A Global Assessment of Amphibian Taxonomic Effort and Expertise

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Taxonomy, the description and classification of life's diversity, is a discipline that underpins all biological sciences. Current gaps in taxonomic knowledge and expertise restrict our ability to effectively conserve and manage biodiversity. Among vertebrates, amphibians are of particular concern; they are highly threatened yet poorly known. We found that resident expertise in amphibian taxonomy is concentrated in economically rich but relatively species-poor countries in North America and Europe. However, much expertise is exported; most experts work on species elsewhere, in biodiverse Asia or South America. Unexpectedly, age pyramids of taxonomists revealed healthy levels of participation among young researchers, though available expertise remains inadequate across most of the globe. Our results strongly suggest that many amphibian species are becoming extinct before they are described, and provide concrete support for the widespread calls to increase taxonomic expertise worldwide.

Keywords: Amphibia, biodiversity, extinction, Red List, taxonomy

E. O. Wilson (2004) called taxonomy "the pioneering explo-ration of life on a little known planet"; Robert May (2004) wrote, "taxonomy provides the bricks, and systematics, the plan, with which the house of biological sciences is built." Although taxonomy has advanced immensely since Carl Linnaeus's 1758 *Systema Naturae*, only 1.5 million to 1.8 million species have been formally described out of Earth's estimated 10 million (Wilson 2004). At current rates of approximately 10,000 new descriptions per year, we are far from completing the inventory of life on Earth (May 2004). Advances in molecular biology and information technology are creating the conditions for a substantial acceleration in the taxonomic enterprise (Janzen 2004, Godfray 2007), but such progress is hampered by a widespread shortage of the formal skills needed for proper species identification and description (Wheeler 2004, House of the Lords 2008). Gaps in taxonomic knowledge and a lack of trained taxonomists restrict our ability to manage and conserve biological diversity (Mace 2004). This "taxonomic impediment" (Samper 2004, SCBD 2008) is particularly acute for highly diverse taxa, such as invertebrates, and species-rich regions, such as the tropics (Gaston and May 1992), yet this problem affects even resource-rich countries, such as the United Kingdom (House of the Lords 2002, 2008), and well-known taxa, such as birds (Collar 1997). Among vertebrates, amphibians are of particular concern, as they are still poorly known and are highly threatened. Half of the currently recognized amphibian species have been described only since 1960, and a quarter are considered "data deficient," meaning that available data are insufficient for an assessment of conservation status by the International Union for Conservation of Nature (IUCN) Red List of Threatened Species (IUCN 2009). Of data-sufficient species, 41% are classified as globally threatened by drivers such as habitat loss, overexploitation, and highly infectious and lethal disease (Stuart et al. 2004, IUCN 2009).

Here, we analyze global patterns among amphibian taxonomists—where they are based, where they work, and variation in their age distribution—and how these relate to patterns of amphibian diversity and threat, as a contribution to a better understanding of the taxonomic impediment and as guidance for future investment in taxonomic capacity building and knowledge.

Investigating patterns of taxonomic effort and expertise

Investigating global patterns of taxonomic effort and expertise is not straightforward for any taxon given the absence of centralized databases for who the experts are and where they work. We took advantage of two recent global-scale efforts that brought together the existing literature on amphibian taxonomy (Frost 2007) and data on the distribution and conservation status of all described species (IUCN et al. 2006). We then complemented these with data that we collected about experts who have recently published on amphibian taxonomy.

The Amphibian Species of the World (ASW) database (Frost 2007) is a searchable catalog of all recognized species that includes current scientific name, previously existing synonyms and combinations, and citations of respective publications. Searching the database by year yields the new names and combinations

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published that year. The Amphibians on the IUCN Red List (AIUCNRL; IUCN et al. 2006) is a comprehensive assessment of the conservation statuses of amphibian species, including distribution maps, as part of the IUCN Red List of Threatened Species (IUCN et al. 2006). The Red List is a widely used system for classifying species at high risk of extinction. By 2006, the AIUCNRL had assessed and mapped 5817 amphibian species, including 1811 classified as globally threatened (in vulnerable, endangered, or critically endangered categories; IUCN 1994) and 1337 classified as data deficient. The AIUCNRL also provided the date of description for each species.

From the ASW, we linked 1879 species—for which 2656 taxonomic studies were published between 1994 and 2003—to the names of the 639 authors of those publications, and to 1879 species distribution maps according to the AIUCNRL. The 1994–2003 period was selected in order to maximize congruence with the Amphibian Red List, which was first published in 2004. The list of publications obtained corresponds to both new descriptions (when a taxon is first recognized as unique, either as a species or as a subspecies) and to subsequent taxonomic revisions (e.g., when a subspecies is elevated to a species). Out of the 1879 species analyzed, 924 were described in the 1994–2003 period. Studies had between 1 and 9 authors (mean = 2.0, standard deviation [SD] = 0.99). We searched the literature (e.g., Applegarth 2007) and the Internet, and established direct e-mail contact to obtain further information for each author. We were able to obtain information on the city where each author is based (for 88% of authors across 233 cities), the country (and consequently continent) where each author is based (for 97% of authors across 58 countries), and each author's year of birth (within a 10-year age class, for 64% of authors). We assumed that an author "works" in a given geographical area if at least one of the species she or he studied is mapped as present in that area, and we were thus able to establish the continent where each author works.

Data caveats. Several important caveats apply to these data. (a) The taxonomic studies on which this analysis is based vary in their methods, species concept employed, and most likely in the reliability of their conclusions. The population of researchers ranges from those who do classical morphological species descriptions to those who do taxonomy using acoustic data to those doing broad phylogeographic studies using molecular techniques. We use the term taxonomy in a broad sense to include work on systematics. (b) The authors of a given taxonomic paper are not necessarily all taxonomists in a strict sense, and in multiauthor publications the level of input from each author often varies. Nonetheless, a broad set of skills is needed to do taxonomic work, and by definition, all authors of the papers have contributed to the taxonomic results. For this reason, we consider all 639 authors as contributors to global taxonomic efforts, but refer to them as authors or experts rather than as taxonomists. (c) The pool of authors considered in this analysis is only a subset of the existing taxonomic expertise, globally as well as within any given region. We inevitably missed authors who did not publish between 1994 and 2003, or who wrote articles not included in the ASW database. Furthermore, this analysis does not include people who have expertise in taxonomy but do not publish taxonomic articles. In any case, we hope that by choosing a recent 10-year period and covering 639 authors, we obtained results that are representative of the current relative distribution of amphibian taxonomic expertise and effort. Thus, numbers presented should be interpreted in relative terms and not their absolute values. (d) Researchers often move among institutions and even countries. We used the most recent mailing addresses we could find, but these may not be the same addresses the authors had when they published the papers in our analysis. (e) Authors with permanent positions are likely to constitute a more stable workforce, but our data did not provide information on whether authors had permanent or temporary positions, or whether they volunteered their work (e.g., amateurs, retired researchers). A population dominated by young authors is not necessarily a guarantee of a strong workforce over the long run if younger researchers are subsequently forced out of taxonomy by a lack of long-term positions. However, any data on authors' type of employment would have been difficult to interpret, as the degree to which institutional tenure is available to researchers varies from country to country. (f) Our data are probably biased against non–English speaking authors, particularly those from Asia. The ASW database is more likely to miss publications from countries such as China and India, which have large research communities but a tradition of publication in local, relatively obscure journals. Moreover, some Chinese surnames

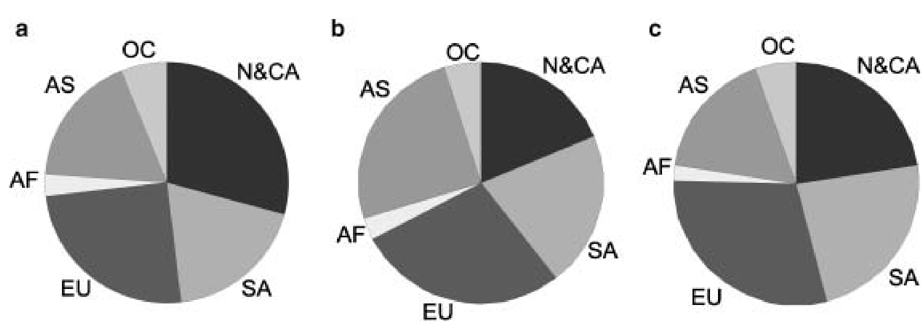

Figure 1. Continental distribution of taxonomic expertise among (a) our sample of authors working in amphibian taxonomy (Frost 2007), according to their area of residence (1993–2004; n *= 619); (b) authors for whom we were unable to determine age* (n *= 208); and (c) authors of papers in* Zootaxa *(May 2001 through May 2009;* n *= 5663; Magnolia Press 2009). The continents are North and Central America (N&CA), South America (SA), Europe (EU), Africa (AF), Asia (AS), and Oceania (OC). The spatial extent of each continent is presented in figure 3. Panels (a) and (b) exclude 20 authors whose continent of residence was unknown.*

are very common, and we may have failed to distinguish all authors with the same surname. We performed Web searches in English, Spanish, Portuguese, French, and Italian, but Asian authors proved particularly difficult to trace. Accordingly, numbers of authors of unknown age are disproportionately high in Asia ($\chi^2 = 7.44$, degrees of freedom [DF] = 1, $p < 0.01$) and low in North and Central America ($\chi^2 = 11.06$, DF = 1, $p < 0.001$; figure 1) in relation to the distribution observed for all authors. (g) Data on years of birth are also likely to be less extensive both for the youngest authors, who are more likely to have changed institutional addresses, and the oldest, who are less likely to have data available on the Internet or an e-mail address.

Mapping taxonomic expertise and effort

We mapped resident taxonomic expertise by plotting the cities where authors are institutionally based (figure 2a). We compared the national (table 1) and continental (figure 1c) distribution of expertise with that of authors in *Zootaxa*, a leading zoology taxonomy journal (5663 authors of 5009 papers describing 11,404 new taxa between May 2001 and May 2009; Magnolia Press 2009). There is a remarkable similarity between the two, in terms of both continental distribution (figure 1; statistically indistinguishable as long as the Americas are considered together; $\chi^2 = 7.87$, DF = 1, $p > 0.05$) and top countries (table 1; perfect agreement between the top five countries; 13 out of the top 15 countries coincide). This similarity suggests that our sample is representative of the broader group of zoological taxonomists, at least in terms of where they are institutionally based. Maps of taxonomic effort and of amphibian diversity (figure 2b, 2c, 2d, 2f) were plotted on a geodesic discrete global grid system, defined on an icosahedron and projected to the sphere using the inverse icosahedral Snyder equal area projection (Sahr et al. 2003). This corresponds to a hexagonal grid composed of individual units (cells) that retain their shape and area (approximately 12,500 square kilometers, similar to a 1-degree-by-1-degree rectangle at the equator) over the globe. We obtained global patterns of taxonomic effort (figure 2b) by mapping where each author worked, assuming that an author worked in a given area if at least one of the species she or he studied was present, and then counting the number of authors working in each cell. For species with very large ranges, this may produce a spillage effect, explaining why taxonomic effort is mapped even in areas of very little taxonomic activity (e.g., in Myanmar, a spillover from China). Taxonomic effort was also mapped in relation to local amphibian diversity as the number of authors divided by overall number of amphibian species (figure 2c).

Table 1. Top 16 countries in terms of number of resident authors publishing in amphibian taxonomy papers and in Zootaxa*, ranked in decreasing order of number of authors. For context, we also present each country's population (in 1999 or the nearest year for which data were available, and the number of authors per 10 million country habitants.*

	Amphibian taxonomy papers				*Zootaxa* authors			
Rank	Country	Authors	Country population (millions)	Authors per 10 million habitants	Country	Authors	Country population (millions)	Authors per 10 million habitants
1	United States	147	279	5.3	United States	955	279	34.2
2	Brazil	56	169	3.3	Brazil	895	169	53.0
3	China	49	1253	0.4	China	520	1253	4.2
4	Germany	48	82	5.8	Germany	258	82	31.4
5	Australia	36	19	19.0	Australia	248	19	131.0
6	France	18	59	3.1	Argentina	236	36	64.8
7	Italy	17	57	3.0	United Kingdom	170	59	29.0
8	Colombia	14	40	3.5	France	163	59	27.8
9	Russia	14	147	1.0	Mexico	162	97	16.7
10	India	14	998	0.1	Spain	150	40	37.6
11	Argentina	13	36	3.6	Japan	133	127	10.5
12	United Kingdom	13	59	2.2	Italy	121	57	21.3
13	Spain	13	40	3.3	Russia	121	147	8.2
14	Mexico	10	97	1.0	Canada	110	30	36.2
15	Canada	9	30	3.0	Turkey	87	66	13.1
16	South Africa	9	43	2.1	India	86	998	0.9

Source: Frost 2007, Magnolia Press 2009, UNSD 2009.

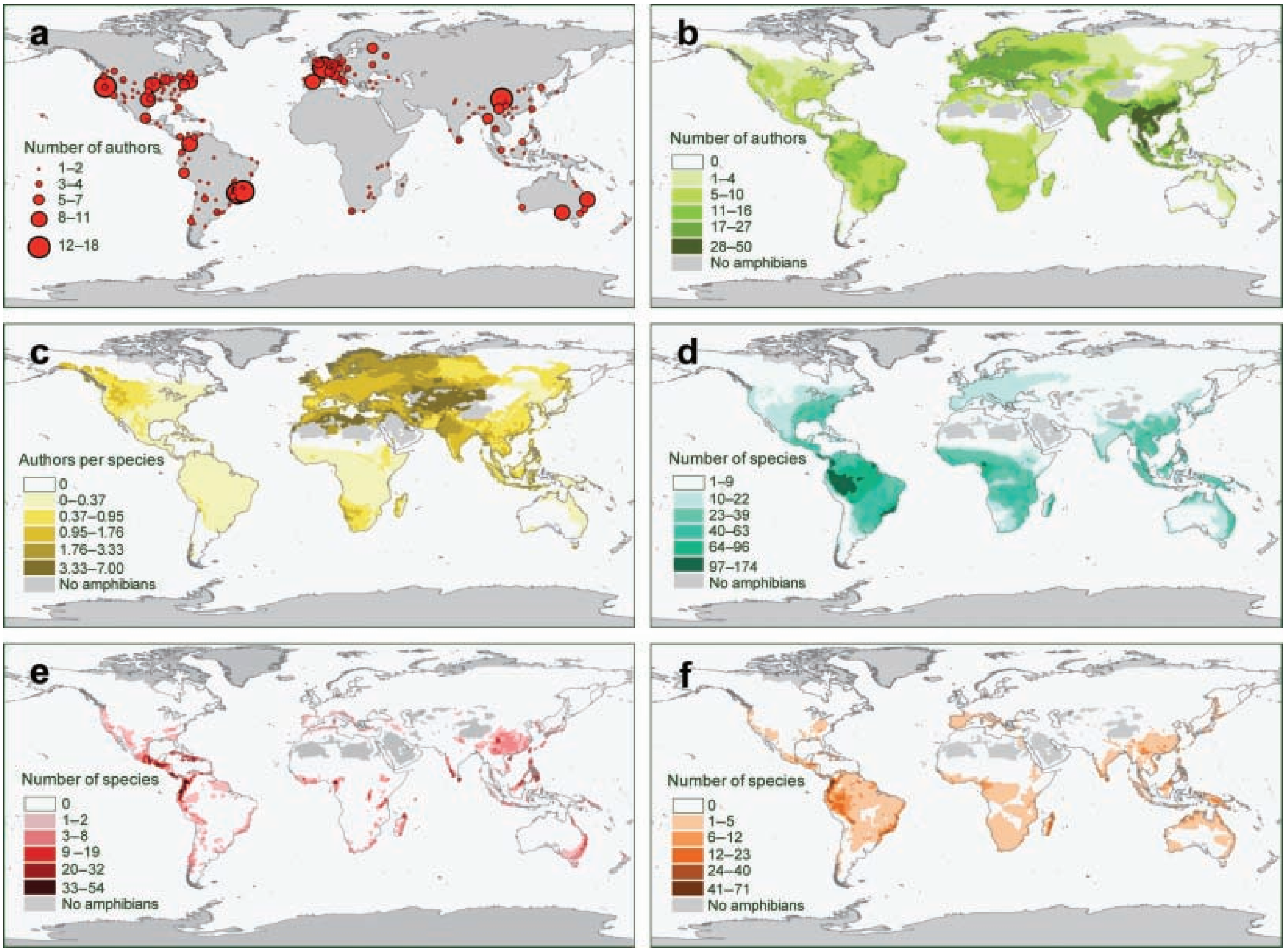

Figure 2. Global patterns of expertise and effort on amphibian taxonomy and how they relate to patterns of amphibian diversity. (a) The number of authors per city (resident expertise); circle size is indicative of the number of authors in each city. (b) The number of authors working in each cell across a global hexagonal grid (taxonomic effort). (c) The number of authors working in each cell per amphibian species present. (d) The number of amphibian species per cell. (e) The number of globally threatened species in each cell, according to the International Union for Conservation of Nature Red List of Endangered Species. (f) The number of recently described species (since 1980) in each cell (IUCN et al. 2006).

For context, we have also mapped global amphibian species richness (number of species per cell; figure 2d) and richness in globally threatened species according to the IUCN Red List (figure 2e), which are indicative of regions where taxonomic investment is likely to be most urgent. A map of species described since 1980 indicates where taxonomic knowledge has increased most substantially in recent years (figure 2f).

The distribution of authors according to their institutional base (figure 2a) confirms the widespread concern (Gaston and May 1992, Parnell 1993) that the centers of global taxonomic expertise are strongly biased toward regions with higher economic power, rather than to the places they are most urgently needed. Indeed, we found that 46% of all authors were based in the United States, Canada, and Western Europe (areas that constitute 63% of the global gross domestic product [GDP]), significantly more than expected given the human populations of these areas ($\chi^2 = 741$, DF $= 1$, $p < 0.001$) or amphibian diversity ($\chi^2 = 1439$, DF $= 1$, $p < 0.001$). In contrast, Africa (2% of the global GDP) conspicuously lacks in expertise: Less than 3% of all authors are based there, significantly less than would be expected given its human population ($\chi^2 = 62$, DF $= 1$, $p < 0.001$) or amphibian diversity ($\chi^2 = 71$, DF $= 1$, $p < 0.001$). Nonetheless, a somewhat more equitable distribution of taxonomic expertise was found in some species-rich regions: Brazil had significantly more resident authors than would be expected from its human population ($\chi^2 = 85$, DF $= 1$, $p < 0.001$), although fewer authors than would be expected given its species diversity ($\chi^2 = 8.4$, DF $= 1$, $p < 0.01$), whereas China had more resident authors than would be expected from its degree of amphibian diversity ($\chi^2 = 3.9$, DF $= 1$, $p < 0.05$), but fewer than would be expected from its human population ($\chi^2 = 46$, DF $= 1$, $p < 0.001$).

The distribution of taxonomic effort—that is, where authors work, determined by the distribution of their study species (figure 2b)—followed a different pattern from the distribution of residential expertise (figure 2a; comparison of distribution across continents: $\chi^2 = 461.70$, DF = 5, $p < 0.001$). This is presumably a result of professional mobility: Taxonomists often work with species native to continents other than where they are based, as was the case with 40% of the authors in our sample. The strongest concentration of taxonomic effort was found in south and southeast Asia; South America was also relatively well studied. As expected, there was high effort in Europe, though less was found in the United States. Africa remained very poorly covered.

The professional mobility of experts

We quantified how many authors work or are based on each continent. For each age class we determined how many authors are "mobile" in the sense of working in at least one continent other than the one where they are based (figure 3). The classification of countries into continents (figures 1, 3, 4) follows traditional political boundaries, but is somewhat arbitrary. Russia was considered part of Europe (even though most of its territory is generally considered to be in Asia) because all Russian authors are based (figure 2a)—and most taxonomic work is done (figure 2b)—west of the Urals. Taxonomic independence was defined as the percentage of experts working on a continent who are also based there. Most of our results are presented at the continental level, but within each continent there are countries that affect the results disproportionately (e.g., China in Asia, Brazil in South America; table 1), with other countries having much less or nonexistent taxonomic expertise. Thus, our results at the continental level cannot be interpreted to apply to individual countries within each continent.

We found that continents varied substantially in their taxonomic self-sufficiency, with economically poorer regions more dependent on imported expertise (relationship between taxonomic independence and 2003 GDP per capita [UNDP 2005]: $r_s = 0.89$, $n = 6$, $p < 0.05$). Africa was the only continent with most (80%) working taxonomists based elsewhere (figure 3a). Europe and North and Central America were net exporters of expertise; most of their resident authors (76% and 57%, respectively) work on other continents (figure 3b). Most researchers working in Asia and South America are based there, but these continents also receive substantial expertise from Europe and North and Central America (figure 3a). Professional mobility therefore helps tip the balance of taxonomic effort toward biodiversity-rich regions. However, this does not occur in proportion to need (figure 2c): We found that the 5% most diverse cells (mostly located within tropical South America and tropical Africa) had a much lower ratio of working authors to native species (mean = 0.15, SD = 0.02, $n = 553$) than did the other cells (mean = 0.77, SD = 4.22, $n = 10{,}516$; means are significantly different: $t = 204{,}296$; DF = 11,067; $p < 0.001$).

Age distributions of experts

We plotted age distributions for all 411 authors for whom we were able to obtain year of birth data, per continent (figure 3), using 10-year intervals. We used the age of each author in 1999, in the middle of our study period (1994–2003). At the global level, our results do not support the concern that taxonomists are an aging population (Parnell 1993, Simonetti 1997, House of the Lords 2008). Across most continents, the dominant cohort corresponded to authors in their thirties (figure 3), which is to be expected given that taxonomy requires several years of training. In general, numbers declined progressively in older cohorts, as would be expected from a combination of career change, retirement, and death. However, there was variation in the age distributions of authors based on different continents (figure 3b), and we found a particularly notable contrast between a younger population in South America and an aged population in Asia (Kolmogorov-Smirnov test: $D = 0.212$, $p < 0.05$). Older cohorts ($\geq$ 40 years old) were disproportionately dominant for authors based in Asia ($\chi^2 = 5.84$, DF = 1, $p < 0.025$), Oceania ($\chi^2 = 4.38$, DF = 1, $p < 0.05$), and North and Central America ($\chi^2 = 4.07$, DF = 1, $p < 0.05$) in relation to the age distribution in South America. This may be a result of the overall population demography in the authors' countries of origin, as the United States, Canada, Australia, and China have aging populations, unlike South American countries such as Brazil and Colombia (UNSD 2009). (It is worth noting that Europe, with an aging overall population but a relatively young population of resident experts, does not fit this pattern.) This trend may also reflect real differences in investment in the taxonomic training of younger generations, as levels of training are generally considered to be declining in several developed countries, such as Australia (Mather 2004), but increasing in some South American countries (Parnell 1993), such as Brazil (de Carvalho et al. 2005). In Asia, a noticeable generation gap for resident authors in their fifties in 1999 (i.e., authors who were born in the 1940s; figure 3b) does not seem to be related to the underlying population age structure (UNSD 2009) and is almost certainly a result of China's Cultural Revolution (1966 to 1976). During this time, schools were closed and academics were forced to work in the countryside, negatively affecting the development of potential taxonomists (Encyclopedia Britannica, *www.britannica.com/EBchecked/topic/146249/Cultural-Revolution*).

Temporal changes in the numbers of amphibian species

We plotted the cumulative number of species described over time, per continent (figure 4a), and the number of species described per decade according to their conservation status (figure 4b; IUCN et al. 2006). The date of description corresponds to the moment a taxon was first recognized as unique, as either a species or a subspecies; in many cases, elevation to species status happened only subsequently. The figures therefore correspond to the number of species that are currently recognized among the taxa described on any given date. These may be substantially higher than the number of species that were recognized at the time, given changes in the criteria for considering a species as separate (Agapow et al. 2004).

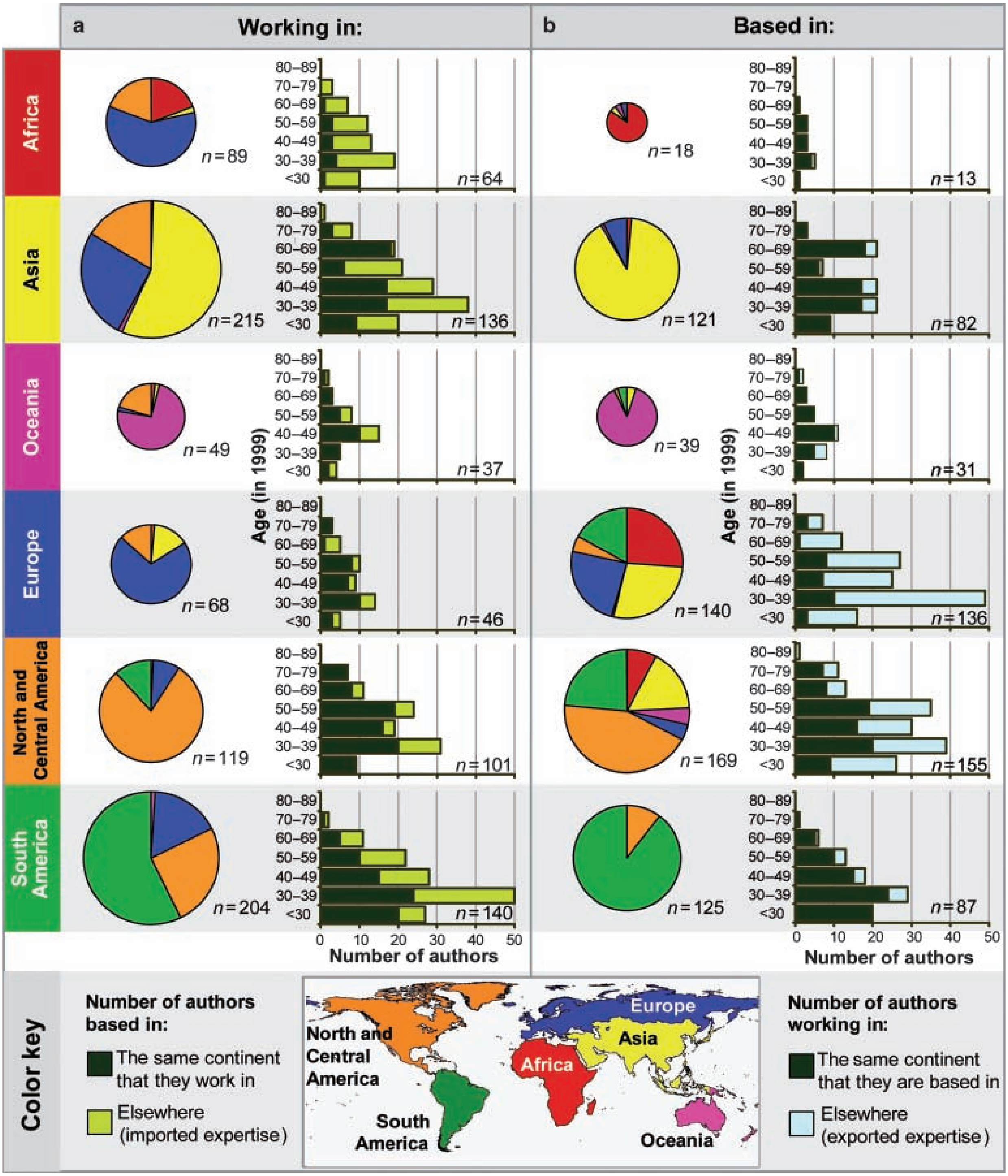

Figure 3. Professional mobility and distribution of age classes for authors either (a) working or (b) based in each continent. (a) For each continent (rows), the size of the pie chart (and respective value of n*) represents the total number of authors working there, whereas pie chart slices indicate the relative distribution of continents where those authors are based (see map for color key). Histograms represent the age distribution of the authors working on each continent (*n *= number of authors for which the year of birth was known), and each bar is coded for authors based on that same continent (dark green) or elsewhere (light green). (b) For each continent (rows), pie chart size (and respective value of* n*) represents the total number of authors based there, whereas pie chart slices indicate the relative distribution of the continents where those authors work. Histograms represent the age distribution of authors based on each continent (*n *= number of authors for which the year of birth was known), and each bar is coded for authors who work on that same continent (dark green) or elsewhere (light blue). Authors can be based in only one continent but they can work in several.*

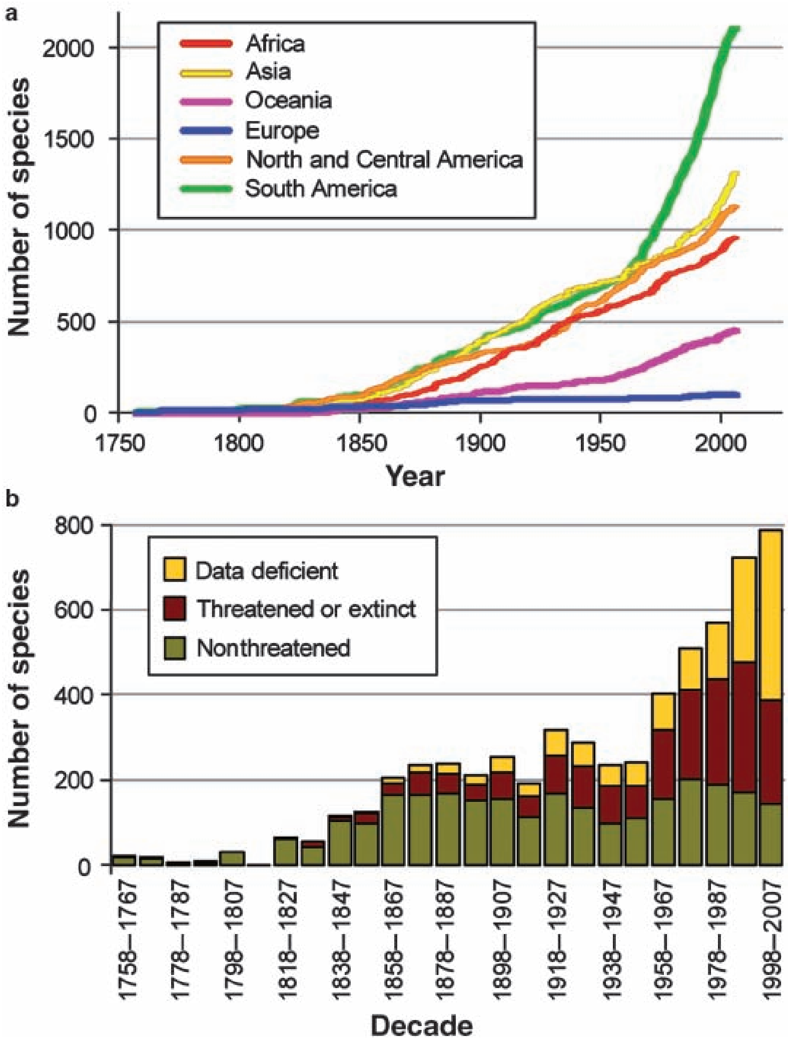

Figure 4. Temporal changes in the numbers of amphibian species. (a) Cumulative number of species described over time, per continent. (b) The number of species described per decade according to species' conservation status (IUCN et al. 2006). The date of description corresponds to the moment a taxon was first recognized as unique (either as a species or subspecies); in many cases elevation to species status happened only subsequently. The figures therefore correspond to the number of species that are currently recognized among the taxa described at any given date. These numbers may be substantially higher than the numbers of species that were recognized at the time, given that the criteria for considering a species as separate have changed considerably over this time period.

We found that, with the possible exception of Europe, numbers of described species have increased steadily over the past centuries (figure 4a). Until 1960, South America appeared to have similar overall diversity to Asia or North and Central America, but the number of recognized species has tripled since then, probably reflecting increased taxonomic effort (Parnell 1993, de Carvalho et al. 2005). Despite the low taxonomic effort in Africa (figures 2b, 2c, 3a), the number of described species continues to increase steeply (figure 4a; Vieites et al. 2009). Even regions with a relatively high taxonomic capacity, such as Oceania and North and Central America, have a relatively low ratio of authors to species (figure 1c), with steep rates of new species descriptions (figure 4a). At a ratio of two working authors for every three native species, Europe appears to be the only continent where amphibian taxonomic expertise is sufficient; however, taxonomic work is not finished there, either, as the number of described species increased 19% between 1980 and 2006 (figure 4a).

Most of the recently described species for which a Red List assessment was possible (i.e., excluding data-deficient species) are classified as globally threatened with extinction (figure 4b). Such a high proportion of threatened species would not be expected if the amphibians described were mainly from remote and relatively intact regions, such as the Amazon or Congo river basins. Instead, most discoveries (figure 2f) come from areas marked by extensive habitat loss and high levels of endemism (Myers et al. 2000), which have high concentrations of threatened species (figure 2e).

The outlook for global amphibian taxonomy

Some of our results suggest that, at least for amphibian taxonomy, the global situation is somewhat more positive than generally assumed. First, although a geographical bias does exist in the institutional base of taxonomists toward economically wealthy regions with poor amphibian diversity, there are already reasonably large numbers of authors based in biodiversity-rich countries such as China and Brazil (figure 2a). Similar results were found for authors of papers in the journal *Zootaxa* (figure 1c, table 1), suggesting that our sample of amphibian taxonomists is representative of broader zoological taxonomy. Second, there is a net transfer of expertise from the regions of the world with the most resources to those that need it the most (figure 3). Third, we found that the age distribution of authors, particularly of those working in Asia and South America, demonstrated a dominance of young authors (figure 3a), suggesting good long-term prospects for taxonomic efforts on these biodiversity-rich continents.

However, taxonomic effort in several regions relied too heavily on imported expertise, which is a severely inadequate replacement for local expertise over the long term, as nonresidents are likely to move elsewhere if conditions become difficult—for example, in the event of funding shortages or civil unrest. In Madagascar, for instance, political change in 1975 created a 10-year hiatus in herpetological fieldwork (Raxworthy 2003), and the recent coup there is leading to new disruption (Bohannon 2009). Training young taxonomists from biodiversity-rich countries is a more sustainable form of expertise transfer, and a very high priority for Africa in particular. But beyond training, the establishment of an adequate population of resident taxonomists will require long-term support of the institutions in which their careers can flourish, such as museums and universities.

Our data also provide reasons for concern about the global state of amphibian taxonomy. With the possible exception of Europe, taxonomic effort seems insufficient on all continents: Numbers of described species (figure 4) show no sign of stabilizing, indicating that the amphibian taxonomic enterprise is far from complete and that substantial investment is still needed. Even in Europe, further investment in taxonomic work is warranted, as most of its resident expertise is deployed to biodiversity-rich areas (figure 3).

Large numbers of amphibian species still await description, and the task ahead for taxonomists is monumental and extremely urgent. More than 40% of species for which threat status is known are at risk of extinction, mostly as a result of habitat loss (IUCN et al. 2006) but also from overexploitation (particularly in Asia) and disease (particularly in Australia and the Americas; Stuart et al. 2004, Lips et al. 2006). Furthermore, recently described data-sufficient species are disproportionately threatened (figure 4b), and most discoveries (figure 2f) come from areas where extensive habitat loss coincides with extraordinary endemism (Myers et al. 2000). It is therefore likely that many amphibian species are being lost before they are even known to science, and long before we can learn about their unique ecologies and roles in ecosystems. We suspect the same is true of even lesser-known groups, such as plants and invertebrates.

Our results support urgent calls for a concerted global investment in taxonomic efforts (SCBD 2008), with an emphasis on the training and career development of local experts in biodiversity-rich regions. Although taxonomy on its own cannot guarantee species' long-term persistence, it is fundamental to conservation and management efforts (Mace 2004). Indeed, without a formal classification of the living world there can be no understanding of what exists to be conserved (Collar 1997).

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