income countries is the investment in large and expensive international research infrastructures in certain fields (Csomós et al., 2020) There might be a U-shaped relationship between collaborationrates and the economic status of the nations.

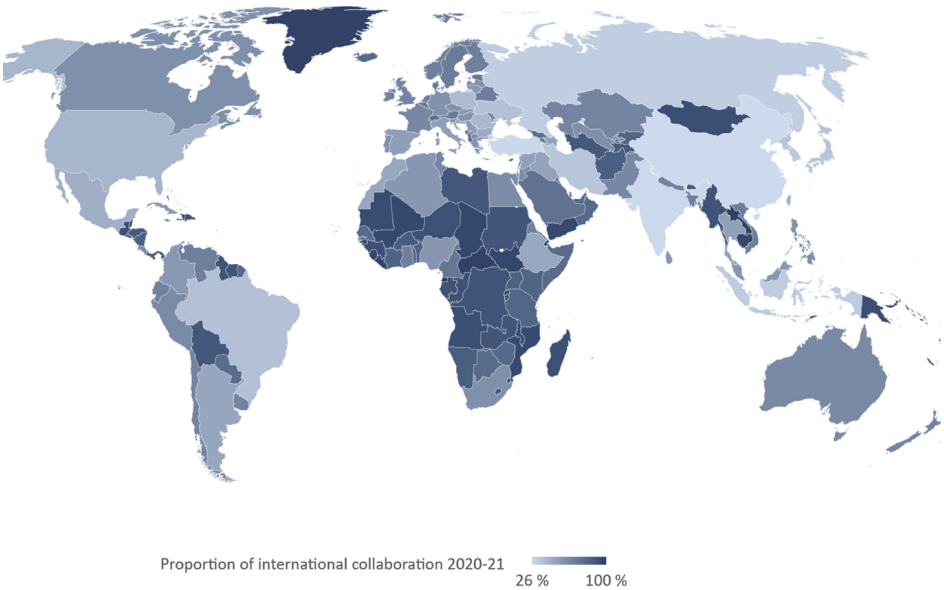

Figure 4. Proportion of international collaboration by country/region, 2020-2021

Table 1 shows the average rate of international collaboration by country income groups as classified by the World Bank. Here, the averages have been weighted according to the size of the countries in terms total number of publications. The results show a U-shaped pattern, but our further analysis revealed that the correlation between the level of income and the collaboration rate of countries is relatively weak.

Table 1. Average proportion of international collaboration by country income groups, 2020-2021.

Country group	Number of countries/regions	Average rate of international collaboration (weighted)
Low income	27	74%
Lower middle income	55	42%
Upper middle income	54	33%
High income	72	54%

In order to provide further insight into the collaboration patterns of different

country groups, we analyzed intergroup relations. Here, we investigated the proportion of articles from different country groups that involved co-authorship with other country groups. The results for the 2020-2021 period combined are illustrated in Figure 5. As can be seen, 15% of the articles from high-income countries had co-authors from upper-middle-income countries. Conversely, 25% of the publications from upper-middle countries had co-authors from high-income countries. Although the number of collaborative articles underlying these two calculations is identical, the proportions differ. This is due to the fact that the total population of papers representing the divisor in the calculation differs and is much higher for the high-income countries. This effect is most pronounced in the case of collaboration between high- and low-income countries. Overall, 54% of the publication of low-income countries involve collaboration with high-income countries, while the obverse proportion is 0.6 %, only. The asymmetry may even occur in the topic of the research. Most of the many studies that focus on health problems in high-income countries only involve authors from the same group of countries, while most of the few studies that focus on health problems in low-income countries involve authors in both groups of countries (Jacobsen, 2009).

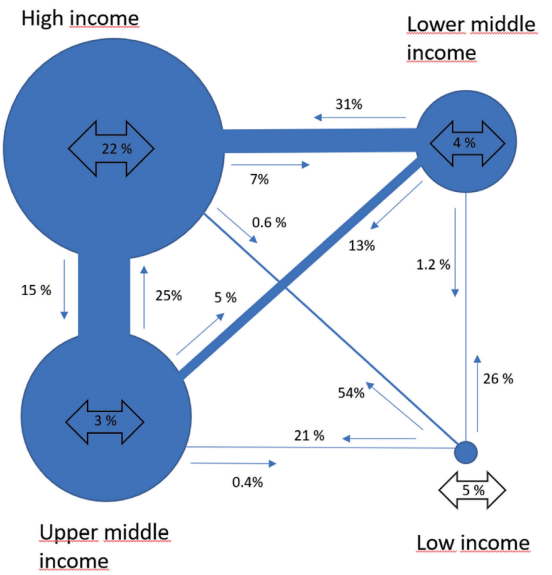

Figure 5. Collaboration patterns across country income groups, 2020-2021. Proportions of all publications.* *) N, high-income countries = 3.489.452 publications. N, upper middle-income countries = 2.071.524 publications. N, lower middle-income countries = 772.785 publications. N, low-income countries = 36.005 publications. Double counts excluded (publications with authors from more than one country/region in each country group).

The figure also shows the proportion of publications involving collaboration between different countries within each country group (marked with a double arrow).

For the high-income countries, this proportion is 22%, while it is much lower for the other country groups (3-5%). Thus, the international collaboration profile of the latter groups is mainly directed towards high-income countries.

Our analyses confirm that the size of countries influences collaboration rates (Luukkonen et al., 1992). Countries/regions with smaller publication output have on average higher shares of international collaboration than larger countries. However, also here the correlation is modest. The linear correlation coefficient based on data for the 30 largest countries in publication volume is -0.37 (Y=-680117X+573003), while it is -0.35 when extending the dataset to the 60 largest countries.

We have further analyzed how the collaboration rate has developed at country/region levels over the four decades, see Table 2. There are large differences in the

Table 2. Proportion of publications involving international collaboration by country/region.* Five-year time-periods (1981-2020) and most recent two-year period (2020-2021)

	1981-1985	1986-1990	1991-1995	1996-2000	2001-2005	2006-2010	2011-2015	2016-2020	2020-2021	Overall change (pct. Points)
Switzerland	25 %	32 %	37 %	44 %	52 %	61 %	66 %	73 %	75 %	50
Saudi Arabia	24 %	16 %	16 %	22 %	33 %	46 %	72 %	75 %	75 %	51
Belgium	22 %	28 %	34 %	41 %	48 %	55 %	62 %	70 %	73 %	51
Sweden	19 %	24 %	30 %	37 %	44 %	52 %	58 %	66 %	70 %	51
Denmark	22 %	26 %	33 %	43 %	48 %	55 %	58 %	66 %	70 %	48
Netherlands	17 %	21 %	26 %	35 %	42 %	49 %	56 %	65 %	68 %	51
UK	13 %	16 %	21 %	28 %	36 %	42 %	50 %	60 %	65 %	52
France	15 %	19 %	25 %	32 %	39 %	46 %	52 %	61 %	63 %	48
Pakistan	26 %	27 %	27 %	33 %	33 %	32 %	42 %	53 %	63 %	37
Australia	13 %	16 %	20 %	27 %	35 %	40 %	47 %	58 %	62 %	49
Egypt	18 %	20 %	22 %	27 %	31 %	38 %	49 %	54 %	61 %	43
Canada	16 %	19 %	23 %	30 %	36 %	41 %	47 %	55 %	59 %	43
South Africa	12 %	13 %	17 %	28 %	38 %	40 %	46 %	53 %	59 %	47
Germany**	11 %	18 %	24 %	30 %	38 %	44 %	49 %	55 %	58 %	47
Portugal	37 %	35 %	37 %	39 %	43 %	46 %	48 %	55 %	58 %	21
Malaysia	26 %	33 %	32 %	36 %	35 %	32 %	35 %	45 %	56 %	30
Spain	10 %	17 %	25 %	29 %	33 %	36 %	43 %	50 %	52 %	42
Italy	17 %	22 %	25 %	30 %	33 %	39 %	43 %	50 %	51 %	34
Taiwan, China	23 %	17 %	16 %	15 %	16 %	19 %	24 %	37 %	44 %	21
Mexico	26 %	27 %	31 %	35 %	38 %	39 %	39 %	42 %	44 %	18
USA	7 %	9 %	12 %	17 %	21 %	27 %	32 %	39 %	41 %	34
Poland	17 %	24 %	34 %	35 %	35 %	31 %	29 %	34 %	38 %	21
Brazil	20 %	24 %	30 %	30 %	28 %	24 %	27 %	34 %	36 %	16
Japan	6 %	8 %	11 %	14 %	18 %	23 %	27 %	32 %	34 %	28
Iran	31 %	32 %	29 %	24 %	21 %	19 %	20 %	26 %	34 %	3
South Korea	32 %	28 %	25 %	20 %	22 %	24 %	27 %	30 %	33 %	1
Russia***	5 %	4 %	15 %	25 %	31 %	30 %	28 %	26 %	30 %	25
China	17 %	19 %	21 %	20 %	18 %	18 %	20 %	25 %	26 %	9
India	6 %	8 %	11 %	14 %	18 %	19 %	18 %	21 %	26 %	20
Turkey	27 %	20 %	20 %	18 %	17 %	16 %	18 %	23 %	26 %	-1

*) Limited to the World' 30 largest scientific countries/regions by publication numbers in 2020-2021, ranked by decreasing proportions of international collaboration in 2020-2021

**) Average for East and West Germany in the periods 1981-85 and 1986-1990

***) Figures for Soviet Union used in the periods 1981-85 and 1986-1990

temporal developments, suggesting that the internationalization process has affected countries very differently. Half of the countries have increased the proportion of international collaboration by more than 40 percentage points. Four countries stand out with low rates of change because the percentage shares have followed a U-shaped development: Iran, South Korea, China, and Turkey. The scientific production of these countries within Web of Science has grown immensely during the last forty years. Most articles with international collaboration were with USA as the partner in the beginning, and the frequency of international collaboration was typical of small countries, as explained above. The frequency initially decreased with their growth, and then increased again as they became important partners for countries all over the world.

We checked whether our measurement of the internationalization process is influenced by the inclusion in Web of Science of mainly domestic journals from some countries. We found that the international collaboration rates in most countries are almost identical when excluding such journals, except for some smaller Latin American countries.

5 Developments in different areas of research

Changes and differences of time are also observed at the level of areas and fields of research. In 2020-2021, the rate of international collaboration was highest in *Biology* as well as in the category covering the *Multidisciplinary journals* (35%). The temporal trend shows that the internationalization process also has been strongest in these categories. Forty years ago, the collaboration rate was highest in *Mathematics and statistics* and in *Physics*. At the other end, we find the *Humanities* where one out of ten articles (11%) have authors from more than one country in 2020-2022. The main reason for the low percentage is that most publications in this area of research are single-authored (Puuska et al., 2014). However, both the humanities and the social sciences have had a remarkable change during the forty years from almost only relying on single authorship to more widespread use of co-authorship and international collaboration.

Using the more fine-grained WoS-classification system, the subfields shown in Table 4 have the highest proportions of international collaboration. On the top, we find Astronomy & Astrophysics where more than half of the publications involve such authorship in 2021-2021. In general, disciplines requiring large research infrastructures or global multi-centers tend to have high international collaboration rates (Coccia & Wang, 2016).

Table 3. Proportion of publications involving international collaboration by area of research. Five-year time-periods (1981-2020) and most recent two-year period (2020-2021)

	1981-1985	1986-1990	1991-1995	1996-2000	2001-2005	2006-2010	2011-2015	2016-2020	2020-2021	Overall change (pct. points)*
Biology	6 %	8 %	10 %	16 %	22 %	27 %	30 %	34 %	35 %	29
Multidisciplinary jnls	7 %	8 %	13 %	16 %	23 %	26 %	31 %	34 %	35 %	28
Geosciences	8 %	9 %	11 %	16 %	22 %	26 %	29 %	32 %	33 %	25
Business stud & economics	6 %	8 %	9 %	12 %	16 %	17 %	22 %	27 %	32 %	26
Mathematics & statistics	10 %	13 %	15 %	18 %	21 %	22 %	25 %	29 %	30 %	20
Physics	10 %	12 %	15 %	18 %	20 %	24 %	25 %	28 %	30 %	20
Biomedicine & molecular biosci.	7 %	9 %	12 %	16 %	19 %	22 %	24 %	26 %	27 %	20
Agriculture, fisheries & forestry	4 %	6 %	8 %	12 %	16 %	19 %	22 %	26 %	27 %	23
Computer & information sci.	6 %	8 %	7 %	7 %	8 %	14 %	18 %	23 %	27 %	21
Materials science	7 %	8 %	11 %	14 %	18 %	19 %	19 %	25 %	26 %	19
Psychology	3 %	4 %	6 %	9 %	12 %	16 %	20 %	24 %	26 %	23
Chemistry	6 %	8 %	11 %	14 %	17 %	18 %	20 %	24 %	25 %	19
Health sciences	4 %	5 %	7 %	10 %	14 %	16 %	20 %	23 %	25 %	21
Engineering	5 %	6 %	7 %	8 %	9 %	14 %	17 %	22 %	25 %	20
Clinical medicine	4 %	5 %	7 %	10 %	14 %	17 %	19 %	22 %	22 %	18
Social sciences	3 %	4 %	5 %	6 %	9 %	12 %	14 %	18 %	22 %	19
Humanities	1 %	1 %	1 %	2 %	3 %	6 %	8 %	10 %	11 %	10

*) Change in percentage points from 1981-85 to 2020-21.

Table 4. Proportion of publications involving international collaboration by WoS-categories.* Five-year time-periods (1981-2020) and the most recent two-year period (2020-2021)

	1981-1985	1986-1990	1991-1995	1996-2000	2001-2005	2006-2010	2011-2015	2016-2020	2020-2021	Overall change (pct. points)**
Astronomy & Astrophysics	18 %	21 %	25 %	29 %	32 %	42 %	46 %	52 %	53 %	35
Evolutionary Biology	10 %	12 %	16 %	24 %	33 %	38 %	43 %	49 %	50 %	40
Palaeontology	12 %	12 %	16 %	25 %	32 %	39 %	44 %	48 %	50 %	38
Tropical Medicine	17 %	23 %	31 %	37 %	43 %	42 %	44 %	47 %	48 %	31
Parasitology	10 %	14 %	20 %	27 %	31 %	34 %	40 %	45 %	43 %	33
Physics, Particles & Fields	20 %	20 %	24 %	27 %	29 %	33 %	37 %	42 %	43 %	23
Ecology	5 %	7 %	9 %	16 %	24 %	30 %	35 %	39 %	41 %	36
Biodiversity Conservation	5 %	6 %	8 %	14 %	21 %	29 %	33 %	38 %	40 %	35
Geochemistry & Geophysics	11 %	14 %	19 %	24 %	31 %	34 %	37 %	39 %	39 %	28
Neuroimaging	2 %	5 %	6 %	10 %	17 %	23 %	30 %	37 %	39 %	37
Physics, Nuclear	21 %	21 %	25 %	30 %	31 %	32 %	34 %	39 %	38 %	17
Mineralogy	14 %	17 %	21 %	26 %	33 %	33 %	36 %	39 %	38 %	24
Geography, Physical	8 %	9 %	13 %	19 %	27 %	29 %	35 %	37 %	38 %	30
Meteorology & Atmospheric Sci.	6 %	9 %	10 %	16 %	24 %	30 %	33 %	37 %	38 %	32
Mycology	7 %	9 %	14 %	20 %	25 %	30 %	33 %	38 %	37 %	30

*) Limited to the 15 WoS categories with the highest proportion of international collaboration in 2020-2021.
**) Change in percentage points from 1981-85 to 2020-21.

6 Discussion and conclusion

We have analyzed the growth and patterns of international research collaboration over the past four decades since 1980. Globally, the proportion of publications featuring such collaboration has increased from 5% in 1980 to 26% in 2021. However, this share is based on deduplication of all publications where two or more countries are involved. The share is significantly higher when analyzed at the country level. Of the world's 30 largest research nations, 21 have proportions above 40%, and none have proportions below 26%. Some countries have proportions above 70%.

The extent of international research collaboration represents a significant difference in how science is carried out today, compared to the recent past (Aksnes et al., 2008). Our study shows that all countries are increasingly involved in international collaboration, but the intensity and trends differ considerably among them. Why do these developments and differences appear? We have addressed some factors of importance in this paper.

The more general factor contributing to the overarching changes are the expansion and integration of the global research and publishing system, and the increased investments in mobility and collaboration. Other factors contribute to differences among the countries. One of them is that international collaboration tends to be more prevalent in smaller countries than in larger ones. This factor was identified at an early stage (Aksnes et al., 2008; Frame & Carpenter, 1979; Luukkonen et al., 1992). For researchers in a large country such as the United States, there are many potential collaborators within the country, whereas this is not necessarily the case in a smaller country like Iceland. Hypothetically, if the individual states within the US were independent countries, this would result in much higher rates of international collaboration because all inter-state collaboration would then be counted. Still, it should be emphasized that country size explains only a limited part of the variation in collaboration rates across nations.

Geographical closeness and similarity in specialization were also identified as important factors at an early stage (Luukkonen et al., 1992). The findings of this paper also suggest that the economic development of the countries may explain some of the variance as well as the general pattern of relations between groups of countries with different levels of income.

Some of our findings demand understanding of geopolitical relations and changes. A clear example is the low rate of – and lack of increase of – international collaboration with Iran. Political sanctions affect this country's science system (Butler, 2019). The shared investments in the EU Framework programs may explain the strong increases in collaboration activity among European countries (Csomós et al., 2020; Hoekman

et al., 2013). Perhaps still understudied is how the same "EU factor" influences Europe's relations with other parts of the world. China and the USA, the two largest science-producing countries, have for a long time emerged also as the most important scientific collaboration partners in the world, both in absolute numbers and in relative intensity (Fuchs et al., 2021), but their relation has been deteriorating recently (Tang et al., 2021; Zweig, 2021), and China seems to seek other partners (Rousseau et al., 2023). Further studies could investigate not only how global scientific collaboration is developing in general, but also how new configurations of close collaborations are emerging within and among different parts of the world.

Our study also highlights that high-income countries continue to play a significant role in the global research landscape, not only due to the volume of their research output but also as the primary collaborative partner for researchers from other regions of the world. Although this pattern was presumably even stronger in the past when China and other booming countries were minor research nations, a significant portion of collaborative linkages still flow towards the high-income countries.

Other aspects of international collaboration have also been analyzed in the paper. International collaborative articles have an even more important role in the global knowledge system measured by scientific impact. They tend to receive more citations, and overall, 37 percent of the citations went to such papers in 2021. Again, at the level of individual countries, the figures would be much higher than the global average, surpassing the countries' proportion of international collaboration.

Finally, international collaboration rates across fields and over time have been analyzed, showing that such collaboration tends to be most prevalent in natural science disciplines. The disciplinary hierarchy identified in the literature several decades ago (Frame & Carpenter, 1979; Luukkonen et al., 1992) still exists, although with some changes, but the extent of collaboration in all fields is now clearly at higher levels than previously observed.

A limitation of our study is that co-occurrences of countries in publications are counted without considering the number of contributing authors from each country/region, thereby disregarding the resources that each country/region contributes with in each collaboration project. Other counting methods, such as fractional counting, would have provided different results (Gauffriau, 2021; Thelwall et al., 2023b). An alternative could be to introduce fractional counting methods at the country level (e.g., Leydesdorff & Park, 2017) while at the same time ensuring comparability across fields of research to provide an indicator of the relative intensity of collaboration (Sivertsen et al., 2019). Methodological developments in this direction could be combined with a deeper analysis of how new configurations are emerging in global research collaboration. Our overview of major developments over four

decades presented here would then provide a framework for further progress in the study of international collaboration patterns.

Author contributions

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