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The changing world dynamics of research performance

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Abstract
In recent years, a notable diversification in the geographical representation of the World's top universities could be observed. Chinese universities play an increasingly prominent role in these rankings, thus indicating that we might be in the midst of a regional shift in academic performance. To explore this dynamics, we analyze seven years' worth of data used for university rankings by academic subjects from the Academic Ranking of World Universities (ARWU). We focus on China, Europe, the USA, and other global regions of the world. We find that China has indeed seen an unprecedented growth in Engineering and Life Sciences research, positioning itself rather firmly as a leader in these fields. Conversely, the USA leads in the Social Sciences, while Europe excels in Geography, Ecology, Public and Business Administration, and Pharmacy. Other regions worldwide stand out in Transportation Science, Nursing, and Hospitality & Tourism Management. These results reveal the evolving landscape of global academic research, highlighting regional strengths and emerging world trends in subject-specific excellence.

Keywords Research dynamics · Academic excellence · Geographical diversification · University rankings

Mathematics Subject Classification C55 · C80 · I20 · I23

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Introduction

In the evolving landscape of global higher education (HE), the ranking of universities has emerged as a tool for assessing the quality and impact of academic institutions worldwide. University rankings serve as a straightforward and accessible method of evaluation and assessment. The main goal of these rankings is to assist various stakeholders - such as students, parents, policymakers, funding bodies, and the universities themselves - in making well-informed decisions regarding the qualities and performance of higher education institutions (HEIs) based on different criteria (Nassa and Arora, 2021). In turn, the quest for excellence in higher education has led regions and countries to adopt diverse strategies aimed at enhancing their global standing in such ranking systems. One could argue that universities are learning to game the ranking systems rather than genuinely innovating in policy. Therefore, a clear description and understanding of the evaluation process is pivotal for enabling HEIs and stakeholders to comprehend the achieved rank and trends. In the 1980s, U.S. News & World Report began to provide annual consumer-type information about USA universities (Aghion et al., 2008). The published rankings were and still are influencing how schools allocate resources and prioritize programs (Hazelkorn, 2008; Moed, 2017). Over the following decades, ranking tables in various subject domains have emerged (Nassa and Arora, 2021; Vernon et al., 2018).

One of the first global university rankings was established by Shanghai Jiao Tong University with the release of Academic Ranking of World Universities (ARWU) or Shanghai Rankings in 2003 ShanghaiRanking Consultancy (2003). The ARWU ranking system is score-driven Docampo and Cram (2014) and uses six objective indicators to rank world universities ShanghaiRanking Consultancy (2003). The importance of the ARWU ranking system is acknowledged by governments and university administrators around the world Docampo and Cram (2014), Shehatta and Mahmood (2016). Several other ranking systems exist like the U.S. News & World Report, Carnegie Classification, Center for World University Ranking, QS World University Ranking, Times Higher Education World University Rankings (THES), CWTS Leiden Ranking and SCImago Institutions Rankings World Report to name just a few Vernon et al. (2018), Frenken et al. (2017). Building on this context, the reliability and robustness of these ranking systems, particularly ARWU and THES, have been scrutinized in academic circles.

A pivotal study by Saisana et al. used a multi-modeling approach to assess the validity of these rankings Saisana et al. (2011). Their findings highlight the greater reliability of macro-regional inferences compared to assessments at the individual university or country level, underscoring the need for a nuanced understanding when interpreting these rankings. Furthermore, Dobrota and Dobrota delved into the sensitivity and uncertainty of the ARWU ranking, focusing on the impact of excluding the award factor (Nobel Prizes and Fields Medals) Dobrota and Dobrota (2016). Their research showed that an alternative ranking without this factor increased certainty and stability, pointing to the necessity for a critical reevaluation of the criteria used in university rankings. Vernon et al. conducted a systematic review of 13 university ranking systems and discovered that generally accepted academic quality indicators are lacking in these systems. They suggest that future efforts should focus on better exploring the measurement of university research performance through comprehensive and standardized indicators Vernon et al. (2018).

The historical dominance of the USA in global university rankings, attributed partly to its economic prowess, contrasts with the rapid ascent of Chinese universities. This ascent surpasses that of countries with similar resources, marking a significant shift in the global academic hierarchy Li et al. (2011). Since 2012, China's total number and global share of articles included in the Nature Index have increased. This upward trend corresponds with data from the larger Web of Science (WoS) database. Between 2005 and 2015, the country's global share of articles, as well as those that are highly cited, more than doubled, as reported in a 2017 Nature News article titled "Charting China's rising dominance in science" U.S. News & World Report L.P. (2024). In 2016, China surpassed both the USA and the EU in the volume of scientific publications Tollefson (2018). Although there have been several discussions regarding the quality of these publications, China has notably advanced in the creativity and innovation of its contributions Wagner et al. (2020). China has risen to the first place in top cited papers, accounting for 27.2% of the most cited papers published in 2018, 2019, and 2020, compared to the USA's 24.9%. Following them was the United Kingdom with 5.5%; Japan ranked 10th Brainard and Normile (2022). The concerted efforts by the Chinese government, through initiatives like Project 985, have been instrumental in propelling Chinese universities to global prominence Song (2018), Zong and Zhang (2019). These initiatives, coupled with substantial investments in R&D and a focus on governance reforms, underscore China's strategic approach to establishing world-class universities. Moreover, the role of technological innovation and policies in China's success story, highlights the multifaceted strategies employed to achieve rapid progress in technology and research Li et al. (2020). The emphasis on government policies, entrepreneurship, and supply chain structures has facilitated China's remarkable achievements in sectors like electronics, further solidifying its position as a global leader in innovation and higher education.

Comparisons between individual world regions indicate that Chinese universities have shown notable improvements in their positions in terms of scientific productivity over the last decade Carta et al. (2021). Carta et al. find that universities in the European Union have lost some of their leading positions during the same period, highlighting the challenges Europe faces in a rapidly changing global scientific environment. The comparison between the European Union and China also shows that China is experiencing a continuous process of catching up with the European Union in terms of the level of economic innovativeness Kowalski (2021). American universities have also lost some of their positions compared to Chinese universities and private companies, but they have still remained key players in the global scientific arena Carta et al. (2021). The comparison of higher education policies in China and the USA shows that there is a greater emphasis on innovation and intellectual property protection in the USA, while China is accelerating its efforts to enhance technological development and promote domestic innovations Jin et al. (2023). Significant differences in student tuition fees and teacher salaries are also evident He et al. (2020).

Regarding the trend in scientific productivity, it is also worth mentioning the impact of private companies, especially e-technology companies, which are improving their positions in comparison to universities, particularly in terms of innovations. This highlights the increasing importance of the private sector in the global innovation ecosystem and the potential shift of focus from academic research to innovations driven by the private sector Carta et al. (2021). In this context, it's also important to emphasize the various economic and regulatory frameworks that influence industrial development in individual regions Jawad et al. (2019). Kowalski also finds that China is reducing the innovation gap compared to the USA, Europe, and Japan by importing existing technology and strengthening internal capabilities to use and improve these technologies Kowalski (2022).

The primary objective of this paper is to analyze the regional patterns of research topics ranked by the ARWU Global Ranking of Academic Subjects from 2017 to 2023. This period has witnessed a notable increase in universities from diverse regions making it to the top, especially those from China. Our analysis focuses on four key regions: China, Europe, the USA, and other countries, examining their leading positions and the growth in specific research areas. For details of the countries included in the selected four regions, refer to Table 1. In China, the emphasis on Engineering and Life Sciences has driven its academic ascent. In contrast, the USA's academic strength lies in Social Sciences, while Europe leads in Geography, Ecology, Public and Business Administration, and Pharmacy. The distinctive character of other countries is represented by their focus on Transportation Science, Nursing, and Hospitality & Tourism Management. This exploration aims to shed light on the shifting dynamics of global academic excellence, providing valuable insights into the evolving priorities and strengths of regions around the world.

It is worth noting that evaluating academic performance cannot be directly linked to any university ranking system, as academic performance is complex and multi-dimensional. Thus, ranking systems differ, giving various weights to different aspects of academic assessment. We therefore utilize the ARWU Ranking and compare the results with the U.S. News & World Report Best Global University Ranking as two of the oldest and most prominent ranking systems. There have been several evaluations regarding the quantity and volume of scientific publications as well as the top cited papers, as noted above. The special point and research question aim to determine how these ranking systems reflect previous analyses Tollefson (2018), Brainard and Normile (2022), Gaida et al. (2024), exploring a novel research perspective to see to what extent the ranking system justifies its use as a proxy for academic excellence.

Materials and methods

In this study, we utilized data from the Academic Ranking of World Universities (ARWU), specifically their global ranking of academic subjects. This system categorizes a broad range of academic subjects into five principal scientific areas (*SA*): Engineering, Life Sciences, Medical Sciences, Natural Sciences, and Social Sciences. These scientific areas play a crucial role in understanding the structure and breadth of the ranking system, as they encompass a wide range of academic disciplines. For a detailed breakdown of the subjects included in each scientific area, refer to Table 2 and Fig. 7. Importantly, each academic subject within these scientific areas is composed of a varying number of listed universities, ranging from as few as 50 to as many as 500, reflecting differences in the size and global representation of the subject. It is crucial to account for these variations in order to ensure a fair comparison and impact across subjects. To address this, we will next describe how the data was preprocessed and how the final scores were computed to maintain consistency and comparability across subjects with differing numbers of listed universities.

Adjusting for sample size variability

We sourced data from ARWU website, specifically focusing on their global ranking of academic subjects ShanghaiRanking Consultancy (2003). Although the number of listed universities in each academic subject varies, ranging from 50 to 500, the available scores are only provided for the top 50 universities in each subject, regardless of the total number of listed institutions within that subject. In this analysis, we recognize that this variability impacts the representation of academic subjects. For instance, in subjects with larger representation, such as Electrical or Mechanical Engineering, the top 50 universities constitute the top 10% of the total list of 500 institutions. Conversely, in smaller subjects, such as Marine/Ocean Engineering or Aerospace Engineering, the top 50 universities encompass the entire set of listed institutions. To ensure a more equitable comparison across academic subjects with varying sample sizes, we adjusted our methodology. While we continue to focus on the top 50 universities, for which the total scores are provided, we use only the top 10th percentile of universities within a academic subject. Thus, the percentiles are calculated based on the entire list of institutions for each subject. This approach maintains consistency while ensuring that the subject sizes are accurately reflected in the final aggregated scores.

Data procesing

The methodology employed by the ARWU in ranking academic subjects is meticulously detailed, encompassing various facets of academic performance. For each academic subject, specific weights are assigned to these facets, culminating in the calculation of a total score, $TS_j(i)$, for university i within a given subject j. Given the variability of $TS_j(i)$ across different subjects, we introduce the concept of a relative total score $\left(RTS_j(i)\right)$, calculated as a percentage of the university's $TS_j(i)$ relative to the highest total score among the top 10th percentile of universities $\left(TS_{j,\max}\right)$ within the same subject. In our analysis, $\left(TS_{j,\max}\right)$ determined from the selected sample of the top 10th percentile of universities within each subject, ensuring that comparisons across subjects with varying sample sizes are fair and consistent.

$$RTS_j(i) = 100 \times \frac{TS_j(i)}{TS_{j,\max}}, \tag{1}$$

where $RTS_j(i)$ serves as an indicator of a university's (i) performance within its respective academic subject (j).

Acknowledging that multiple universities from a given region can rank among the top 10th percentile, our analysis places particular emphasis on the ranking positions of these institutions. $Rank_j(i)$ refers to the rank of university i within a given subject j. $Rank_j(i)$ is crucial as it reflects the relative standing of universities, providing insight into the competitive landscape. To afford greater significance to $Rank_j(i)$, beyond merely considering the aggregate $TS_j(i)$ of all regionally represented universities in the top 10th percentile, we apply a weight to this sum by elevating the realtive $Rank_j(i)$ to the third power. This approach is designed to accentuate differences between university rankings more markedly. The rank-weighted measure for a university i, for a subject j within a given region r denoted as $\Omega_{j,r}$, is calculated as follows:

$$\Omega_{j,r} = \sum_{i \in r} \left(RTS_j(i) \times \left(1 - \frac{Rank_j(i) - 1}{N_{j,10\%}} \right)^w \right). \tag{2}$$

In Eq. 2, $Rank_j(i)$ represents the rank of university i for a specific academic subject j. The top-ranked university is assigned a value of 1, the second a value of 2, and so forth. As our analysis focuses only on the top 10th percentile of universities, we normalize the rank by the number of universities within this percentile, denoted as $N_{j,10\%}$. $RTS_j(i)$ has been in detail defined in Eq. 1. The parameter w is a weighting factor, and in our case, we use $w = 3$ to emphasize the importance of highly ranked universities. By applying this cubed weighting to the rank, we ensure that top-ranked universities have a stronger influence on the composite measure, amplifying their contributions. With this approach, we enhance the contribution of the performance of top-ranked institutions and mitigate the "mass effect" of the broader performance across many lower-ranked institutions. In the Supplement, Fig. 8 demonstrates that calculations for different values of parameter w $(w = 1, 2, 3, 4, 5)$ yield solutions in a robust, well-defined narrow region, where the value $w = 3$ provides a good balance between the pull of scale (broad performance across many institutions) and the pull of rank (performance of top institutions).

In continuation we define the rank-weighted measure for a Scientific Area (SA) within a region (r), denoted as $\Omega_{SA,r}$, as the cumulative sum of $\Omega_{j,r}$ for all academic subjects (j) within that SA (where $j \in SA$). This measure is mathematically represented as follows:

$$\Omega_{SA,r} = \sum_{j \in SA} \Omega_{j,r}, \tag{3}$$

where $\Omega_{SA,r}$ is the measure for a specified academic subject (j) within the region (r).

The number of universities in a particular subject (j) within the region (r) will be labeled as $N_{j,r}$ and is calculated using the formula:

$$N_{j,r} = \sum_{i \in r} 1, \text{ for all } i \text{ participating in } j \text{ within region } r. \tag{4}$$

To aggregate the number of universities across all subjects (j) within a specific scientific area (SA) (where $j \in SA$) and within a particular region (r), we use the following formula:

$$N_{SA,r} = \sum_{j \in SA} N_{j,r}. \tag{5}$$

This final expression in Eq. 5 computes the total number of universities participating in any subject within the SA for a specified r, ensuring a comprehensive overview of academic involvement within that scientific area.

Gini coefficient calculation

The Gini coefficient, a widely used metric to quantify inequality, is calculated to evaluate the distribution of university performance across different regions. The Gini coefficient ranges from 0 (perfect equality) to 1 (maximum inequality), where a lower value indicates more equal distribution and a higher value indicates greater concentration of performance among a few universities. The formula for the Gini coefficient is as follows:

$$G_j = 1 - \frac{2}{N-1} \sum_{i=1}^{N} (N + 1 - i) \cdot RTS_j(i). \tag{6}$$

In Eq. 6, G_j represents the Gini coefficient for academic subject j. The number of universities considered is denoted as N. In our analysis, we compute the Gini coefficients for each individual academic subject and analyze them over time and within specific scientific areas.

Results

Utilizing the comprehensive dataset from the Global Ranking of Academic Subjects by ShanghaiRanking Consultancy, this section outlines the findings of our multifaceted analysis. Initially, we explore the global landscape of higher education, examining the distribution of top-tier universities worldwide and the diversity of countries represented within the top 10th percentile across various research areas. Our investigation spans from 2017 to 2023, a period that reveals significant shifts in the geographical distribution of academic excellence. The core of our analysis centers on four distinct regional blocs: China, Europe, USA, and a collective category comprising other countries globally.

This analysis delineates the evolving participation of these regions within the global echelon of universities, segmented into five primary research areas: Engineering, Life Sciences, Medical Sciences, Natural Sciences, and Social Sciences. We meticulously chart the progression and developmental trends of these research areas within each region, showcasing the dynamic shifts in the number of universities ranked within the top 10th percentile and their respective regional universities' share from 2017 to 2023. Furthermore, we introduce the Gini indices to illustrate the distribution, identifying research areas where specific regions demonstrate dominance or exhibit a broad spread across multiple regions.

Delving deeper, our analysis extends to the examination of individual academic subjects within these regions, identifying not only the distribution but also highlighting the subjects that stand out due to their prominence within each region. Given the extensive range of academic subjects, special emphasis is placed on those that have shown remarkable prominence in their respective regions. This nuanced approach allows us to uncover the intricate landscape of global academic excellence, showcasing the evolving dominance and specialization in specific areas of research.

Global distribution of top 10th percentile

This subsection examines the global performance of universities, focusing on the diversity and geographical distribution of institutions ranked within the top 50 according to the ARWU's academic subject rankings. Fig. 1A highlights a significant trend towards greater global inclusion, with the number of countries represented in the top 50 increasing from 83 in 2017 to 104 in 2023. This growth, exceeding 25%, signifies a move towards a more globally integrated scientific community. A closer look at regional shifts reveals notable changes among the four primary regions under consideration: China, Europe, the USA, and the rest of the world. Notably, the proportion of Chinese universities in this elite group has escalated from 11.5% in 2017 to 20.2% in 2023 (see Fig. 1B). In contrast, Europe has experienced a decline from 34.5% in 2017 to 30.4% in 2023, and the USA's share has decreased from 26.8% in 2017 to 22.6% in 2023. Meanwhile, the representation of universities from the rest of the world has remained relatively stable, hovering around 27%. These shifts underscore the dynamic nature of global academic excellence and highlight the rising prominence of Chinese universities on the international stage.

Regional dynamics of research areas

Our analysis delves into the global distribution and performance dynamics of the top 10th percentile universities across five fundamental research areas: Engineering, Life Sciences, Medical Sciences, Natural Sciences, and Social Sciences. We scrutinize these dynamics

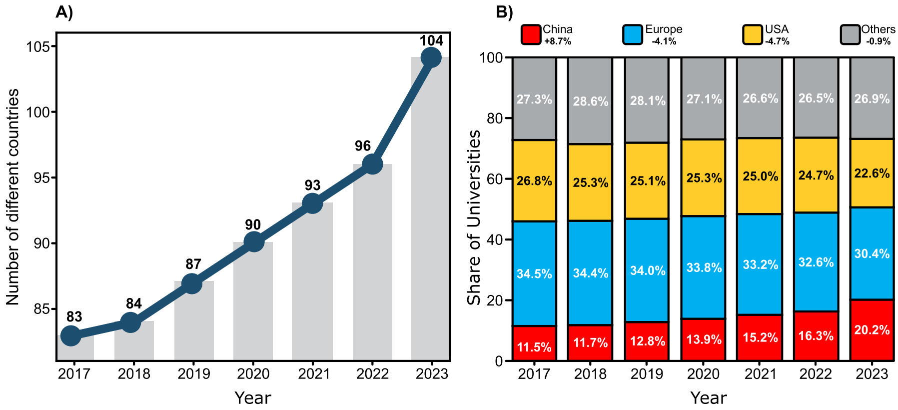

Fig. 1 Global distribution trends of universities by region (2017–2023). **A** Line graph demonstrates the year-over-year growth in the number of countries with universities ranked within the entire ARWU academic subject rankings database, highlighting an increase from 83 countries in 2017 to 104 in 2023, indicative of a more globally diverse scientific community. **B** Stacked bar graph visually captures the yearly distribution of universities by region, with color coding for China (red), Europe (blue), the USA (orange), and other regions (gray). It underscores the rise in representation from Chinese universities, juxtaposed with modest declines from European and American institutions. The share of universities from other regions remains relatively unchanged, showcasing stability outside the primary observed shifts

within four distinct geographical regions: China, Europe, the USA, and the other countries worldwide. This investigation spans from 2017 to 2023, aiming to capture the evolving landscape of global academic excellence. Fig. 2 meticulously catalogs the count of universities $\left(N_{SA,r}\right)$ ranked in the top 10th percentile, alongside their corresponding total weights $\left(\Omega_{SA,r}\right)$ for each research area across the specified years. This comprehensive dataset provides a granular insight into the shifting patterns of academic prominence and the relative weight of contributions from each region.

To ensure broader generalization of the results, we have also examined the data presented in Fig. 2A alongside the U.S. News & World Report Best Global University Ranking. Data for 2023 are available from the U.S. News & World Report ranking U.S. News & World Report L.P. (2024), and as shown in Fig. 2B, the number of universities ranked within the top 10th percentile $\left(N_{SA,r}\right)$ aligns fully with the results from the ARWU ranking (see Fig. 2A, upper panel). It is important to note, however, that while the relative shares of specific scientific areas can be meaningfully compared, the absolute measures cannot be directly compared because the number of academic subjects within specific scientific areas varies. Tables 2 and 3 provide a comprehensive list of academic subjects categorized under each scientific area. Table 2 details academic subjects within scientific areas of the ARWU ranking, whereas Table 3 organizes the subjects from the U.S. News & World Report ranking into these same five scientific areas, ensuring consistency and facilitating comparative analysis.

Fig. 2 elucidates the variation in both the number of universities ranked within the top 10th percentile (denoted as $\left(N_{SA,r}\right)$) (see Fig. 2A,B) and their cumulative total weights $\left(\Omega_{SA,r}\right)$ (see Fig. 2A) across the different regions during the period from 2017 to 2023. A noteworthy observation from Fig. 2A is the pronounced upward trajectory seen in China, marking a significant stride in its academic standing. To furnish a more detailed understanding of these regional dynamics, we dissect the shifts in both $\left(N_{SA,r}\right)$ and $\left(\Omega_{SA,r}\right)$ across all regions, with a particular focus on the changes from 2017 to 2023, as depicted

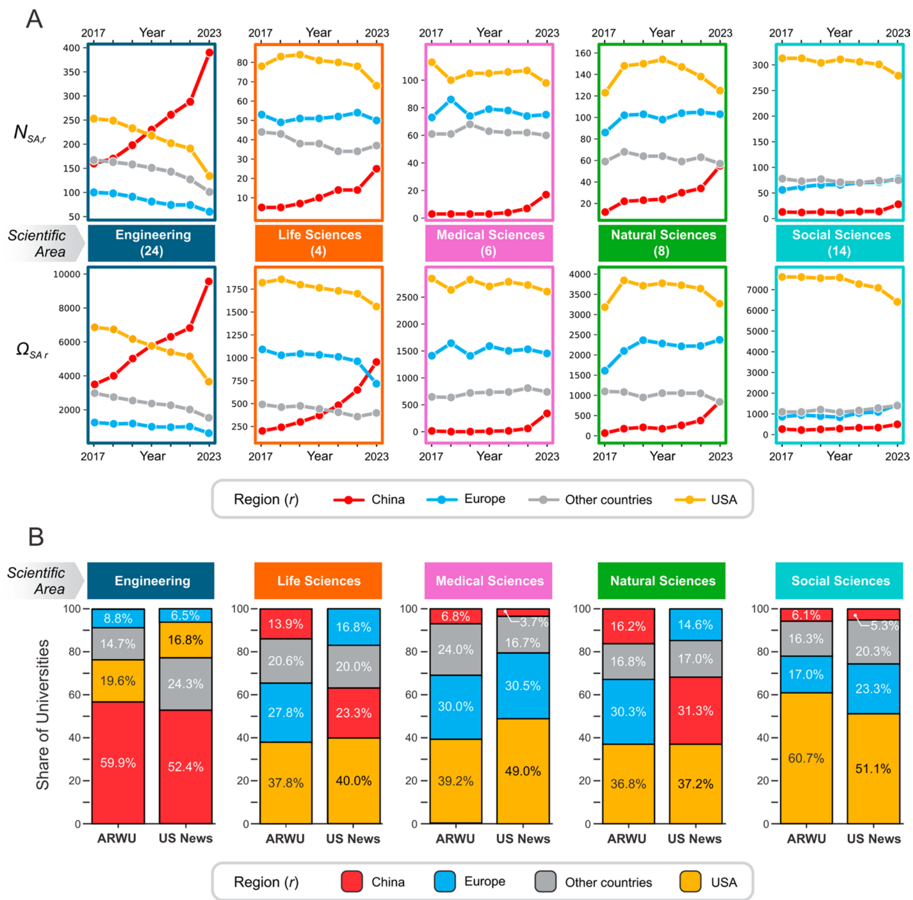

Fig. 2 **A** Distribution and total weights of top 10th percentile universities across scientific areas (2017-2023). The figure presents the annual count of universities ranked within the top 10th percentile $\left(N_{SA,r}\right)$ and their cumulative total weights $\left(\Omega_{SA,r}\right)$ across five key scientific areas - Engineering, Life Sciences, Medical Sciences, Natural Sciences, and Social Sciences - spanning from 2017 to 2023. The data is segmented by region, offering insights into the dynamic shifts in global academic standings over the period. **B** The relative share of universities ranked within the top 10th percentile in 2023, presented comparatively for the ARWU Ranking and the U.S. News & World Report Best Global University Ranking

in Fig. 3A and B. In the case of China, the data reveal a remarkable surge in prominence within the Engineering and Life Sciences sectors, indicated by substantial increases in both $\left(N_{SA,r}\right)$ and $\left(\Omega_{SA,r}\right)$. This contrasts sharply with the trends observed in other regions where, notably within the same fields, there are declines. Specifically, the USA and Europe experience downturns in their representation and influence in Engineering and Life Sciences, as marked by their respective negative changes. Conversely, the 'other countries' category shows an opposite trend with an unspecified positive change, suggesting a diversification in the global academic landscape. While Engineering and Life Sciences exhibit these notable fluctuations, the analysis reveals a markedly different scenario in the Medical Sciences, Natural Sciences, and Social Sciences areas. Here, the dynamics are characterized by significantly less variation, indicating a more stable distribution of academic excellence across

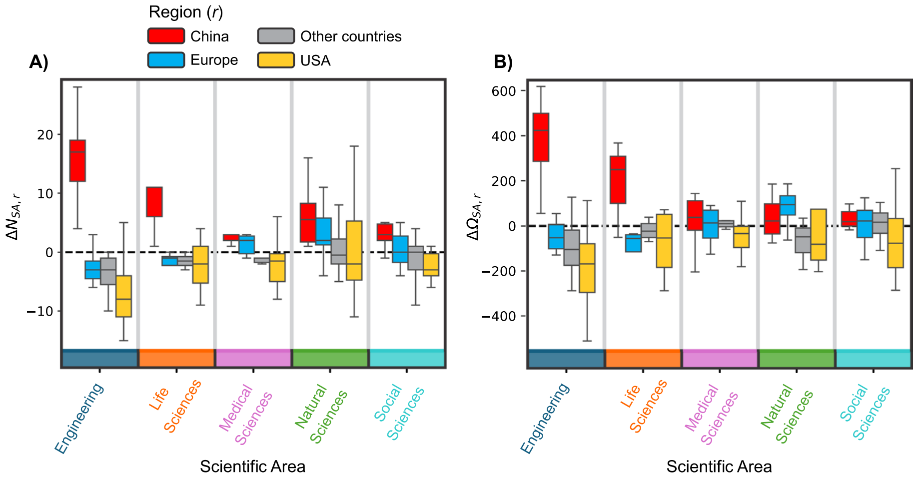

Fig. 3 Regional Dynamics and Trends in Research Areas (2017-2023). The evolution of research areas within the regions of China, Europe, the USA, and other countries from 2017 to 2023: **A** the changes in the number of top 10th percentile universities $\left(\Delta N_{SA,r}\right)$ and **B** the change in their total weights$\left(\Delta \Omega_{SA,r}\right)$ across these regions, highlighting the shifts in academic prominence and influence in specific fields of study over the selected period

these fields. This stability suggests that while certain regions may be advancing rapidly in specific areas, the global distribution of expertise in other domains remains more evenly spread.

Our investigation further delves into the distinctively heterogeneous characteristics of the most rapidly evolving research fields, particularly Engineering and Life Sciences. Our objective is to scrutinize the disparities that exist among universities engaged in these swiftly advancing disciplines. A pivotal finding from our analysis is the significant elevation of the Gini coefficient in these fields, as depicted in Fig. 4. The Gini coefficient, a statistical measure of distributional inequality, underscores a pronounced trend towards increased specialization and regional concentration within these domains. This phenomenon signals a move towards greater geographical localization of cutting-edge research

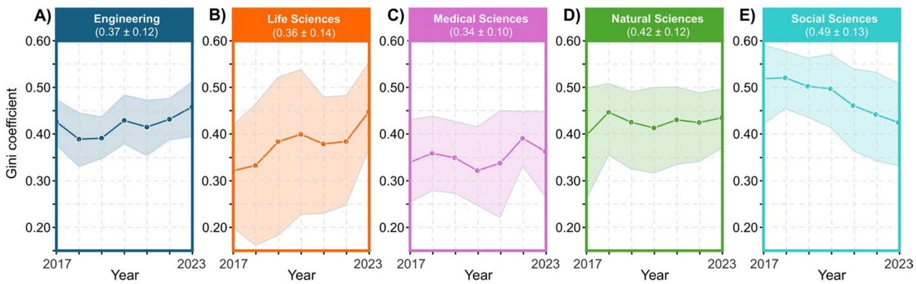

Fig. 4 Trend of Gini coefficient values across academic disciplines from 2017 to 2023. The charts display the mean Gini coefficient and its standard deviation for each field: **A** Engineering, **B** Life Sciences, **C** Medical Sciences, **D** Natural Sciences, and **E** Social Sciences. The shaded areas represent the range of standard deviation, indicating the variability within each sector

areas, which, while highlighting regional strengths, also raises important considerations regarding the potential implications for global collaboration and the dissemination of knowledge. The growing concentration suggests a need for a balanced approach to fostering both excellence and inclusivity in global scientific endeavors.

The pronounced heterogeneity observed within the Engineering and Life Sciences research areas, quantified through the Gini coefficient as depicted in Fig. 3, underscores a notable concentration of academic excellence in specific regions. This graphic representation facilitates a deeper understanding of the shifting dynamics of academic specialization and the potential impact on global research collaboration and knowledge exchange. Specifically, these areas are currently becoming more heterogeneous, as a high increase in the Gini coefficient is observed in the year 2022. In contrast, the Medical Sciences exhibit no discernible trend in this period, indicating a stable distribution of academic activity. The Social Sciences, which already possess a relatively high Gini coefficient, demonstrate a negative trend, pointing towards a gradual shift towards homogeneity in research concentration.

Regional dynamics of academic subjects

In this subsection, we narrow our focus to a detailed examination of the distribution and evolution of academic subjects across various regions. Fig. 5 presents top ranked academic subjects within the selected regions: China, Europe, the USA, and other countries. This analysis utilizes the latest available data for 2023, juxtaposed against the distribution from 2017, to highlight changes and trends in academic focus areas. In these visualization, only the highest-ranked subject in each region is displayed, providing a clear and straightforward representation of regional academic strengths. A key observation is the sustained academic dominance of the USA across both years, with multiple disciplines maintaining top positions. Notably, the comparison between the years 2017 and 2023 unveils a marked expansion in the academic footprint, particularly in the field of Engineering. This visual proliferation of academic subjects' underscores China's growing influence and specialization within the global academic community.

We proceed with an in-depth examination, shifting our focus to the distribution and prominence of academic subjects within specific regions. Fig. 6 catalogs academic subjects that have achieved the highest regional university scores ($\Omega_{j,r}$) across various subjects. These subjects are ranked based on their $\Omega_{j,r}$ values, which indicate not only the prevalence and academic success within the region but also their distinctiveness compared to other global regions. Consequently, a subject ranked first in a region is identified as the most preeminent and distinctive in its field compared to its global counterparts.

Analysis of the data presented in Fig. 6 reveals that Engineering dominates the academic landscape in China, with cutting-edge fields such as Nanoscience & Nanotechnology ranking among the top five subjects. This suggests a strategic emphasis and substantial advancements in these areas. In the USA, the leading academic subjects uniformly emerge from the Social Sciences, indicating a concentrated excellence in this domain. Europe, on the other hand, is distinguished by its leadership in Geography, Ecology, Public and Business Administration, and Pharmacy, showcasing a diverse range of strengths. The composite category of other countries is characterized by specializations in Transportation Science, Nursing, and Hospitality & Tourism Management, reflecting unique regional focuses and contributions to global academia. Moreover, a comparison of the $\Omega_{j,r}$ values between

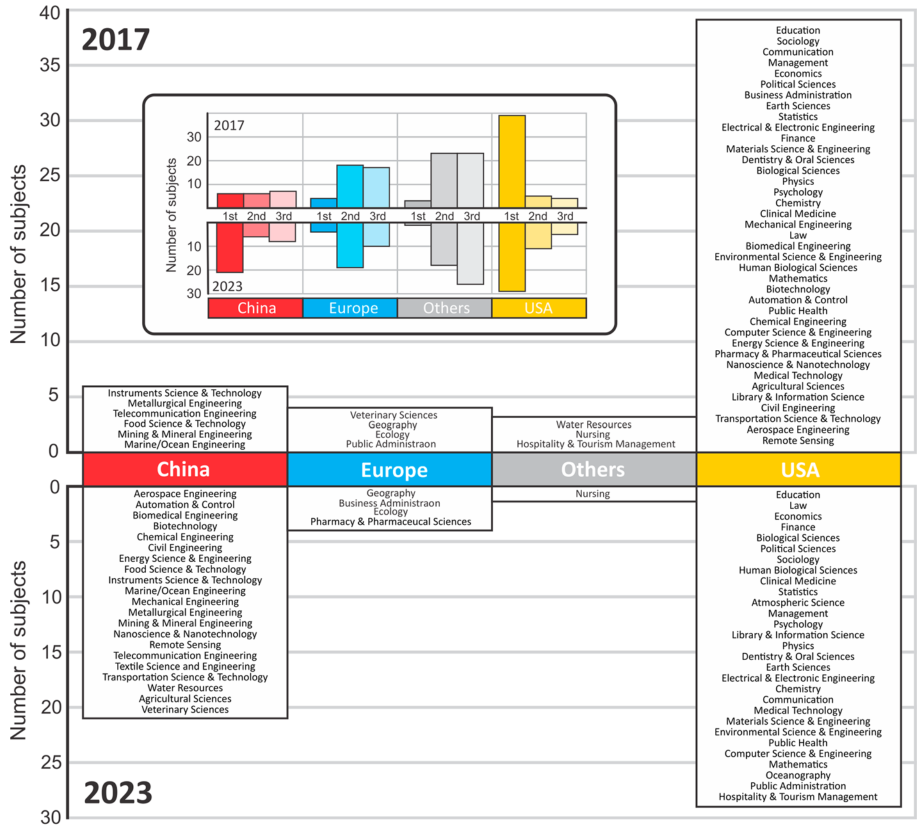

Fig. 5 Visual representation of the top-ranked academic subjects across different regions, including China, Europe, the USA, and other countries. The figure highlights the leading academic subject in each region for the years 2017 and 2023, offering a comparative view of regional academic strengths and areas of specialization. The analysis underscores the sustained academic dominance of the USA, as well as China's growing influence, particularly in the field of Engineering

2017 and 2023 highlights a significant increase in China's relative standing, suggesting a rapid advancement and growing global influence in its flagship subjects. This trend underscores the dynamic evolution of academic excellence and the shifting paradigms of global research priorities.

Discussion and conclusion

This study embarked on an in-depth examination of the distribution and evolution of academic excellence as represented by the ARWU's ranking of universities across various research areas and subjects from 2017 to 2023. Our findings illuminate significant regional dynamics and shifts in the global academic landscape, with a particular focus on the disciplines of Engineering, Life Sciences, Medical Sciences, Natural Sciences, and Social Sciences. One of the most striking observations is the marked ascendancy of Chinese universities, especially in the fields of Engineering and Life Sciences. The

2017

China

Rank	Category	Subject	Ωj,r
1	Engineering	Instruments Science & Technology	575.1
2	Engineering	Metallurgical Engineering	557.6
3	Engineering	Telecommunication Engineering	455.8
4	Engineering	Food Science & Technology	365.6
5	/	/	/

Europe

Rank	Category	Subject	Ωj,r
1	Life Sciences	Veterinary Sciences	532.5
2	Natural Sciences	Geography	502.0
3	Natural Sciences	Ecology	421.9
4	Social Sciences	Public Administration	332.1
5	/	/	/

Other countries

Rank	Category	Subject	Ωj,r
1	Engineering	Water Resources	424.9
2	Medical Sciences	Nursing	363.7
3	Social Sciences	Hospitality & Tourism Management	258.1
4	/	/	/
5	/	/	/

USA

Rank	Category	Subject	Ωj,r
1	Social Sciences	Education	982.8
2	Social Sciences	Sociology	867.7
3	Social Sciences	Communication	774.0
4	Social Sciences	Management	768.6
5	Social Sciences	Economics	757.8

2023

China

Rank	Category	Subject	Ωj,r
1	Engineering	Instruments Science & Technology	966.9
2	Engineering	Nanoscience & Nanotechnology	830.5
3	Engineering	Mechanical Engineering	736.1
4	Engineering	Food Science & Technology	721.8
5	Engineering	Chemical Engineering	706.8

Europe

Rank	Category	Subject	Ωj,r
1	Natural Sciences	Geography	683.3
2	Social Sciences	Business Administration	510.2
3	Natural Sciences	Ecology	490.1
4	Medical Sciences	Pharmacy & Pharmaceutical Sciences	400.9
5	/	/	/

Other countries

Rank	Category	Subject	Ωj,r
1	Medical Sciences	Nursing	384.7
2	/	/	/
3	/	/	/
4	/	/	/
5	/	/	/

USA

Rank	Category	Subject	Ωj,r
1	Social Sciences	Education	862.7
2	Social Sciences	Law	821.3
3	Social Sciences	Economics	736.4
4	Social Sciences	Political Sciences	658.0
5	Social Sciences	Sociology	657.4

Fig. 6 Comparative analysis of leading academic subjects by region for 2017 and 2023, ranked by their $\Omega_{j,r}$ score. This figure presents a focused view on the regional academic excellence by highlighting the top 5 ranked academic subjects within each main category for individual regions. The visualization showcases the five most prominent subjects in each region, capturing the shifting academic landscape. It serves to illustrate changes in regional academic leadership and the evolving priorities in research and development

data, as depicted in Fig. 5, indicates that China's investment in these areas has not only increased its global academic footprint but also highlighted emerging subjects such as Nanoscience and Nanotechnology. This trend resonates with the broader strategic priorities of China in bolstering its scientific and technological capabilities, reflecting a national agenda to position itself as a leader in global innovation (Zhou and Leydesdorff, 2006; Wang et al., 2019; Xie et al., 2014). China's advancements in nanotechnology, especially in agriculture and food industries, are notable. Yata et al. discuss the significant investment in nanoscience for agriculture and food, highlighting China's leading role in nano-agriculture research and the growth in patent grants in these fields Yata et al. (2018). This supports the notion of China's aggressive push into modern technologies such as nanoscience and its broader implications for regional economic development. Conversely, our analysis reveals a relative decline in the dominance of universities from the USA and Europe in these fields in which China is overtaking the dominance, albeit maintaining a robust presence across a wide spectrum of academic subjects, particularly from the Social Sciences and many others. This shift may suggest a realignment of academic strengths and focal areas, potentially driven by changing societal, economic, and technological landscapes Marginson (2016). For example, Widener outlines the USA sustained leadership in science and engineering, albeit with increasing competition from nations like China Andrea Widener (2018). This reflects the USA strong position in biotechnology, IT, and aerospace, supported by significant R&D investments and a robust innovation ecosystem.

Table 1 Countries of the four selected regions involved in ARWU ShanghaiRanking Consultancy (2003) and U.S. News & World Report academic rankings U.S. News & World Report L.P. (2024)

ARWU country list	Region	U.S. News & World Report country list
China, Taiwan, Macau, Hong Kong	(4) China (4)	China, Taiwan, Macao, Hong Kong
Austria, Belgium, Bulgaria, Croatia, Republic of Cyprus, Czech Republic, Czechia, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, United Kingdom	(28) Europe (14)	Austria, Belgium, Croatia, Denmark, Finland, France, Germany, Ireland, Italy, Poland, Portugal, Spain, Sweden, United Kingdom
Australia, Brazil, Canada, Chile, Cyprus, Egypt, Iceland, India, Iran, Israel, Japan, Korea, Malaysia, Netherlands, New Zealand, Norway, Pakistan, Qatar, Russian Federation, Saudi Arabia, Serbia, Singapore, South Africa, Switzerland, Tunisia, Türkiye, Vietnam	(27) Other (21)	Algeria, Australia, Brazil, Canada, Iran, Israel, Japan, Malaysia, Netherlands, New Zealand, Norway, Pakistan, Russia, Saudi Arabia, Singapore, South Africa, South Korea, Switzerland, Thailand, Vietnam
United States	(1) United States (1)	United States
(60) Total (40)		

It is worth noting that our analysis, which takes into account the rankings of universities, is merely a rough proxy for true academic performance, as academic excellence is comprehensive and multi-dimensional. On the other hand, we must bear in mind that the relationship between academic excellence and the results of a ranking system is bidirectional. Not only is there a possibility that the ranking system is a rough or even inadequate proxy for academic performance, but it might also be an early indicator of some unresolved, hidden deficiencies in real academic excellence that have not yet been evaluated by any ranking system. This could mean that reality will shift even more towards decreasing performance in the future. From this perspective, our results are indicative, showing China's strong positioning in Engineering, with close to 60% of all the universities in the top 10th percentile. For comparison, some other measures, for example, the recent evaluation by the ASPI's Critical Technology Tracker Gaida et al. (2024), indicate that China's global lead extends to 37 out of 44 technologies that ASPI is now tracking. This covers a range of crucial technology fields including defense, space, robotics, energy, the environment, biotechnology, artificial intelligence (AI), advanced materials, and key quantum technology areas. The ratio of 37/44, or 84%, raises even more concern than our general assessment of 60% concerning the broad scientific area of Engineering. Therefore, ranking systems are still very broad, and the comprehensive understanding of academic excellence is even broader; however, some breakthrough technologies and the most groundbreaking ideas are developed from the most unique and frontier fields. Hence, we have also included measures like the score $\Omega_{j,r}$, which not only includes the number of universities but also their rank ($Rank_j(i)$), using the power of three to accentuate the importance of highly ranked universities.

Additionally, our analysis also shows that the utilization of the Gini coefficient to measure the heterogeneity of academic subject distribution underscores a growing specialization and regional concentration, particularly in rapidly developing

Table 2 Academic subjects included in the ARWU ranking by scientific areas, with the number of listed universities for each academic subject indicated in parentheses

Natural Sciences (8)	*Engineering (23)*
Mathematics (# = 500)	Mechanical Engineering (# = 400)
Physics (# = 500)	Electrical Electronic Engineering (# = 200)
Chemistry (# = 500)	Automation Contro (# = 200)
Earth Sciences (# = 500)	Telecommunication Engineering (# = 300)
Geography (# = 300)	Instruments Science Technology (# = 300)
Ecology (# = 500)	Biomedical Engineering (# = 300)
Oceanography (# = 500)	Computer Science Engineering (# = 500)
Atmospheric Science (# = 500)	Civil Engineering (# = 300)
	Chemical Engineering (# = 500)
Life Sciences (4)	Materials Science Engineering (# = 500)
Agricultural Sciences (# = 500)	Nanoscience Nanotechnology (# = 400)
Biological Sciences (# = 500)	Energy Science Engineering (# = 400)
Human Biological Sciences (# = 500)	Environmental Science Engineering (# = 400)
Veterinary Sciences (# = 300)	Water Resources (# = 200)
	Food Science Technology (# = 300)
Social Sciences (14)	Biotechnology (# = 500)
Economics (# = 500)	Aerospace Engineering (# = 50)
Statistics (# = 500)	Marine/Ocean Engineering (# = 50)
Law (# = 500)	Transportation Science Technology (# = 200)
Political Sciences (# = 500)	Remote Sensing (# = 100)
Sociology (# = 200)	Mining Mineral Engineering (# = 100)
Education (# = 300)	Metallurgical Engineering (# = 200)
Communication (# = 400)	Textile Science and Engineering (# = 50)
Psychology (# = 200)	
Business Administration (# = 500)	*Medical Sciences (6)*
Finance (# = 200)	Clinical Medicine (# = 500)
Management (# = 500)	Public Health (# = 500)
Public Administration (# = 200)	Dentistry Oral Sciences (# = 300)
Hospitality Tourism Management (# = 300)	Nursing (# = 300)
Library Information Science (# = 100)	Medical Technology (# = 400)
	Pharmacy Pharmaceutical Sciences (# = 500)

The italic text represents the scientific areas, while the number in brackets indicates the number of academic subjects included in a specific scientific area. The table categorizes fields into Natural Sciences, Engineering, Life Sciences, Medical Sciences, and Social Sciences. ShanghaiRanking Consultancy (2003)

research fields. This finding raises pertinent questions about the implications for global research collaboration and knowledge dissemination, echoing concerns about the increasing geographical localization of academic expertise Wagner et al. (2015) Moreover, the study's insights into the dynamics of academic subjects, as visually represented through Word Clouds, offer a unique lens on the evolving priorities within the global academic community. The prominence of certain subjects within specific regions underscores the influence of socio-economic, cultural, and political factors in shaping academic agendas Hazelkorn (2015). To address the challenges

Table 3 Academic subjects included in the U.S. News & World Report ranking by scientific areas, with the number of listed universities for each academic subject indicated in parentheses

Natural Sciences (10)	*Engineering (13)*
Biology and Biochemistry (# = 750)	Artificial Intelligence (# = 200)
Chemistry (# = 1500)	Chemical Engineering (# = 250)
Condensed Matter Physics (# = 250)	Civil Engineering (# = 250)
Geosciences (# = 500)	Computer Science (# = 750)
Mathematics (# = 500)	Electrical and Electronic Engineering (# = 500)
Meteorology and Atmospheric Sciences (# = 100)	Energy and Fuels (# = 400)
Microbiology (# = 250)	Engineering (# = 1000)
Optics (# = 250)	Materials Science (# = 1000)
Physical Chemistry (# = 750)	Mechanical Engineering (# = 200)
Physics (# = 1000)	Nanoscience and Nanotechnology (# = 200)
	Polymer Science (# = 200)
Life Sciences (4)	Space Science (# = 250)
Agricultural Sciences (# = 400)	Water Resources (# = 100)
Biotechnology and Applied Microbiology (# = 250)	*Medical Sciences (14)*
Cell Biology (# = 250)	Cardiac and Cardiovascular Systems (# = 250)
Food Science and Technology (# = 250)	Clinical Medicine (# = 1000)
Plant and Animal Science (# = 500)	Endocrinology and Metabolism (# = 250)
	Gastroenterology and Hepatology (# = 200)
Social Sciences (5)	Immunology (# = 250)
Arts and Humanities (# = 250)	Infectious Diseases (# = 500)
Economics and Business (# = 400)	Molecular Biology and Genetics (# = 400)
Education and Educational Research (# = 100)	Neuroscience and Behavior (# = 500)
Environment/Ecology (# = 1000)	Oncology (# = 500)
Social Sciences and Public Health (# = 750)	Pharmacology and Toxicology (# = 500)
	Psychiatry/Psychology (# = 500)
	Public, Environmental and Occupational Health (# = 450)
	Radiology, Nuclear Medicine and Medical Imaging (# = 250)
	Surgery (# = 250)

The italic text represents the scientific areas, while the number in brackets indicates the number of academic subjects included in a specific scientific area. U.S. News & World Report L.P. (2024)

posed by the increasing specialization and regional concentration in academia, particularly in swiftly evolving domains, recent studies underscore the value of interdisciplinary research and cross-border collaborations. He et al. developed the spatial research leadership rank, highlighting the significance of cross-linguistic-border collaborations and research leadership in enhancing the global academic network, thereby offering new avenues to mitigate the risks associated with academic specialization He et al. (2021). Furthermore, Momtazmanesh et al. emphasize the crucial role of international and transdisciplinary approaches in bridging science with society, advocating for a borderless scientific community to confront global challenges Momtazmanesh et al. (2021). Their consensus from the USERN congress advocates for international scientific collaboration to promote knowledge dissemination and strengthen the global research network. These contributions illustrate the critical need for fostering cross-disciplinary and cross-border partnerships to counterbalance the growing focus on specialization and ensure the broad dissemination of knowledge and innovation, crucial for global academic advancement.

Our study has illuminated the pressing need for continued investigation into the forces shaping regional dynamics within global higher education and research policy. This imperative is echoed by recent scholarly work, which points to government funding, international collaboration networks, and policy initiatives as pivotal factors that could influence academic rankings and subject specialization. Li's analysis on the efficacy of performance funding policies in enhancing STEM degree completion rates serves as a testament to the potential of targeted financial strategies in guiding institutional priorities towards areas of high demand Li (2020). Furthermore, Morris, Muchira, and Dobrowolski's exploration into the response of university policy to shifts in government funding reveals the profound impact such changes can have on educational practices and outcomes Morris et al. (2023).

In drawing our analysis to a close, we assert that this paper contributes vital insights into the evolving competitive dynamics of the global academic landscape, underscoring the fluidity of regional dominance and academic specialization. As we stand at the crossroads of unparalleled global challenges and opportunities, the findings presented herein lay a foundational framework for policymakers, educators, and researchers. This framework not only facilitates a deeper comprehension of current trends but also empowers stakeholders to actively shape the trajectory of higher education and scientific exploration moving forward. The path ahead calls for a concerted effort to harness the potential of international cooperation and policy innovation, ensuring that the global academic community can effectively respond to and capitalize on the shifting paradigms of research and education.

Appendix A Supporting information

See Figs 7 and 8

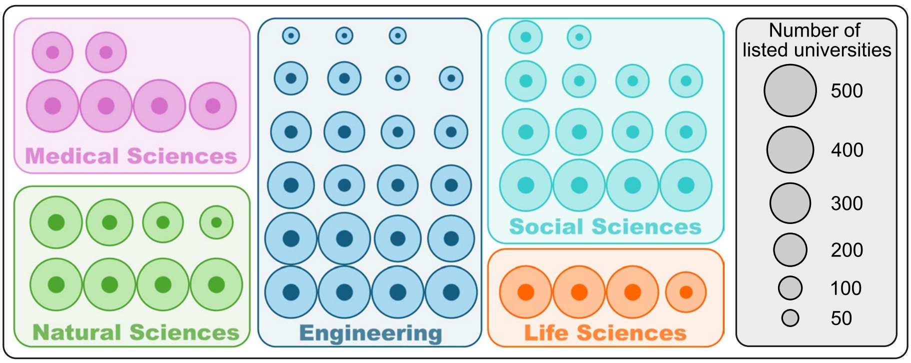

Fig. 7 Distribution of the number of listed universities across different scientific areas for the ARWU dataset. Each bubble represents an academic subject within a scientific area: Medical Sciences, Natural Sciences, Engineering, Life Sciences, and Social Sciences. The size of each bubble corresponds to the total number of listed universities, as indicated by the legend. The inner circles within each bubble denote the top 10th percentile of universities, illustrating the most prestigious institutions within an academic subject

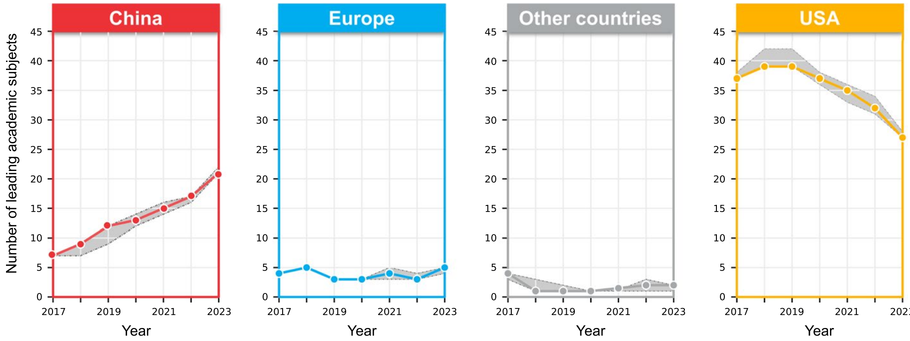

Fig. 8 Temporal dynamic of the number of first-ranked academic subjects for different regions (China, Europe, USA, and others) from 2017 to 2023. The academic subjects have been ranked according to the calculated values of $\Omega_{j,r}$ (see Eq. (2)) for different values of the parameter w ($w = 1, 2, 3, 4, 5$). The calculated trajectory for $w = 3$ is denoted with a solid line, while the upper and lower values ($w = 1$ and $w = 5$) are denoted with dotted and dot-dotted lines, respectively

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Data availability The data underlaying this article are available at https://github.com/ReneMarkovic/World-University-Rankings.git

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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