

# Biodiversity, Taxonomic Infrastructure, International Collaboration, and New Species Discovery

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*Geographic and political factors affect global research in many areas of biology with substantial field components. Progress in new species discovery continues to be undermined by sociopolitical impediments. The number of new species discovered from individual countries in 1 year is highly dependent on taxonomic infrastructure and country-scale biodiversity. Publication patterns suggest that alpha taxonomy is a higher research priority in high-biodiversity countries than in low-biodiversity countries. Alpha-taxonomy articles with authors affiliated with high-biodiversity, low-taxonomic-infrastructure tropical countries have very high rates of international collaboration, underscoring its importance in the discovery of new tropical species. Most new species descriptions include specimens collected less than 5 years prior to publication, which indicates the importance of ongoing collection efforts. National and international policies that strengthen both the taxonomic infrastructure of high-biodiversity countries and collaborations between high-biodiversity and high-taxonomic-infrastructure countries are necessary to accelerate global biodiversity discovery, given the current rapid rate of species extinctions.*

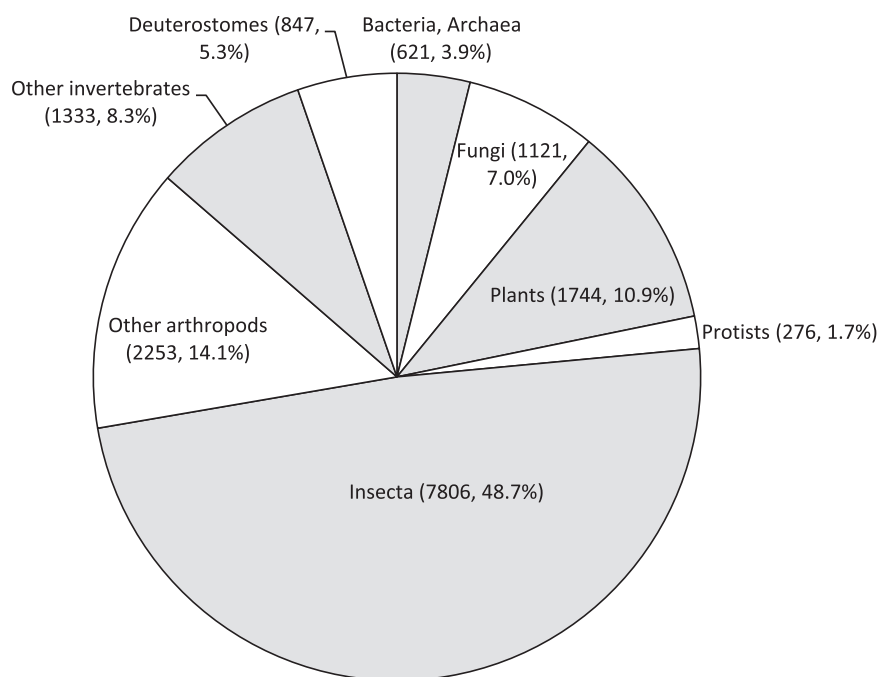
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**T**horough description and delineation of the world's species and accurate species identification are crucial for activities as vital as understanding Earth's biodiversity and its losses; properly diagnosing and treating outbreaks of diseases and pests; and tracking the spread of invasive species, including arthropod pests. The value of biodiversity has been estimated by some authors (e.g., Losey and Vaughan 2006, McNeely et al. 2009, Maier 2012), and many species being discovered today have potential positive or negative impacts on human health and economic interests, including new species of human pathogens (e.g., Matthias et al. 2008), potential disease vectors (e.g., Gomes Hutchings and Mureb Sallum 2008), potential new crop plants (e.g., Stoffelen et al. 2008, Wilkin et al. 2008), plant pests and pathogens (e.g., Grobbelaar 2008, Karaca et al. 2008), and solvent-metabolizing bacteria (e.g., Kuisiene et al. 2008).

The size of the world's taxonomic workforce is believed to be a mere 4000–6000 people (MacLeod et al. 2010), many of whom are avocational taxonomists (Acorn 2009). Although the decline of taxonomic expertise in recent decades has been widely discussed (Evenhuis 2007, House of Lords 2008, Wheeler 2008), there are some indications that the number of authors describing new species worldwide has actually been growing (Joppa et al. 2011a, Bacher 2012, Costello et al.

2012). To bolster taxonomic efforts in the United States, the US National Science Foundation has invested tens of millions of dollars in the Partnerships for Enhancing Expertise in Taxonomy (PEET) grant program since 1995, and similar programs have been developed in other countries (Rodman and Cody 2003). A new age of discovery (Giam et al. 2012) in biological taxonomy is now being driven by such efforts, combined with growing interest in biodiversity issues and the emergence of new tools, such as eTaxonomy and other cyberinfrastructure (e.g., Rilke et al. 2013), molecular phylogenetics, and the growing but somewhat controversial application of DNA barcoding (see, e.g., Mitchell 2011 and the references therein).

Although future advances toward a more integrative taxonomy (*sensu* MacLeod et al. 2010, Padial et al. 2010, Cesari et al. 2011) may continue to fuel this growth, several impediments are believed to stifle global and local alpha-taxonomic activities today. Two geographic or political issues that have been explored in this context are the limited taxonomic infrastructure in many tropical countries where megadiversity hotspots exist (Speers and Edwards 2008, Giam et al. 2012) and limited access to high-biodiversity regions by scientists from countries with more robust taxonomic infrastructure. Access limitations may be due



**Figure 1.** Proportions of 16,001 new extant species found in a survey of the 2008 literature that are in each major organismal group. A full list of counts in taxonomic groups down to the family level is provided in supplemental table S1.

to factors such as political isolationism (Bankowska and Sterzynska 1997), political unrest or general safety issues (Bohannon 2009, Hanson et al. 2009) or the expense of conducting large-scale collecting expeditions thousands of miles from one's home institution. So far, the impacts of the disparities in the spatial distributions of biodiversity and taxonomic effort and expertise have been quantified only within specific taxonomic groups, including mosquitoes (Foley et al. 2007), land mammals (Giam et al. 2012), and amphibians (Rodrigues et al. 2010, Giam et al. 2012). Tancoigne and colleagues (2011) also considered this issue for animal taxonomy in general but limited the analysis to a sample of 748 articles from the journal *Zootaxa*.

To determine the impacts of geopolitical factors on the rates at which new species are being discovered on a global scale, across all taxonomic categories, we surveyed the distribution of localities for all specimens assigned to newly described species—from bacteria to mammals—in 1 year's worth of the published literature (2008). The influences of various geographical and sociopolitical factors on current species discovery were analyzed on the basis of the country-level distributions of specimens assigned to the new extant species (NES). In addition, we examined the publication patterns of alpha-taxonomy articles by authors affiliated with individual countries and the prominence of international collaboration in taxonomic publications.

## General characteristics of the new species literature

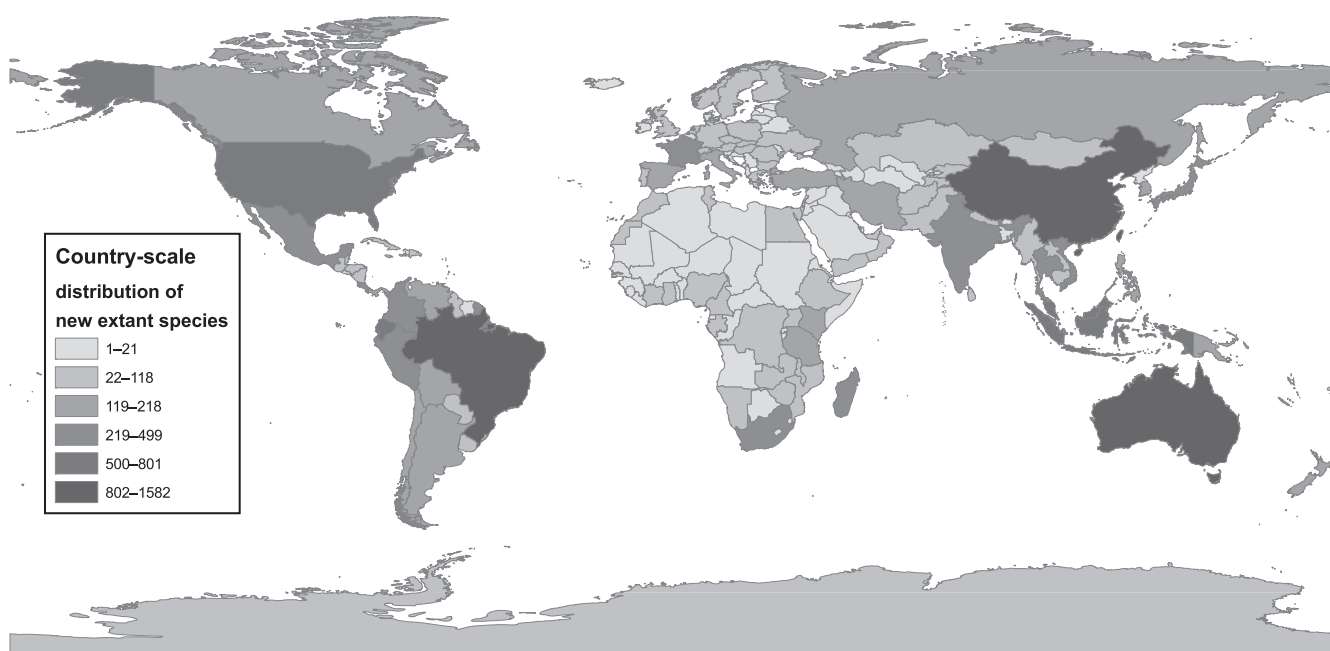
New species descriptions are widely distributed in the published literature, appearing in the 2008 issues of 988 of the 2512 journals and monograph series surveyed (supplemental data set S1). We had access to 819 of these 988 titles and were able to extract geographic data for 18,164 new species, including 16,001 NES (supplemental data set S2) and 2163 new paleontological species (supplemental data set S3). The 18,164 new species were described in 7009 distinct articles and monographs. These figures represent 89.2% of the total new species (20,365) and 87.8% of NES (18,225) reported for the 2008 literature in the *State of Observed Species 2010* report (IISE 2010). The SOS reports provide taxonomic data but not geographic data. The 16,001 NES were analyzed further.

## Taxonomic distribution of NES

The taxonomic distribution of NES (figure 1, supplemental table S1) in this survey is similar to that reported in the IISE (2010). Arthropods dominate both surveys (figure 1), with insects representing slightly less than half (49.3%) of the NES in our survey. However, taxonomists continue to discover new species across the full taxonomic spectrum—including 765 new extant vertebrate species in 2008 (figure 1). Most authors placed the new species they described into a family, although some were listed as *incertae sedis* or *family indeterminate*. We placed the remainder into families using online databases, such as the Integrated Taxonomic Information System (see the supplemental material). This process yielded 2123 families (data set S2a), which is only a crude estimate, because of the controversial nature of family-level taxonomy in some groups. The largest family, Coleoptera: Staphylinidae, which contains over 55,000 known species, also had the greatest number of new species (708) described in 2008. Similarly, the largest plant family, Orchidaceae, which contains approximately 26,000 known species, had the greatest number of new plant species (223) described in 2008.

## Geographic distribution of new species discovery

With the exceptions of South Africa and Madagascar, new species discovery in the Afrotropical region lagged behind that in the Neotropical, Indomalayan, and Australasian regions (figure 2 and supplemental figure S2), which is consistent with the overall pattern of numbers of known species from these regions (Mittermeier and Mittermeier 1997). Areas that are generally regarded as historically well



**Figure 2.** Geographic distribution of new extant species described in 2008 publications. The species counts represent the species from all states and territories for each country currently recognized by the United Nations. For example, the counts for geographically disjointed political territories, such as Alaska and French Guiana, are included in the counts for the United States and France, respectively. A color version of this map is provided in figure S2.

sampled continue to yield hundreds of new species every year, as was recently discussed for Europe by Fontaine and colleagues (2012). For example, in our survey, we found 801 species for the United States; 215 for Russia; 82 for Germany; 143 for Canada (supplemental table S2); and many more for the European portions of France (100), Spain (182), and the United Kingdom (64), excluding NES from their remote territories.

We could not assign 354 extant and 68 paleontological specimen localities to a country, because of insufficient information or because the specimens were collected far offshore (supplemental table S3). Although the world's oceans and seas cover over 70% of its surface, only 275 (1.6%) of the 16,001 NES included specimens collected in these habitats. This discrepancy may be consistent with the description of the open oceans as a biological desert (Ryther 1969). However, Ryther (1969) used that term to describe commercial fish production potential and overall measures of primary productivity, the latter of which is now known to be several times higher than Ryther's (1969) figures (Laws 2013). Authors studying marine microbes have declared that the historical biological desert paradigm of the deep ocean has shifted to one of a rainforest, thanks to a rich microbial diversity that has come to light only in recent decades (e.g., Deming 1998, Wang et al. 2010). Other studies have suggested a depth bias in our knowledge of marine biodiversity, with midwater regions described as "drastically underrepresented" compared with either surface or seafloor habitats (Webb et al. 2010).

Half of all NES country records were in the top 14 countries, where the term *country* refers to United Nations (UN)-recognized states and territories (data set S2): China (1582), Australia (1035), Brazil (1018), the United States (801), Indonesia (692), Ecuador (676), Malaysia (631), Mexico (499), Japan (461), India (432), Costa Rica (373), Peru (370), Thailand (362), and South Africa (357). The complete list of NES counts for all of the countries is given in table S2. Only 9 UN-recognized sovereign states had no NES in our survey: Bosnia and Herzegovina, Guinea-Bissau, Kiribati, Kosovo, Liechtenstein, Nauru, San Marino, Tuvalu, and Vatican City.

### The monograph effect

The number of NES described in each article varied from 1 to 422, with the majority (78.05%) including only 1 or 2 NES (supplemental table S4). Because large monographs often represent multiple years of effort and are focused on a particular taxon, country, or region, it is important to consider whether the monographs in the 1-year survey produced NES counts for individual countries and taxa that may not represent a typical year. Thirteen publications in the survey each included more than 50 NES (supplemental table S5). However, they included high proportions of the NES counts for individual countries in only a few cases, such as the monograph with 422 out of 677 (62%) NES for Taiwan and another with 36 of 80 (45%) for Brunei (tables S2 and S5). Clearly, if those two monographs were not published in 2008, the NES counts for Taiwan and Brunei

would have been much lower. In other cases, monographs were focused on countries or regions with relatively high NES counts among the remainder of the surveyed literature. For example, five monographs included 281 out of 648 (43%) NES for Ecuador, and five of them included 161 out of 631 (26%) for Malaysia (tables S2 and S5). Because several of the monographs were focused on either the Neotropics or Southeast Asia, it seems reasonably likely that a few NES-rich monographs may be focused on various taxa in these regions in any given year. Most of the monographs were focused on large taxonomic groups; however, they included 422 out of 461 (92%) NES for Crustacea: Ostracoda and 187 out of 349 (54%) for Insecta: Trichoptera (data set S2a, table S5).

### The roles of biodiversity and taxonomic infrastructure in country-level NES discovery

Although many countries with high NES counts are generally considered to be high-biodiversity countries, we tested whether country-level NES data could shed light on the impact of sociopolitical factors on the global scientific community's description of NES from different countries. A multiple linear regression analysis was applied to determine the impact of several key geographic and sociopolitical factors on country-level NES counts. The factors considered (and their proxies) are political stability (the State Fragility Index), social development (United Nations Education Index), economic status (per capita gross domestic product [GDP]), biodiversity (the number of known plant species), climate (rainfall and average latitude), the level of land development (the percentages of forest and agricultural land), and taxonomic infrastructure (the number of taxonomic Web of Science [WoS] articles with author affiliations from each country). The taxonomic infrastructure proxy (TIP) figures were obtained with a WoS query with ("new species" or "n sp" or "sp n" or "sp nov") in the topic search field and 2008 as the year of publication, which yielded 5767 articles, or 82.3% of the 7009 articles with new species descriptions found in our survey of 2507 journals (data set S1).

These factors were chosen because they are likely to affect either the number of undescribed species that may be in each country or the efforts of local or foreign taxonomists directed toward describing new species from the country in question. In addition, country-level data for them are available for a large number of countries across the developed–developing world spectrum. The variables, data sources, some caveats of the biodiversity proxy and TIP, and the relationship between country area and the biodiversity proxy are discussed in greater detail in the supplemental materials. Some other relevant variables, such as taxonomy funding levels or numbers of practicing taxonomists, could not be included because of a general lack of data, whereas others, such as the World Bank's overall research and development expenditures, were excluded, because data for a large percentage of developing countries are lacking.

The developed equation (MacLeod et al. 2010) indicated that the biodiversity and taxonomic infrastructure proxies were the two most important variables:

$$\log(\hat{N}) = -3.0 + 1.18 \log(P) + 0.34 \log(T),$$

where  $\hat{N}$  is the predicted NES;  $P$  is the number of known plant species in the country, as a proxy for biodiversity; and  $T$  is the TIP.

The positive coefficients (1.18 and 0.34) of the two attributes indicate that higher numbers of NES generally occurred in countries with higher biodiversity or higher taxonomic infrastructure, which is consistent with common knowledge. These two attributes explain 80.20% ( $R^2 = .802$ ) of the total variation, which suggests that country-scale biodiversity and taxonomic infrastructure largely determine NES values. According to the application of the LMG (Lindeman–Merenda–Gold) metric from Lindeman and colleagues (1980), the former accounts for 53.83%, whereas the latter accounts for 26.37%; that is, biodiversity is just over twice as important as taxonomic infrastructure in determining NES values. Plots of NES versus the biodiversity proxy and TIP as individual factors show similar respective  $R^2$  values, and both have stronger correlations with NES than does country area (supplemental figure S1). Although we expected a correlation with biodiversity, we were somewhat surprised that, even after centuries of collection expeditions by scientists from around the world, the local taxonomic infrastructure in high-diversity countries still influences species-discovery rates.

### The importance of international collaboration in taxonomy

Many visions for improving the state of taxonomy research in the future call for increasing collaboration—particularly international collaboration (e.g., Wheeler et al. 2012)—but what is the current state of international collaboration in the taxonomic literature? The proportions of taxonomic WoS articles that have author affiliations from more than one country reveal marked differences in collaboration behavior by taxonomists affiliated with countries that have differing ratios of taxonomic infrastructure to NES. Table 1 shows collaboration data for each of the 29 countries that satisfy two criteria: (1) the number of either NES with specimens from the country or taxonomic WoS articles from 2008 with author affiliations from the country (TIP) is greater than 100 and (2) the other figure is greater than 20. The first criterion focuses the analysis on the countries with the greatest global impact on taxonomy, either in terms of publications or specimens. The second criterion eliminates the high degree of uncertainty in ratios of very small numbers. For example, 1/5 (0.20) is very different from 2/5 (0.40), but, in this case, a numerator of 1 or 2 may simply reflect a single article's being published in December 2008 rather than in January 2009 and may not really represent a twofold difference in the scope of taxonomic work in a country.



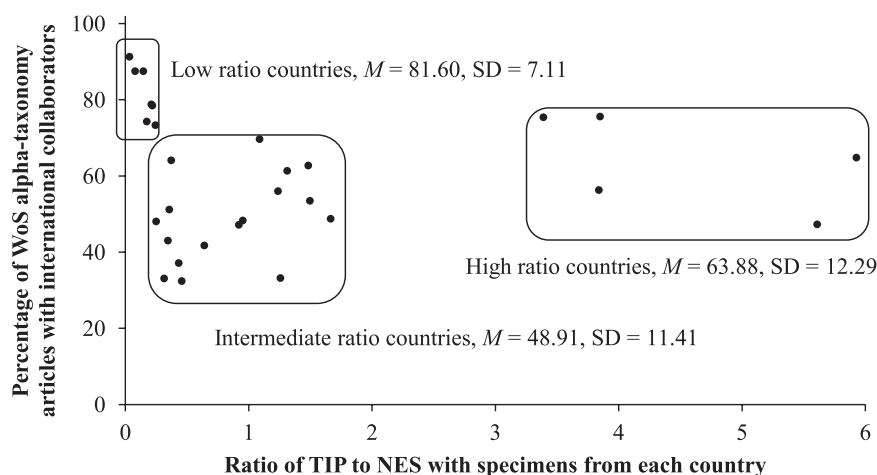
**Table 1. New extant species (NES), Web of Science (WoS) taxonomy articles, and international collaboration for 29 key countries in 2008.**

Country	NES	Taxonomic infrastructure proxy (TIP)	TIP:NES ratio	Percentage with international collaboration			Top collaborator	Number of collaborating countries
				Alpha-taxonomy articles	All WoS articles	Difference between the previous two cells		
Germany	82	486	5.93	64.81	43.03	21.79	United States	71
Poland	23	129	5.61	47.29	31.75	15.54	United Kingdom	32
Netherlands	33	127	3.85	75.59	47.78	27.81	Germany, United States	45
Czech Republic	31	119	3.84	56.30	42.53	13.78	United States	41
United Kingdom	108	366	3.39	75.41	39.11	36.30	United States	69
United States	801	1333	1.66	48.76	23.73	25.03	Canada	87
Italy	125	187	1.50	53.48	38.62	14.86	United Kingdom	41
Canada	143	212	1.48	62.74	40.78	21.96	United States	45
Spain	215	282	1.31	61.35	37.21	24.13	United States	54
South Korea	187	235	1.26	33.19	25.29	7.90	China	21
Russia	215	266	1.24	56.02	31.60	24.41	United States	38
France	285	310	1.09	69.68	45.93	23.75	United States	60
Argentina	187	178	0.95	48.31	40.95	7.37	United States	25
Japan	461	424	0.92	47.17	23.42	23.75	United States	46
Turkey	161	103	0.64	41.75	15.92	25.83	Germany	24
Brazil	1027	469	0.46	32.41	24.72	7.69	United States	39
China	1582	684	0.43	37.13	22.92	14.22	United States	36
New Zealand	210	78	0.37	64.10	47.75	16.36	United States	34
South Africa	357	127	0.36	51.18	43.75	7.43	United States	37
Mexico	499	172	0.34	43.02	41.87	1.15	United States	28
India	433	136	0.31	33.09	18.02	15.07	United States	29
Australia	1035	258	0.25	48.06	40.11	7.95	United States	38
Iran	185	45	0.24	73.33	19.01	54.32	United Kingdom	28
Thailand	362	79	0.22	78.48	51.34	27.14	Japan	15
Chile	157	33	0.21	78.79	50.14	28.64	Spain	15
Venezuela	202	35	0.17	74.29	46.43	27.86	United States	19
Panama	165	24	0.15	87.50	86.71	0.79	United States	9
Vietnam	305	24	0.08	87.50	75.95	11.55	Russia	14
Indonesia	692	23	0.03	91.30	78.31	12.99	Japan	10
Total <sup>a</sup>	5262			36.77	19.46	17.32		

*Note:* The countries are sorted by the "TIP:NES ratio" column. <sup>a</sup>The total figures are not sums or averages, because many articles have author affiliations from more than one country; they were derived from the pool of WoS alpha-taxonomy articles with author affiliations from any one of the countries listed in this table.

The TIP:NES ratio indicates the level of taxonomic infrastructure in each country relative to the total global effort being expended on the flora and fauna of that country. The countries with the highest ratios are at the top of the list and have high levels of taxonomic infrastructure relative to the number of NES discovered with specimens from the country. For example, 82 NES had specimens from Germany, but 486 new species articles from the WoS had author affiliations in Germany. Clearly, many of the new species described by Germany-affiliated authors were from countries other than

Germany. Intermediate ratios in the middle of the list characterize countries with relatively high levels of both indigenous NES and taxonomic infrastructure. Countries with low ratios appear at the bottom of the list, and they tend to be high-biodiversity countries with limited taxonomic infrastructure. For example, 692 NES had specimen localities in Indonesia, but only 23 new species WoS articles had author affiliations in Indonesia. This indicates that a great deal of the taxonomic effort on the flora and fauna of Indonesia is being expended by taxonomists working outside of the country.



**Figure 3. Relationship between international collaboration rates and the ratio of taxonomic infrastructure proxy (TIP) to new extant species (NES) discovered in each country. The TIP value is the number of Web of Science (WoS) taxonomy articles with author affiliations in a given country. The countries with a low ratio (less than 0.25) tend to be tropical, high-biodiversity countries and show the highest average international collaboration rate. The countries with the highest ratios (more than 3.3) are in Europe and show an intermediate level of international collaboration. However, among the three groups, only the low and intermediate ratio groups show a statistically significant difference in average international collaboration rates.**

Overall, the rate of international collaboration among the WoS new species articles (36.77%) was substantially higher than the international collaboration rate among all WoS records with affiliations from these countries (19.46%), as it was for each of the 29 individual countries (table 1). Only four of these countries (Brazil, China, India, and South Korea) had international collaboration rates among the WoS new species articles below 40%. Clearly, international collaboration plays a major role in taxonomic research among all countries. The United States was often the top collaborator country—that is, the country with the greatest number of collaborative articles—which is not surprising, given the large number of articles with US affiliations. In other cases, the top collaborator appears to have been dictated by either geographic proximity (e.g., China is South Korea's top collaborator) or historical affiliations (e.g., Spain is Chile's top collaborator).

The seven countries with TIP:NES ratios less than 0.25, such as Indonesia and Vietnam, had the highest percentages of international collaborations, with an average of 81.60% (standard deviation [SD] = 7.11%; figure 3), and their limited numbers of articles with local affiliations resulted in comparatively low numbers of collaborating countries, with an average of 15.71 (SD = 6.37%; table 1). These figures are consistent with high international interest in their biodiversity and the limited production of articles by authors affiliated with these countries outside of international collaborations. The latter point is not unique to the field of taxonomy; the results in table 1 in the *All WoS articles* column, which

include all fields of study, also show international collaboration rates of more than 50% for many of the countries with the lowest TIP:NES ratios.

The 17 countries with intermediate TIP:NES ratios, between 0.25 and 1.66 (table 1, United States through Australia), such as Brazil and India, had the lowest percentages of international collaborators, with an average of 48.91% (SD = 11.41%; figure 3), and intermediate numbers of collaborating countries, with an average of 40.12 (SD = 15.90). The high numbers of both indigenous NES and affiliated articles combined with modest proportions of collaboration relative to other countries are consistent with a strong focus on local flora and fauna by taxonomists affiliated with these countries.

For the five countries with TIP:NES ratios between 3.39 and 5.93, such as the United Kingdom and Germany, the percentage of articles with international collaborators was intermediate, with an average of 63.88% (SD = 12.29%; figure 3), whereas the number of collaborating countries was highest, with an

average of 51.60 (SD = 17.46; table 1). These figures are consistent with an interest in a geographically broad spectrum of the Earth's biodiversity by taxonomists affiliated with these countries; the numbers of affiliated publications far outnumbered NES discoveries among their local flora and fauna. The United States had the highest numbers of both publications and collaborating countries, with coauthors affiliated with 87 different countries among its 2008 WoS alpha-taxonomy articles.

### The roles of specimen collecting issues and policies in species discovery

The type specimen lists for many new species described in 2008 included specimens collected in the nineteenth century (e.g., *Myopa hirsuta* in Stuke and Clements 2008). Data on the time lag between specimen collection and new species description can reveal the relative importance of *current* expeditions, defined here as collection within 5 years of publication, and *legacy* specimens, defined here as collection more than 10 years prior to publication, in new species discovery. Although specimen year data were not collected for all 16,001 NES in the survey, data were obtained for five random samples of new species described in 2008 WoS articles. Cases in which specimen-locality countries and author-affiliation countries are either overlapping or mutually exclusive (supplemental table S6) can indicate the roles of current and legacy specimens in both internationally collaborative and local species-discovery efforts.

The specimen collection years among the 150 species sampled were highly variable, ranging from 1848 to 2008, and included 4 (2.7%) and 11 (7.3%) species with specimens collected in the nineteenth century and prior to 1958 (i.e., 50 years prior to publication), respectively. Overall, 58% of the species included recently collected specimens (table S6), and 37% and 26% of them included specimens collected at least 10 or 20 years prior to publication, respectively. These data suggest that, although legacy museum collections do contain many undescribed species, the majority of new species descriptions include recently collected specimens.

For each of the three country sets listed in table S6, data were obtained for 30 species for which the specimen-locality and author-affiliation countries were the same (table S6). Species with specimens collected within 5 years (67%), at least 10 years (27%–33%), and at least 20 years (13%–20%) prior to publication had similar proportions for each group. Table S6 shows data for cases in which the authors affiliated with the set-1 countries—the United States and Europe—described species from either set-2 or set-3 countries, such as Brazil and Madagascar, respectively, without any coaffiliations from countries in sets 2 or 3 (the sets are defined in table S6). In both cases, the proportions of new species with recently collected specimens (43%–47%) were lower than those for cases in which the author-affiliation and specimen-locality countries matched (67%). In addition, the percentages of specimens collected more than 10 years prior to publication were higher when specimen-locality and author-affiliation countries did not match (40%–60%) than when they did match (27%–33%) among the three sets. Together, these data suggest that legacy specimens are more common when authors describe new species from outside of their current affiliations and that recently collected specimens appear more frequently when specimen localities and author affiliations coincide. Although this is not surprising, these observations further underscore the importance of ongoing collection efforts in species discovery.

Over the past two decades, international taxonomic collaboration has operated under the guidelines of several policies designed to protect the rights of indigenous people to regulate access to their local biological diversity by researchers from other countries (e.g., UN 1992, CBD 2010). Some authors have expressed concern that, in addition to reigning in the exploitation of these resources, these policies may also, to some degree, impede international collaboration in taxonomy (e.g., Prathapan et al. 2006, Jinna and Jungcurt 2009, Cock et al. 2010, Martinez and Biber-Klemm 2010). However, the data presented here suggest that international collaboration is currently a major feature of taxonomic research across the full developed–developing country spectrum. A more comprehensive survey, which includes data for new species described before and after the implementation of these policies, would be necessary to determine any direct effects of the policies on either species-discovery or international-collaboration rates. In addition, a more comprehensive analysis of various aspects of specimen collection dates, such as differences among taxonomic groups, between marine and terrestrial habitats, and those among individual countries, would be an interesting topic for further study.

### Taxonomy as a research priority

The degree to which a particular issue is prioritized in the research enterprise of a country is indicated by its proportion in the research output from that country. On the basis of this criterion, new species discovery tends to be a much higher research priority in high-biodiversity countries than in low-biodiversity countries. Globally, alpha-taxonomy articles occupy less than 1% of the WoS-indexed literature, although they grew from 0.34% in 2008 to 0.41% in 2012—an average annual increase of 5.14%. Some of this growth was due to the expansion of the megajournal *Zootaxa*; when it is excluded from the results, the percentages for 2008 and 2012

**Table 2. Taxonomy as a research priority based on its prominence among all Web of Science (WoS) publications with author affiliations from all countries in the indicated continent.**

Region	2008			2012		
	All WoS <sup>a</sup>	Taxonomy <sup>b</sup>		All WoS	Taxonomy <sup>b</sup>	
		Number	Percentage		Number	Percentage
Latin America	64,345	940	1.46	79,362	1222	1.54
Africa	27,278	224	0.82	38,408	304	0.79
Australia, Oceania	53,732	341	0.63	70,957	478	0.67
Asia	327,329	1628	0.50	445,481	2428	0.55
Europe (including Russia)	602,503	2397	0.40	676,241	3200	0.47
Middle East	62,390	226	0.36	92,044	378	0.41
United States and Canada	545,787	1,481	0.27	576,337	1745	0.30
Total	1,653,639	5,767	0.34	1,837,872	7559	0.41

Note: These counts are based on all author-affiliation countries listed in the country field of the WoS records. <sup>a</sup>These data represent WoS alpha-taxonomy articles with author affiliations in the region indicated and were obtained using year-of-publication queries of 2008 or 2012 appended with *and* (“new species” or “n sp” or “sp n” or “sp nov”) in the topic field.

**Table 3. Taxonomy as a research priority based on its prominence among all Web of Science (WoS) publications with author affiliations from individual countries.**

Region	Country	2008			2012		
		All WoS <sup>a</sup>	Taxonomy		All WoS <sup>a</sup>	Taxonomy	
			Number	Percentage		Number	Percentage
Latin America	Brazil	34,486	469	1.36	43,940	657	1.50
	Mexico	10,711	172	1.61	12,625	210	1.66
	Argentina	8289	178	2.15	9748	202	2.07
	Chile	4888	33	0.68	7073	45	0.64
	Colombia	2544	35	1.38	3876	53	1.37
Africa	South Africa	8662	127	1.47	12,374	156	1.26
	Egypt	4761	15	0.32	8225	26	0.32
	Tunisia	2487	13	0.52	3470	25	0.72
	Nigeria	2493	3	0.12	2486	5	0.20
	Algeria	1455	2	0.14	2120	8	0.38
	Morocco	1463	4	0.27	2009	9	0.45
Australia, Oceania	Australia	46,161	258	0.56	62,034	387	0.62
	New Zealand	8363	78	0.93	10,274	96	0.93
Asia	China	117,170	684	0.58	197,566	1163	0.59
	Japan	92,864	424	0.46	92,403	447	0.48
	South Korea	39,785	235	0.59	56,059	310	0.55
	India	43,365	136	0.31	54,182	300	0.55
	Taiwan	24,823	99	0.40	30,740	122	0.40
	Singapore	8990	49	0.55	12,705	54	0.43
	Malaysia	3469	23	0.66	9477	70	0.74
	Thailand	5306	79	1.49	7486	136	1.82
	Vietnam	1077	24	2.23	1922	66	3.43
	Indonesia	996	23	2.31	1670	29	1.74
Europe (including Russia)	United Kingdom	129,368	366	0.28	147,749	413	0.28
	Germany	110,685	486	0.44	123,541	601	0.49
	France	76,282	310	0.41	84,042	404	0.48
	Italy	63,909	187	0.29	73,151	237	0.32
	Spain	51,098	282	0.55	65,835	386	0.59
	Netherlands	36,836	127	0.34	45,470	176	0.39
	Switzerland	26,597	84	0.32	32,137	112	0.35
	Russia	30,331	266	0.88	30,757	415	1.35
Middle East	Turkey	23,491	103	0.44	29,602	118	0.40
	Iran	13,602	45	0.33	26,778	131	0.49
	Israel	14,750	29	0.20	15,623	26	0.17
	Saudi Arabia	2278	21	0.92	8306	61	0.73
	Pakistan	3448	16	0.46	6455	28	0.43
United States and Canada	United States	490,181	1333	0.27	515,600	1582	0.31
	Canada	70,226	212	0.30	78,170	241	0.31

*Note:* Data are shown for the top eight countries in Europe (including Russia) and all other countries with more than 1500 affiliated WoS records for 2012. See table 2 for the queries used.

shift from 0.34% and 0.41% (table 2) to 0.30% and 0.34%, respectively—an average increase of 3.33%. The percentages of 2012 WoS alpha-taxonomy articles were higher among articles with author affiliations in Latin America (1.54%), Africa (0.79%), and Australia and Oceania (0.67%) than for

Asia (0.55%), Europe (including Russia, 0.47%), the Middle East (0.41%), and the United States and Canada (0.30%) (table 2). As with the global figures, the percentages for each region except Africa also increased between 2008 and 2012.



Table 3 shows data at the country level for both 2008 and 2012 for the eight European countries with the highest numbers of WoS articles and for all other countries with over 1500 WoS articles in 2012. For some countries, such as South Africa and Russia, the percentages of alpha-taxonomy articles were considerably higher than those for their region, whereas for others, such as Chile, Nigeria, and the United Kingdom, they were considerably lower. Within Asia, new species articles tend to occupy a much larger proportion of the published literature from tropical countries, such as Thailand, Vietnam, and Indonesia, than from countries outside or only partially in the tropics. However, Malaysia and Singapore are exceptions to this pattern. The consistency of all of the patterns noted above between the 2008 and 2012 data suggests that they are truly representative of the publishing patterns of the countries and regions involved.

### Speculations on the future of new species discovery

On the basis of a current rate of approximately 20,000 new species described per year, an estimate of 8 million undescribed species (Strain 2011) suggests that about 400 years would be required to describe all of the species on Earth, an unacceptable time frame, given the current rates of extinction (Padial et al. 2010). There are signs that the discovery of new species is gaining momentum. Our data indicate a modest increase in both the number and the proportion of WoS records that include new species descriptions. Recent initiatives such as the Census of Marine Life ([www.coml.org](http://www.coml.org)) and iNaturalist ([www.inaturalist.org](http://www.inaturalist.org)) are overcoming some of the geographic constraints that have traditionally impeded global species discovery. Scientists who do have access to undersampled, politically isolated countries should increase specimen-collection activities there—such as the expeditions of Polish taxonomists in North Korea (e.g., Bankowska and Sterzynska 1997). Increasing overall funding levels for systematics research would help alleviate the concern that “we still need more taxonomists” (Bacher 2012, p. 66), to which one response was “Where should that effort be concentrated?” (Joppa et al. 2011b).

The growth of taxonomic discovery in some high-biodiversity countries, such as Brazil (Tancoigne et al. 2011), is beginning to shift the geographic disparity between taxonomists and biodiversity. The patterns in NES discovery rates found here indicate that one priority should be increasing the local taxonomic efforts by scientists in the high-biodiversity countries that are characterized by either relatively few current publications, such as Madagascar and Ecuador, or NES figures that seem low in light of those countries' known biodiversity, such as in Bolivia and Peru. Today, alpha taxonomy tends to be a higher research priority among high-biodiversity- than among low-biodiversity-country-affiliated authors (table 2). This fact may simply reflect the access that scientists affiliated with tropical countries such as Mexico have to an abundance of undescribed species or the modest expense of taxonomy relative to many other fields of scientific investigation. Despite high collaboration rates,

many biodiverse countries still show only limited local taxonomic activity, as is reflected in the extremely low numbers of affiliated WoS new species publications.

Grant programs such as PEET and the recommendations of the UN-sponsored International Platform for Biodiversity and Ecosystem Services (Perrings et al. 2011) emphasize international collaborations that fully engage host-country scientists and the training of local taxonomists during collection expeditions to such countries. The continuing efforts of locals after the international visitors return home would undoubtedly increase the spatial, seasonal, and taxonomic thoroughness of field sampling and the rates of species discovery in megadiverse regions. However, the degree to which these collaborations succeed in stimulating long-term local efforts is unclear.

Consider Madagascar as an example. Only 12 WoS taxonomy publications in 2008 had Madagascar affiliations. However, Madagascar has over 40,000 students enrolled in its six universities, according to the Southern African Regional Universities Association ([www.sarua.org](http://www.sarua.org)), and the Thèse Malgaches en Ligne database ([www.bu.univ-antananarivo.mg/theses2/statAction.action](http://www.bu.univ-antananarivo.mg/theses2/statAction.action)) contains over 15,000 academic theses, about 10% of which are devoted to local flora and fauna. With a per capita nominal GDP of US\$458, Madagascar's indigenous taxonomic workforce could be greatly expanded with very modest international investments in training and student scholarships.

The methods of analysis used here could be applied to other areas of global field biological research, such as biological conservation or biodiversity studies, to determine whether the same characteristics found here for taxonomy apply to field-oriented biology in general. A greater understanding of the forces influencing field biological research on a global scale could inform policies and funding decisions in the contexts of broader development issues and initiatives.

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### Supplemental material

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### References cited

- Acorn J. 2009. Amateurs and abandoned science. *American Entomologist* 55: 128, 127.
- Bacher S. 2012. Still not enough taxonomists: Reply to Joppa et al. *Trends in Ecology and Evolution* 27: 65–66.
- Bankowska R, Sterzynska M. 1997. Faunistic investigations conducted in North Korea by researchers from the Institute of Zoology, Polish Academy of Sciences from 1959 to 1990. *Fragmenta Faunistica* 40: 247–253.

- Bohannon J. 2009. Madagascar's coup endangers science and scientists. *Science* 323: 1654–1655.
- [CBD] Convention on Biological Diversity. 2010. COP 10 Decision X/1. Access to genetic resources and the fair and equitable sharing of benefits arising from their utilization. CBD. (16 December 2013; [www.cbd.int/decision/cop/?id=12267](http://www.cbd.int/decision/cop/?id=12267))
- Cesari M, Giovannini I, Bertolani R, Rebecchi L. 2011. An example of problems associated with DNA barcoding in tardigrades: A novel method for obtaining voucher specimens. *Zootaxa* 3104: 42–51.
- Cock MJW, van Lenteren JC, Brodeur J, Barratt BIP, Bigler F, Bolckmans K, Cónsoli FL, Haas F, Mason PG, Parra JRP. 2010. Do new access and benefit sharing procedures under the Convention on Biological Diversity threaten the future of biological control? *BioControl* 55: 199–218.
- Costello MJ, Wilson S, Houlding B. 2012. Predicting total global species richness using rates of species description and estimates of taxonomic effort. *Systematic Biology* 61: 871–883.
- Deming JW. 1998. Deep ocean environmental biotechnology. *Current Opinion in Biotechnology* 9: 283–287.
- Evenhuis NL. 2007. Helping solve the “other” taxonomic impediment: Completing the *Eight Steps to Total Enlightenment and Taxonomic Nirvana*. *Zootaxa* 1407: 3–12.
- Foley DH, Rueda LM, Wilkerson RC. 2007. Insight into global mosquito biogeography from country species records. *Journal of Medical Entomology* 44: 554–567.
- Fontaine B, et al. 2012. New species in the Old World: Europe as a frontier in biodiversity exploration, a test bed for 21st century taxonomy. *PLOS ONE* 7 (art. e36881).
- Giam X, Scheffers BR, Sodhi NS, Wilcove DS, Ceballos G, Ehrlich PR. 2012. Reservoirs of richness: Least disturbed tropical forests are centres of undescribed species diversity. *Proceedings of the Royal Society B* 279: 67–76.
- Gomes Hutchings RS, Mureb Sallum MA. 2008. Two new species of *Culex* subgenus *Melanoconion* (Diptera: Culicidae) from the Amazon forest. *Zootaxa* 1920: 41–50.
- Grobbelaar E. 2008. On the identity of *Ootheca bennigseni* Weise, *O. mutabilis* (Schönherr) and *O. meridiana* sp. n. (Chrysomelidae: Galerucinae), bean and cowpea pests in the Afrotropical Region. *African Entomology* 16: 7–22.
- Hanson T, Brooks TM, da Fonseca GAB, Hoffmann M, Lamoreux JF, Machlis G, Mittermeier CG, Mittermeier RA, Pilgrim JD. 2009. Warfare in biodiversity hotspots. *Conservation Biology* 23: 578–587.
- House of Lords. 2008. Systematics and taxonomy: Follow-up report with evidence. Stationery Office. HL Paper no. 162. (16 December 2013; [www.publications.parliament.uk/pa/ld200708/ldselect/ldsctech/162/162.pdf](http://www.publications.parliament.uk/pa/ld200708/ldselect/ldsctech/162/162.pdf))
- [IISE] International Institute for Species Exploration. 2010. State of Observed Species 2010: A Report Card on our Knowledge of the Earth's Species. Arizona State University, IISE. (16 December 2013; [http://species.asu.edu/SOS\\_2010](http://species.asu.edu/SOS_2010))
- Jinna S, Jungcurt S. 2009. Could access requirements stifle your research? *Science* 323: 464–465.
- Joppa LN, Roberts DL, Pimm SL. 2011a. The population ecology and social behaviour of taxonomists. *Trends in Ecology and Evolution* 26: 551–553.
- . 2011b. Taxonomy that matters: Response to Bacher. *Trends in Ecology and Evolution* 27: 66.
- Karaca G, Tepedelen G, Belghouthi A, Paul B. 2008. A new mycoparasite, *Pythium lycopersicum*, isolated in Isparta, Turkey: Morphology, molecular characteristics, and its antagonism with phytopathogenic fungi. *FEMS Microbiology Letters* 288: 163–170.
- Kuisiense N, Raugalas J, Spröer C, Kroppenstedt RM, Chitavichius D. 2008. *Bacillus butanolivorans* sp. nov., a species with industrial application for the remediation of n-butanol. *International Journal of Systematic and Evolutionary Microbiology* 58: 505–509.
- Laws EA. 2013. Evaluation of *in situ* phytoplankton growth rates: A synthesis of data from varied approaches. *Annual Review of Marine Science* 5: 247–268.
- Lindeman RH, Merenda PF, Gold RZ. 1980. Introduction to bivariate and multivariate analysis. Scott, Foresman.
- Loosey JE, Vaughan M. 2006. The economic value of ecological services provided by insects. *BioScience* 56: 311–323.
- MacLeod N, Benfield M, Culverhouse P. 2010. Time to automate identification. *Nature* 467: 154–155.
- Maier DS. 2012. What's So Good about Biodiversity? A Call for Better Reasoning about Nature's Value. Springer.
- Martinez SI, Biber-Klemm S. 2010. Scientists—Take action for access to biodiversity. *Current Opinion in Environmental Sustainability* 2: 27–33.
- Matthias MA, et al. 2008. Human leptospirosis caused by a new, antigenically unique *Leptospira* associated with a *Rattus* species reservoir in the Peruvian Amazon. *PLOS Neglected Tropical Diseases* 2 (art. e213).
- McNeely JA, Mittermeier RA, Brooks TM, Boltz F, Ash N. 2009. The Wealth of Nature: Ecosystem Services, Biodiversity and Human Well-Being. International League of Conservation Photographers.
- Mitchell A. 2011. DNA barcoding is useful for taxonomy: A reply to Ebach. *Zootaxa* 2772: 67–68.
- Mittermeier RA, Mittermeier CG. 1997. Megadiversity: Earth's Biologically Wealthiest Nations. CEMEX.
- Padial JM, Miralles A, de la Riva I, Vences M. 2010. The integrative future of taxonomy. *Frontiers in Zoology* 7: 16.
- Perrings C, Duraipappah A, Larigauderie A, Mooney H. 2011. The biodiversity and ecosystem services science-policy interface. *Science* 331: 1139–1140.
- Prathapan KD, Rajan PD, Narendran TC, Viraktamath CA, Subramanian KA, Aravind NA, Poorani J. 2006. Biological Diversity Act, 2002: Shadow of permit-raj over research. *Current Science* 91: 1006–1007.
- Rilke S, Najmi U, Schnittler M. 2013. Contributions to “e-taxonomy”: A virtual approach to the flora of Mongolia (FloraGREIF). *Feddes Repertorium* 123: 219–232.
- Rodman JE, Cody JH. 2003. The taxonomic impediment overcome: NSF's Partnerships for Enhancing Expertise in Taxonomy (PEET) as a model. *Systematic Biology* 52: 428–435.
- Rodrigues ASL, Gray CL, Crowter BJ, Ewers RM, Stuart SN, Whitten T, Manica A. 2010. A global assessment of amphibian taxonomic effort and expertise. *BioScience* 60: 798–806.
- Ryther JH. 1969. Photosynthesis and fish production in the sea. *Science* 166: 72–76.
- Speers L, Edwards JL. 2008. International infrastructure for enabling the new taxonomy: The role of the Global Biodiversity Information Facility (GBIF). Pages 87–94 in Wheeler QD, ed. *The New Taxonomy*. CRC Press.
- Stoffelen P, Noirot M, Couturon E, Anthony F. 2008. A new caffeine-free coffee from Cameroon. *Botanical Journal of the Linnean Society* 158: 67–72.
- Strain D. 2011. 8.7 million: A new estimate for all the complex species on Earth. *Science* 333: 1083.
- Stuke J-H, Clements DK. 2008. Revision of the *Myopa testacea* species-group in the Palaearctic Region (Diptera: Conopidae). *Zootaxa* 1713: 1–26.
- Tancoigne E, Bole C, Sigogneau A, Dubois A. 2011. Insights from Zootaxa on potential trends in zoological taxonomic activity. *Frontiers in Zoology* 8: 5.
- [UN] United Nations. 1992. Convention on Biological Diversity. United Nations. (16 December 2013; [www.cbd.int/doc/legal/cbd-en.pdf](http://www.cbd.int/doc/legal/cbd-en.pdf))
- Wang J, Li Y, Bian J, Tang S-K, Ren B, Chen M, Li W-J, Zhang L-X. 2010. *Prauserella marina* sp. nov., isolated from ocean sediment of the South China Sea. *International Journal of Systematic and Evolutionary Microbiology* 60: 985–989.
- Webb TJ, vanden Berghe E, O'Dor R. 2010. Biodiversity's big wet secret: The global distribution of marine biological records reveals chronic under-exploration of the deep pelagic ocean. *PLOS ONE* 5 (art. e10223).
- Wheeler QD. 2008. Introductory: Toward the new taxonomy. Pages 1–17 in Wheeler QD, ed. *The New Taxonomy*. CRC Press.

- Wheeler QD, et al. 2012. Mapping the biosphere: Exploring species to understand the origin, organization and sustainability of biodiversity. *Systematics and Biodiversity* 10: 1–20.
- Wilkin P, Rajaonah MT, Jeannota VH, Hladik A, Jeannota VL, Hladik CM. 2008. An endangered new species of edible yam (*Dioscorea*, *Dioscoreaceae*) from Western Madagascar and its conservation. *Kew Bulletin* 63: 113–120.

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