Fifty years of capacity building in the search for new marine natural products

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The Convention on Biological Diversity, and the Nagoya Protocol in particular, provide a framework for the fair and equitable sharing of benefits arising from the utilization of biological resources and traditional knowledge, and ultimately aim to promote capacity-building in the developing world. However, measuring capacity-building is a challenging task due to its intangible nature. By compiling and analyzing a database of scientific peer-reviewed publications over a period of 50 y (1965 to 2015), we investigated capacity-building in global marine natural product discovery. We used publication and authorship metrics to assess how the capacity to become scientifically proficient, prolific, and independent has changed in bioprospecting countries. Our results show that marine bioprospecting is a dynamically growing field of research with continuously increasing numbers of participating countries, publications, and scientists. Yet despite longstanding efforts to promote equitability and scientific independence, not all countries have similarly increased their capacity to explore marine biodiversity within their national jurisdiction areas. Although developing countries show an increasing trend in the number of publications, a few developed countries still account for almost one-half of all publications in the field. Multiple lines of evidence suggest that economic capacity affects how well countries with species-rich marine ecosystems can scientifically explore those resources. Overall, the capacity-building data analyzed here provides a timely contribution to the ongoing international debate about access to and benefit-sharing of biological resources for countries exploring biodiversity within and outside their national jurisdiction areas.

marine bioprospecting | biological resources | benefit-sharing

Marine biodiversity is unanimously acknowledged as a largely untapped reservoir of biological resources, particularly for drug discovery and development by the pharmaceutical sector and also for other biotechnology branches, such as cosmetic and nutraceutical industries (1). The increasing demand for new natural products, together with the world's progress toward a bio-based economy (2), has led to ever- increasing efforts in marine bioprospecting (3–5), the search for new marine materials, enzymes, and chemical compounds of biological origin. However, marine bioprospecting is an expensive endeavor with an uncertain return on investment. Intellectual property mechanisms are often used to protect users who invest in the bioprospecting process, with arguable scientific and monetary benefits for providers who have jurisdiction over the biological resource (6, 7), that is, the country where the biological sample is collected. Consequently, much policy debate has been centered on developing legal frameworks to entitle providers with benefits from rights over the knowledge, innovations, and practice benefits gained from collected organisms (8, 9).

This issue has been addressed by the Convention on Biological Diversity (CBD) and, more recently, by the Nagoya Protocol on Access and Benefit-Sharing (10). These documents provide an international framework for contracting parties to take measures in relation to access to biological resources, benefit-sharing, and compliance. Benefit-sharing obligations can be monetary (e.g., access fees, royalties, joint ownership of intellectual property rights) or nonmonetary (e.g., the sharing of research results, collaboration and cooperation in scientific research, institutional capacity-building) (10). Nevertheless, nonmonetary benefits might result in significant monetary value in the long term (11). Access and use of biological resources often lead to international research collaborations between User (i.e. research and publication) and Provider (i.e. geographic origin) countries, along with training, technology transfer, coauthorship in scientific journal articles, and other activities that improve the capacity of Provider countries to exploit and sustainably manage their biological diversity (12–14). Although the CBD advocates a sustainable use of biological diversity and promotes benefit-sharing and scientific cooperation, its effect on biodiversity and bioprospecting research remains unclear, with potentially negative effects on conservation and collaborative efforts between developed and developing biodiversity-rich countries (8, 15, 16).

Capacity-building is one of the CBD's strategic goals and a key feature of the Nagoya Protocol. The Protocol provides specific guidelines to guarantee that User and Provider parties cooperate in the development of capacity to conduct research and the strengthening of human resources and institutional capacities,

Significance

This research deals with the development of capacity-building through marine bioresearch from a scientific standpoint, particularly through a new approach based on publication and authorship metrics. By using a 50-y dataset on the discovery of marine natural products, this study draws verifiable conclusions on capacity-building, a process that is often difficult to quantify. This is a stepping-stone toward evidence-based capacity building for bioprospecting as originally envisioned in the framework of high-level international fora, such as the Convention on Biological Diversity and, more recently, the Nagoya Protocol.

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SOCIAL SCIENCES

PHARMACOLOGY

with a particular focus on provider parties in developing countries. In science, capacity-building refers to the development, strengthening, and retention of the human, technological, and institutional resources and skills necessary to independently conduct scientific work. Capacity-building is often measured by the number of publications, successful grant applications, career progressions, patent claims, financial outcomes, and technology transfers, among other parameters (17–19); however, these approaches often fail to comprehensively measure the usefulness or social impact of research, because they do not account for benefits to the research community and individuals that accrue from authorship in publications. An alternative way to measure capacity-building in science is by studying the nature of scientific collaborations, such as coauthorship and order of authorship in scientific articles published in peer-reviewed journals (18, 20).

Here we assess how the capacity to become scientifically proficient, prolific, and independent has developed in countries performing marine bioprospecting over a period of 50 y (1965 to 2015). Using several publication and authorship metrics, we analyze peer-reviewed bioprospecting studies, particularly publications reporting new marine natural products regardless of any intention to look for bioactivity or subsequent interest in the development of new marine drugs. The underlying assumption of our study is that in addition to classic metrics like the absolute number of publications, authorship metrics can capture additional aspects of capacity-building. For example, a country with an increasing proportion of lead authorship over time (i.e., as either first or last author) would thereafter also show increasing scientific capacity (21). We compiled both metrics—the number of publications and the proportion of lead authorships—for periods before and after 1993, the year when the CBD was enforced. In addition, because marine bioprospecting also relies on the financial capacity of a given country and on the marine biodiversity present in each exclusive economic zone (EEZ), we analyzed capacity-building in view of each country's gross domestic product (GDP), as well as marine species richness within each EEZ.

Results

Over the entire examined period from 1965 to 2015, there was a steep increase in the total number of yearly publications of new marine natural products (Fig. 1). Both the number of countries with authors that took part in the conducted research and publication ("User countries") and the countries of origin for the published compounds ("Provider countries") increased rapidly during the 1970s and 1980s and stabilized at a high level toward the 2000s (*SI Appendix*, Fig. S1). However, the contribution to this body of literature is highly imbalanced across all users; only three countries (the United States, Japan, and China) account for nearly one-half of all user publications in the field. Countries that traditionally have strong capacities in marine research, such as France and Italy, maintained continuous and stable bioprospecting activity throughout the entire period, as both User and Provider countries (Fig. 1 *A* and *B*). In addition, developing countries, such as Indonesia, Thailand, and most notably China, have built a large capacity for marine bioprospecting in recent decades. Over a period of less than 30 y, China has become the most active marine bioprospector, accounting for 19% of all publications since 1993, when the CBD began to be enforced, and 31% of all publications between 2010 and 2015. In contrast, traditionally important providers of biological material as India, Papua New Guinea, and Palau (*SI Appendix*, Fig. S2), still have a limited and slowly growing publication record as Users. Consistent with the increase in the number of publications, the overall number of unique authors involved in marine natural products research increased steeply from 1965 to 2015 (*SI Appendix*, Fig. S3).

Although increasing numbers of User and Provider countries are participating in marine natural products research, and there is an increasing number of annual publications, there are pronounced differences among countries in the scientific role taken. Many countries with limited monetary resources (lower 60th GDP percentile) are not participating as lead authors in publications that explore their own biodiversity (Fig. 2 *A* and *B*). For example, Palau and Indonesia have been able to increase both the number of publications as Provider countries from a handful to several hundred after 1993, but the proportions of authorship and lead authorship among those publications remain low. India, on the other hand, has been able to increase the number of publications after 1993 and has been more successful in scientific participation, as indicated by the high proportion of both authorships and lead authorships. China, the most prolific Provider country after 1993, not only participates in almost all publications exploiting its own resources, but also shows a consistent leadership position (Fig. 2 *A* and *B*). These patterns resemble

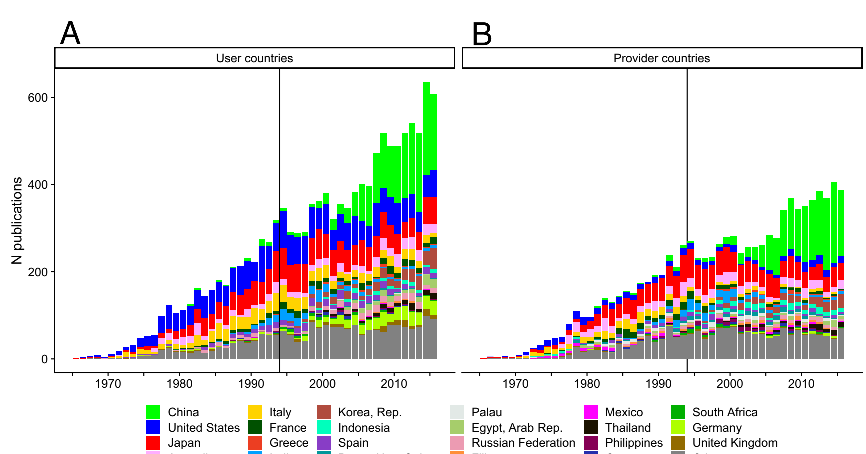

Fig. 1. Trends in the number of publications by User and Provider countries engaged in marine bioprospecting between 1965 and 2015. Countries were ranked by their total number of publications as user (*A*) or provider (*B*). The top 10 in each category were color-coded (for ranks, see *SI Appendix*, Fig. S2). In addition, User and Provider countries were color-coded to demonstrate patterns of relevance, such as increasing or decreasing trends in publications or authorship, in a total of 23 highlighted countries. The remaining 55 countries grouped as "Other" show only a small number of publications or have a fragmented publication record. For a similar overview of these countries, see *SI Appendix*, Fig. S4. The vertical line indicates the time point of enforcement of the CBD convention (December 31,1993).

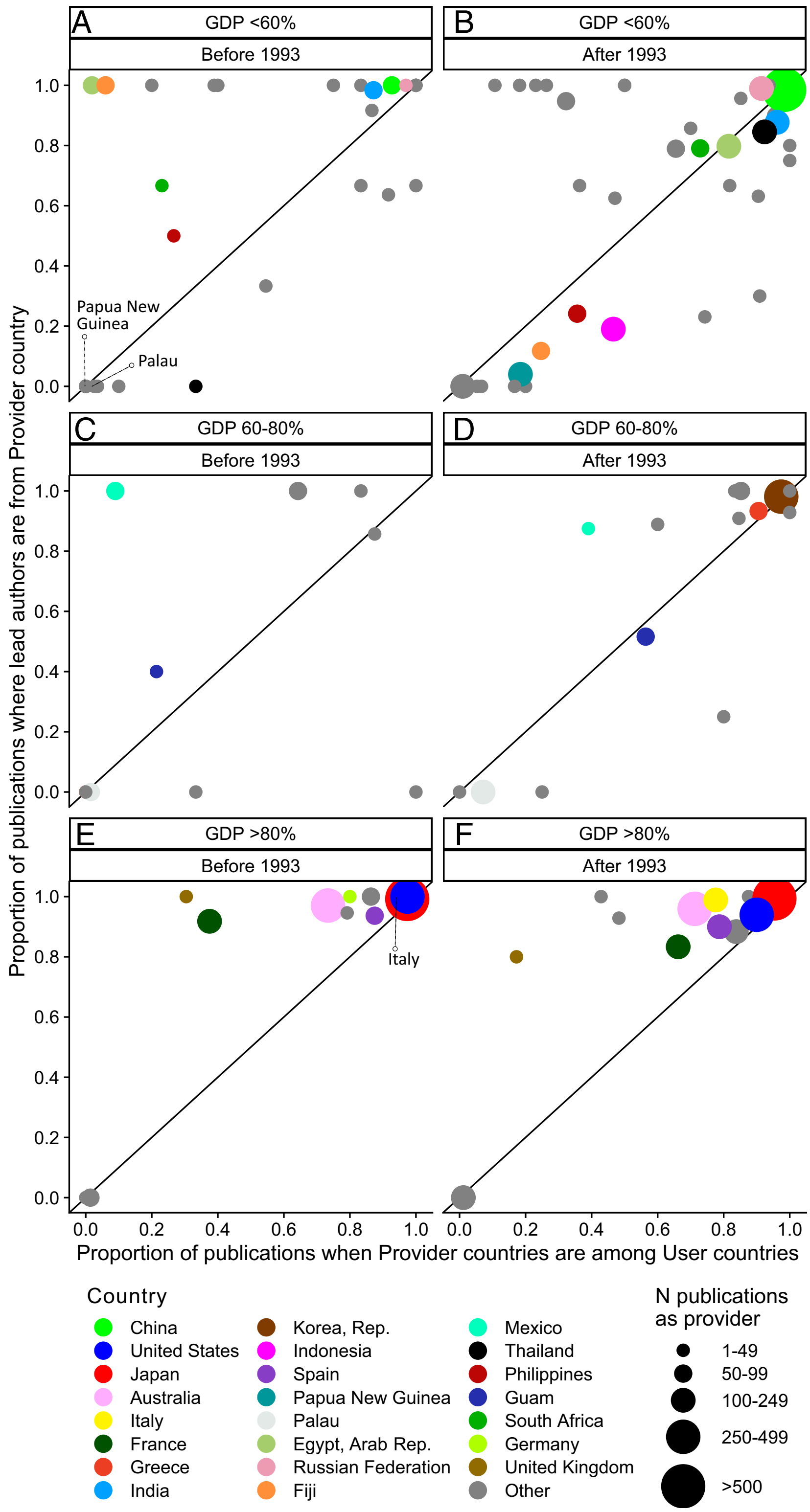

Fig. 2. Contrast between two aspects of capacity-building among Provider countries before (*A*, *C*, and *E*) and after (*B*, *D*, and *F*) December 31, 1993, when the CBD was enforced, and grouped by GDP percentile (*A* and *B*: lower 60%; *C* and *D*: 60 to 80%; *E* and *F*: >80%). The *x*-axis indicates the proportion of publications where the providing countries are also User countries, i.e., participating in exploiting their own resources. The *y*- axis indicates whether Provider country authorships were as lead author or not. For example, as in the case of Indonesia after 1993, 0.5 on the *x*-axis and 0.2 on the *y*-axis indicate that at least one author affiliated with this country appears in 50% of all publications and is lead author (first or last position) in 20% of those publications. Hereafter, countries that are above the 1:1 line are lead authors in most publications they participate in, whereas countries below the 1:1 line may participate frequently, but not necessarily as lead author (e.g., Guam). We calculated these proportions directly from all publications for the respective period; therefore, there is no SE associated with these values.

those of most developed countries, which show only little change in their role in leading scientific efforts (Fig. 2 *E* and *F*). For example, Japan, the United States, and Australia, which are the most productive Provider countries after China (*SI Appendix*, Fig. S2), not only have the largest shares in all User publications, but also maintain high shares in both regular and lead authorships.

Lead authorship differences among countries are also visible from the perspective of "facilitation" or "utilization" of resources from third parties, that is, the lead authorship position of a User country when the Provider country is present or absent (Fig. 3). Most countries with low GDP per capita (except China and Russia after 1993) have a substantially lower proportion of lead authorships as User countries when the Providers are present (Fig. 3 *A* and *B*). In high-GDP countries, the situation is changing over time and with implementation of the CBD. Before 1993, most countries in this group (except the United States) showed an equally high proportion of lead authorship publications when Provider countries were present or absent (close to 1), whereas after 1993, some high-GDP countries (e.g., Australia, Italy, Germany, the United Kingdom, the United States) decreased the proportion of lead authorships in the absence of Provider countries while maintaining a high lead authorship in their presence (Fig. 3 *E* and *F*). Noteworthy changes are also observable for China, Mexico, South Africa, and the Philippines, which greatly increased their proportion of lead authorships after 1993 when the Provider country was among the coauthors (Fig. 3).

The model that we implemented to investigate interactions between economic status and marine species richness shows a significant nonlinear interactive effect of GDP and richness (*SI Appendix*, Table S1 and Fig. S5). Our results indicate that before 1993, Provider countries with high marine biodiversity exploited their resources only if the economic resources were given (along a GDP gradient). After 1993, this pattern was somewhat ameliorated, so that emerging threshold countries (i.e., countries rapidly expanding their investment in research and development in marine bioprospecting, such as China, India, Indonesia, and Mexico) were able to increase their scientific output and exploit their marine biodiversity. Despite the large uncertainty (R^2 = 0.27), the model suggests that economic capacity may be a requirement for exploiting marine biodiversity ($P < 0.05$) (*SI Appendix*, Table S1).

Discussion

Are Developing Countries on the Rise? The rising number of User and Provider countries participating in marine natural products research, together with the increasing number of annual publications, indicates that the capacity for marine bioprospecting is increasing globally. From the advent of marine natural products research onward, an increasing number of User countries have been sampling from a limited number of Provider countries; however, toward the end of the observation period, this pattern inverted towards an increased capacity of Provider countries to bioprospect their own marine biodiversity. This trend can be interpreted in two ways: on the one hand, it might demonstrate capacity-building in marine bioprospecting by Provider countries, while on the other hand, it could reflect an increasingly complex legal framework for countries wishing to explore marine biological resources outside their EEZ. However, for several high GDP countries (e.g., the United States, Germany, Italy, the United Kingdom), the Users-to-Providers publication ratio has increased between the two observation periods (before and after 1993) (*SI Appendix*, Fig. S6), suggesting that several countries still conduct a large share of their marine bioprospecting outside their EEZ. The dominance of the same high-GDP countries in the global distribution of research efforts has been similarly recorded when other metrics are used, such as number of publications (22) and number of patents (17) associated with marine genetic resources, as well as publication counts in deep-sea research (23).

Developing countries such as Palau and Papua New Guinea, as well as threshold countries like India and Indonesia, which are traditionally important sources of biological material, still show a limited capacity to lead in the biodiscovery of new marine compounds. Palau and Papua New Guinea, for example, did not have a single lead author publication between 1965 and 2015 despite featuring an increasing number of publications as coauthors (Fig. 2). India was able to increase the number of publications as a Provider country and, in more recent years, to participate in almost all of them as a coauthor. However, the proportion of lead author publications for India decreased slightly, probably because the scientific community from the Northern Hemisphere turned to India as a promising but still largely untapped source of new marine compounds (24). In contrast, a subtle increase in the proportion of lead authorship has been recorded for countries such as Egypt, Indonesia, and Mexico since the 2000s (*SI Appendix*, Fig. S6), which might be associated with increased efforts to implement the decisions of the latest CBD conventions, particularly on issues concerning access and benefit-sharing (25).

Our findings demonstrate the enduring heterogeneity in the capacity of Provider countries to perform research and publish the findings associated with the chemical diversity of their own marine bioresources. Such inequitable distribution among countries has already been reported for the capacity to undertake genomic research targeting marine life (22). However, the increasing number of Provider countries might be a positive sign of capacity-building. From the 1970s to the 2010s, Provider countries with only a small individual share in the overall record of publications (summarized as Other), but representing around one-third of all published compounds, have experienced a slow but steady increase in the proportions of lead author publications, from just below 30% in the 1970s to >40% in the 2010s. Nevertheless, there is still a clear separation of lead authorship proportion by GDP, with poorer countries showing a <20% proportion of lead authorship since the 1970s, with no pattern of increase over time (Fig. 2*D*). China, an emerging threshold country with massive GDP increases, has likely also increased investment in research programs that explore Chinese marine biodiversity, which might explain the surge of publications as Provider and User after the year 2000.

Our expectation would be that capacity-building manifests through an increasing proportion of lead authorships in countries with high marine biodiversity. Such countries are mainly tropical developing coastal/island nations within or close to biodiversity hotspot ecosystems, such as coral reefs. This expected pattern could be driven by the high genetic and species richness of flagship marine ecosystems (26) and thus high chemical richness. While species richness is here used as a proxy for chemical richness, it is important to note that the two are not linearly related (3, 4). Despite the significance of species richness driving the number of publications of User countries, our results indicate that economic status is a more significant driver of a country's capacity to explore its own bioresources than its biodiversity levels (*SI Appendix*, Fig. S5 and Table S1).

Effect of the CBD on Authorship Metrics. Article 1 of the CBD highlights the sustainable use of biological diversity and the fair and equitable sharing of the benefits arising from the utilization of biological resources as one of its main goals (10). Overall, the capacity for marine natural products research increased significantly after 1993, the year that the CBD was enacted. However,

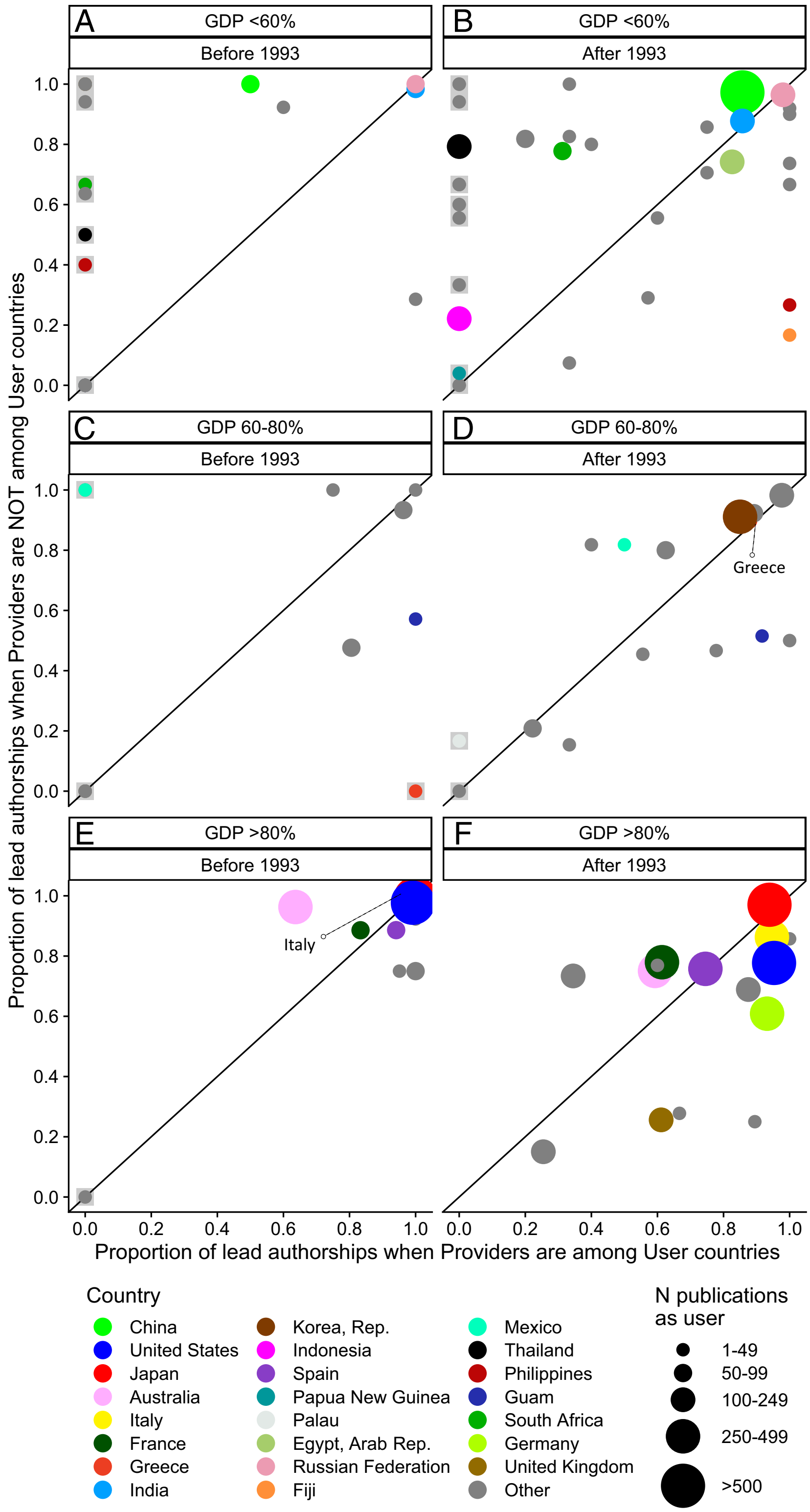

Fig. 3. Proportion of lead authorship in User countries when Provider countries are among users (*x*-axis) vs. when Provider countries are not among User countries (*y*-axis) before (*A*, *C*, and *E*) and after (*B*, *D*, and *F*) December 31, 1993, when the CBD was enforced, and grouped by GDP percentile (*A* and *B*: lower 60%; *C* and *D*: 60 to 80%; *E* and *F*: >80%). For example, as in the case of Australia before 1993, 0.6 on the *x*-axis indicates that the country is lead author in only 60% of the publications where the Provider country is also participating as User but close to 100% when Provider countries are not among User countries. Hereafter, points that lie below the 1:1 line indicate that a User country has fewer lead authorships when Provider countries are present. This might be an indication of User countries being actively engaged in the scientific capacity of Provider countries through multinational collaborations. Points above the 1:1 line show that a country has more lead authorship when the providers are absent, which may indicate that countries are frequently leading projects when they explore their own or other countries' marine biodiversity. The gray shading at zero values indicates that a country did not participate in any publications in which Provider countries were present (*x*-axis zero values) or absent (*y*-axis zero values). We calculated these proportions directly from all publications for the respective period; therefore, there is no SE associated with these values.

accurately measuring the efficacy of multilateral or global research agreements is a difficult task, because causal inference of capacity building and equitable sharing of benefits is not always possible. Nonetheless, our results indicate that the role of developing and threshold countries, which often harbor high marine richness, improved significantly after 1993. For instance, Australia was able to maintain its proportion of publications as a User country when biological samples were taken from their jurisdiction areas (Fig. 2 *E* and *F*). This might be associated with the enforcement of the CBD, along with stronger national restrictions blocking external users from accessing biodiversity without collaboration with local partners, as has been observed in Queensland (Australia) through the Biodiversity Act of 2004 (27). For instance, South Africa also notably increased its publication and authorship metrics (Figs. 2 and 3), which might be associated with the use of the experience and technical expertise driven by capacity-building programs organized by the private sector, along with governmental support (28). However, it is important to note that implementation of the Nagoya Protocol on Access and Benefit-Sharing differs among countries, and there is no universal rule on the access to marine bioresources for scientific research.

Bioprospecting projects are certainly being conducted in accordance with the access and benefit-sharing provisions of the CBD in numerous countries. Although our results show some quantitative evidence for ongoing capacity-building in developing and threshold countries, particularly when comparing results before and after implementation of the CBD in 1993, it is important to acknowledge the limitations of our present dataset. Publication and authorship metrics allow for a comprehensive assessment of international collaborations and shifts in scientific roles within publication outputs; however, a multimetric and overarching approach to measuring capacity-building is needed to draw a more differentiated picture between User and Provider countries and to better frame the development of future policies.

Monitoring Capacity-Building. Capacity-building is among the top priorities identified by the CBD, the Cartagena Protocol on Biosafety, and the Nagoya Protocol on Access and Benefit Sharing for the effective implementation of these instruments. While capacity-building is often presented as an intangible concept associated with the process by which individuals, organizations, and the society in general obtain, improve, and retain resources and competencies, it can also be evaluated as an exchange of knowledge and scientific collaborations (12, 13). Like other fields of research, marine bioprospecting has experienced rapid growth worldwide, particularly since the 1980s. China is now a major player in marine bioprospecting, with its contributions to this research field keeping pace with economic growth and worldwide influence on research output. The improved global capacity for marine bioprospecting is also supported by the increasing number of countries engaged in biodiscovery and reporting of new biological diversity (e.g., chemical, genetic), as well as by the growing capacity of Provider countries to exploit their own marine biological resources. While the increased capacity for marine bioprospecting is evident, it is important to highlight that measuring scientific capacity is challenging, as resource partitioning between Provider and User countries can be rapidly monopolized by a few countries with the necessary research funds, technology, and skilled human resources to undertake bioprospecting efforts. Indeed, the authorship metrics here investigated provide a focused but also narrow approach to capacity-building.

While reliable, consistent, quantifiable, and comparable data are often difficult to find, it is important to combine publication and authorship metrics with other approaches to measure capacity-building. For instance, it certainly would be relevant to take into account quantitative data referring to technology, funding distribution, and knowledge transfer in international collaborations, awarded grants, visiting scientists, and mentoring, as well as more diffuse metrics, such as the extent of collaboration (29, 30). Although such information could be available for some countries, it also must be critically evaluated. For instance, technology transfer as the movement of goods between countries might not be a reliable capacity-building metric, as proper training and development of human resources, together with adequate funding to support high-end technology, are also needed (31).

Using country case studies to better understand how each country is implementing the access to its marine bioresources and benefit-sharing is critical to highlight examples of capacity-building, as well as to pinpoint potential issues associated with "biopiracy" (25). Such case studies should be headed by the bioprospecting community and by policymakers to provide feasible and customized solutions, as illustrated in the Queensland Biodiversity Collaboration (32). Another example to consider is the International Cooperative Biodiversity Groups Program promoted by the US government to further develop equitable sharing of biodiversity benefits in the context of drug discovery, biodiversity conservation, and economic development (7, 11). Linking such information with scientific indicators, investment in science, and country-specific regulations on access and benefit-sharing will enable an assessment of how the Nagoya Protocol is being implemented and alternative ways to improve it. The lack of legal clarity and coordination, along with vague definitions in the Nagoya Protocol, can jeopardize international collaboration and research targeting biodiversity due to the use of restrictive and complex regulations associated with the transfer of biological material and data (9).

Future work should focus on both the individual trajectories of countries that have already developed their capacity to bioprospect marine resources and the global patterns of cooperation in marine natural products research. For instance, long-term studies focusing on international collaborations, access to biological material, funding, and technology transfer will be able to evaluate whether norms of inclusive innovation and those of responsible research and innovation are being followed (16, 20). Ultimately, such information can be used to address how effectively international protocols, such as the Nagoya Protocol, are being implemented and resulting in improved capacity-building and fair and equitable benefit-sharing.

Materials and Methods

Database Creation, PDF Mining, and Filtering. We used the MarinLit database to compile a reference list of all studies published in the past 50 y (1965 to 2015) reporting new marine chemical compounds. MarinLit is a comprehensive database that covers all marine chemical compounds reported in journal articles (33). The search query included publications reporting new chemical compounds collected from any marine taxa. The full bibliographic data were extracted, together with taxonomic information of collected organisms and collection site data. Using this search string, we downloaded 10,158 PDF publications from 278 scientific journals using the ETH Zurich library services and Google Chrome's Paperpile add-on. Of these, 9,862 publications contained detailed taxonomic and geographical information about the biological sources of new marine chemical compounds. Collection site data were used to identify the country with jurisdiction on the collection site (i.e., the Provider country). Using the CERMINE algorithm (34), the metadata of interest (author names, author affiliation country, and author position within the coauthors list) were extracted from PDFs. Although CERMINE performs with high overall accuracy, we manually checked all extracted entries for correctness against the original PDF. Names marked with asterisk, which usually refers to the corresponding author, were not considered lead authors.

User and Provider Countries. Our database included publications from 125 countries that were either the country of origin of the described compound ("Provider country") or the country where an author participating in the study was based in ("User country"). For each study, there could be multiple User countries, due either to multiple authors from institutes in different countries or from single authors with multiple host institutions. Some of the studies also contained multiple Provider countries, which, however, represented only 1.15% of the dataset. We removed all entries from countries with fewer than 10 publications as either a Provider or a User country (94 publications from 47 countries; <1% of the dataset), so that 9,768 publications from 78 countries remained. We then ranked all countries by the total number of publications as a User or Provider country and color-coded the 10 highest ranking countries in either category (*SI Appendix*, Fig. S2). In addition, Users and Providers were color-coded to demonstrate patterns of relevance, such as strongly increasing or decreasing trends in publications or authorship, in a total of 23 highlighted countries. The remaining 55 countries grouped as "Other" show only a small number of publications or have a fragmented publication record.

Capacity-Building Metrics and Supporting Data. Apart from the number of publications as a User or Provider Country (Fig. 1), we used authorship—the position within the list of authors participating in publication—as a metric for scientific capacity. We calculated the proportion of lead authorship (first or last position) (21) for each country as the number of publications with lead authorship divided by the total number of publications by that country as User and Provider each year. We assumed that the order of authors in marine chemistry research follows general scientific practices; that is, the first and last authors are the principal investigators or took a main role in the study. However, it is important to note that the order of authors might not be systematic in every discipline, which might be a caveat for the explanatory power of this metric.

To investigate how economic capacity may affect scientific capacity, we added data on the per capita GDP for all 78 countries over the last 50 y, which we obtained from the World Bank (35). For better visual inspection, we summed the per capita GDP for each country over the 50 observed years, ranked all countries, and divided the dataset into three percentile groups: countries in the lower 60th percentile, countries in the 60th to 80th percentile, and countries in the upper 80th percentile of GDP. We then explored two contrasts of capacity building for Provider countries (Fig. 2) and User countries (Fig. 3). First, we compared the ratio of lead authorships and nonlead authorships among countries and GDP groups. This contrast examines how often Provider countries participate in the scientific exploitation of their own resources as lead authors or as nonlead authors (Fig. 2), which could be considered two stages of scientific capacity building (19, 29). We then explored how often User countries are the lead author in publications with or without Provider countries (Fig. 3), which may indicate whether some countries are actively engaged in multinational scientific collaborations. Finally, by visualizing average values for each contrast for the periods before and after 1993, we explored whether the CBD had any influence on capacity building in marine research (*SI Appendix*, Fig. S5).

To examine whether having a high economic capacity or a high marine richness facilitates the publication of scientific literature, we implemented a generalized additive model (GAM), using the *mgcv* library (36) in R version 4.0.0. We chose a GAM because it handles nonlinearity well and can also account for temporal structures. The GAM tested for main and interactive effects of economic capacity (GDP, per capita, logarithmized) and marine richness as a Provider country (S, logarithmized) on the number of publications (per decade). The nonlinear parts of the model were run with a thin plate regression spline and generalized cross-validation for knot selection.

Data Availability. Data for this study are available in MarinLit (pubs.rsc.org/marinlit/).

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