Can We Name Earth's Species Before They Go Extinct?

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Some people despair that most species will go extinct before they are discovered. However, such worries result from overestimates of how many species may exist, beliefs that the expertise to describe species is decreasing, and alarmist estimates of extinction rates. We argue that the number of species on Earth today is 5 ± 3 million, of which 1.5 million are named. New databases show that there are more taxonomists describing species than ever before, and their number is increasing faster than the rate of species description. Conservation efforts and species survival in secondary habitats are at least delaying extinctions. Extinction rates are, however, poorly quantified, ranging from 0.01 to 1% (at most 5%) per decade. We propose practical actions to improve taxonomic productivity and associated understanding and conservation of biodiversity.

Why is discovering species important? Species provide the most practical metric for distinguishing habitats and tracking progress in exploring Earth's biodiversity. They are as fundamental to biology as elements are to chemistry and particles to physics and are the first step in exploring biology. Once species are described, more detailed studies can look at populations and genetic and biochemical diversity. Species inventories draw attention to where taxonomic effort will discover most new species, including resources and ecosystems. Having a standard list of species names is essential for quality assurance in biological and ecosystem sciences and natural resource management. Another reason to discover species is to improve understanding of which and how many species will become extinct.

A meeting of conservation biologists or ecologists is hardly complete without worries about extinction rates, that many millions of species are yet to be discovered, and that the taxonomic workforce is decreasing. We contend that at least two of these three concerns are mistaken. We do not dispute that we are in a human-caused mass extinction phase with many species committed to extinction, but actual extinctions have been fewer than arguably expected. With a realistic surge of effort, most species could be named within the present century. Recent analyses have narrowed estimates of how many species may now live on Earth, but estimates of extinction rates are less quantifiable, varying by a factor of more than 100. In this review, we compare recent estimates of species richness and extinction rates on Earth in the context of trends in the size and distribution of the taxonomic workforce. We suggest actions that would enable most species on Earth to be named in this century and that could be achieved at less cost than efforts to discover life on other planets.

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What Species Are Known

The incomplete Catalogue of Life (*1*) currently lists >1.3 million species, and an expert-validated inventory of an anticipated 230,000 marine species is more than 95% complete (*2*). These inventories try to account for known synonyms (species described more than once), but more are being created as taxonomic revisions remove others (*3*). Reconciling synonyms may take decades. For example, 93% of all cetacean names are synonyms (i.e., 9 out of 10) (*4*); more than 80% of names in some alga genera (*5*); 32% for insects (*6*); 33% to 88% for groups of seed plants (*7*); 38% for world mollusks, 50% for marine fish, and 81% for freshwater fish in Europe (*8*); and 40% for all marine species (*2*). Thus, we consider 20% of the currently estimated 1.9 million described species to be undiscovered synonyms, reducing this to 1.5 million valid described species (*8*).

The Unknown Species

Modern estimates of eukaryotic (nonbacterial) species on Earth have ranged from 2 million to 100 million (*8*). Recent studies have provided a firmer basis for debate about global species richness, because they are based on broad-scale empirical data and new statistical models that provide confidence limits (*9*). Mora *et al.* extrapolated the rate of discovery of selected higher taxa to predict 8.7 million (±1.3 million SE) eukaryotic species globally, of which 25% (2.2 million ± 0.18 million standard error) were marine (*10*); Costello *et al.* used rates of description of 1/3 of named species to predict a total of 0.3 million marine and 1.7 million terrestrial species (*8*). These approaches and expert opinion estimated that 0.3 to 0.7 and 0.7 to 1.0 million marine species may exist, respectively (*2*). Another model applied to species description rates for 112,000 species of plants predicted that 30% more remained to be discovered, whereas experts estimated 18% (*11*). In addition, modeling of uncertainty of the number of species of arthropods on tropical trees suggested that there may be 6.1 to 7.8 million terrestrial arthropod species (90% confidence intervals of 3.6 to 13.7 million) (*12*, *13*). Collectively, these new estimates suggest that there is likely to be ~5 ± 3 million species on Earth. Previous estimates of 30 to 100 million based on potential deep-sea diversity and estimates of insect host specificity now seem highly unlikely (*8*, *12*).

How Many Taxonomists?

If we narrowly define taxonomists as the people describing species new to science, then—contrary, for example, to statements made to a U.K. House of Lords committee (*14*)—recent decades have had two to three times as many taxonomists as before the 1960s (*8*). This is true for a range of groups and regions [e.g., (*8*, *11*, *15*)] and is supported by an increasing number of publications describing new species in all regions of the world (Fig. 1A). A survey of literature and institutions using a broad definition of a taxonomist estimated that there may be 30,000 to 40,000 worldwide (*16*). During the period 2000 to 2009, more than 8600 people described 30,484 species in the terrestrial and marine databases analyzed by Costello *et al.* (*8*). That 166,000 species were described in this period indicates that there may be 47,000 taxonomists describing species new to science. However, overall there are fewer species being described per author, suggesting that it may already be harder to discover new species (*8*, *11*, *15*). This apparent decline in species per author does not appear to have been due to an increasing proportion of people who only describe one or two species in their lifetimes. For example, over the past century, 42 to 44% of authors described only one marine species per decade (*2*), and the skewness of the frequency distribution of terrestrial and marine species described per author has not shown any trend (*8*).

The impression that the number of taxonomists was declining may be because taxonomists tend to be best known when near retirement and because of the dilution of traditional taxonomy among new biology specializations. For example, there was a 12% decline in traditional taxonomic expertise in the Natural History Museum (NHM) (London) over 15 years as they were replaced by specialists in molecular biology (*17*). There is no evidence that most taxonomists are near retirement in any country. In 1999, marine taxonomists in Europe had a median age of 40 to 44 years and an average age of 47 (*18*). In Canada, the median age of taxonomic experts was 39, with an average of 36 (*19*), whereas in the United Kingdom, 57% were in their 40s or 50s (*17*).

Where Are The Taxonomists?

The numbers of taxonomists may be decreasing in some institutions of the countries that formerly led the field of taxonomy [e.g., (*14*)], but not for South America, at least (*20*). The increasing number of taxonomists is partially due to the increase in taxonomists based in South America and Asia (Fig. 1B). For example, 80% of 1200 people requesting insect specimens from NHM during 1986 to 1991 and 78% of 271 institutions borrowing plant specimens from Kew in 1989 were from Europe and North America (*21*). However, only 51% of 5148 authors of papers in *Zootaxa* from 2001 to 2008 were from the same regions (*22*). The proportion of authors of papers describing new species from these regions decreased similarly from 72% to 68% to 56% per decade, although the actual number of publications increased (Fig. 1). This increase in the proportion of taxonomists based in the Southern Hemisphere and Asia-Pacific region is appropriate because most species occur in these regions (*8*, *23*, *24*).

Extinction Rates?

Certified extinctions in better known groups of vertebrates have been at rates comparable to the mass extinctions in the geological past [e.g., (*25*, *26*)]. However, there is evidence that contemporary extinctions have not been as high as some had predicted (*27*), for several reasons: effective conservation efforts (*28*, *29*); species surviving in managed landscapes (e.g., agricultural, secondary forest) (*30*); and "extinction debt" (*31*). Although retention of pristine environments is essential for the conservation of some locally endemic species (*32*, *33*), more than half of forests in the tropics are secondary forest (*30*). Conservation can take advantage of this delayed extinction to protect key environments and restore habitats and populations. More than 90% of the mammals and birds that have gone extinct recently (within 500 years) were hunted by humans and associated species, particularly those introduced to islands with predator-naive endemic species (*34*), and present threats to marine species are still almost entirely from hunting.

How to extrapolate from the extinct and currently most threatened species to all species is uncertain because: (i) the risk of extinction varies between taxa (*26*, *35*), (ii) future extinctions may be more driven by habitat and environmental change, and (iii) surviving species may be more resilient by occupying secondary habitats and/or at low population sizes. Only <5% of all known species have been assessed for extinction risk (*36*). Most current models predict <5% extinction per decade (*25*–*27*), although the impact of climate change on extinctions is particularly uncertain because species may adapt and/or adjust their distribution (*37*, *38*). Although marine species may be able to adapt their distribution to climate (temperature) change more easily than terrestrial species (*39*), climate-change induced acidification, stratification, and deoxygenation are the kind of changes that contributed to mass marine extinctions millions of years ago. Thus, global-scale environmental change presents an even greater risk of an anthropogenic mass extinction event than the causes of the recent directly human-mediated extinctions. Another concern is that local threats, such as habitat loss, hunting, and harvesting, are now acting synergistically with climate change (*35*, *40*).

Species Description Versus Extinction Rates

Current taxonomic effort has described an average of 17,500 species per year over the past decade, rising above 18,000 per year since 2006 (*41*). At this rate of description, if there are 2 million species on Earth then most will have been described by 2040; if 5 million, by the year 2220 (Fig. 2). If description rates are increased to 20,000 species per year, then 3.5 million will be described by 2100. It may get harder to discover new species as most are found, but this may be offset by proportionally more taxonomic effort in less studied localities and taxa.

If extinction rates are as high as 5% per decade, then regardless of how many species exist on Earth, more than half will be extinct within 150 years. If most species are unknown to science, then their extinction will also be unknown, further compromising estimates of extinction rates. However, at the rates considered more realistic (i.e., <1% per decade) (*27*), the rate of species description greatly outpaces extinction rates whether there are 2 or 10 million species on Earth. However, in contrast to the relatively constant rate of species description in recent decades, actual extinction rates may become nonlinear if their causes act synergistically.

Increasing Taxonomic Productivity

Taxonomic productivity could be enhanced through several activities (Table 1). The Convention on Biological Diversity has responded to the need for taxonomy by establishing the Global Taxonomy Initiative (GTI), which has assessed countries' taxonomic needs and proposed strategies to increase taxonomic effort (*42*). Indeed, we may now be in the greatest period of biological discovery. Thus, there is no

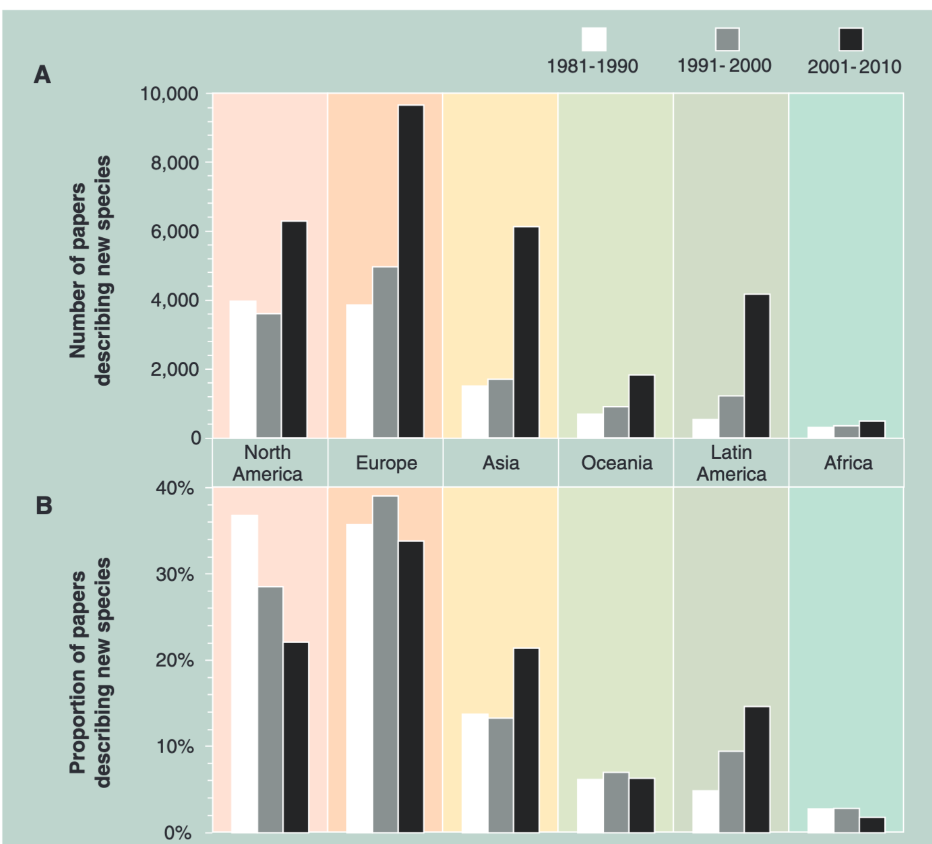

Fig. 1. (**A**) The number of papers describing species new to science increased in all geographic regions from 1981 to 1990 (white bar), to 1991 to 2000 (gray bar), and 2001 to 2010 (black bar) (n = 10,819, 12,703, and 28,596 publications, respectively). (**B**) However, the proportion of papers from North America decreased, and the proportion from Asia and Latin America increased. Data compiled from the Web of Science and Zoological Record by Lohrmann *et al.* (*58*).

justification for believing that discovering species is fruitless because so few have been described, there are insufficient taxonomists, and so many species are or soon will be extinct [e.g., (*43*, *44*)].

The infrastructures for publishing taxonomic information and data exist and can continue to improve, while their archival requirements are not especially demanding (*45*). Standardized species distribution data can be published and integrated through the Global Biodiversity Information Facility, Ocean Biogeographic Information System, and associated databases; authoritative species inventories through scholarly databases that are part of Species 2000 and the World Register of Marine Species (*1*, *4*); and wider biodiversity information through numerous web sites and content aggregators that are online and open-access. The bottleneck in making progress is not technology; it is having enough people involved and their activities coordinated, and historic knowledge captured in open-access online databases. The U.S. National Science Foundation's Partnerships for Enhancing Expertise in Taxonomy research program was a pioneer in this field but has not been replicated in Europe or elsewhere (*46*).

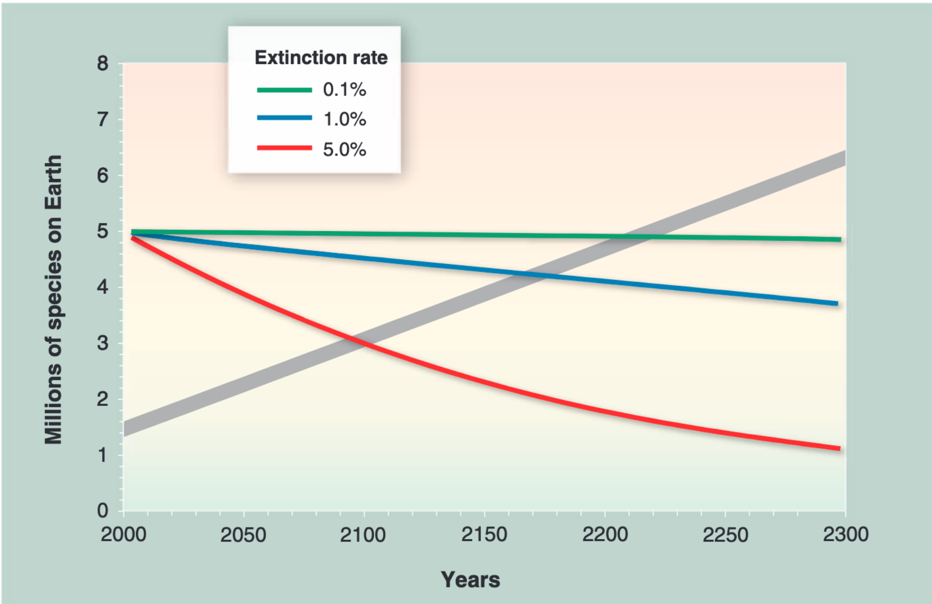

Fig. 2. Comparison of the number of species left to describe if decadal extinction rates are at 0.1% (green line), 1% (blue line), or 5% (red line) with the number of described species (gray line) if the past decade's average of 16,000 species per year continues.

Table 1. Actions to increase the species description rates and taxonomic efficiency.

Publication process
• More taxonomic revisions of species groups so as to recognize synonyms and clarify their relationships
• Reduce the time in prepublication peer review and editing
• More rapid publication through immediate online publication when a paper is accepted
• Mandatory online registration of new species
Online open-access databases
• Completion of expert-validated open-access inventories of all described species on Earth, linked to literature, distribution, and other information by cooperatives of taxonomists
• Greater online interoperability between publications, databases, and scholarly Web sites so that authoritative information is more easily detected
• Open access to taxonomic literature that helps identify species and recognize undescribed species
Specimen collection, description, and curation
• Coordinated field sampling for species in geographic areas and habitats that are likely to add substantially to the world's collections
• Recognizing that no country can have experts in all taxa, proactive international cooperation should facilitate exploration, discovery, and description of new species
• Use of digital imaging and molecular technologies to accelerate the description of species
• Increased availability and access to museum and herbarium specimens, particularly type specimens through exchanges, loans, and on-line imaging; increased support for taxonomists to visit collections and other taxonomists
Global coordination and resources
• Global coordination among the scientific community, both professional and amateur, to share knowledge and fill gaps in expertise
• New appointments of taxonomists in countries with rich diversity
• Financial support from government and nongovernment sources to support open access to taxonomic publications and scholarly databases and fill gaps in expertise.

Is Discovering All Species Practical?

If each species is considered a book of knowledge for which we lack a title page, then we need to catalog 0.5 to 6.5 million more books. Ten times more books are already in the U.S. Library of Congress, and each book may have taken as much or more effort to produce as one species description. But many people write books, not just those who are employed to do so. Opening up taxonomic literature to the public, as is already the case for birds [e.g., (*47*)], mammals, fish, flowering plants, butterflies, and some other invertebrates, will help more people study and discover species (Table 1). Already, half of all new species of European animals, including the less charismatic species, are being described by amateurs (*48*). The increasing accessibility of information through the Internet and mobile telephones is already providing new opportunities to aid species identification.

As fewer species remain to be discovered, it will become harder to maintain the rate of discovery without the assistance of a larger community of observers. New molecular methods of discriminating species will help this process of classification—including recognition of sibling and synonymous species—but will not necessarily increase the rate of description (*49*, *50*). Greater accessibility of species descriptions will help reduce the creation of synonyms. Because of synonymies, revisions of previously described species are as critical to estimating global species richness as are descriptions of new species. There is some evidence that fewer synonyms are being created (*2*), but this may also reflect the time lag to recognize them. Immediate online publication accelerates access to species information without the need to wait for the print issue of the journal (*51*). Some have questioned the need for prior peer review in taxonomy because its absence will speed up publication [e.g., (*52*)], and others (*53*) have proposed a more radical open-access Internet-based "publish-as-you-go" model whereby a species' information would be online before its formal naming.

Recognizing that almost all science journals are now published online, the codes of botanical and zoological nomenclature now accept descriptions of new species in publications in electronic-only journals that have an International Standard Serial or Book Number (ISSN or ISBN) and are preferably archived on different continents in electronic and print form (*54*, *55*).

New scientific names for fungi will be registered in MycoBank. Names of bacteria were effectively standardized in 1980, and new names must be published in the *International Journal of Systematic and Evolutionary Microbiology*. Such coordination and standardization of species nomenclature is critical to minimize confusion and must be supported (*52*). The convergence of expert-edited and automated tools for linking with publications could further help quality assurance in taxonomy. For example, by cross-linking authoritative online species databases (e.g., Global Species Databases in Species 2000 and World Register of Marine Species) to species names in publications (e.g., Biodiversity Heritage Library and Index of Organism Names) and registration systems (e.g., MycoBank and ZooBank).

The scale of this taxonomic challenge must not be underestimated. A 1-month survey of seabed in New Caledonia found 127,652 specimens and 2738 species of mollusks, of which 80% were new to science (*56*). A sample of 24,000 specimens of insects from the canopy of 10 trees in Borneo took 2 years to sort to 5000 morphospecies and included 739 morphospecies of chalcid wasps from 1455 specimens (*57*). Most species are rare and, not surprisingly, most described species are only known from single specimens and localities [e.g., (*6*)]. The museums and herbaria of the world probably contain more than 400 million specimens, with millions more in other collections—perhaps several billion in all (*52*). Marine taxonomists estimated that there were 65,000 undescribed marine species in collections (*2*), suggesting that about 0.5 million unnamed species may already be in collections. A full-time taxonomist might examine a few thousand specimens, and describe a hundred species, a year. Thus, the equivalent of 500 taxonomists over 10 years is needed to describe this backlog of undescribed species in collections, and this effort needs to be complemented by new field expeditions.

Conclusion

The estimates of how many species are on Earth (5 ± 3 million) are now more accurate than the moderate predictions of extinction rates (0.01 to 1% per decade). The latter suggest 500 to 50,000 extinctions per decade if there are 5 million species on Earth. Our review suggests that currently species are more likely to be described than become extinct, but this may change if extinction rates increase. We endorse the recommendations of Wheeler *et al.* (*52*) to improve taxonomic effort. They estimate US$0.5 to $1 billion per year would provide a tenfold increase in global taxonomic effort globally and result in the description of all species within 50 years.

The United Nations ended the 2011 Year of Biodiversity with a declaration that we are in the Decade of Biodiversity. As part of the convention and GTI, most countries have repeatedly agreed to cooperate to discover all biodiversity, and databases now provide metrics of progress and effort (e.g., species described, number of authors involved, and locations with data). This knowledge underpins assessments [e.g., International Union for Conservation of Nature and Natural Resources (IUCN) Red Lists] that produce increasingly accurate figures on what species exist on Earth, their distribution, and the threats to their survival.

Society should be concerned with the loss of biodiversity, in terms of habitats, species, and natural resources, just as it is with human health along with food and water supply and the quality of people's lives. All of these are interconnected. Overestimates of how many species may exist on Earth and the rates of extinction are self-defeating because they can make attempts to discover and conserve biodiversity appear hopeless. As we show here, they are also inaccurate, and more taxonomic resources will reap benefits in the discovery and conservation of life on Earth. Taxonomists are not in danger of extinction. They are increasing in numbers and will become more in demand as more species mean more diagnostic challenges to discriminate species, whether they are pests, pathogens, food, ecological keystone, or endangered species. We believe that with modestly increased effort in taxonomy and conservation, most species could be discovered and protected from extinction.

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