Org Divers Evol (2015) 15:619–629
DOI 10.1007/s13127-015-0202-1

FORUM PAPER

ORGANISMS DIVERSITY & EVOLUTION

Lack of well-maintained natural history collections and taxonomists in megadiverse developing countries hampers global biodiversity exploration

Omid Paknia · Hossein Rajaei Sh. · André Koch

Received: 7 September 2014 / Accepted: 21 January 2015 / Published online: 7 February 2015

Abstract Recently, there have been controversial discussions regarding the decline in the number of taxonomists as the main bottleneck for the discovery and complete assessment of global biodiversity. In addition, we here review and highlight the eminent role of natural history collections in exploring the global species diversity by discussing the current conditions of institutional infrastructure in biologically megadiverse developing countries (MDCs). To our knowledge, this is the first critical assessment, which primarily focuses on these biologically wealthy nations. We show that in addition to the taxonomists' shortage, the lack of well-maintained collection infrastructure represents the main bottleneck for biodiversity exploration in MDCs. No campaign to inventory biodiversity at national or global scale in a foreseeable timeframe can be successful without the creation of more positions for taxonomists and the expansion of existing or the establishment of new natural history collections in MDCs, respectively. Considering the lack of sufficient financial resources in many MDCs, we suggest that joint political priority of industrialized and developing countries should be given to the enduring maintenance and sustainable support of institutional infrastructures, if Convention on Biological Diversity targets for 2020 are to be addressed expediently.

Keywords Biodiversity loss · Developing countries · Megadiversity countries · Species discovery · Biodiversity collections · Taxonomy

Global biodiversity and its protection

Environmental destruction of natural habitats is proceeding rapidly on our planet, causing an irreversible loss of global biodiversity (see Dirzo et al. (2014) for review). In 2002, signatory states of the Convention on Biological Diversity (CBD) adopted a set of targets to be committed and achieved by the international community for a significant reduction in the rate of biodiversity loss by 2010. By the end of the program, however, it became apparent that these ambitious targets have not been met at the global scale (Butchart et al. 2010). Having failed to reach targets set to decrease rates of biodiversity loss by 2010 (Adenle 2012), CBD parties agreed on a set of new goals for 2020, known as the Aichi Biodiversity Targets (www.cbd.int/sp/targets). Keeping in mind that several targets explicitly mention "known species", one can easily predict, however, that also most of these new ambitious targets will not be met (Secretariat of the Convention on Biological Diversity 2014) because the majority of the global biodiversity is not yet inventoried and described. This in turn is an essential prerequisite to efficiently protect and maintain the global natural

O. Paknia (✉)
Institute of Animal Ecology and Cell Biology, TiHo Hannover, Bünteweg 17d, 30559 Hannover, Germany
e-mail: omid.paknia@ecolevol.de

O. Paknia
e-mail: omid.paknia@gmail.com

H. Rajaei Sh.
State Museum of Natural History Stuttgart, Rosenstein 1, 70191 Stuttgart, Germany
e-mail: hossein.rajaei@smns-bw.de

A. Koch
Zoological Research Museum Alexander Koenig, Leibniz Institute for Animal Biodiversity, Adenauerallee 160, 53113 Bonn, Germany
e-mail: andrepascalkoch@web.de

Present Address:
A. Koch
State Natural History Museum, Pockelsstr. 10, 38106 Brunswick, Germany

heritage for future generations. Currently, approximately 1.9 million different species are known to science, but estimates of total global species diversity greatly vary between 8 and 50 million (Mora et al. 2011; Caley et al. 2014). For example, in Brazil alone an estimated 1.8 million species (CI 1.4 to 2.4 million) are predicted to occur (Lewinsohn and Prado 2005). For conservation issues and priority settings, those nations with the highest species diversity on earth (i.e. discovered and still undiscovered) have been selected and grouped together into 17 biologically megadiverse countries (Mittermeier et al. 1997; see Table 1). It has been calculated that discovering and describing all unknown species would require thousands of taxonomists working for centuries, and merely for the animal kingdom it would cost between US$263 and US$364 billion (Carbayo and Marques 2011; Mora et al. 2011). Consequently, there have been controversial discussions regarding the decline in the number of taxonomists as the main bottleneck for the discovery and complete assessment of the global biodiversity (Bacher 2011; Drew 2011; Joppa et al. 2011; Wägele et al. 2011; Tancoigne and Dubois 2013; but see Costello et al. (2013a, b) for a general counter-argument and Lohrmann et al. (2012) for a Germany-based view point). In order to remove or at least reduce the "taxonomic impediment", CBP parties established the Global Taxonomy Initiative (GTI) in 1998 with a diverse programme of operational objectives and planned activities (see http://www.cbd.int/gti/).

In this paper, we argue that in addition to the taxonomists' shortage, the lack of well-maintained and well-equipped natural history collections, particularly in megadiverse developing countries (MDCs), might be the main challenge for the successful exploration of the global biodiversity. Reviewing the third national reports regarding the "Decisions on Taxonomy" of Article 7 of the Convention reveals that 13 out of 17 biologically megadiverse countries have failed to develop a plan to implement the suggested actions by CBD. Among the listed actions are (1) ensuring that institutions responsible for biological diversity inventories and taxonomic research are financially and administratively stable, (2) the investment of a long-term basis in development of appropriate infrastructure for the national taxonomic collections, (3) providing training programmes in taxonomy and work to increase its capacity of taxonomic research and (4) establishing and expanding bilateral partnerships between institutions in developed and developing countries (Convention on Biological Diversity 2013). At a larger scale, only 12 out of 91 developing countries, the reports of which have been analysed by CBD, have developed a plan for the suggested actions (Convention on Biological Diversity 2013), and only about one third of all parties have nominated GTI National Focal Points (Convention on Biological Diversity 2014). No need to say that the GTI project seems not largely successful and widely accepted also due to the lack of funding behind the program.

A recent study estimated that the exploration of the whole global species diversity needs about six times the number of the currently existing voucher specimens in international research collections (Wheeler et al. 2012). This would represent an increase from currently about 3 billion voucher specimens to the impressive number of 18 billion preserved specimens worldwide. Since most international natural history museums and herbaria were founded more than a century ago, these biodiversity institutions have nowadays often reached the capacity of their collection store rooms. Therefore, it is obvious that this necessarily strong increase in voucher specimens cannot take place without being accompanied by the expansion of existing and/or the establishment of additional natural history collections. This growth of new taxonomic infrastructure should ideally happen in the MDCs of the tropics, where a large amount of the global species diversity is found (Scheffers et al. 2012; see also Table 1).

Most biologically wealthy countries are poor in natural history collections

Approximately 40 % (i.e. 2756 facilities) of all 7039 database-registered biodiversity collections are housed by the 17 biologically megadiverse countries of the world. This high percentage, however, shrinks to merely 3 % (i.e. 224 facilities) when only the eight MDCs, such as Madagascar, Indonesia, or Peru, are considered (Fig. 1; Table 2). While the USA, Australia, and China together possess 1823 biodiversity collections (i.e. 26 % of all facilities worldwide), the remaining 14 non-industrialized megadiversity countries have merely about 900 collections, which represent only 13 % of all available biodiversity infrastructure and repositories. Especially Madagascar and the Democratic Republic of the Congo, probably the two African nations with the highest species diversity and biological wealth on the continent, lack suitable infrastructure (see Table 2). As a direct consequence, a substantial amount of biological material and voucher specimens collected in the past (including name-bearing holotypes of newly described species) is deposited outside the country of origin (Fig. 2). One reason for this circumstance certainly is that almost no museums or collections existed in those countries in the past. In order to evaluate the present situation of natural history collections in MDS, we investigated the dimension of type specimens that have in recent years been stored outside their countries of origin. To this end, we exemplarily searched and analysed all 2008 to 2013 papers of ZooKeys, a peer-reviewed open access journal for systematic zoology (www.pensoft.net/journals/zookeys/), for newly described species from the 17 biologically megadiverse countries and extracted information about the location of

Table 1 Biodiversity data: the 17 megadiversity countries in relation to their population, area and the number of species descriptions per country. Plant, vertebrate, (includes only freshwater fish) and butterfly species numbers refer to Mittermeier et al. (1997), while those of tiger beetles (Cicindelidae) are from Cassola and Pearson (2000). Numbers of publications of new species descriptions per country for the time periods are taken from Lovejoy et al. (2010)

Country	Category	Plant species	Vertebrate species	Butterfly species	Tiger beetle species	Population (Mio.)	Area (× 1000 km^2)	No. of species descriptions per country			
								1980–1989	1990–1999	2000–2009	Trend
Australia	Industrialized	15,638	2167	n.s.	116	23	7686	530 (7)	1016 (6)	1650 (7)	→
China	Industrialized	27,100–30,000	3414	1200	101	1354	9561	189 (10)	582 (10)	3627 (2)	↑
USA	Industrialized	18,956	2441	n.s.	120	313	9372	2916 (1)	3171 (1)	5413 (1)	→
Brazil	Emerging	50,000–56,000	6131	3132	203	192	8511	110 (17)	394 (13)	1566 (8)	↑
India	Emerging	17,000	2972	n.s.	208	1210	3287	666 (5)	374 (14)	791 (15)	↓
Malaysia	Emerging	15,000	2050	n.s.	115	28	329	n.s.	n.s.	n.s.	n.s.
Mexico	Emerging	18,000–30,000	2969	2237	122	112	1972	103 (18)	175 (21)	581 (18)	→
Philippines	Emerging	8000–12,000	1343	n.s.	130	92	300	n.s.	n.s.	n.s.	n.s.
South Africa	Emerging	23,400	1568	n.s.	98	50	1221	142 (14)	275 (17)	444 (20)	↓
Colombia	Developing	45,000–51,000	4874	3100	78	46	1141	n.s.	n.s.	n.s.	n.s.
DR Congo	Developing	11,000	2819	1650	128	67	2344	n.s.	n.s.	n.s.	n.s.
Ecuador	Developing	17,600–21,100	2650	2200	89	14	283	n.s.	n.s.	n.s.	n.s.
Indonesia	Developing	37,000	4227	1900	237	237	1916	5 (26)	9 (26)	90 (25)	→
Madagascar	Developing	11,000–12,000	911	n.s.	176	20	587	n.s.	n.s.	n.s.	n.s.
PNG	Developing	15,000–21,000	1791	n.s.	79	7	475	n.s.	n.s.	n.s.	n.s.
Peru	Developing	18,000–20,000	3441	3532	96	30	1285	n.s.	n.s.	n.s.	n.s.
Venezuela	Developing	15,000–21,070	3395	2316	58	27	912	n.s.	n.s.	n.s.	n.s.

Shown in parentheses is the ranking of species descriptions per country of the G20 nations plus six EU countries

↑ increasing ranking in species descriptions per country, ↓ decreasing ranking in species descriptions per country, → stagnating ranking in species descriptions per country, *n.s.* not specified

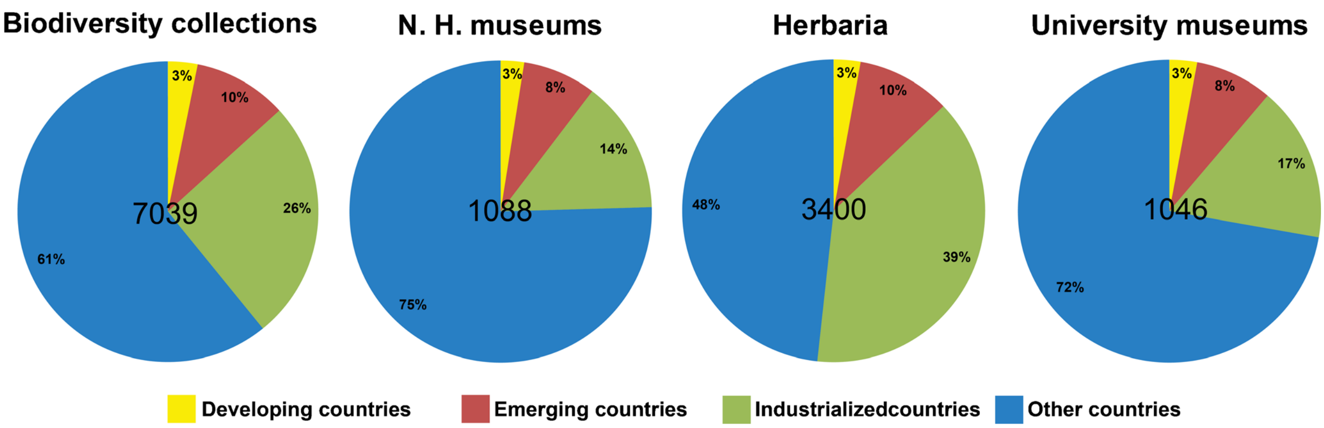

Fig. 1 Distribution of global biodiversity repositories (i.e. natural history collections including herbaria and university museums) in 17 biologically megadiverse countries in comparison with the rest of the world (*blue*); industrialized megadiverse countries (*green*) include Australia, China and the USA; the six emerging countries (*red*) are Brazil, India, Malaysia, Mexico, Philippines and South Africa; the eight megadiverse developing countries (*yellow*) comprise Colombia, the Democratic Republic of the Congo, Ecuador, Indonesia, Madagascar, Papua New Guinea, Peru and Venezuela. In the *middle* of each graph, total numbers of the respective biodiversity collection categories are given (sources: Biodiversity Collections: Global Registry of Biodiversity Repositories (GRBio), available at http://www.grbio.org; note that "repository" refers to any institution that owns and manages biological collections. This includes the herbaria registered in Index Herbariorum, natural history collections, zoos, botanical gardens, biobanks, culture collections and others. Herbaria: Index Herbariorum available at http://sciweb.nybg.org/science2/IndexHerbariorum.asp; University Museums: UMAC Worldwide Database of University Museums & Collections, available at http://publicus.culture.hu-berlin.de/collections; all last retrieved on 22 August 2014)

holotype depositions. In total, our literature survey yielded 1427 species descriptions including all animal taxa covered by ZooKeys from, for instance, amphipods and Lepidoptera to crustaceans and mammals. Numbers of new species covered by our sampling range from only seven (Philippines) to 521 (China). On average, 72.5 % of the holotypes of the recently described species are located in natural history collections inside their countries of origin, but this percentage varies greatly among the world's 17 megadiverse countries. While industrialized nations such as Australia and China reach nearly 100 % coverage (but merely 66.7 % in the USA, where only 30 new species were described within our data sampling), in developing countries such as Mexico and Ecuador significantly fewer than 15 % of all holotypes are kept inside their countries of origin (i.e. only 4.2 % or one out of 24 and 11.2 % or 10 out of 89 holotypes, respectively). The situation is worse in the DR Congo, Madagascar, and Papua New Guinea, where no holotypes out of 10, 17 and 56 recently described animal species have been deposited in collections inside the country of origin (see Fig. 2). The probability (and possibility) of specimen deposition seems better in South Africa, India, Peru, and Venezuela, where about 50 % of the holotype specimens of newly described species remained inside the country of origin. This percentage increases to about 75 % for Indonesia and Brazil.

We are aware that the data basis of our sampling is rather limited and that deposition of (type) material not only depends on the presence of suitable natural history collections in a given country. Also, policy guidelines, the nationality of the investigators and other factors are responsible for the final deposition of biological voucher specimens. Governments of Brazil and Indonesia, for instance, have decided that primary types of newly collected and described species have to stay in the country of origin because they are national heritage and property.

Precise and complete information about the number and distribution of all taxonomists worldwide is currently not available (the homepage of the World Taxonomist Database is unfortunately no longer active at http://www.eti.uva.nl/tools/wtd.php), and the former data were probably strongly biased toward English-speaking researchers from Europe and North America. Nevertheless, the number of taxonomists in a certain country significantly correlates with the number of available biodiversity facilities (Fig. 3). Altogether it is presumed that more than 2000 registered taxonomists work in the 17 megadiversity countries of the world, i.e. more than 40 % of the approximately 5000 international experts of species diversity (but see the speculation by Costello et al. (2013b) that there may be more than 40,000 taxonomists worldwide). However, this high percentage shrivels to only 16 % when the three industrialized countries are excluded and to merely about 2 % for the eight MDCs, which have only 121 registered taxonomists in total (World Taxonomist Database 2012). Although available data from Brazil (see Marques and Lamas (2005)) suggest that the numbers of registered taxonomists are underrepresented by about 50 % (i.e. 542 working Brazilian taxonomists as compared to merely 213 formerly listed in the World Taxonomist Database until 2012), this would only increase the number of active taxonomists in MDCs to about 250, which still represents a vast lack of biodiversity expertise in these focal countries (for details, see Table 2).

Table 2 Numbers of natural history collections and taxonomists in the 17 megadiversity countries as compared to the rest of the world. Note that the total number of biodiversity collections does not represent the sum of herbaria, natural history museums and university museums in a given country. Source of data is the same as for Fig. 1

Country	Economic category[a]	Region	No. of natural history museums	No. of university museums[b]	No. of herbaria	Total no. of biodiversity collections	No. of registered taxonomists[c]
USA	Industrialized	N-America	102	115	370	1185	997
Australia	Industrialized	Australia	12	62	46	160	206
China	Industrialized	Asia	22	54	336	478	65
Brazil	Emerging	S-America	16	62	135	259	213
Mexico	Emerging	N-America	4	23	65	123	138
India	Emerging	Asia	33	0	73	156	207
Malaysia	Emerging	Asia	4	0	11	36	29
Philippines	Emerging	Asia	4	7	12	29	18
South Africa	Emerging	Africa	14	6	54	106	84
Colombia	Developing	S-America	9	20	28	62	40
Ecuador	Developing	S-America	3	0	15	22	10
Peru	Developing	S-America	1	12	16	27	18
Venezuela	Developing	S-America	7	0	19	46	34
DR Congo	Developing	Africa	0	0	13	10	0
Madagascar	Developing	Africa	1	0	2	8	2
Indonesia	Developing	Asia	2	0	11	35	14
PNG	Developing	Australia	1	0	4	14	3
Megadiverse countries total			235	302	1210	2756	2078
Only MDCs			24	39	108	224	121
World total			957	1088	~3400	7039	4947

[a] There is no universal agreed-upon criterion for classification of countries. This categorization is according to the International Monetary Fund's World Economic Outlook Report (International Monetary Fund 2012)

[b] University museums include Natural History and Natural Science collections

[c] Numbers of registered taxonomists per country were taken from the World Taxonomist Database (http://www.eti.uva.nl/tools/wtd.php, last retrieved on 4 July 2012). The homepage of this database, however, is no longer available, and data are probably strongly biased toward English-speaking researchers

The eminent role of natural history collections in global biodiversity exploration

Here we highlight the eminent role of biodiversity collections in exploring the global species diversity by discussing the current situation of research collections and associated infrastructures in MDCs, where a large amount of undescribed species is expected (Mittermeier et al. 1997). Biodiversity exploration in many megadiverse developing and emerging countries suffers from the lack of adequate and well-maintained research collections in the following ways:

1. Absence of natural history collections prevents accumulation and maintenance of biological material (e.g. voucher specimens, tissue samples, DNA libraries, and reference collections). Although more biodiversity assessment projects have been conducted at large scales in MDCs within the last 20 years [see, for instance, the Rapid Assessment Program by Conservation International operating on a global scale (e.g. Alonso et al. 2011) and the BIOTA Africa project (www.biota-africa.org/) based in several African nations (Jürgens et al. 2010)], only a small amount of the collected material remains in the countries of origin mainly due to the lack of appropriate infrastructures including well-trained curatorial staff (e.g. Polhemus et al. 2008). For example, Afrotropical ants and dragonflies collected during the BIOTA Africa project have been mainly deposited in entomological collections of major German museums or even in private collections (Clausnitzer 2005; Fischer 2012; F. Hita Garcia, personal communication). The same appears to be true for ants recently collected from Ecuador, which are now deposited at the Harvard Museum of Comparative Zoology (Ryder Wilkie et al. 2010). Absence of natural history museums

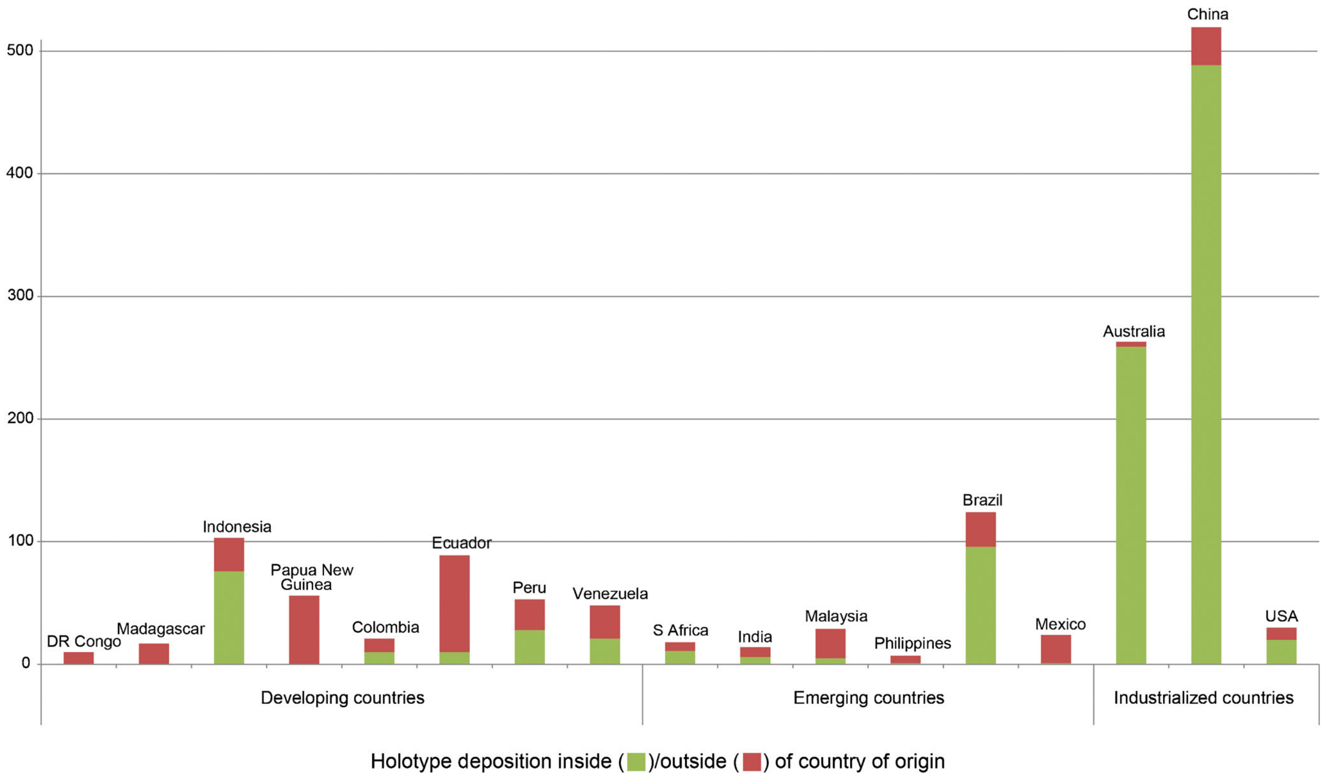

Fig. 2 Locations of holotype deposition of 1427 newly described animal species from the 17 biologically megadiverse countries. Data including all taxa from amphipods to mammals were gathered by surveying all papers that have been published between 2008 and 2013 in ZooKeys, a peer-reviewed open access journal for systematic zoology (www.pensoft.net/journals/zookeys/)

and related collection infrastructures prevents establishment, maintenance and development of reference collections. Reference collections contain name-bearing type specimens, specimens that have been compared with the original type specimens or material that have at least been identified and confirmed by a taxonomic expert of the

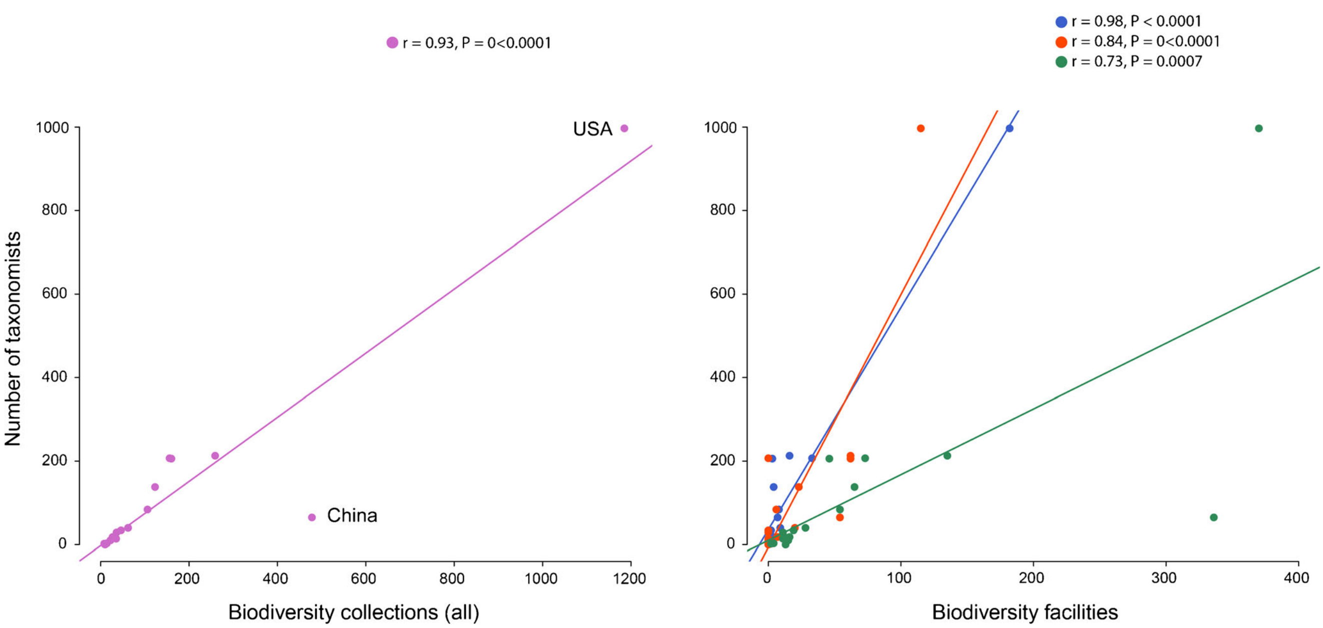

Fig. 3 Correlation between the number of taxonomists and biodiversity collections in the 17 biologically megadiverse developing countries (see legend of Fig. 1 for details). Shown are the correlations between species experts and all repositories (*left*) and natural history museums (*blue*), herbaria (*green*) and university museums (*red*), respectively (*right*)

respective organism group. These specimens are the most essential part of each research collection and are a key source for describing and characterizing regional and national faunas and floras. All countries and particularly the MDCs need reference collections to facilitate in-country species identifications. Nevertheless, about 64 % of newly described species from MDCs are still deposited in overseas museums (Fig. 2). For instance, not a single holotype of 83 newly described species from Madagascar, DR Congo and Papua New Guinea (published in ZooKeys journal between 2008 and 2013) has been deposited in their countries of origin (see Fig. 2). Of 101 new *Trigonopterus* beetle species that were recently described from the island of New Guinea (Riedel et al. 2013), all 32 holotype specimens from the national territory of Papua New Guinea have been deposited in the State Museum of Natural History at Karlsruhe, Germany, due to the lack of adequate research collections within the source country (A. Riedel, personal communication). The situation is slightly better in emerging countries, such as Brazil and South Africa (e.g. Marques and Lamas 2005), where research collection infrastructures and taxonomic training programmes have been established for biodiversity exploration [but see the pessimistic perspectives by Herbert (2001) and Smith et al. (2008) for the latter country]. By contrast, less than 5 % of 814 newly described species of our sample from the three industrialized megadiversity countries, i.e. Australia, China and USA, have been deposited outside of the country of origin (Fig. 2).

2. Research collections can play a substantial role in the taxonomic education of students in MDCs. This achievement would be possible only by introducing them to the rich biodiversity of their home countries. Offering valuable biodiversity courses in various biological disciplines will promote the interest of new generations of academics in professional careers related to biodiversity, i.e. taxonomy, systematics, ecology, and nature conservation (Pearson et al. 2011). Appreciating taxonomy as a hypothesis-driven and analytical science rather than merely descriptive (Haszprunar 2011) suggests that the education of new generations of taxonomists is a long-term, time-consuming and challenging process. Even the rise of modern technologies such as molecular methods and web-based information services has (since now) not been able to make taxonomy an easier and faster process because the quality of species descriptions has likewise been improved (Sangster and Luksenburg 2015). Young taxonomists are not expected just to name and describe species. They are also expected to know species by providing and testing hypotheses, which are related to ecology, evolutionary biology and genealogical relationships of species (de Carvalho et al. 2007; Koch et al. 2012). In order to achieve this fundamental knowledge, young taxonomists have to be trained for a long time in suitable research collections and facilities. As a result, the adequate availability of research collections and natural history facilities would be important for the taxonomists' community in MDCs, enabling them to make a major step forward in educating new generations of taxonomists. Recently, Sluys (2013) suggested that due to the analytical nature of taxonomy, there is only one way to overcome the taxonomic impediment and to speed up the discovery and documentation of the world's undiscovered biodiversity, and this is the training of more taxonomists.
3. Research collections attract amateur taxonomists or citizen scientists. Since long way back, self-taught (amateur) species experts (sometimes called parataxonomists) have made influential contributions to biodiversity exploration in Europe and North America (Pearson et al. 2011; Wägele et al. 2011). As a result, taxonomic research has received a large input from amateur scientists in addition to professional taxonomists working at natural history museums and botanical gardens. At times when the number of professional taxonomists is much lower than the real demand (Drew 2011; Wägele et al. 2011), citizen scientists can play a crucial role in discovering and describing biodiversity also in MDCs. Their contributions, however, rely on the existence of research collections, to receive training and support from professionals, storage of specimens in well-maintained infrastructures and access to type material, libraries and laboratory facilities. The role of the parataxonomists or citizen scientists is important not only in the scientific but also in a social context since they can transfer their awareness and appreciation of the natural surroundings gained by training in natural history museums and herbaria to their social milieu (Alberch 1993).
4. Lack of research collections prevents communication and the establishment of effective networks between scientists and the wider society. However, public awareness is critical for the success of biodiversity exploration and long-term conservation. General knowledge about "biological richness" is very low in most MDCs (Wemmer et al. 1993), where scientists need more public and governmental support for the documentation and analysis of the national natural heritage. Every local natural history museum and botanical garden has a positive impact on the public consciousness, for instance, by sharing new species discoveries and by developing educational programmes and exhibitions about the national wealth of fauna and flora. However, single national collections and museums in the capitals of various MDCs (see Table 2) are certainly not enough to meet all of these requirements of future biodiversity researchers and hardly reach the rural population with their educational messages and contents. Biological collections could not only provide a concrete sense of communication between scientists and the

society but also play a vital role for societies by contributing to public health and safety (Suarez and Tsutsui 2004). Specifically, research collections could contribute significant insights to the study of diseases in MDCs, where, not surprisingly, likewise the diversity of pathogens and vectors is the highest in the world.

5. Even if there are occasionally suitable research collections in MDCs, assessment of species diversity severely suffers from the lack of well-trained taxonomists, the lack of relevant taxonomic literature and access to type specimens. This has been emphasized, for instance, by Agosti (2006). Although it seems irrelevant, these shortcomings should be considered as a direct reflection of research collection deficiency in MDCs (see #2). In Brazil, for example, the ratio of vertebrate taxonomists to the number of vertebrate species is among the lowest in the world, almost 40 times lower than in the USA (Bernard et al. 2011). While taxonomic catalogues of some groups such as mammals and birds appear to be nearly complete in some megadiverse countries (e.g. Paglia et al. 2013), experts have suggested that collections should be re-investigated for misidentified and cryptic species (Bickford et al. 2007; Bernard et al. 2011). The number of taxonomists is increasing in some megadiversity countries with strong economic growth rates, such as China and Brazil, but this cannot be generalized and transferred to other biologically wealthy countries because some, in contrast, show a fast decreasing trend (Dar et al. 2012). Especially MDCs, such as Madagascar and Indonesia, face alarming situations in this aspect with only very few actively working taxonomists. Consequently, also the number of species descriptions during the last 30 years is very low in these countries (Table 2).

Conclusions

The necessary steps towards a global biodiversity assessment

Recently, the Nagoya Protocol, a specific obligation on Access and Benefit Sharing (ABS), adopted from the third objective of the Convention on Biological Diversity, entered into force in October 2014 (http://www.cbd.int/abs). These ABS legislations will significantly increase the complexity and difficulty of scientific sampling and their international transfer. On the other hand, it makes sure that the MDCs (and other CBD parties) benefit from any biodiversity research projects that are based on their genetic resources. Although the Nagoya Protocol might be a powerful tool to ensure that voucher specimens, particularly types, remain in the countries of origin, in reality it will be beneficial for all parties only if well-maintained collection infrastructures along with well-trained taxonomists or collection managers exist in MDCs.

For most megadiverse countries in the world, there is too little collection infrastructure and consequently too few positions for taxonomists available to enable them to work with their biota in the way they should in order to obtain a national biodiversity inventory. Several obstacles to establishment of new natural history collections and the expansion of existing facilities in MDCs in the past have been identified, including lack of financial sources and technological capability (Convention on Biological Diversity 2006). However, the reduction of these obstacles seems to be more linked with finding the necessary political will within responsible governments than the absence of means and know-how to do it. Therefore, we identify and suggest the following necessary steps towards a global biodiversity assessment:

1. Reinforce the political will of MDC governments—The political will should be targeted by critical assessments of taxonomic necessities and national requirements (e.g. Grieneisen et al. 2014). Such assessments should be provided for each developing country by its taxonomists and those scientists who directly and/or indirectly benefit from taxonomy science. These critical reports should state clearly if and how the lack of taxonomic infrastructure impedes the biodiversity exploration directly and many other topics, such as conservation and environmental management, indirectly. In recent years, such assessments have been frequently published by taxonomists from developed countries, pointing out that the decline of taxonomists or professional positions related to taxonomy are the central challenge for biodiversity exploration and conservation (e.g. Hopkins and Freckleton 2002; Pearson et al. 2011). This view, although valid for economically developed countries, cannot be generalized to all developing and emerging nations since recent studies show that the numbers of professional taxonomists are increasing in single emerging countries with prospering economies, such as Brazil and India (e.g. Joppa et al. 2011; Marques and Lamas 2005).
2. Open new funding sources for biodiversity exploration—For many MDCs, the shortage of financial resources is the major barrier to realising the taxonomic needs. New funding sources, such as a biodiversity tax on tourist safaris or on entrance fees to national parks, could at least partly fill these financial gaps (for further potential funding sources, see the bilateral project about pharmaceutical products below). Worthwhile evaluations will encourage and help policy-makers to set priorities for the scarce financial resources of their countries. In addition, industrialized nations, such as Australia, the EU, Japan, and the USA, should feel responsible not only for humanitarian challenges but also for global biodiversity

exploration and facilities and provide funding for developing countries with limited monetary sources. At the same time, governmental planning should be directed into sustainable development in MDCs in order to guarantee that financial sources are indeed used for their intended biodiversity purposes.

3. Expand international biodiversity collaborations—A close mutual network of collaborations between natural history museums and other institutes at the regional or global scale has the potential as a short- or/and mid-term solution for those megadiverse countries, which face lack of collection infrastructure (Grieneisen et al. 2014). Such collaborations have existed in a wide variety of forms [e.g. see the BIOTA Africa project or the Partnerships for Enhancing Expertise in Taxonomy (PEET)], yet they often lack a clear vision in some crucial aspects, e.g. infrastructure establishment and maintenance, improvement and storage of voucher specimens in MDCs, from which all parties can benefit (e.g. Rodman and Cody 2003). Developed countries could implement programs that support long partnership collaborations with MDCs for enhancing taxonomic infrastructure. An example for such collaboration might be the recently announced initiative of the German Federal Ministry of Education and Research (BMBF) which aims to support research about "identification and use of naturally occurring substances in Indonesia for drug development" (www.bmbf.de/foerderungen/23396.php). This program, although just focusing on a part of Indonesian biodiversity, also includes fieldwork and the discovery and characterization of new or insufficiently known species that might harbour pharmaceutically active substances. If successful, however, this novel program could yield additional funding for broader species exploration or the establishment of collection infrastructure in Indonesia. Future biodiversity exploration projects and collaborations should be more firmly targeted at problems related to lack of infrastructure and taxonomic expertise, providing a robust platform for the establishment and development of new and existing natural history museums in MDCs. Ideally, future collaborations should not only be a bilateral developed–developing collaboration, but multilateral. Such multilateral collaborations are vital for low-income MDCs, which cannot invest by their own efforts sufficient financial resources into maintenance and development of natural history museums. In this respect, natural history collections in developing countries could benefit significantly from partnerships with institutions from other developing countries from the same geographical region or continent, forming a regional network of biodiversity excellence. This was exactly the ultimate goal of the BioNET International project (http://www.bionet-intl.org) launched in 1993 to help in building the taxonomic capacity needed in developing countries by establishing locally operating partnerships and focal points. In 2011, however, the project was discontinued due to lack of funding by the international community.
4. Continue digitization of voucher specimens and relevant biodiversity data—Digital (virtual) reference collections have received much attention recently as a suitable solution for accessibility of historical collections to all taxonomists, especially those from countries that these vouchers came from. Historically, most, if not all, collected materials of major expeditions from MDCs were deposited in European or North American collections (e.g. Wheeler 1922). These historical collections are still very valuable today as they contain high numbers of type specimens or even series of already extinct species (Hawksworth and Cowie 2013). Digitalization of collections and open access to biodiversity data, such as through the Global Biodiversity Information Facility, can support the work of taxonomists especially in MDCs. Therefore, more governments should join digitization projects that aim to finally cover all voucher specimens in natural history collections worldwide. Although as of August 2014 more than 95,000,000 specimen records are listed by the GBIF portal, digital pictures are available only for 1,226,000 voucher specimens (i.e. merely about 1.3 %), and a high percentage (>80 %, retrieved 26.12.2014) represent purely observational data.

Furthermore, for taxonomists, species identification at genus level is often possible from digital photos, but particularly in morphologically uniform, i.e. cryptic species, groups, physical voucher specimens are essential for correct species identifications. Also automated digital identification, despite much recent technical enhancements (Deans et al. 2012; MacLeod et al. 2010), is not able to visualize and record internal or microscopic structures. As a result, natural history museums in Europe and the USA, which hold large amounts of material from MDCs, should also be encouraged to facilitate direct access of this material for local scientists. In addition, further important information such as isotope composition, morphological ultrastructure or the genetic signature of a specimen cannot be replaced by digital vouchers that capture merely the outer appearance (the phenotype). As a consequence, providing physical reference collections at the local or national scale remains an ultimate need for all MDCs.

We need more taxonomists and better-maintained natural history collections in megadiverse developing countries

Our study should be treated as the very first critical assessment which focuses on biologically megadiverse developing countries and demonstrates current challenges, priorities and possible solutions for the biodiversity dilemma in MDCs. Our understanding of the taxonomic needs of biologically megadiverse countries is still limited, but we argue that these needs are different from developed countries.

It is quite clear that we need large joint international efforts to speed up species discoveries and descriptions by re-implementing taxonomically oriented curricula at universities, establishing cooperative taxonomic research infrastructures at a national and international scale and integrating efforts of citizen scientists. Additionally, we need reference collections to continuously document species distributions, which are a prerequisite to describe and analyse the impact of human-induced climate change and socio-economic effects (Shaffer et al. 1998). All the above-mentioned challenges cannot be replaced by digital libraries. Even using novel molecular applications, such as DNA barcoding (e.g. Nagy et al. 2012), requires suitable reference collections to link sequences and voucher specimens. As the number of taxonomists, especially of those working on invertebrates, cannot be substantially increased in the short term to describe all still unknown species of the world, biodiversity collections should be prepared to store voucher specimens that have no Linnean name but instead digital images and barcodes that serve as unique identifiers. Improving the severe situation in MDCs is a very challenging goal that requires substantial investigations for establishing new biodiversity research collections and permanent maintenance.

In summary, we conclude that no campaign to inventory regional and global biodiversity can be sustainable and successful without the establishment and development of new natural history collections and opening more positions for taxonomists in MDCs. This fundamental lack of infrastructure and management of human resources represents a serious bottleneck for global biodiversity exploration, which must be considered by governmental decision-makers in MDCs and the international community if CBD targets for 2020 and beyond are to be addressed expediently.

Acknowledgments We are very thankful to Donat Agosti, Charles Oliver Coleman, Brian L. Fisher, Bernhard Misof, Robert Neal and Rudolf Meier for their constructive comments and suggestions on earlier versions of the present manuscript. In addition, we thank Alexander Riedel (Staatliches Museum für Naturkunde Karlsruhe, Germany) and Francisco "Paco" Hita Garcia (California Academy of Sciences, San Francisco, CA, USA) for information regarding the deposition of their (type) material. Finally, we acknowledge the fruitful comments by three anonymous reviewers who helped us enhance the quality of this manuscript.

References

Adenle, A. A. (2012). Failure to achieve 2010 biodiversity's target in developing countries: how can conservation help? *Biodiversity and Conservation, 21*(10), 2435–2442.

Agosti, D. (2006). Biodiversity data are out of local taxonomists' reach. *Nature, 439*(7075), 392. doi:10.1038/439392a.

Alberch, P. (1993). Museums, collections and biodiversity inventories. *Trends in Ecology & Evolution, 8*(10), 372–375. doi:10.1016/0169-5347(93)90222-b.

Alonso, L. E., Deichmann, J. L., McKenna, S. A., Naskrecki, P., & Richards, S. J. (2011). *Still counting… biodiversity exploration for conservation: the first 20 years of the rapid assessment program*. Arlington: Conservation International.

Bacher, S. (2011). Still not enough taxonomists: reply to Joppa et al. *Trends in Ecology and Evolution, 27*, 65–66.

Bernard, E., Aguiar, L. M. S., & Machado, R. B. (2011). Discovering the Brazilian bat fauna: a task for two centuries? *Mammal Review, 41*(1), 23–39. doi:10.1111/j.1365-2907.2010.00164.x.

Bickford, D., Lohman, D. J., Sodhi, N. S., Ng, P. K. L., Meier, R., Winker, K., et al. (2007). Cryptic species as a window on diversity and conservation. *Trends in Ecology and Evolution, 22*(3), 148–155. doi:10.1016/j.tree.2006.11.004.

Butchart, S. H. M., Walpole, M., Collen, B., van Strien, A., Scharlemann, J. P. W., Almond, R. E. A., et al. (2010). Global biodiversity: indicators of recent declines. *Science, 328*(5982), 1164–1168. doi:10.1126/science.1187512.

Caley, M. J., Fisher, R., & Mengersen, K. (2014). Global species richness estimates have not converged. *Trends in Ecology & Evolution, 29*(4), 187–188.

Carbayo, F., & Marques, A. C. (2011). The costs of describing the entire animal kingdom. *Trends in Ecology and Evolution, 26*(4), 154–155.

Cassola, F., & Pearson, D. L. (2000). Global patterns of tiger beetle species richness (Coleoptera: Cicindelidae): their use in conservation planning. *Biological Conservation, 95*(2), 197–208.

Clausnitzer, V. (2005). An updated checklist of the dragonflies (Odonata) of the Kakamega Forest, Kenya. *Journal of East African natural history, 94*(2), 239–246.

Convention on Biological Diversity. (2006). Guide to the global taxonomy initiative. http://www.cbd.int/doc/publications/cbd-ts-30.pdf. (Vol. 30, pp. 195).

Convention on Biological Diversity. (2013). National reports analyzer. http://www.cbd.int/reports/analyzer.shtml. Accessed 15 Oct 2013.

Convention on Biological Diversity. (2014). Global taxonomy initiative. http://www.cbd.int/gti/focalpoints.shtml.

Costello, M. J., May, R. M., & Stork, N. E. (2013a). Can we name earth's species before they go extinct? *Science, 339*(6118), 413–416. doi:10.1126/science.1230318.

Costello, M. J., Wilson, S., & Houlding, B. (2013b). More taxonomists describing significantly fewer species per unit effort may indicate that most species have been discovered. *Systematic Biology, 62*(4), 616–624.

Dar, G., Khuroo, A. A., Reddy, C., & Malik, A. H. (2012). Impediment to taxonomy and its impact on biodiversity science: an Indian perspective. *Proceedings of the National Academy of Sciences, India Section B: Biological Sciences, 82*(2), 235–240.

de Carvalho, M., Bockmann, F., Amorim, D., Brandão, C., de Vivo, M., de Figueiredo, J., et al. (2007). Taxonomic impediment or impediment to taxonomy? A commentary on systematics and the cybertaxonomic-automation paradigm. *Evolutionary Biology, 34*(3), 140–143. doi:10.1007/s11692-007-9011-6.

Deans, A. R., Yoder, M. J., & Balhoff, J. P. (2012). Time to change how we describe biodiversity. *Trends in Ecology & Evolution, 27*(2), 78–84. doi:10.1016/j.tree.2011.11.007.

Dirzo, R., Young, H. S., Galetti, M., Ceballos, G., Isaac, N. J., & Collen, B. (2014). Defaunation in the Anthropocene. *Science, 345*(6195), 401–406.

Drew, L. W. (2011). Are we losing the science of taxonomy? *Bioscience, 61*(12), 942–946.

Fischer, G. (2012). *Ecology, biogeography and responses to habitat degradation of a highly diverse rainforest ant community and taxonomy of Afrotropical Pheidole Westwood (Hymenoptera, Formicidae)*. University of Bonn.

Grieneisen, M. L., Zhan, Y., Potter, D., & Zhang, M. (2014). Biodiversity, taxonomic infrastructure, international collaboration, and new species discovery. *Bioscience, 64*(4), 322–332. doi:10.1093/biosci/biu035.

Haszprunar, G. (2011). Species delimitations—not 'only descriptive'. *Organisms Diversity and Evolution, 11*(3), 249–252.

Hawksworth, D., & Cowie, R. (2013). The discovery of historically extinct, but hitherto undescribed, species: an under-appreciated element in extinction-rate assessments. *Biodiversity and Conservation, 22*(11), 2429–2432. doi:10.1007/s10531-013-0542-0.

Herbert, D. G. (2001). Museum natural science and the NRF: crisis times for practitioners of fundamental biodiversity science. *South African Journal of Science, 97*, 168–172.

Hopkins, G. W., & Freckleton, R. P. (2002). Declines in the numbers of amateur and professional taxonomists: implications for conservation. *Animal Conservation, 5*(3), 245–249. doi:10.1017/s1367943002002299.

International Monetary Fund. (2012). World economic and financial surveys. Washington, DC 20090, USA

Joppa, L. N., Roberts, D. L., & Pimm, S. L. (2011). The population ecology and social behaviour of taxonomists. *Trends in Ecology and Evolution, 26*, 551–553.

Jürgens, N., Haarmeyer, D., Luther-Mosebach, J., Dengler, J., Finckh, M., & Schmiedel, U. (2010). *Biodiversity in southern Africa. Volume 1: patterns at local scale—the BIOTA Observatories*. Klaus Hess.

Koch, A., Huelsken, T., & Hoffmann, J. (2012). The young systematists special issue—promoting the scientific work of early career scientists in taxonomy and systematics. *Organisms Diversity and Evolution, 12*, 1–2.

Lewinsohn, T. M., & Prado, P. I. (2005). How many species are there in Brazil? *Conservation Biology, 19*(3), 619–624. doi:10.1111/j.1523-1739.2005.00680.x.

Lohrmann, V., K. Vohland, M. Ohl, and C. Häuser. (2012). Taxonomische Forschung in Deutschland—Eine Übersichtsstudie. Netzwerk-Forum zur Biodiversitätsforschung Deutschland Museum für Naturkunde Berlin Berlin http://biodiversity.de/images/stories/Downloads/taxo-studie-01-2012.pdf.

Lovejoy, T. E., Brouillet, L., Doolittle, W. F., Gonzalez, A., Green, D. M., Hall, P., et al. (2010). *Canadian taxonomy: Exploring biodiversity, creating opportunity*. Council of Canadian Academies.

MacLeod, N., Benfield, M., & Culverhouse, P. (2010). Time to automate identification. *Nature, 467*(7312), 154–155.

Marques, A. C., & Lamas, C. J. E. (2005). Taxonomia zoológica no Brasil: estado da arte, expectativas e sugestões de ações futuras. *Papeis Avulsos de Zoologia, 46*, 139–174.

Mittermeier, R. A., Goettsch Mittermeier, C., & Robles Gil, P. (1997). *Megadiversity: Earth's biologically wealthiest nations*. Mexico: Cemex Monterrey.

Mora, C., Tittensor, D. P., Adl, S., Simpson, A. G. B., & Worm, B. (2011). How many species are there on Earth and in the ocean? *PLoS Biology, 9*(8), e1001127.

Nagy, Z. T., Sonet, G., Glaw, F., & Vences, M. (2012). First large-scale DNA barcoding assessment of reptiles in the biodiversity hotspot of Madagascar, based on newly designed COI primers. *PLoS ONE, 7*(3), e34506.

Paglia, A. P., da Fonseca, G. A. B., Rylands, A. B., Herrmann, G., Aguiar, L. M. S., Chiarello, A. G., et al. (2013). Annotated checklist of Brazilian mammals—2nd edition. *Occasional Papers in Conservation Biology, 6*, 1–76.

Pearson, D. L., Hamilton, A. L., & Erwin, T. L. (2011). Recovery plan for the endangered taxonomy profession. *Bioscience, 61*(1), 58–63.

Polhemus, D. A., Michalski, J., & Richards, S. J. (2008). *Pseudagrion fumipennis*, a remarkable new species of damselfly from New Guinea (Odonata: Zygoptera: Coenagrionidae). *Tijdschrift voor Entomologie, 151*(1), 51.

Riedel, A., Sagata, K., Surbakti, S., Tänzler, R., & Balke, M. (2013). One hundred and one new species of Trigonopterus weevils from New Guinea. *ZooKeys* (280), 1–150.

Rodman, J. E., & Cody, J. H. (2003). The taxonomic impediment overcome: NSF's partnerships for enhancing expertise in taxonomy (PEET) as a model. *Systematic Biology, 52*(3), 428–435.

Ryder Wilkie, K. T., Mertl, A. L., & Traniello, J. F. A. (2010). Species diversity and distribution patterns of the ants of Amazonian Ecuador. *PLoS ONE, 5*(10), e13146.

Sangster, G., & Luksenburg, J. A. (2015). Declining rates of species described per taxonomist: slowdown of progress or a side-effect of improved quality in taxonomy? *Systematic Biology, 64*(1), 144–151. doi:10.1093/sysbio/syu069.

Scheffers, B. R., Joppa, L. N., Pimm, S. L., & Laurance, W. F. (2012). What we know and don't know about Earth's missing biodiversity. *Trends in Ecology and Evolution, 27*(9), 501–510.

Shaffer, H. B., Fisher, R. N. & Davidson, C. (1998). The role of natural history collections in documenting species declines. *Trends in Ecology and Evolution, 13*, 27–30.

Sluys, R. (2013). The unappreciated, fundamentally analytical nature of taxonomy and the implications for the inventory of biodiversity. *Biodiversity and Conservation, 22*(4), 1095–1105. doi:10.1007/s10531-013-0472-x.

Smith, G. F., Buys, M., Walters, M., Herbert, D., & Hamer, M. (2008). Taxonomic research in South Africa: the state of the discipline. *South African Journal of Science, 104*, 254–256.

Suarez, A. V., & Tsutsui, N. D. (2004). The value of museum collections for research and society. *Bioscience, 54*(1), 66–74.

Tancoigne, E., & Dubois, A. (2013). Taxonomy: no decline, but inertia. *Cladistics, 29*(5), 567–570. doi:10.1111/cla.12019.

Wägele, H., Klussmann-Kolb, A., Kuhlmann, M., Haszprunar, G., Lindberg, D., Koch, A., et al. (2011). The taxonomist—an endangered race. A practical proposal for its survival. *Frontiers in Zoology, 8*(1), 25.

Wemmer, C., Rudran, R., Dallmeier, F., & Wilson, D. E. (1993). Training developing-country nationals is the critical ingredient to conserving global biodiversity. *Bioscience, 43*(11), 762–767.

Wheeler. (1922). Ants of the American Museum Congo expedition: a contribution to the myrmecology of Africa. Order of the Trustees. *American Museum of Natural History.*

Wheeler, Knapp, S., Stevenson, D. W., Stevenson, J., Blum, S. D., Boom, B. M., et al. (2012). Mapping the biosphere: exploring species to understand the origin, organization and sustainability of biodiversity. *Systematics and Biodiversity, 10*(1), 1–20. doi:10.1080/14772000.2012.665095.

World Taxonomist Database. (2012). World taxonomist database. http://www.eti.uva.nl/tools/wtd.php (04.07.2012).