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Perspectives on the Global Disparity in Ecological Science

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Currently, countries with the highest human development index (HDI) dominate the production of ecological research. This is problematic because ecology is a discipline that is highly relevant to the challenges facing countries with lower indices. We characterize the full state of current inequity at the authorship and editorial levels, investigating the relative role of gross domestic product (GDP) versus research investment in driving publication patterns. We find that the representation of low HDI countries decreases dramatically from authorship to editorial levels. GDP was the best predictor of publication rate for high HDI countries, whereas research investment was an equal or better predictor for low HDI countries. In light of our results, we propose an alternative model of knowledge sharing and production that emphasizes (a) increasing equity in the communication of ecological science at a global scale, (b) expanding ecology funding in low HDI countries, and (c) prioritizing ecological science in low HDI regions.

Keywords: human development index, scientometrics, editorial boards, environmental crisis

The advancement of scientific research is unquestionably a global pursuit. Given the potential for science to improve human well-being, there are innumerable reasons for global involvement in the scientific process of investigation, peer review, and publication. Foremost among these is that science should serve the public good and doing so requires the representative participation of that public in the scientific process (Kelty and Panofsky 2014). However, participation in science across the globe is far from proportionate. As of the 1990s, the countries in the highest quartile of human development dominated the production of scientific research (May 1998). Although some countries in lower quartiles have made major recent gains in the past 20 years (Holmgren and Schnitzer 2004, Kelty and Panofsky 2014), the most recent analysis across scientific disciplines reported that 99% of publications indexed by the Institute for Scientific Information (ISI) from 1997 to 2001 had one or more authors from a highly ranked country based on the human development index (HDI), a metric correlated with gross domestic product (GDP) but that incorporates social-development indices (May 1998, Cahill 2002, King 2004). The causes for this striking disparity can be loosely divided into proximate and ultimate groups.

Proximate causes include a host of social, economic, and logistical challenges facing scientists in low HDI countries. These include limited access to basic and higher education, both within country and abroad (Altbach 2004); low English language proficiency (Laurence 2013); financial and bureaucratic barriers to publication (Marquina and Rebello 2013); struggling local journals (Laborde 2009); poor infrastructure (Wishart and Davies 1998); and weak public, private, and popular support of science (Harmon 2011). In addition, low HDI countries have difficulty competing in a global marketplace for academics, resulting in the chronic "brain drain" of scientists from low HDI countries moving to high HDI regions (Jonkers and Tijssen 2008). Ultimately, each of these proximate causes is rooted in a historical context of colonialism, imperialism, and globalization that has produced—and continues to reproduce—patterns of global inequality (Wallerstein 2011).

Previously proposed solutions to the global disparity in scientific publications have generally emphasized one of two routes: The first involves foreign aid, whereby organizations in high HDI countries invest in *in situ* capacity building or provide research funding to low HDI countries (Wishart and Davies 1998). This is undoubtedly vital in the short term (Waldron et al. 2013), and there is evidence that productivity per research dollar is higher in low HDI countries (Holmgren and Schnitzer 2004); however, foreign aid is problematic as a long-term solution, because it cannot attain the necessary scale (Easterly 2003). The second approach involves linking scientific development to general economic growth in GDP, whereby science either drives or is driven by economic growth (King 2004). This implicitly assumes that the relationship between GDP and scientific production is equally strong in high and low HDI regions. However, a

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GDP-based approach does not necessarily make equal sense for all scientific disciplines.

Ecology as a unique discipline

We contend that the discipline of ecology is particularly unique in the development context for four reasons: (1) Urgency: The global environment is in crisis because of the interactive effects of climate change, land-use change, and other forms of ecosystem degradation (Solomon et al. 2009). (2) Cost: Relative to other sciences, ecology is primarily an understanding based and not technological science (Lawton 1998) and therefore is typically less expensive to implement and apply, meaning that it does not necessarily require a country to have a large GDP or extensive national development of the physical sciences. (3) Scale: Ecology is predominantly a place-based science, typically requiring extensively localized data collection, interpretation, and application (Clark and Dickson 2003). Global models of ecological processes are common, such as those involving the carbon cycle, but they still require validation based on regional- and local-scale processes. (4) Relation to economics: Ecological processes and systems are increasingly either recognized as a part of human economies in the form of ecosystem services (Costanza et al. 1998) or recognized as viable development goals that should be independent from economics (e.g., reducing greenhouse gas emissions). Consequently, a major part of solving global environmental crises should be much more rapid development of ecological science in low HDI countries (Wishart and Davies 1998).

Several previous studies have analyzed geographic patterns in ecology publications. Holmgren and Schnitzer (2004) compared ecology publications from 1990 to 2002 across Latin America with those in the United States and Canada in the 20 journals with the highest impact factors. They found that only 6% of publications had an author from Latin America, and for the top 10 highest impact factor journals, this percentage declined to 4%. Stocks and colleagues (2008) focused on ecology research conducted in tropical countries and found that 62% of articles had a lead author from a foreign, often high HDI country. These past works have provided insight into some inequities within ecology publication, but a more global picture of inequity requires consideration of all countries and editorial board membership, as well as publication patterns. It also requires considering that divergent editorial policies among journals may produce substantial variation in equity from one journal to another. Previous studies have hypothesized that variation in GDP and in research and development funding drive the disparity between high and low HDI countries (May 1997); however, it is not known whether these drivers are equally important in both regions.

Given the urgent need for ecological science and the global implications of ecological work, we analyze all ISI-indexed ecology journals to (a) examine the current state of global inequality in ecology research across 185 nations and (b) determine whether GDP or other factors, such as research investment, deserve emphasis in ecological science development efforts. We conduct two main analyses. The first addresses our question of inequity and examines the overall representation of high and low HDI countries in all 123 indexed journals, the top 20 highest impact factor journals, first-author publications, editorial boards, and posteditorial review. We also characterize the variation in the representation across journals relative to the global distribution of population and GDP. Our second analysis addresses GDP and investigates the relationship between publication number and the nation's GDP, investment in research and development (R & D), and the number of researchers. Conducting these varied analyses helps us to identify and discuss the crucial barriers to increased international representation in the field of ecology.

Methods

We chose to use the Institute for Scientific Information (ISI) Web of Science database to obtain publication authorship data. ISI is among the largest and most frequently used global, multilanguage publication databases (Falagas et al. 2007). Although the ISI is reportedly biased against including regional journals and non-English-language journals (Holmgren and Schnitzer 2004), the ISI database is appropriate for our study because our aim is to assess ecology publications that are visible at global rather than at regional scales. Furthermore, other recent studies have examined regional databases such as Scielo (Meneghini and Packer 2007).

Equitability of representation by HDI category. To analyze representation, we queried articles from 132 journals in the ISI Journal Citation Reports subject category *ecology* published in 2013. This search returned 15,012 publications for 185 countries. We blocked countries into high and low human development. Following the UNDP (United Nations Development Program), we classify *high HDI* countries as those in the upper quartile of HDI scores and *low HDI* countries as those in the remaining lower three quartiles (UNDP 2013). In 2014, there were 47 high and 140 low HDI countries. Although the HDI index is closely correlated with GDP (Cahill 2002), it is a standard metric used by international-development agencies. Our HDI categories generally overlap with regions often referred to as *developed* versus *developing* or the *Global North* versus the *Global South*. We believe using HDI makes our results intelligible to a broad audience and provides a quantitative alternative to other existing categorization schemes.

We grouped publications into four categories of ecology journal impact factor and authorship order: (1) all journal impact factors and all authors, (2) all journal impact factors and first authors, (3) the top 20 journals with the highest impact factors and all authors, and (4) the top 20 journals with the highest impact factors and first authors. We also analyzed representation in editorial review and postreview stages. For the editorial review stage, we examined the top 20 highest impact factor journals and used journal websites to determine editorial board membership and the countries where current board members were based. For the postreview stage, we used the Faculty of 1000 list for ecology from the F1000 website to determine the countries where current members were based. Editorial and Faculty of 1000 data were gathered in June of 2013. The impact factors used to classify journals were based on the 2012 ISI release (most relevant for 2013 publication patterns). In each of the above categories, we reported the average proportion of authors or editors in high versus low HDI countries across journals to generate an estimate of standard error (except for F1000, which was not replicated).

We were also interested in the distribution of variance among journals in author representation from high versus low HDI countries. To explore this, we generated a density plot showing the proportion of authors from high HDI countries across journals (figure 1). To provide a context for this figure, we include the expected location of the peak if representation was perfectly matched to the global distribution of GDP or to the global population distribution.

Regression analysis. For the regression analysis, we queried ISI over a 10-year period that corresponded to available UNDP data on GDP and other development indices that were averaged over the years 2003–2012. This search returned 136,516 publications (search criteria reported in supplemental material S1). We obtained data on GDP for 185 countries for which data was available from 2003 to 2012. GDP is expressed as total GDP in Purchasing Power Parity at constant 2011 USD. We did not use per capita GDP, because this is partly captured by HDI and is more likely to reflect individual wealth as opposed to funding available to researchers. We used a multiple regression approach to examine the impact of three predictor variables on the total number of publications per country from 2003 to 2012: GDP, the proportion of GDP invested in R & D (both public and private), and the number of researchers per million people. The impact of these three predictor variables was assessed for the same four categories of publication/authorship used above: (1) all impact factors and all authors, (2) all impact factors and first authors, (3) the top 20 highest impact factors and all authors, and (4) the top 20 highest impact factors and first authors. Each category was separated into the same high and low HDI groups of countries used in our other analyses. We averaged impact factors across years from 2003 to 2012 and then used those values to select the journals with the highest 20 impact factors.

All analyses and figures were produced in R (R Core Team 2014). To compare the importance of the three predictors of publication number in our regression model, we used the RELAIMPO package (Grömping 2007). In addition, we were interested in comparing the relative importance of each predictor across our publication/authorship categories rather than specifying a precise regression model through model fitting. We estimated the relative contribution of each predictor to the overall R^2 of the model using the LMG metric with bootstrapped confidence intervals. LMG estimates the relative importance of each predictor at all possible entry points into the model and averages across these individual R^2 values. Estimates for each predictor are then adjusted to sum to 100%.

Results

We found that representation declined substantially with increasing profile of publication and editorial involvement. Twenty-two percent (SE = 0.018) of all publications had an author from a low HDI country, whereas this percentage declines to 3% (SE = 0.006), 2% (SE = 0.005), and 4% (SE = NA) in first-author top 20 publications, editorial boards, and F1000, respectively (figure 1a, $p < 0.0001$ for all high and low HDI pairs, ANOVA). The number of countries with at least one researcher publishing was greater for high HDI countries in every category (figure 1b, $p < 0.0001$ for all high and low HDI pairs, ANOVA). Between 10 and 26 high HDI countries were present in the publication and editorial survey, representing between 21% and 57% of all high HDI countries, whereas only between 2 and 14 low HDI countries are present in the survey, representing between 1% and 10% of all low HDI countries.

We observed substantial variation in first-author representation among journals (figure 2). For all journals, the density distribution peaks at 90% of authors from high HDI countries with a strong negative skew. Despite a strong overrepresentation of high HDI countries, there are still a small number of journals that do have equitable representation relative to either GDP or population. This was not the case for the top 20 journals that showed a leptokurtic distribution, with over 87.5% of first authors from high HDI countries for every journal. Overall, 15 journals had no authors from any low HDI country.

The total number of publications was strongly correlated with GDP for high HDI countries in all four journal/authorship categories (R^2 = 0.58–0.69, figure 3). For low HDI countries, the strength of the correlation was weaker (R^2 = 0.26–0.55), especially in the top 20 high impact factor journals, in which it was only 0.26. In the multiple regression, our post-hoc analysis of the relative importance of GDP relative to R & D investment and researcher density showed that GDP was the most important predictor (contributing greater than 50% to the R^2) in high HDI countries. In contrast, in low HDI countries, investment in research was equally or more important than GDP, contributing as much as 47% to the R2 in the first-author top impact factor publications (figure 4). Researcher density contributed weakly to the model (generally not more than 10% of R^2) and did not differ between high and low HDI countries.

Discussion

Our overarching finding is that (a) the representation of researchers from low HDI countries declines dramatically with increasing journal profile and editorial involvement

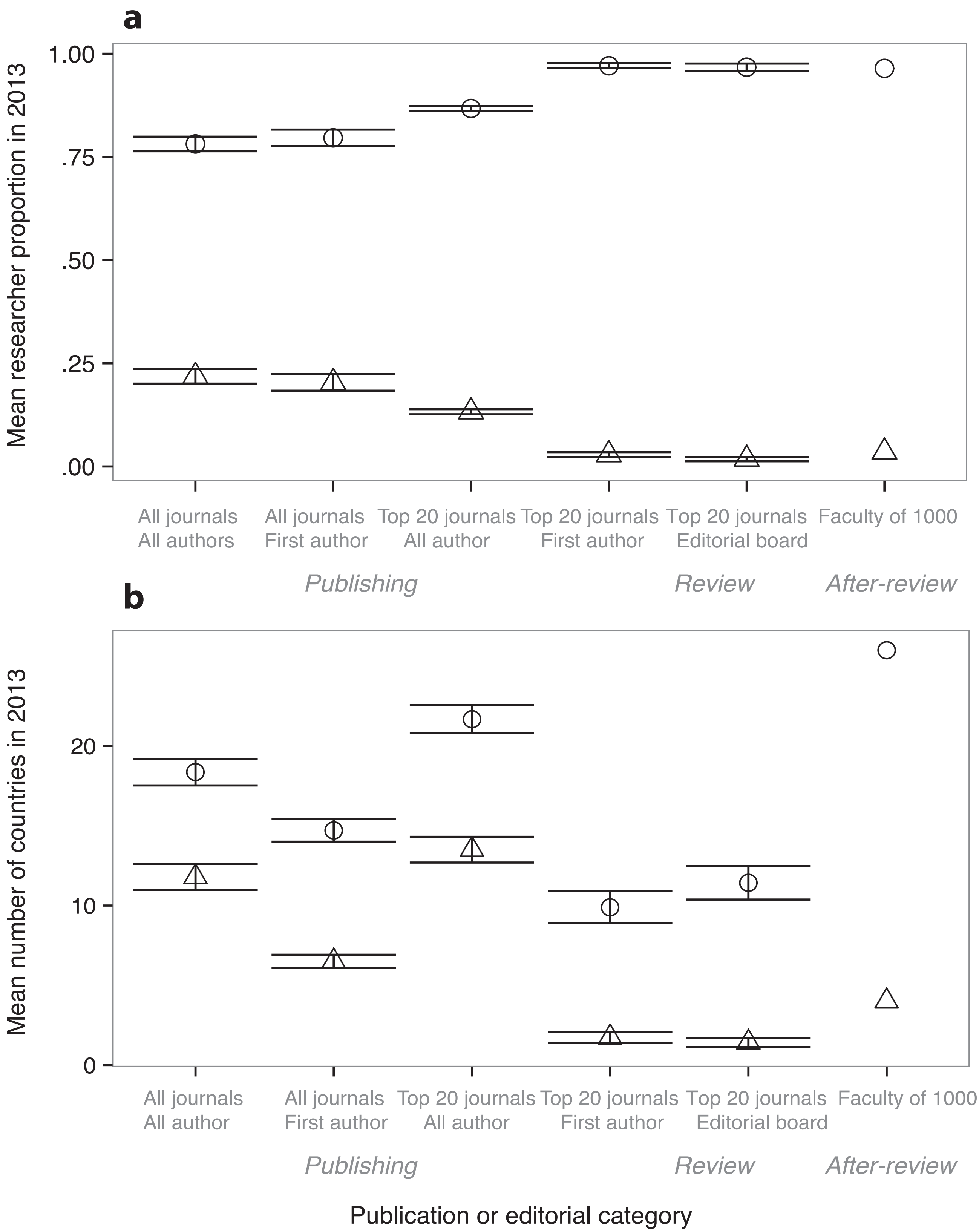

Figure 1. The representation of high human development index (HDI, open circle) versus low HDI (open triangle) researchers (a) and countries (b) in publication, review, and postpublication review for 2013. Values are averaged across journals, except for "Faculty of 1000," which is not replicated. N = 132 for the all journals *categories. The error bars represent the standard error.*

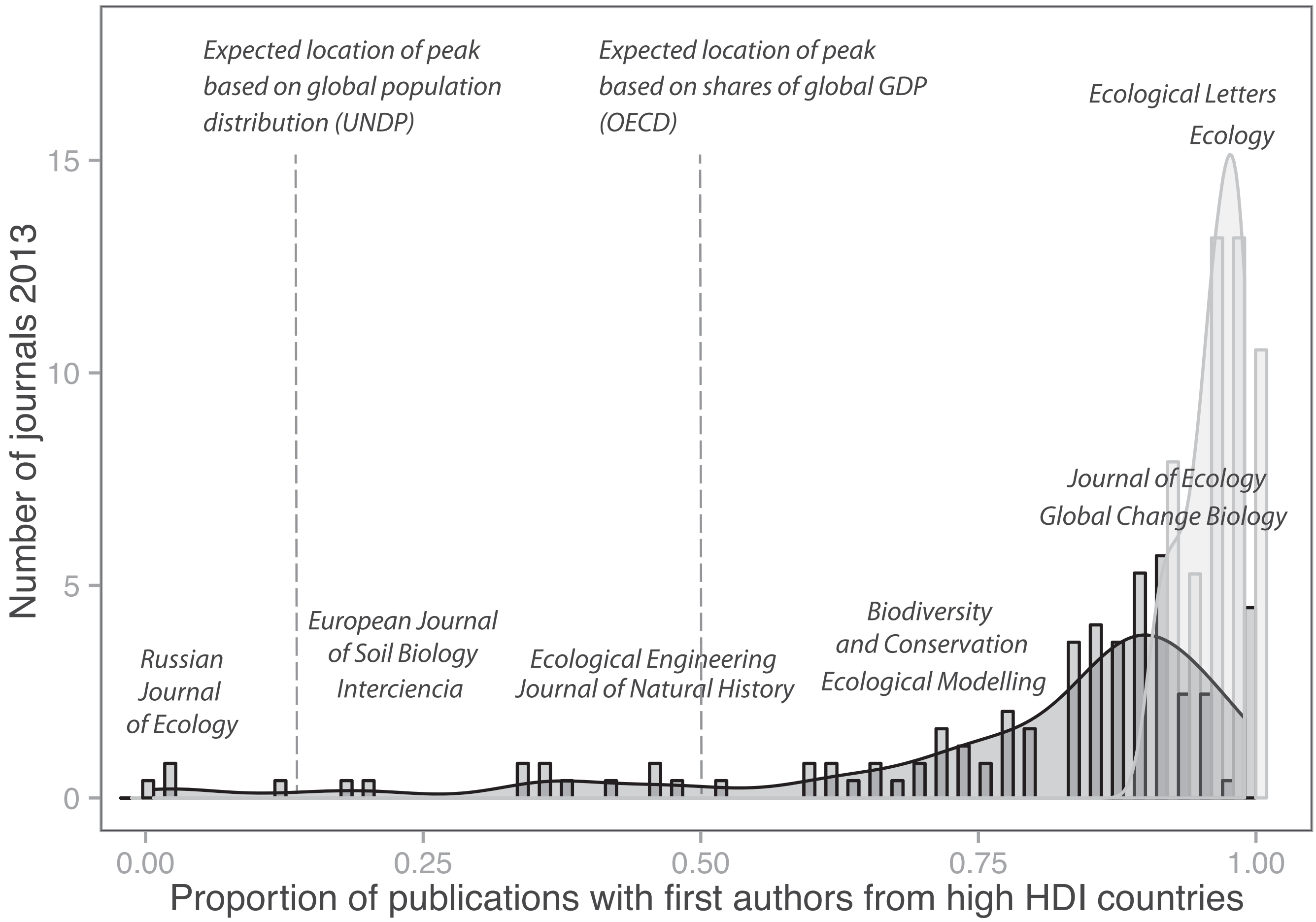

Figure 2. A histogram overlaid with the density plot of the proportion of articles in 2013 from high human development index (HDI) countries in all ISI-indexed journals (dark grey,* n *=123) and the top 20 journals with the highest average impact factor from 2003 to 2012 (light grey,* n *= 20). The* all journals *category includes the top 20 journals.* Density *represents the number of journals for a given proportion. Example journal titles are listed with proportions that are near to each breakpoint of 0, .25, .50, .75, the peak for all journals, and the peak for the top 20 journals.

and (b) scientific-development factors other than GDP, specifically investment in research, are especially important for enhanced publication rates in low HDI countries. We discuss the implications of these results for advancement in peer-review systems and for prioritizing ecology research. We conclude by identifying deeper qualitative inequities and with a plea for greater emphasis on the global communication of ecological science.

Leaky pipeline. Our study is the first to examine ecology editorial board and F1000 membership along an HDI axis. We find that parallel to patterns observed for women in science (Amrein et al. 2011), the membership of these boards is almost exclusively researchers from high HDI countries and that this representation drops an order of magnitude from representation seen in general authorship. This result is consistent with nearly homogenous high HDI board membership in other fields (Ozbilgin 2004). Given that the representation of researchers from low HDI countries in the top 20 journals is similar to that of editorial boards (3% versus 2%), it is possible that low publication success in top-ranking journals may drive low representation on editorial boards. Our results also demonstrate that increasing publication rates and GDP are not enough to rapidly affect changes at the most selective positions in the publication process. Part of the mandate of the most visible journals in ecology is to communicate science internationally. Indeed, many journals are self-described as international forums. The power of editorial boards and associated reviewers can be seen in the effect of journal placement (in journals with a higher impact factor) on article citation rates. A recent study across the sciences found that journal placement is the primary determinant of citation rates, whereas the country location of the authors had inconsistent effects (Smith et al. 2014, but see Meneghini et al. 2008). Consequently, we urge editorial boards to pay close attention to the geographic and sociopolitical diversity in their membership.

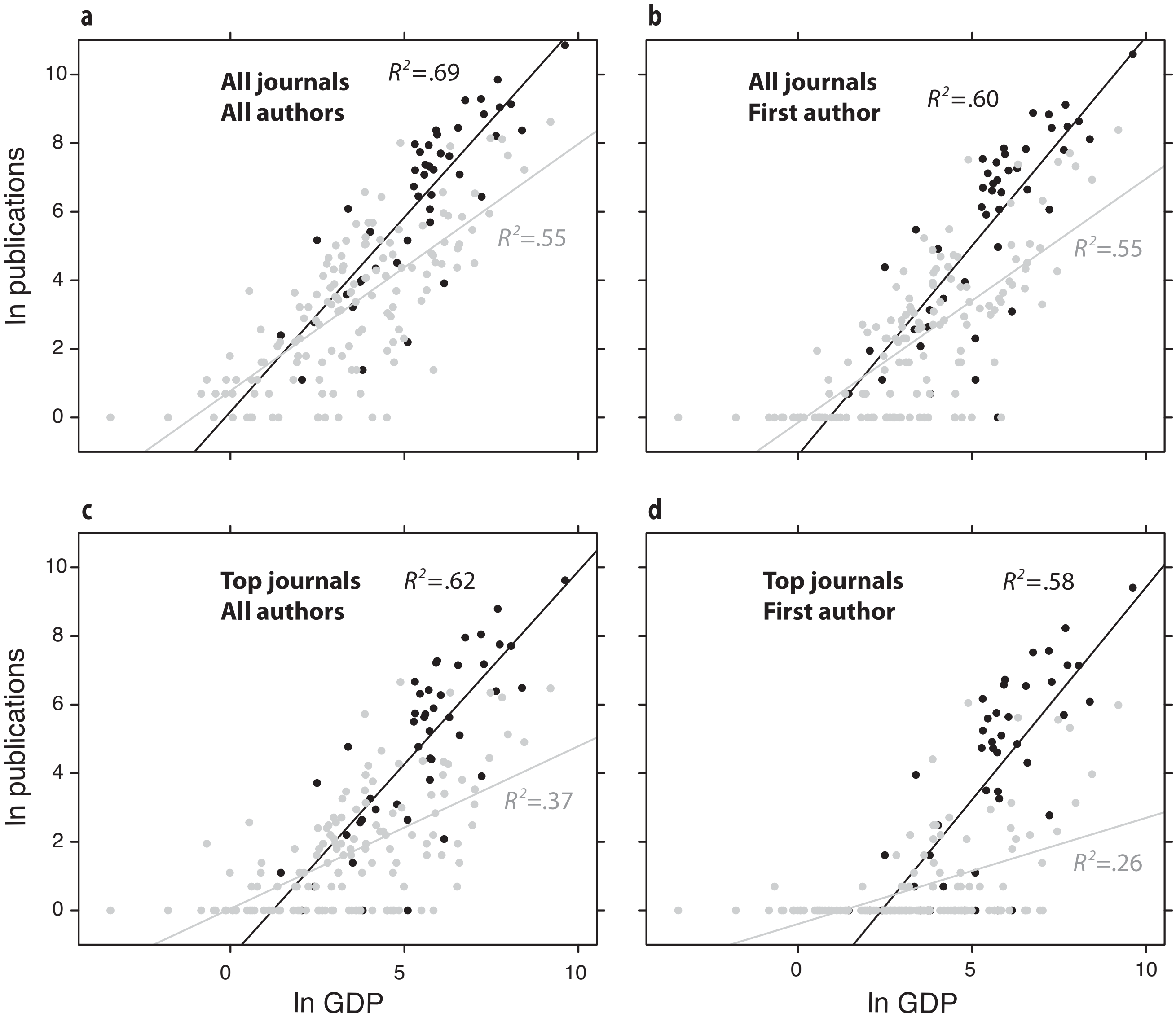

Figure 3. The relationship between the natural log of gross domestic product (GDP, in billions of US dollars) and the natural log of publications (produced from 2003 to 2012) in high human development index (HDI, black dots) and low HDI (gray dots) countries for (a) all journals, all authors; (b) all journals, first authors only; (c) the 20 top impact factor journals, all authors; and (d) the 20 top impact factor journals, first authors only.

Prioritizing ecology. We find that GDP is a better predictor of publication rate in high HDI countries than in low HDI countries. In low HDI countries, our results confirm those of other studies showing that investment in science is crucial (May 1997, Holmgren and Schnitzer 2004, Martínez et al. 2006). This result suggests that national science initiatives in low HDI countries that increase science investment, measured as the percentage of GDP that goes to research, have rapid effects on publication rates. Research-intensive high HDI countries generally commit between 2% and 4% of GDP to R & D, whereas low HDI countries commit between 0% and 2% (UNESCO 2012). In high HDI countries, these commitments to fund public research are established and stable so that growth in GDP increases publication rate. In low HDI countries, commitments to fund public research may be establishing for the first time or increasing so that growth in research investment is driving publication rate instead of GDP.

However, to advance the field of ecology, it is crucial to focus on the percentage of science budgets used for ecological research as opposed to other sciences. Although this data is not available on an international scale, in the United States, approximately 10% of National Science Foundation funding is allocated to biology (AAAS 2014), of which ecology is only a fraction. Additional research is needed to determine specific funding rates for ecology at a global scale, particularly research that accounts for the bureaucratic burden on funds and the possible influences of varying levels of corruption (Qiu 2014). Assuming the fraction of funding for

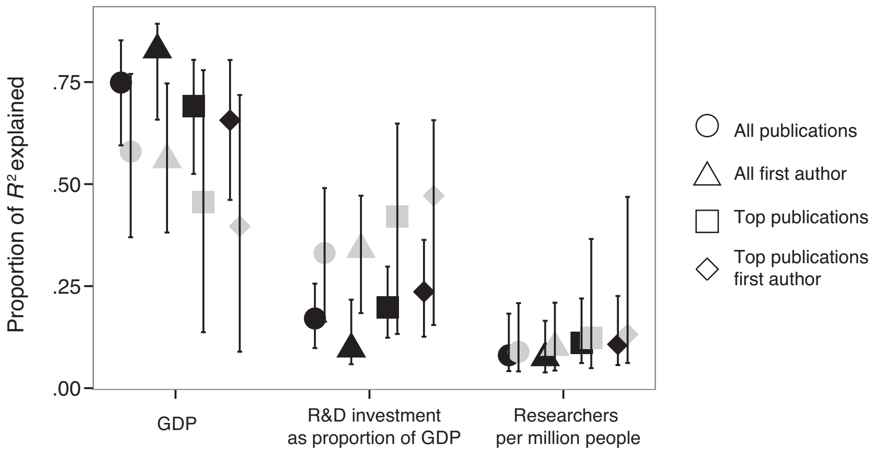

Figure 4. A posthoc regression analysis of contributions to R^2 ***values in a multiple regression model with gross domestic product (GDP), research and development (R&D) investment as a proportion of GDP, and the number of researchers per million people. Black symbols represent high human development index (HDI) countries, and gray symbols represent low HDI countries. The error bars are bootstrapped 95% confidence intervals.***

ecology is similar across high and low HDI countries, then this relatively small ratio of funds allocated suggests that ecology is not prioritized relative to other disciplines.

Although ecology may not be a prioritized research area, we suggest low HDI countries potentially have the greatest opportunity and need to direct resources toward ecology and related development research. This is because the low HDI countries are still establishing and growing their research budgets and may have more flexibility to prioritize funding for ecology research. This could be one possible method of institutionalizing current social movements in low HDI countries such as Buen Vivir in Ecuador and Bolivia, which seeks alternatives to GDP-based development that center on sustainability, environmental justice, and social well-being (Gudynas 2011, Pacheco 2012). Many low HDI countries have large areas of land that have not been developed for resource extraction or agriculture (Laurance et al. 2014). In these cases, waiting for GDP growth to stimulate ecological science is problematic. First, this is because low GDP is chronic in many countries and may not increase fast enough relative to ecological crises. Second, GDP growth frequently occurs alongside environmental degradation (Raupach et al. 2007), thereby constraining ecology to a postdevelopment restoration or hazards science (Cox 2007, Hobbs et al. 2011, Büscher et al. 2012) as opposed to a predevelopment foundational one. We are not suggesting ecology be advanced over livelihoods; instead, we are suggesting that its relationship to sustaining livelihoods be recognized (Persha et al. 2010) and valued in research dollars.

Qualitative inequities. We acknowledge that publication rates do not capture all types of scientific output, nor do they capture the quality of the scientific content within publications. For this review, we did not consider citation rates, patterns of collaboration, researcher mobility, or the source of institutional funding, but past studies have investigated each of these other aspects of research and generally find patterns of inequity that mirror those for publication rate. Citation rates are generally a function of journal impact factor (Smith et al. 2014); however, they can vary on the basis of accessibility. Open-access publications have relatively higher citation rates by authors in low HDI than those in high HDI countries (Evans and Reimer 2009). Citation patterns of individual researchers and their consequences have been studied extensively (Parker et al. 2010), generally revealing a concentration of highly cited researchers in high HDI countries (Basu 2006). Collaborations are based on the reciprocal sharing of resources and expertise, and although international collaboration is increasing dramatically (Smith et al. 2014), high HDI countries collaborate more with other high HDI countries than with low HDI countries (Adams 2012). Numerous programs in high HDI countries (e.g., the US Fulbright Program) and counterparts in some low HDI countries (e.g., the Brazil Scientific Mobility Program) help to enhance mobility. However, in many low HDI countries, opportunities for mobility do not exist. In addition, research institutes operated by high HDI countries, such as the French Institut de Recherche pour le Développement or the US Smithsonian Tropical Research Institute, are based in low HDI countries (Stocks et al. 2008), and we are not aware of any institutes funded by low HDI countries operating in high HDI countries.

Overall, our findings support frameworks proposed in a number of past studies: that the bulk of ecological theory has been developed by researchers in high HDI countries, although much of this work was inspired by the ecosystems of low HDI regions (Martínez et al. 2006). Various authors have argued that this has set up a core–periphery dynamic or a dependency (Palma 1978, Alatas 2003) of low HDI countries on high HDI countries for scientific theory. Currently, the strength of this dependency has been questioned, and there may be more variation in international engagement among researchers than among countries (Duque et al. 2009, Barnard et al. 2012). However, from a historical standpoint, a core–periphery dynamic is supported by our analysis: All of the top 20 impact factor journals in ecology originated in high HDI countries. To move forward from this history, it is crucial to distinguish between the *methodology* of ecological science developed in high HDI countries from the *content* of the science. Methodology is the process that produces a particular theory, whereas content is what the theory states. The methodology of ecological science that is widely recognized to produce advancements is based on an interdisciplinary feedback loop among data, conceptual, and theoretical models; experimental testing and simulation; and the application of science to socioenvironmental problems (Lélé and Norgaard 2005, Benton et al. 2007, Michener and Jones 2012).

Although methodology can be safely extended globally to develop research programs, we suggest that ecologists in low HDI countries approach content from high HDI countries with a critical eye. This is because the content prioritized by high HDI countries may not be in areas of greatest interest or relevance for low HDI countries. For example, population viability analysis (PVA) is an extremely useful tool to interface population ecology with the US Endangered Species Act (Morris et al. 2002). However, PVA analyses may not be warranted for many species in low HDI countries where data may be deficient for PVA analyses or where conservation is run by communities as opposed to government agencies (Danielsen et al. 2003). Another example includes efforts to apply integrated pest management (IPM) to agriculture that have struggled because they fail to account for the realities in low HDI countries that are absent in high HDI countries. These include a greater emphasis among farmers on collective action and a greater skepticism of the IPM framework (Parsa et al. 2014). More generally, in most low HDI regions, indigenous communities are a much larger proportion of the population (Montenegro and Stephens 2006), making large-scale community-based approaches and nontraditional methods of communicating science a necessity (Castillo and Toledo 2000). Ecologists can greatly enhance the global impact of their work with greater global communication during the development of theoretical and applied frameworks and by the vigorous development of original content that is relevant to ecological, economic, and social contexts within low HDI countries.

Shifting the center of ecology

The current and future global distribution of both human population and GDP clearly indicate that low HDI countries should be major contributors of ecological research. There are immense challenges slowing this shift that must be addressed by changes in policy. However, ecologists in both high and low HDI countries have substantial power to catalyze change within the current system. This includes publishing in journals from low HDI countries (Laborde 2009), reading and citing publications from low HDI countries (Meneghini et al. 2008), and publishing their work in non-English languages and as open access (Meneghini and Packer 2007, Evans and Reimer 2009). This also involves reciprocally accepting students from other regions, using mobility grants for research, teaching and assembling multiregional conferences (Jonkers and Tijssen 2008), and engaging in long-term collaboration (Oettl 2012). The movements for open data, software, and distributed secondary synthesis through programs such as SESYNC foster cost-effective scientific activity outside of traditional peer-reviewed journals (Rodrigo et al. 2013), something that could increase the engagement of researchers from low HDI regions. All of these activities are a viable antidote to a scientific world that is increasingly driven by publication quantity and prestige (Fischer et al. 2012). Above all, we hope this article will promote discussion among ecologists about how to attain a more equitable science that responds more effectively to international ecological challenges and a globalized environment and society.

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Supplemental material

The supplemental material is available online at *http://bioscience.oxfordjournals.org/lookup/suppl/doi:10.1093/biosci/biv175/-/DC1*.

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