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Colonial history and global economics distort our understanding of deep-time biodiversity

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Sampling biases in the fossil record distort estimates of past biodiversity. However, these biases not only reflect the geological and spatial aspects of the fossil record, but also the historical and current collation of fossil data. We demonstrate how the legacy of colonialism and socioeconomic factors, such as wealth, education and political stability, impact the global distribution of fossil data over the past 30 years. We find that a global power imbalance persists in palaeontology, with researchers in high- or upper-middle-income countries holding a monopoly over palaeontological knowledge production by contributing to 97% of fossil data. As a result, some countries or regions tend to be better sampled than others, ultimately leading to heterogeneous spatial sampling across the globe. This illustrates how efforts to mitigate sampling biases to obtain a truly representative view of past biodiversity are not disconnected from the aim of diversifying and decolonizing our discipline.

The fossil record is our only direct evidence of how life on Earth has evolved over time, and reconstructions of deep-time biodiversity provide critical insights into future biodiversity change. The fossil record, upon which these reconstructions are based, is known to be incomplete and unevenly distributed across the globe[1–3]. Various taphonomic, geological and anthropogenic factors have been shown to introduce biases into estimates of deep-time biodiversity, extinction and evolution, and decades of research have documented and attempted to analytically mitigate their effects[4–7]. However, considerably less attention has been paid to how historical, social and economic factors influence the global distribution of fossil occurrences, and their consequent effects on our understanding of deep-time biodiversity.

The natural sciences were developed around an extractive process facilitated by European colonialism in the nineteenth century. When zoological and botanical specimens were uncovered during colonial expeditions, they were shipped back to the respective imperial capitals, to be housed in museums, which were rapidly increasing in numbers to accommodate the influx of scientific material[8]. Many specimens collected during the colonial era are still being used for scientific purposes today by researchers based in these countries. Recently, plankton samples collected from the equatorial Pacific Ocean during the HMS *Challenger* expedition in the nineteenth century —that made use of the extensive colonial network and relationships developed by Great Britain during that time for the purpose of scientific exploration[9]—were used for a study led by British authors[10]. Fossil specimens were no exception, and their collection was dominated by imperial systems and exchanges[11]. For example, Charles Darwin aboard the HMS *Beagle* collected fossils in South America that were sent to London and studied by British palaeontologists[12]. These extractive research practices continue to this day within the natural sciences[13], but especially in palaeontology where fossils and their collection underpin the discipline[14].

Compilations of modern biodiversity data show a clear association between knowledge production and wealthier, more politically stable countries, especially in northern America and western Europe[15,16]. This asymmetry in research makes a clear case for 'scientific colonialism', whereby the centre of knowledge of a certain country is located outside of that specific country[17]. Scientific colonialism is often equated with the term 'parachute science', where researchers, generally from higher-income countries, 'drop in' to other countries to conduct research and leave without any engagement with the local community, including local researchers[18]. However, parachute science represents only a small part of this issue. Scientific colonialism also refers to instances when the expertise of local researchers is devalued and laws within these countries are violated[19]. This disjunct hinders local scientists and domestic scientific development, by favouring foreign input and exacerbating power imbalances between those from foreign countries and those located 'on the ground'. Furthermore, this can also lead to mistrust by local scientists towards foreign researchers, affecting future collaborations.

Here we examine the evidence for scientific colonialism in palaeontology by exploring the causal relationship between the global distribution of fossil occurrence data and the legacy of colonialism, alongside associated socioeconomic factors. Using data from the Paleobiology Database (PBDB; www.paleobiodb.org), a publicly accessible database used widely by the palaeontological research community, we assessed which world countries are the main actors in driving global information asymmetry in palaeontology, and whether the accumulation of palaeontological knowledge is observed in certain regions or countries. Our goal is to advance discussions on the challenges of working with the fossil record, as it is critical to understand the imbalances in the production of palaeontological knowledge and its exchange between geographical regions.

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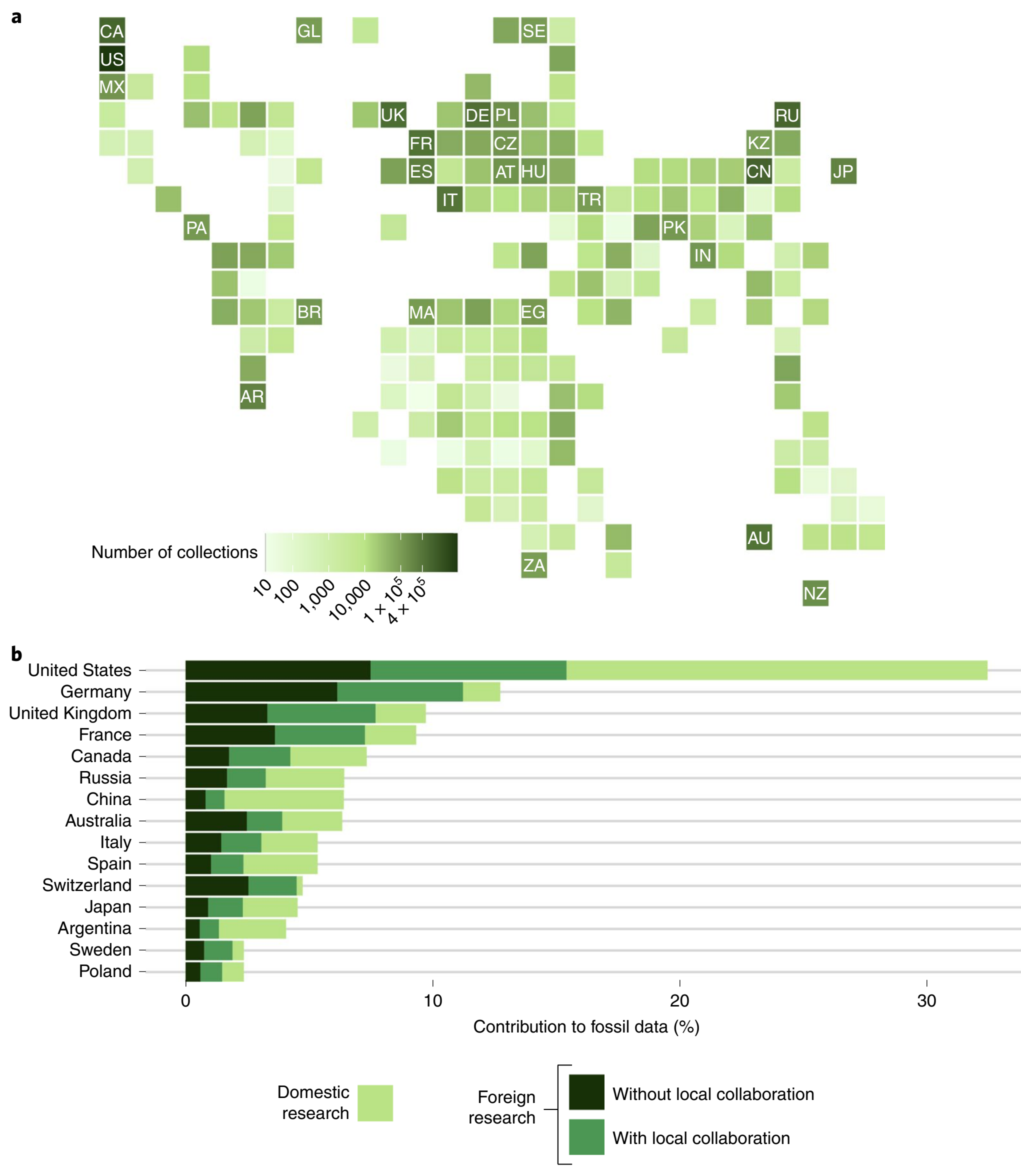

Fig. 1 | Sampling sites of the fossil data analysed in this study and contributions by the top 15 countries to this data. a, The number of fossil localities sampled in each country displayed on a tile grid map to avoid distorting the representation of the data that is typical of standard map projections. Two-letter country codes are shown for countries with greater than 10,000 fossil localities. **b**, Percentage contribution of the top 15 countries to the total fossil data analysed in this study. The colour of each bar represents whether the authors of each country conducted their research domestically (that is, in the same country), in a foreign country, or in a foreign country without collaboration with local palaeontologists. Two-letter country codes: AR, Argentina; AT, Austria; AU, Australia; BR, Brazil; CA, Canada; CN, China; CZ, Czech Republic; DE, Germany; EG, Egypt; ES, Spain; FR, France; GL, Greenland; HU, Hungary; IN, India; JP, Japan; KZ, Kazakhstan; MA, Morocco; MX, Mexico; NZ, New Zealand; PA, Panama; PK, Pakistan; PL, Poland; RU, Russia; SE, Sweden; TR, Turkey; UK, United Kingdom; US, United States; ZA, South Africa.

Results & Discussion

Scientific colonialism in palaeontological research. We observe that palaeontological research represented in the PBDB is predominantly carried out by researchers affiliated with institutions located in high- or upper-middle-income countries; 97% of fossil occurrence data based on the publications catalogued in the PBDB was contributed by authors based primarily in northern America and western Europe (Fig. 1). This pattern is unsurprising, given the history of the discipline and the position of the US and the European Union as leaders in research and development expenditure[20]. Researchers based in the US, who contribute over a third of the total fossil data (Fig. 1b), appear to conduct a similar amount of domestic (that is, within the US) and foreign research (that is, outside of the US by US-based authors). The next top three contributors are researchers in Germany, UK and France, who are each responsible for more than 10% of the total fossil data, and conduct a disproportionate amount of research abroad compared with domestic research; almost half of the former does not involve any local researchers, that is, co-authors with in-country affiliations (Fig. 1b). Among the countries contributing to less than 10% of the fossil data, Switzerland stands out as a country with a high proportion (86%) of palaeontological research conducted in foreign countries. The ratio of domestic to foreign research for countries such as the US, Canada and Australia, as well as countries of Central and Latin America, almost certainly masks ubiquitous within-country colonialist research practices, given the small proportion of researchers from indigenous and other marginalized groups in academic spaces[21–25]. Similarly, for countries that are overseas territories of former colonialist powers, such as Denmark in the case of Greenland or France in the case of French Polynesia, the local indigenous population rarely, if ever, contributes to research based on localities in these regions (Supplementary Table 1 and Extended Data Fig. 1). As such, fieldwork carried out by non-indigenous researchers on colonized or occupied territories (many of which are controlled by the state or federal government) could also be considered a case of scientific colonialism[26]. This, however, cannot be quantified within the scope of this study, but should be considered along with the recommendations made at the end of this Article.

Among the top global data contributors, several countries conduct domestic research with low levels of contribution from foreign co-authors: China (75% of research is domestic), Argentina (66% domestic) and Japan (50% domestic) (Fig. 1b). In a skewed landscape where there is European and North American monopoly, these countries may initially appear as unexpected outliers, but not when their palaeontological research environment is further examined. These countries, along with India, Brazil and Mexico, are examples of 'regional hubs of palaeontological knowledge' (Fig. 2). In these 'regional hubs', most domestic research is carried out by local researchers (Extended Data Fig. 2) and the contribution of local researchers to these countries' research output has been increasing over the past 30 years (Extended Data Fig. 3). Out of these countries, China is the most productive in terms of total research output (Fig. 1b and Extended Data Fig. 3). The establishment of palaeontology in China can be attributed to rapid geological surveying and mapping initiated in the 1950s, the excavation of several world-famous exceptionally preserved Lagerstätten and, recently, the enforcement of laws to retain Chinese fossils within the country (Supplementary Table 2). Similarly, palaeontology is a long-established discipline in Argentina, Brazil and Japan (Supplementary Table 2)—these countries have national palaeontological societies, universities offering palaeontology either as a standalone subject or as part of a wider programme, and national repositories for storing and curating these specimens on top of several funding opportunities for palaeontological research (Supplementary Table 2). These elements have a tremendous effect in shaping the culture and priorities in any discipline, palaeontology included, by acting as a catalyst for its advancement[27]. In the case of India, however, national funding agencies are less likely to provide funding for any work that involves fieldwork or research visits abroad (Supplementary Table 2), which is in contrast to many other countries where such rules do not exist. This represents a barrier to palaeontological research, especially when many Indian specimens are housed in foreign repositories but are inaccessible to Indian researchers because of travel restrictions. More recently, Brazil has been experiencing the same problems, due to the ongoing national political crisis and successive reductions in the country's global scientific investment.

World countries that experience a high incidence of parachute science and are exploited for their palaeontological data are primarily located in the Global South (Fig. 3a). We developed the 'parachute index' to quantify the extent to which countries are impacted by parachute science, on the basis of the log ratio of publications including local researchers versus publications not including any local researchers (Fig. 3). Many African countries are targets of parachute science (Fig. 3 and Extended Data Fig. 4), but only a handful of African countries have the infrastructures discussed above in place for palaeontological research (Supplementary Table 2). Most of the expertise around African fossils resides outside of the continent, with a clear link through colonial history to western European countries (Extended Data Figs. 3 and 5). For example, one quarter of all research conducted in Morocco, Tunisia and Algeria was conducted by French researchers, 17% of research on fossils from Tanzania was conducted by German researchers, and 10% of research on South African and Egyptian fossils was conducted by British researchers. However, researchers from western Europe do not restrict themselves to conducting research in their respective former colonies (Extended Data Fig. 5). Rather, their scientific focus, along with that of the US, is spread globally.

Neocolonialism—whereby extractive research practices developed during European colonial expansion in the nineteenth and twentieth centuries are maintained in the current century by other parties not previously involved in the colonizing agenda—is also apparent from our data. For most of the past three decades, the majority of China's research has been led by local researchers (Extended Data Fig. 3). This focus has shifted in recent years, with a sharp increase observed in the number of publications on fossils collected abroad and no apparent local collaboration or engagement (Extended Data Fig. 3). This switch can be linked to an increasing interest in fossils from Myanmar, especially organisms preserved in amber (Extended Data Figs. 6a, 7). Similarly, Japan has shown an increase in research on Myanmar fossils in the past 10 years, although Japan's geographical focus has generally been wider than China's, with Japanese researchers conducting work not only in Asian countries (China, Mongolia, Thailand), but also in the US and Russia (Extended Data Fig. 5b). In contrast, the palaeontological research of South African and Argentinian researchers has remained mostly regional, that is, in Southern and Eastern Africa and South America, respectively (Extended Data Figs. 3, 6). Some publications by South African researchers on fossil specimens beyond the South African territory came as part of collaborations with countries such as the US (conducted in Tanzania), and the UK and Russia (both in Botswana).

Countries such as Myanmar, the Dominican Republic, Morocco, Mongolia and Kazakhstan are some of the most popular 'research destinations' for foreign researchers, thereby being the greatest targets of parachute science and scientific colonialism (Figs. 2 and 3). In the case of Myanmar and the Dominican Republic, the availability of commercial amber with fossil inclusions has increased the accessibility of this material to foreign researchers[28], which has led to a high number of publications where there is no involvement from local researchers, indicating a clear example of parachute science[29] (Fig. 3 and Extended Data Fig. 3). In Morocco, Mongolia and Kazakhstan, vertebrate fossils seem to be driving this same trend (Extended Data Fig. 7). Vertebrates, whether modern or fossil, enjoy more popular interest than other groups, usually leading to larger financial incentives in terms of funding[30,31]. As such, it is not surprising that vertebrate fossil deposits in many countries tend to attract the attention of foreign researchers. In fact, Mongolia and Morocco, along with other countries such as China, Mexico and Brazil, have been the victims of fossil trafficking and parachute research, especially vertebrate fossils, for decades. Similarly, issues of legality and ethics surrounding Myanmar amber have not deterred researchers from pursuing their endeavours in the field[29].

Mechanisms causing knowledge imbalance in palaeontology. Our results confirm that, on a global scale, socioeconomic and political factors are some of the dominant controls on palaeontological research output (Fig. 4). The human development index (HDI), which represents different socioeconomic factors, such as life expectancy, education and standard of living, has a significant positive relationship with research output ($r = 0.35$, $P < 0.05$; Fig. 4). In turn, HDI is directly linked to the gross domestic product (GDP; $r = 0.71$, $P < 0.05$) of a country and its political stability (global peace index, GPI; $r = -0.28$, $P < 0.05$) (Fig. 4). Similar patterns are observed for countries that could not be included in the model due to data deficiency (Supplementary Table 1), where authors from these data-deficient countries classified as high- or upper-middle-income countries had a higher number of publications (Extended Data Fig. 1). Increasing GDP often results in increased investment into

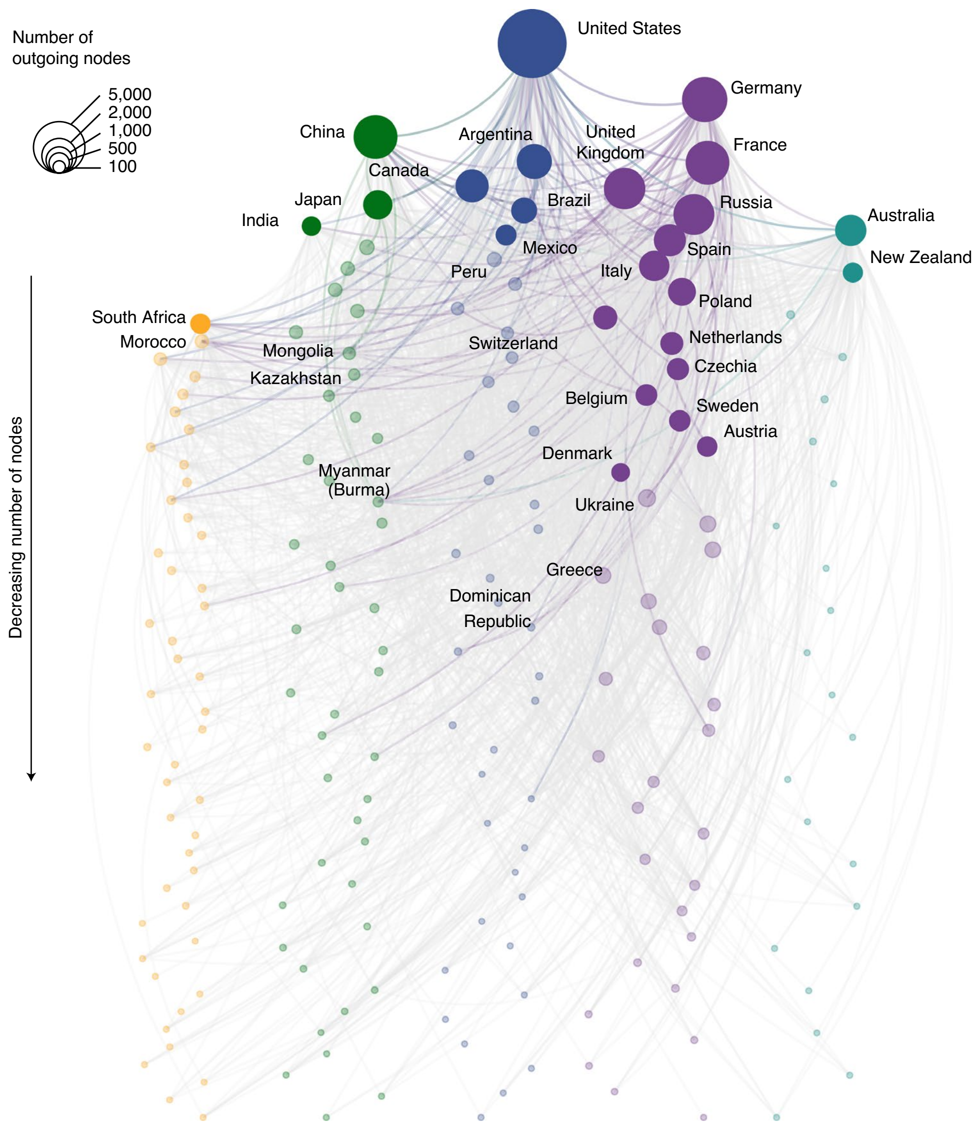

Fig. 2 | Relationship networks among countries, coloured by region, showing the 'research destinations' of researchers in palaeontology. The chords represent connections between the country of authors' institutional affiliations and the country the fossil material was collected from. The size of each country's circle represents the number of publications on foreign fossil material, also represented by the number of outgoing chords. The countries labelled in bold represent countries with more than 30 outgoing chords, that is, the most popular 'research destinations'.

different sectors such as health, education and research and development, thus giving palaeontologists from high-GDP countries a broader set of tools and resources to advance the discipline locally (Supplementary Table 2). This has probably aided the establishment of 'regional hubs' beyond northern American and European countries in the form of emerging economies such as China, India, South Africa, Argentina and Brazil.

European ideologies and culture permeate science[32]. They are not only restricted to previous colonial powers, but are rather ubiquitous across academic structures and political borders, leading to the discrimination and exclusion of marginalized groups that do not conform to this system[33]. Our results show that this colonial legacy (measured here by a binary variable indicating whether a country has benefitted from colonialism; Supplementary Table 3) has the greatest impact on research output in palaeontology ($r=0.50$, $P<0.05$; Fig. 4). This relationship is not unexpected, given the roots and history of the discipline. However, the fact that this is apparent in data collected in the past 30 years suggests that the power dynamics currently observed in the discipline are still analogous to the ones that existed during the age of colonial plunder. Modern palaeontology, like most of the natural sciences, was built on an exploitative system that was the European colonization process – one centred on making highly asymmetric profits – which benefitted the colonizers at the expense of the colonized[34]. The colonial legacy that is reflected in the natural history collections of many of these countries has been at the forefront of many recent discussions[35–37]. Some countries beyond western Europe and northern America, namely China and South Africa, also have their own (neo-)colonial legacy (Supplementary Table 3). Additionally, in modern times, educational institutions and private companies, rather than the nation state, benefit from existing and new colonial structures[38].

In several countries, national political and legal frameworks, through the formulation and enforcement of fossil heritage laws, have promoted local research endeavours[39]. Many countries (for example, Argentina, Brazil and China) restrict exports of fossils to other countries (Supplementary Table 2), meaning that these specimens remain in local repositories that can be accessed more easily by

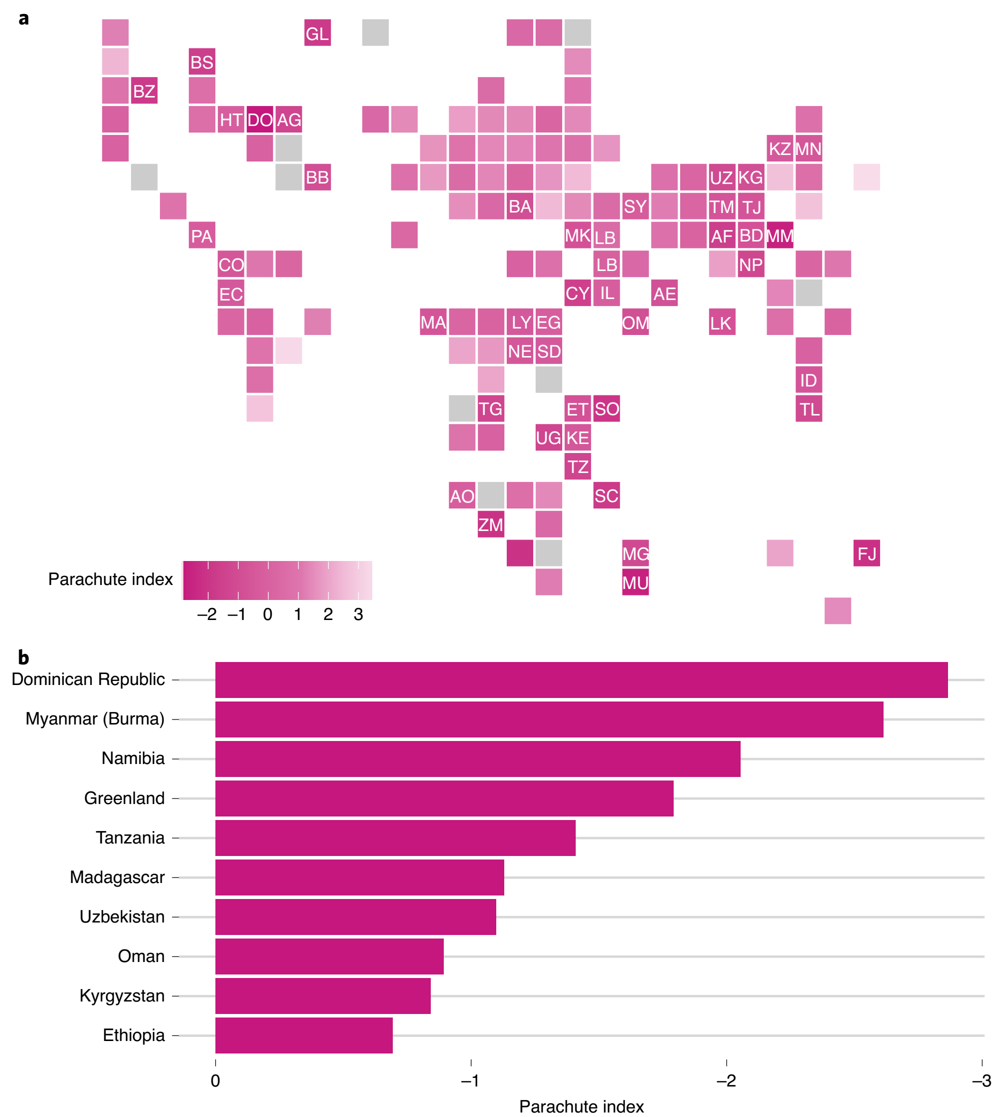

Fig. 3 | World countries experiencing parachute science as measured by the parachute index. a, The parachute index of world countries, where tiles assigned to a country's code indicate those countries that are mentioned in publications by solely foreign researchers (that is, no local collaboration) **b**, The 10 countries (with more than 30 publications in our dataset) that are the worst impacted by parachute science. Negative values indicate greater presence of parachute science, that is, research by foreign researchers that does not involve any local collaborators. Light grey tiles represent countries with no available data. Two-letter country codes: AE, the United Arab Emirates; AF, Afghanistan; AG, Antigua and Barbuda; AO, Angola; BA, Bosnia and Herzegovina; BB, Barbados; BD, Bangladesh; BS, the Bahamas; BZ, Belize; CO, Colombia; CY, Cyprus; DO, the Dominican Republic; EC, Ecuador; EG, Egypt; ET, Ethiopia; FJ, Fiji; GL, Greenland; HT, Haiti; KG, Kyrgyzstan; ID, Indonesia; IL, Israel; KZ, Kazakhstan; KE, Kenya; LB, Lebanon; LK, Sri Lanka; LY, Libya; MA, Morocco; MG, Madagascar; MK, Republic of North Macedonia; MM, Myanmar; MN, Mongolia; MU, Mauritius; NE, Niger; NP, Nepal; OM, Oman; PA, Panama; SC, Seychelles; SD, Sudan; SO, Somalia; SY, Syrian Arab Republic; TG, Togo; TJ, Tajikistan; TL, Timor-Leste; TM, Turkmenistan; TZ, Tanzania; UG, Uganda; UZ, Uzbekistan; ZM, Zimbabwe.

local palaeontologists for research purposes, as compared to when they are reposited in foreign collections. This is especially observed in the case of Brazil, where the stricter enforcement of laws since the 2000s in an attempt to curb this issue has led to increased contributions in terms of the number of publications by Brazilian scientists (Extended Data Fig. 3). In addition, there are laws that regulate research undertaken by foreign researchers, usually by stipulating a requirement for a local collaborator (Supplementary Table 2), which has resulted in an increase in collaborations with local palaeontologists in these countries (Extended Data Fig. 3). However, in the case of Myanmar and the Dominican Republic, the commercialization of amber with fossil inclusions has increased access for researchers from higher-income countries despite the presence of legislation restricting amber or fossil exports, which in turn restricts access for local researchers unable to afford the material[29,40].

The relationship between research output in palaeontology and proficiency in the English language, as measured by the English proficiency index (EPI; Fig. 4), is unsurprising given the reliance of palaeontology, and academia more widely, on literature in English, and is another representation of how academia is entrenched in the colonial process. English is the 'lingua franca' of science and today it dominates peer-reviewed scientific publications across all research fields[41]. Approximately 92% of publications recorded in the PBDB published between 1990 to 2020 are in English, with Chinese, German, French and Spanish making up the majority of the remainder (Extended Data Fig. 8). This monopoly of English-language

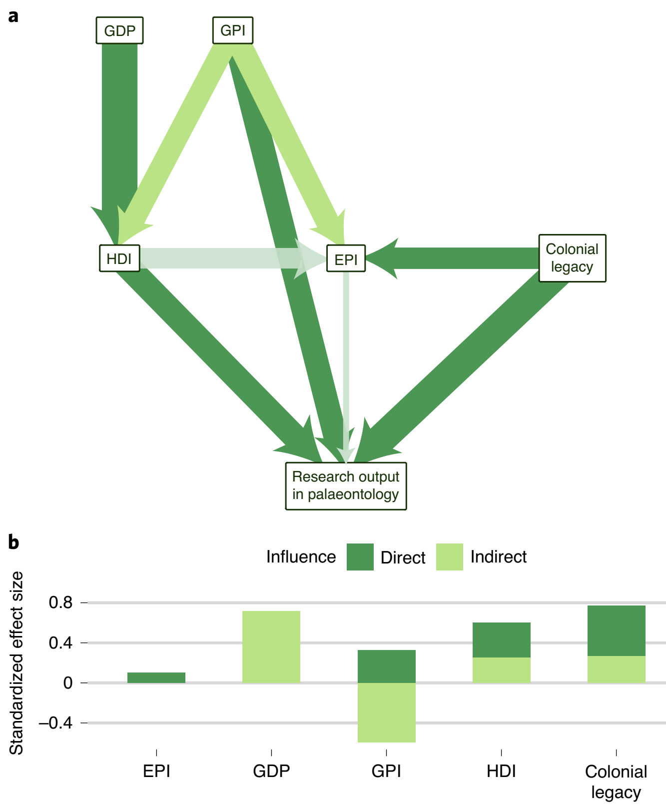

Fig. 4 | Influence of socioeconomic factors and colonial legacy on paleontological research output. a, Path diagram of socioeconomic factors and colonial legacy influencing palaeontological research output. Dark and light green paths represent positive and negative influences, respectively. Paths for which $P > 0.05$ are semi-transparent. Path thickness is proportional to the standardized regression coefficient. **b**, Direct and indirect effects of each of these factors. Acronyms for socioeconomic measures: EPI, English proficiency index; GDP, gross domestic product; GPI, global peace index; HDI, human development index.

knowledge has serious consequences for palaeontology, by disadvantaging researchers for whom English is a secondary language or who are based in countries with low English proficiency, making non-English-language knowledge inaccessible, and impeding the communication of science to under-represented communities[42–46]. This English-language bias is particularly consequential for palaeontological research that relies on compilations of primary studies, as previous work has suggested that ignoring non-English-language studies may bias outcomes of ecological meta-analyses[47]. One simple, yet rarely adopted, solution for palaeontologists would be to actively seek out non-English knowledge during literature searches, which should be implemented through collaboration with native speakers of these languages[47,48]. Similarly, palaeontological journals are increasingly providing authors with the option to submit their manuscript abstracts in multiple languages[48,49].

Conclusions

The fossil record is fundamental to our understanding of the evolution and diversification of organisms through deep time, and the spatial structure of fossil data has been the dominant factor distorting our interpretations of global biodiversity dynamics across the Phanerozoic[6]. However, current compilations of fossil occurrences across the world are far from global; there is discernible geographic variation in where fossils are recovered and reported from[2,5]. Our results demonstrate that efforts to mitigate effects of sampling bias to obtain a truly representative view of past biodiversity are not disconnected from the aim of diversifying our discipline. Spatial sampling biases are borne out not only by geological and physical factors influencing the fossil record, but also by pervasive historical and socioeconomic factors. We thus need to examine these biases more deeply and consider how current research practices in palaeontology are hindering efforts to increase diversity across all aspects of our discipline. This is especially crucial if palaeontology is to play a part in providing a long-term perspective on Earth's biodiversity to sustain current biodiversity through conservation[50].

The first step towards conducting research that is more equitable and ethical is to acknowledge that scientific colonialism is prevalent in palaeontology and that knowledge production is driven by global power relations, as demonstrated here. In many field-based disciplines, where a portion of the work has been undertaken by local scientists, their contribution is sometimes acknowledged in the form of co-authorship. However, there is a notable lack of publications being led by local scientists in many regions outside of North America and Europe (Extended Data Fig. 9). Collaboration in this form may therefore be a representation of subordination, as the privilege of first authorship usually goes to foreign researchers, rather than creating an equitable partnership. Moving forward, developing and advancing palaeontological knowledge will require adopting a research culture where knowledge exchange between researchers from different parts of the world takes place on a level playing field. Many sets of recommendations for curbing scientific colonialism and exploitative research have already been drawn up for other fields such as genomics, marine science and ecology, which are also applicable to palaeontology[13,18,51,52]. Below, we make broad recommendations, on the basis of our results, that should be adopted in palaeontology to transform the discipline into a more inclusive and equitable one.

Equitable, ethical and sustainable collaborations. Collaborations should ideally begin with input from all involved parties to develop research agendas that are built on mutual trust, respect and the needs and interests of local people[52]. To stop the proliferation of parachute science, researchers wishing to conduct research abroad, particularly those from the Global North, should ensure that they are not impeding the research goals of local researchers and connect with local scientists early in the project design to allow for long and sustainable partnerships[53]. Researchers must also take time to learn the regulatory and cultural landscape of a country where they intend to carry out field research to avoid conduct that is unethical or illegal. Alongside providing important scientific expertise, local partnerships can be key to navigating bureaucratic requirements or to grasping local social and cultural norms, but these partnerships should not be sought out for this purpose alone. Institutional student exchange programmes should be utilized not only as a way to train the next generation of palaeontologists to be research leaders in their countries without dependency on foreign expertise, but also to communicate critical perspectives on how research is carried out in different countries and world regions. Typically, discussions regarding the training of students and researchers focus on the capacity of Global North researchers to act as teachers and mentors, but fail to acknowledge how much these researchers can learn immensely from their peers in the Global South with regards to their local knowledge, expertise and practices.

Joint funding schemes. Current academic funding schemes to which principal investigators from high-income countries apply are often nationally or regionally based (for example, the European Research Council). Researchers are typically employed at institutions in the same country or region as the funding body, where they are evaluated on their research output[14]. This individualistic nature of the current system often deters researchers from collaborative capacity building[54]. When strategic funding decisions are not made in consultation with local researchers in the countries where data collection is to be carried out, the research agendas and priorities of these researchers are overlooked or, at best, an afterthought. Even in the case of collaborations with local researchers, the dissemination of results usually occurs in the 'home base' of the principal investigators, marginalizing these local researchers and their contributions. Regional or international funding bodies should ensure long-term funding for palaeontological research in countries by providing joint funding schemes for researchers from different countries. Bilateral and multi-lateral funding partnerships (among high- and middle/low-income countries, and among middle/low-income countries) that already exist in global health research[54] could be applied to the natural sciences. Fossils are found all over the world, meaning palaeontology in particular is ideally suited to these kinds of funding partnerships. Instead of striving towards individualism or competing with each other, palaeontologists from different countries could pool their resources, expertise and efforts to explore a myriad of research questions that have global importance.

Access, management and protection of data. Sustained investment is needed to enhance the capacity of lower-income countries and their institutions to collect, store and organize fossil collections and data locally. The establishment of such local repositories, as well as the development of institutional educational programmes, can serve as centres of training for both local palaeontologists and foreign researchers wishing to build equitable international partnerships. Joint programmes in collection management between countries would also ensure that fossils are retained in domestic repositories and remain accessible to researchers from all over the world. Today, many fossil collections are confined to institutions in the Global North as a result of colonial plunder in the nineteenth and twentieth centuries or scientific colonialism thereafter. Repatriation requests are a sensitive subject for many of these institutions[36]. However, while these discussions are ongoing, the status quo is maintained and researchers from lower-income countries continue to face additional barriers with respect to their research, such as financial or visa restrictions. Similarly, the academic publishing culture contributes to this scientific gatekeeping: high-impact publications in journals based in the Global North may offer more visibility, but researchers from lower-income countries are highly under-represented on the authorship of high-impact palaeontological and ecological publications[55] due to factors such as language barriers, governmental expenditure on research and development, and parachute science[56]. Academic paywalls and exorbitant open access charges also mean that many scientific publications exacerbate existing inequalities by restricting access to scholarly resources[57].

Given the current and recent patterns documented here, widespread systemic changes are urgently required to address ongoing global power imbalances in the discipline of palaeontology that have persisted for more than two centuries. Researchers and their teams should also reflect on their own research practices to identify where their work contributes to scientific colonialism and the ways they can mitigate their impact on the global power imbalance within palaeontology. However, efforts to address and resolve the asymmetry observed in the discipline should be led by funding bodies, research institutions, professional societies and scientific journals, to ensure that existing unethical and exploitative research practices structurally embedded in palaeontology become a thing of the past.

Methods

Affiliation data of researchers. We extracted references from the Paleobiology Database (PBDB; www.paleobiodb.org) that document fossil occurrences published during the past three decades (1990–2020) and recorded the countries affiliated with each author of these publications. These occurrence data are added from the primary literature to the PBDB by individual researchers across the world, and these researchers typically also download these data for use in deep-time biodiversity analyses. We chose to use data from the PBDB because it is the most popular out of the existing large fossil occurrence databases (Supplementary Table 4) and is widely used in large-scale temporal and spatial analyses of biodiversity in the fossil record, especially with the aim of quantifying extinction risk as a result of climate change[58–60]. As such, the references in the PBDB represent the research that is most visible to the wider research community and therefore contributes to these kinds of large-scale studies. It is also important to note that the PBDB originated as a product of a working group based in the US, which later expanded to involve data enterers from various other countries. Yet, the core PBDB 'community' consists mostly of US and European researchers. Therefore, the data compiled in the database probably present a skew towards these countries and certainly a skew towards the English language.

In the PBDB, each record of a fossil occurrence is attributed to references, which are most commonly in the form of peer-reviewed primary literature, but also include books, field guides and PhD theses[61]. Using the download function, we downloaded all bibliographic references for the past 30 years (1990–2020), which comprised a total of 29,039 publications (latest download on 19 January 2021). Then, the affiliate countries of each author on these publications were compiled. This was achieved through: (1) web scraping of the landing page of the publication on the publisher's website ($n=11,037$), and (2) manual entry when (1) was not possible ($n=15,372$). If the publication could not be accessed because the online version was unavailable or is behind a paywall inaccessible to us, we used alternative methods to infer affiliate countries of authors. These included obtaining the information from: (1) another publication by the same author published in the same year as the one of interest, with the assumption that no change in affiliation occurred during that year, (2) personal websites of authors where online curricula vitae or similar were available, (3) academic social networks, such as ResearchGate or Academia.edu, and (4) published obituaries (if the author is deceased). Note that this approach only provides us with information about where researchers are based, but not where they are from. However, institutional affiliations represent a proxy for the funding source of a researcher or working group; for example, a non-German researcher based at an institution in Germany probably obtained their funding from a German or European organization. This thus represents one or more academic entities that allowed a particular research project to take place. Only 2,573 (8.5%) of the downloaded references could not be accessed, and thus could not be assigned affiliation information. Of the 26,409 publications for which affiliation data were accessible for collation, 19,874 (75.3%) were written by more than one author, and 10,300 (39%) had two or more authors from different countries in the author list (that is, represented international collaborations).

The final dataset comprised information on each publication (for example, full title, year of publication, DOI if available, and so on), the affiliate countries (as provided by the authors) of each author on a given publication obtained through the methods described above, and the countries from which the fossil material described within the publication were sampled (hereafter 'research destination') as obtained by the locality information provided in the PBDB. Publications describing fossil occurrences in more than a single country were recorded in the dataset for each country mentioned. If an author was affiliated with two or more institutions, all institutions and their countries were recorded. All the country data were coded into three-letter codes to avoid any discrepancies between spellings (for example, USA vs United States vs United States of America), using the 'countrycode' R package[62]. The number of publications recorded in the PBDB per country was used as a proxy for 'research output'.

Socioeconomic and political data. Research plays an important role in the socioeconomic growth of a country and vice versa. There are several studies highlighting the link between research output and economic indices, the most popular one being the gross domestic product (GDP) or GDP per capita[15,63,64]. GDP data for our study were obtained from the World Bank[65]. In addition, the amount of funding allocated for research and development per country is an important measure of research output in a country[64]. However, as there is not enough information on funding information in the field of palaeontology in different countries, we could not consider this variable in our study.

The HDI was created to emphasize that people and their capabilities should be the ultimate criteria for assessing the development of a country, not economic growth alone[66]. The HDI measures key dimensions in human development, namely, health measured by life expectancy, access to education measured by expected years of schooling of children at school-entry age and mean years of schooling of the adult population, and standard of living measured by the gross national income per capita. HDI data for our study were obtained from the United Nations Development Programme[66].

A strong association between English proficiency and research output has previously been documented in the literature[15,67]. While English proficiency is inherently not a cause for improved research output in different countries, studies show that non-native English speakers are less likely to have their publications accepted for publication than English-speaking countries such as the US or the UK[67,68]. As such, this has led to an over-representation of countries with high English proficiency, which also usually have strong research funding, and an under-representation of researchers from countries with lower English proficiency. For our study, we used the 2020 English proficiency index (EPI), which is based on test data from more than 2 million test takers around the world[69]. As the EPI is not provided for English-speaking countries, that is, where English is the primary language used (Supplementary Table 5), these countries were assigned the highest EPI (EPI = 75). Countries that are listed as English speaking but were included in the EPI evaluations, such as Fiji or Nigeria[70], were assigned their respective EPI scores rather than the highest score.

Finally, research productivity has previously been associated with political stability[15,71]. We used the 2020 global peace index (GPI) as a proxy for political stability[72]. The GPI is calculated by taking several factors into consideration, such as number of and intensity of internal or external conflicts, related deaths, crime and imports or exports of weapons.

Colonial legacy data. We devised a binary variable to assess the influence of colonialism on research output in palaeontology. Countries that have a history of colonialism or have profited from colonialism were assigned '1' and the remaining countries were assigned '0'. We use the term 'colonialism' here to encompass a larger concept beyond European expansion and domination over overseas territories and people[73]. As such, the following criteria were used to categorize countries (listed in Supplementary Table 3) as '1' if they practiced or were involved in: (1) setting up colonies beyond their territories, (2) exploitative colonialism—occupation of a country or region to exploit its population as labour and/or its natural resources as raw material, (3) settler colonialism—occupation with the aim of replacing the original population of the occupied territory[74], (4) internal colonialism—the exploitation of minority groups within a wider society, leading to political and economic inequalities in a region or between regions[75,76], (5) surrogate colonialism—supporting the settlement of a non-native group on territory occupied by an indigenous population[77], and (6) colonial complicity—benefiting from colonization by other countries without actively engaging in the colonialism process[78]. We used the signing of the Treaty of Tordesillas in 1494 as a cutoff point, before which any practice of or profit from colonialism was not taken into consideration. Imperial, or colonial, expansion and conquest was not unknown before this point. However, this treaty put the idea of global domination and power into a form that legitimized colonial possessions of territories and peoples as a political, economic and cultural right, as well as the 'civilizing mission of the savages'[79].

Determining the relationship between authors and research destinations. Analyses were conducted within R (version 4.0.1)[80] using various packages referenced in other sections. Plots were constructed using functions within the 'ggplot2' R package[81]. For simplicity, we assumed that all fossil occurrences per publication were the result of direct access of the author(s) to the fossil material described in the publication, through (1) conducting fieldwork, (2) access to museum collections, or (3) purchase of fossil material. We created a global country network in the form of a directed network using the 'igraph' R package[82], where each node represents a country ($G_{country}$) and each edge shows the number of publications authored by researchers in one country (country A) based on fossil materials collected in another country (country B). $G_{country}$ also includes self-loops, as fossil material in a country where an author is based should in theory be accessible to them. Country networks were also generated per continent and subcontinental region of research destinations, using the classification of the World Bank (Supplementary Table 6). We also computed the 'parachute index' for each country, referring to the term 'parachute science'[18]. The 'parachute index' compares the number of publications on a specific research destination carried out by foreign authors (that is, those not based in the same country as the fossil material being published) as opposed to local authors (that is, those who are based in the same country as the fossil material), measured as log ratios.

Quantifying causal relationships between authors and research destinations. To obtain a more integrated picture of the direct and indirect influences on research output in palaeontology, we conducted confirmatory path analysis (CPA) on the basis of the piecewise fitting of different linear models using the 'piecewiseSEM' R package[83]. This allows the incorporation of both continuous and discrete variables (Supplementary Table 7) and applies a series of statistical techniques, such as multiple regression and factor analysis, to investigate the relationships between one or more variables. We have to emphasize that confirmatory path analysis itself does not provide a means of determining causal relationships, but rather determines the strength of a causal relationship assumed by the analyst. Countries that were data-deficient, that is, countries with missing data for one or more of the variables (Supplementary Table 1) mentioned above were omitted from the model. Many of these tend to be administrative or unincorporated regions of other countries, disputed countries or regions, or regions with conflicts where little or no information is available, for which the United Nations does not provide any official data. Similarly, some of these countries were not included in the EPI or GPI evaluations. The final dataset for the confirmatory path analysis comprised 95 countries in total.

Research output was first modelled as a function of all the above-mentioned socioeconomic factors. However, before this was used in the path model, variable selection using a stepwise algorithm was applied to find the optimal model that minimizes the Akaike information criterion (AIC). Similarly, HDI and EPI were also modelled as a function of all the variables and the same steps were applied to optimize each individual model. The final individual models were then added to the overall path model. The overall path model was evaluated using Shipley's test of directed separation[84], which yields a Fisher's C statistic that can be compared with a χ^2 distribution. If the resulting P value is >0.05, then the model can be said to adequately reproduce the hypothesized causal network.

Reporting Summary. Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability

All relevant data supporting our analyses are available in the Open Science Framework at https://doi.org/10.17605/OSF.IO/6WC7A. Some of the data are replicated in the Supplementary Information. A compilation of all the publications from which metadata were extracted is available in the Open Science Framework at https://doi.org/10.31219/osf.io/f3u9k. A multi-lingual document containing the plain-language summaries for this study can be accessed from the Open Science Framework at https://doi.org/10.31219/osf.io/bptqf and is included in the Supplementary Information.

Code availability

All code generated during this study is available in the Open Science Framework at https://doi.org/10.17605/OSF.IO/6WC7A.

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Author contributions

N.B.R. and E.M.D. conceived and designed the project, curated the data, conducted the analyses, prepared figures and led the writing of the manuscript. T.M.K and P.S.N. contributed to the acquisition of the data. All authors (N.B.R, E.M.D, A.M, T.M.K, P.S.N., A.M.G., D.C.) contributed to collating material for the supplementary information, and to the writing and approval of the final manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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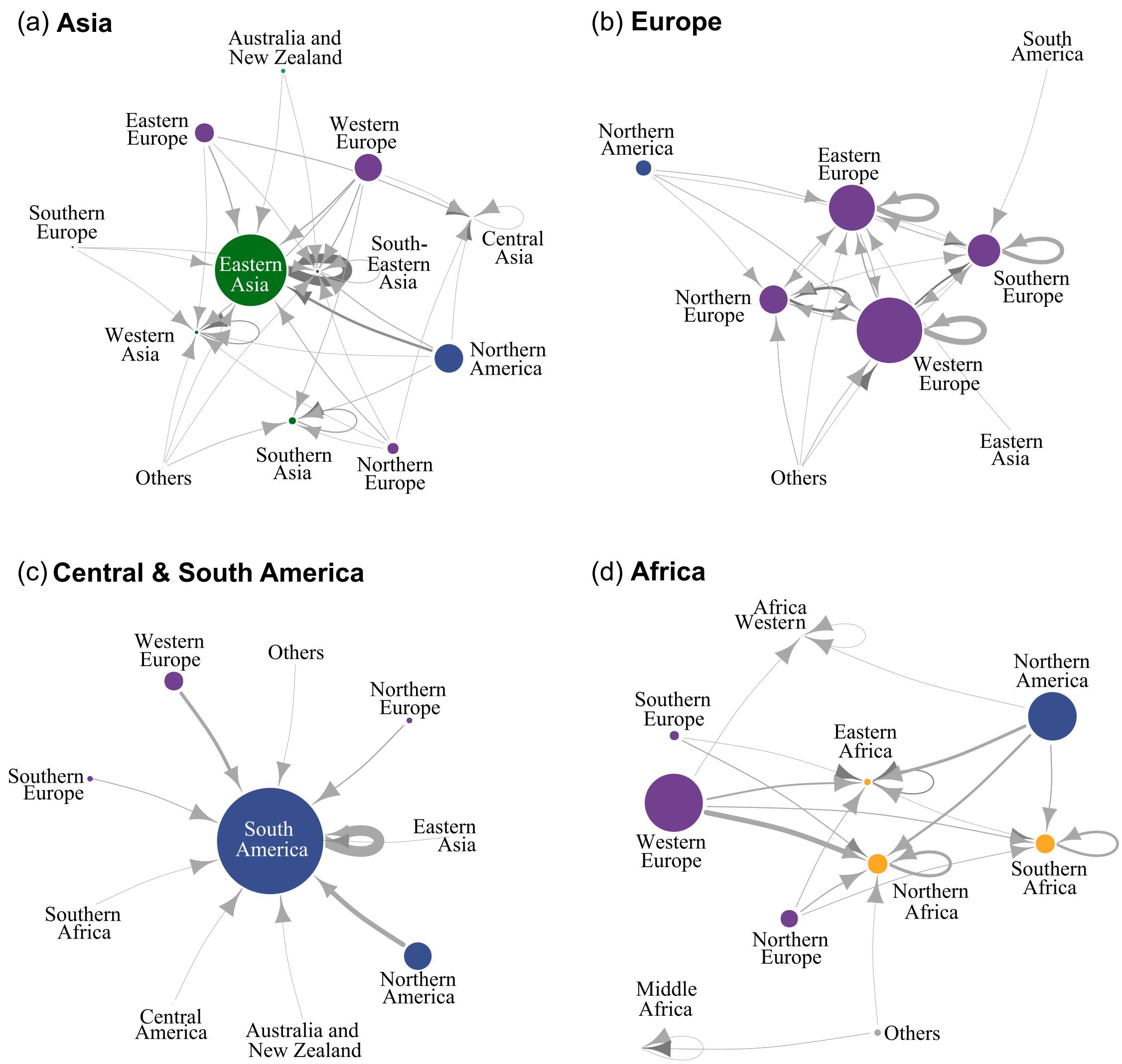
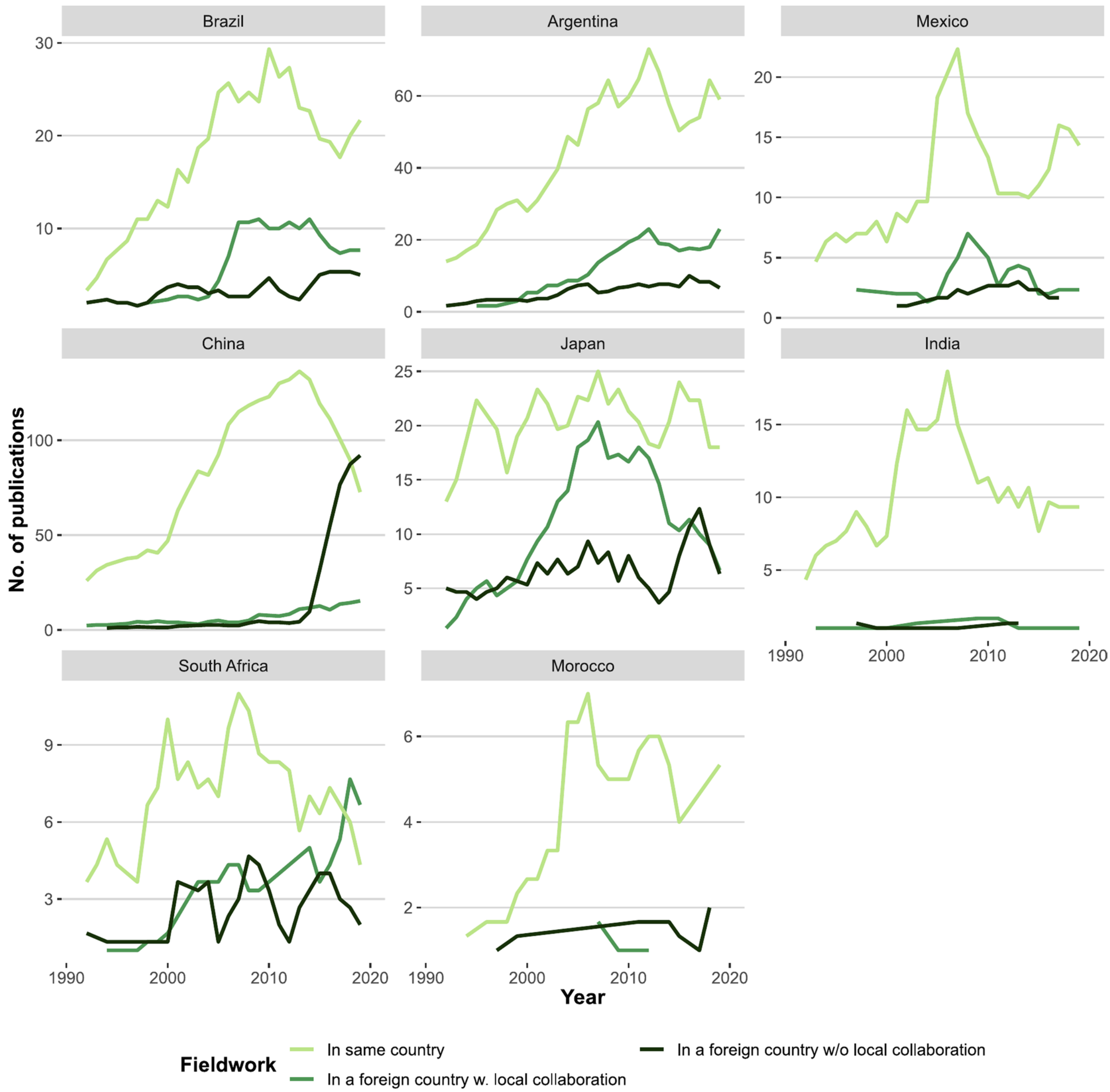
Income classification	Number of publications	Percentage
High	356	45.9
Upper middle	118	25.0
Lower middle	108	13.9
Low	194	15.2

Extended Data Fig. 1 | Total number of publications of researchers from data-deficient countries listed in Table S1, aggregated by income classification.



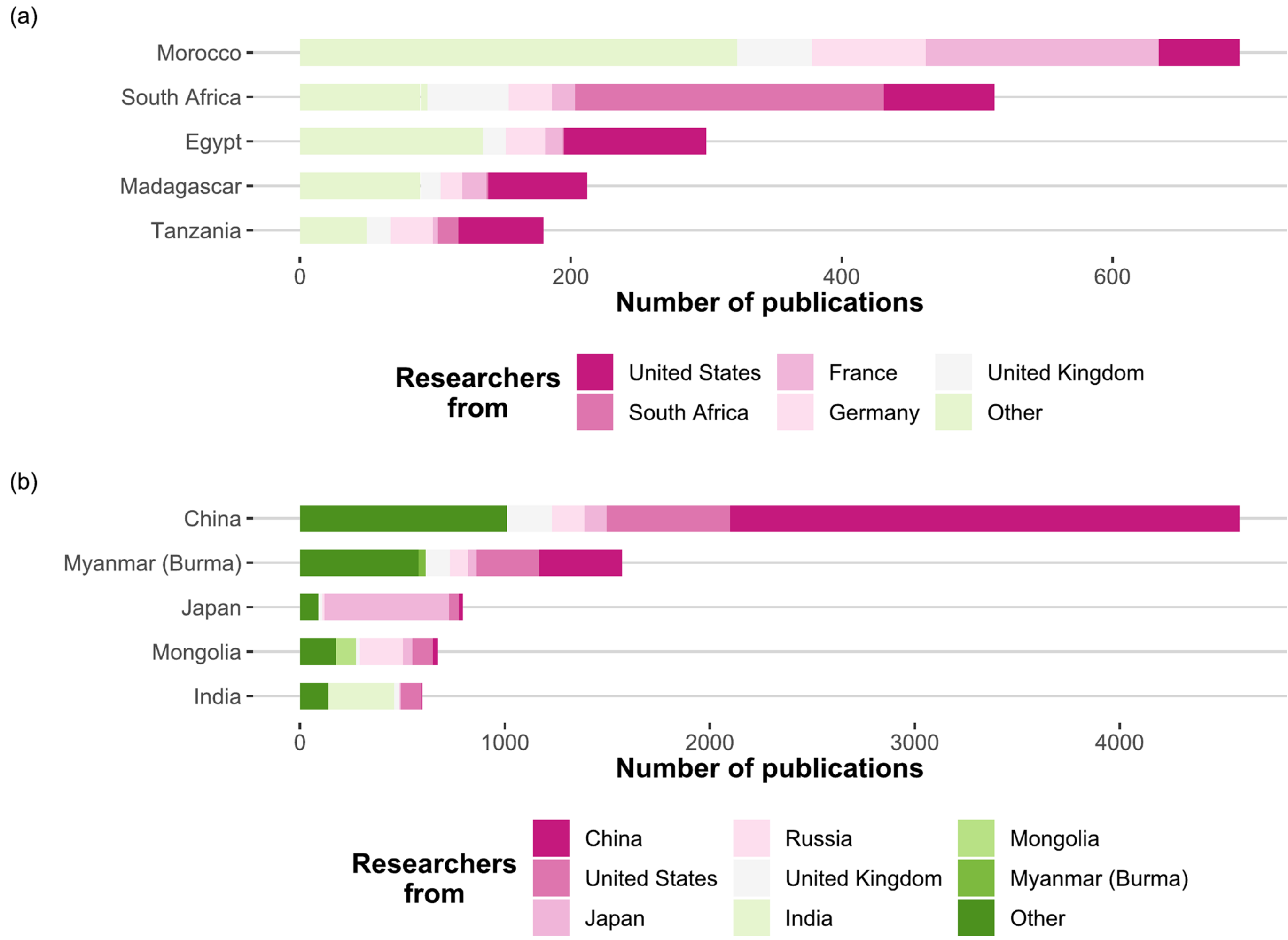
Extended Data Fig. 2 | Authors per region and their selected research destinations in **(a)** Asia, **(b)** Europe, **(c)** Central and South America and **(d)** Africa. The direction of the arrows show the relationship between the region the author is affiliated with and the region where they carry out their research (that is the origin country of the fossil material described in the publications). Self-loops indicate publications concerning a specific region that were by authors from the same region, and the size of circles and thickness of the lines for each region are proportional to the number of publications by authors from the same region.



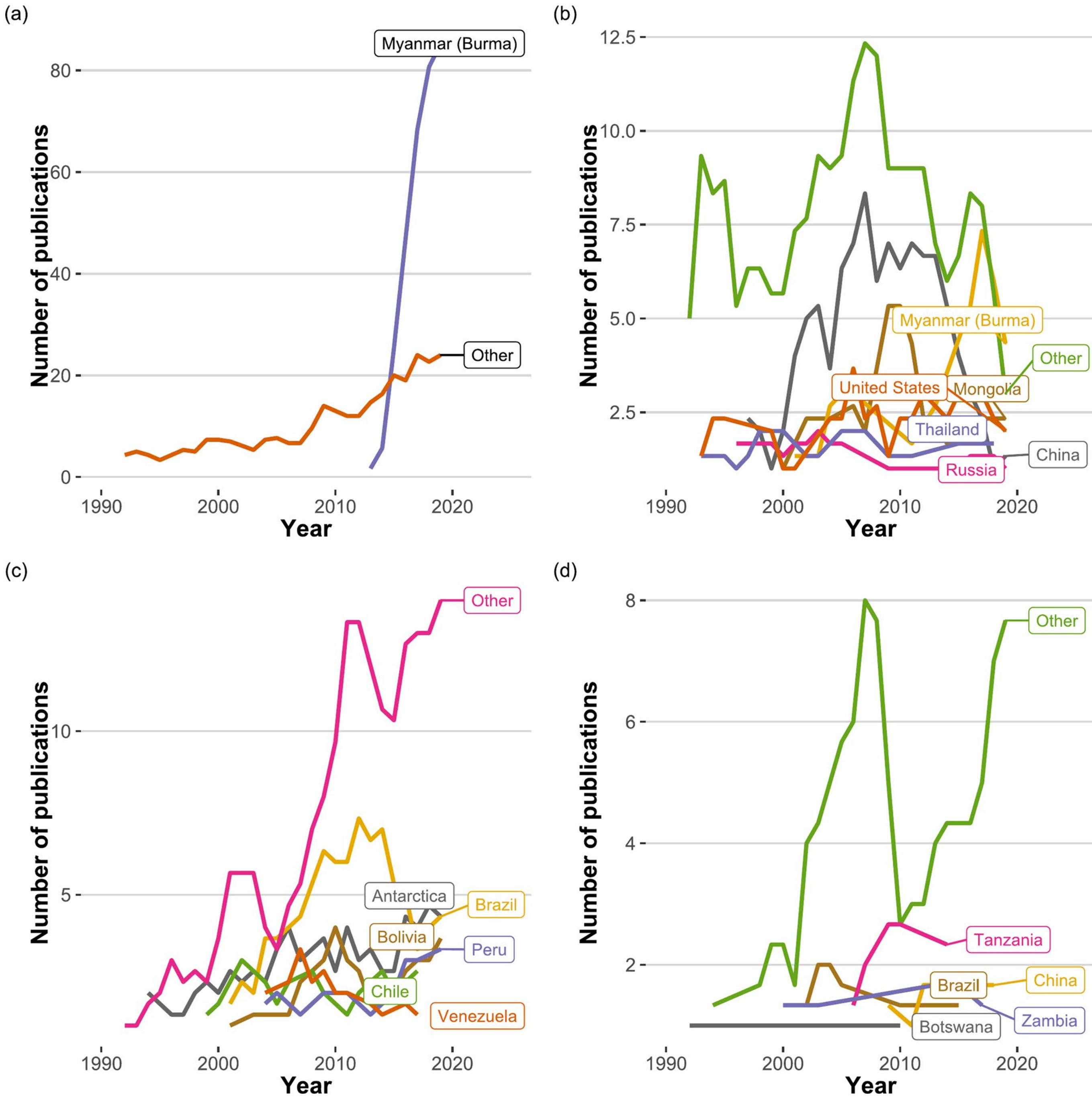
Extended Data Fig. 3 | The top eight countries in Central and South America, Asia and Africa in terms of the number of publications.

Country	Region	Includes local authors: Yes	Includes local authors: No	Parachute Index
Dominican Republic	Caribbean	22	397	-2.89
Myanmar (Burma)	South-Eastern Asia	56	765	-2.61
Namibia	Southern Africa	5	37	-2.00
Tanzania	Eastern Africa	21	86	-1.41
Madagascar	Eastern Africa	32	100	-1.14
Uzbekistan	Central Asia	14	42	-1.10
Oman	Western Asia	25	58	-0.84
Kyrgyzstan	Central Asia	28	64	-0.83
Ethiopia	Eastern Africa	19	37	-0.67
Morocco	Northern Africa	126	241	-0.65

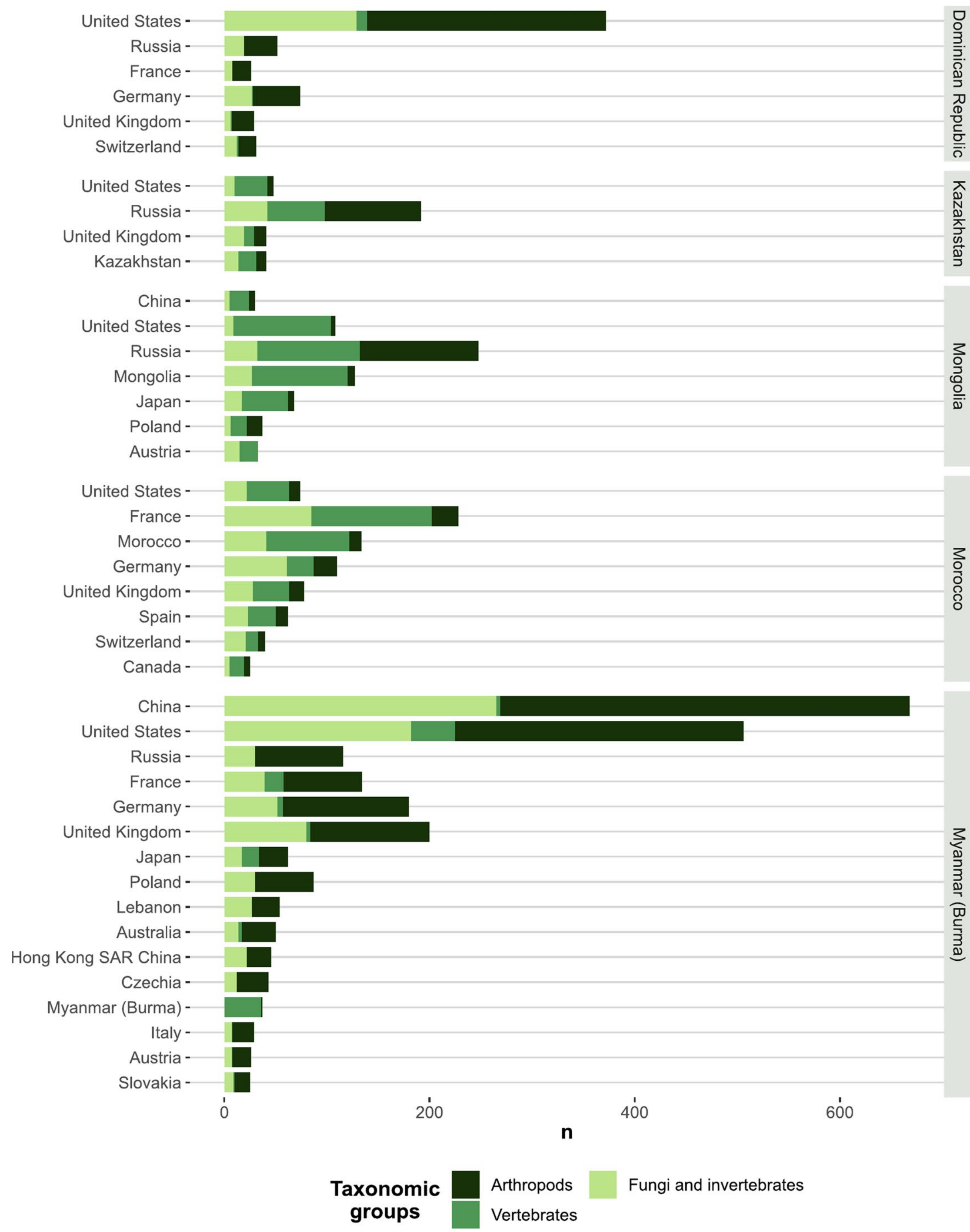
Extended Data Fig. 4 | Top 10 countries experiencing parachute science.



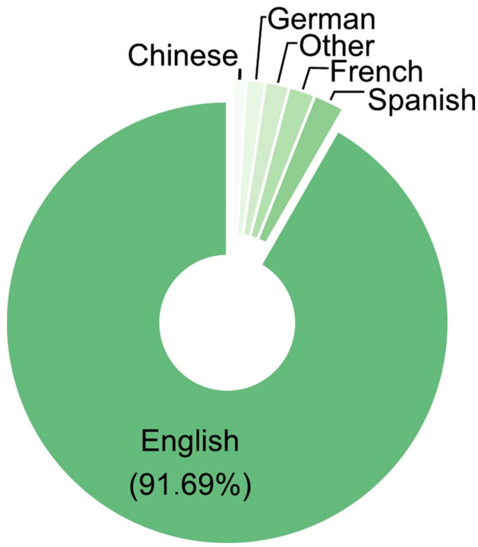
Extended Data Fig. 5 | The top countries in **(a)** Africa and **(b)** Asia where authors publish fossil material from popular research destinations.



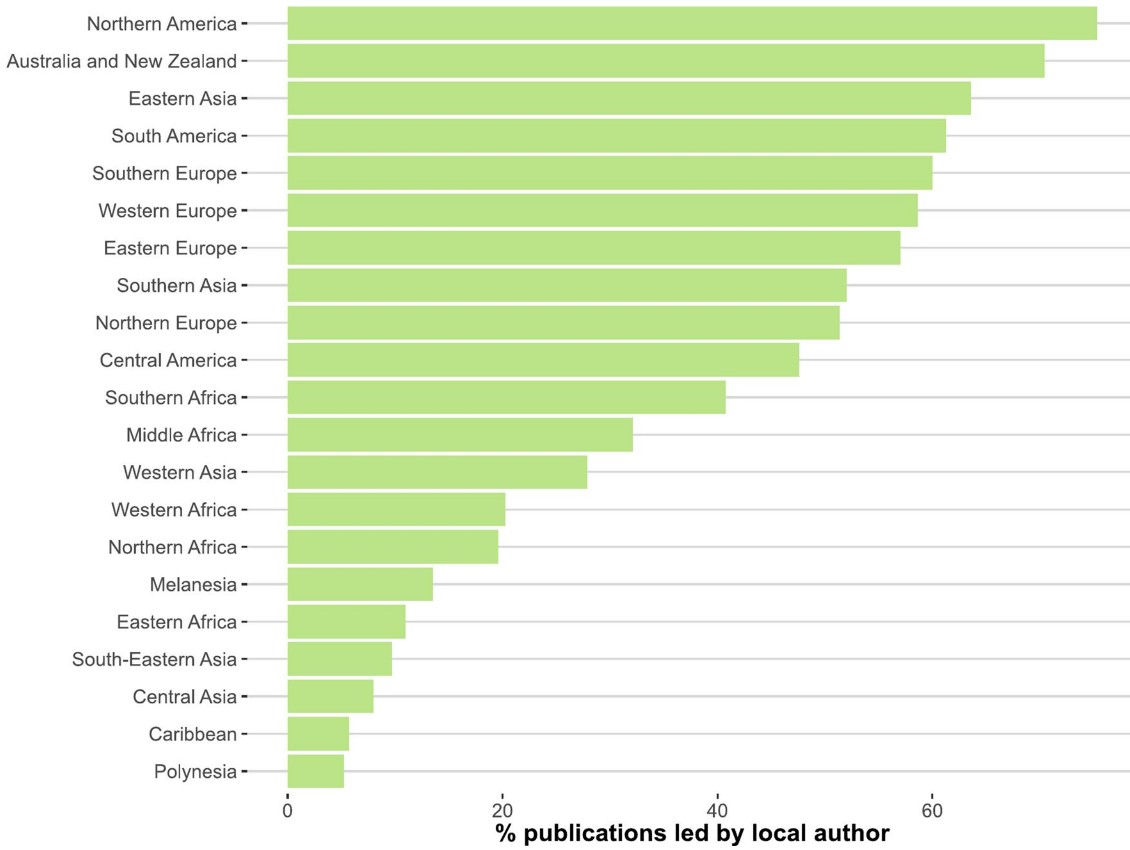
Extended Data Fig. 6 | Number of publications per year by authors in **(a)** China, **(b)** Japan, **(c)** Argentina and **(d)** South Africa, and the foreign countries in which the fossil material in their publications originates.



Extended Data Fig. 7 | Taxonomic groups by the country in which the fossil material originates (in grey boxes on the right) and by the countries that publish on them (on the left).



Extended Data Fig. 8 | Proportions of publications in the Paleobiology Database by languages.



Extended Data Fig. 9 | Proportions of publications on fossil data in a specific country led by a local author, by region.

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Reporting Summary

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For all statistical analyses, confirm that the following items are present in the figure legend, table legend, main text, or Methods section.

n/a	Confirmed	
☐	☒	The exact sample size (*n*) for each experimental group/condition, given as a discrete number and unit of measurement
☐	☒	A statement on whether measurements were taken from distinct samples or whether the same sample was measured repeatedly
☐	☒	The statistical test(s) used AND whether they are one- or two-sided *Only common tests should be described solely by name; describe more complex techniques in the Methods section.*
☐	☒	A description of all covariates tested
☐	☒	A description of any assumptions or corrections, such as tests of normality and adjustment for multiple comparisons
☐	☒	A full description of the statistical parameters including central tendency (e.g. means) or other basic estimates (e.g. regression coefficient) AND variation (e.g. standard deviation) or associated estimates of uncertainty (e.g. confidence intervals)
☐	☒	For null hypothesis testing, the test statistic (e.g. *F*, *t*, *r*) with confidence intervals, effect sizes, degrees of freedom and *P* value noted *Give P values as exact values whenever suitable.*
☒	☐	For Bayesian analysis, information on the choice of priors and Markov chain Monte Carlo settings
☒	☐	For hierarchical and complex designs, identification of the appropriate level for tests and full reporting of outcomes
☒	☐	Estimates of effect sizes (e.g. Cohen's *d*, Pearson's *r*), indicating how they were calculated

Our web collection on statistics for biologists contains articles on many of the points above.

Software and code

Policy information about availability of computer code

Data collection	Data was downloaded from the Paleobiology Database (paleodb.org), World Bank, UNEP, EF EPI (English proficiency, https://www.ef.com/wwen/epi/), Institute for Economics and Peace(https://www.visionofhumanity.org). The final dataset and associated code is accessible at: https://dx.doi.org/10.17605/OSF.IO/6WC7A
Data analysis	All data analyses were conducted within R (version 4.0.1). All relevant code for our analyses is available on the Open Science Framework accessible at: https://dx.doi.org/10.17605/OSF.IO/6WC7A

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors and reviewers. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Portfolio guidelines for submitting code & software for further information.

Data

Policy information about availability of data

All manuscripts must include a data availability statement. This statement should provide the following information, where applicable:

- Accession codes, unique identifiers, or web links for publicly available datasets
- A description of any restrictions on data availability
- For clinical datasets or third party data, please ensure that the statement adheres to our policy

All relevant data and code supporting our analyses are available at https://dx.doi.org/10.17605/OSF.IO/6WC7A. Some of the data is replicated in the Supporting Online Information. A compilation of all the publications from which metadata was extracted is available at https://dx.doi.org/10.31219/osf.io/f3u9k.

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Please select the one below that is the best fit for your research. If you are not sure, read the appropriate sections before making your selection.

☐ Life sciences ☐ Behavioural & social sciences ☒ Ecological, evolutionary & environmental sciences

For a reference copy of the document with all sections, see nature.com/documents/nr-reporting-summary-flat.pdf

Ecological, evolutionary & environmental sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	This study looks at the relationship between fossil data collection and socio economic factors using a quantitative lens for the period 1990-2020.
Research sample	The following datasets were used: Paleobiology Database (paleodb.org): To obtain a list of publications (~30,000) from which affiliations data were extracted and the location of the fossils collected as stated in the publication World Bank: Gross Domestic Product, used as a measure for a country's economic output UNEP: Human Development Index, used as a measure for human development in a country EF EPI (https://www.ef.com/wwen/epi/): English Proficiency Index Institute for Economics and Peace(https://www.visionofhumanity.org): Global Peace Index
Sampling strategy	All the available data was used for sampling purposes
Data collection	N/A
Timing and spatial scale	Time period considered: 1990-2020
Data exclusions	N/A
Reproducibility	N/A
Randomization	N/A
Blinding	N/A

Did the study involve field work? ☐ Yes ☒ No

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

n/a	Involved in the study	
☒	☐	Antibodies
☒	☐	Eukaryotic cell lines
☒	☐	Palaeontology and archaeology
☒	☐	Animals and other organisms
☒	☐	Human research participants
☒	☐	Clinical data
☒	☐	Dual use research of concern

Methods

n/a	Involved in the study	
☒	☐	ChIP-seq
☒	☐	Flow cytometry
☒	☐	MRI-based neuroimaging