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Response to Comments on “Can We Name Earth’s Species Before They Go Extinct?”

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Mora *et al.* disputed that most species will be discovered before they go extinct, but not our main recommendations to accelerate species’ discoveries. We show that our conclusions would be unaltered by discoveries of more microscopic species and reinforce our estimates of species description and extinction rates, that taxonomic effort has never been greater, and that there are 2 to 8 million species on Earth.

Here, we respond to comments on our Review that concluded that most species will be discovered and named before they go extinct due to human activities, because taxonomic effort has never been greater, conservation efforts are reducing extinction rates, and there are 5 ± 3 million species on Earth rather than tens of millions (1). No responses questioned our primary recommendations regarding what is required to accelerate progress in discovering life on Earth, but some questioned some of the details of our arguments or presented more pessimistic views. For example, Laurance (2) and Mora *et al.* (3) concluded that “major uncertainties still cloud our understanding of the amount of extant biodiversity and its fate in the coming centuries” and “multiple sources of uncertainty remain in our knowledge of biodiversity and its rate of loss on Earth...the magnitude of the challenge ahead is considerable and should not be underestimated,” respectively, which reaffirm our conclusions. However, our Review had not “challenged the...view that many species are disappearing before being described” as stated by Mora *et al.* (3). Other comments require a more detailed response.

Estimates of 3 to 5 million species on Earth made over 20 years ago (4–6) are still reasonable (7). They were ignored by Mora *et al.* (3) when they incorrectly stated that our estimate of global species richness of 5 ± 3 million species was because we included some recent low estimates (8). Gaston (6) cited estimates of 2 to 3 million insects on Earth that tend to have been overlooked in favor of the more memorable hyperestimates. In an assessment of all marine species, Appeltans *et al.* (9) found about one-third of species in samples in less studied areas ($n = 100$ studies) were new to science, a similar proportion pre-

dicted by statistical extrapolation of the rate of species description. However, their experts’ opinions predicted that two-thirds of species remained to be discovered. Thus, the three methods estimated the number of marine species to be 0.3 to 1.0 million. The figure of 0.7 to 1.0 million (two-thirds species not named) quoted by Mora *et al.* (3)

from this study related only to the expert opinion, a method they say has “limited empirical basis and considerable subjectivity.” Yet, they overlooked the more empirical and objective estimates in this study.

Laurance (2) and Mora *et al.* (3) suggested that we have greatly underestimated the numbers of microscopic species. Depending on which size categories of species are compared, there can be more species of smaller body size [e.g., (4, 10)]. This is because taxa with typically large body size have relatively few species (e.g., 3% species in taxa >10 cm) (Table 1). About 85% of species are arthropods, worms, and other macro-invertebrates. However, microscopic taxa account for just 11% of known species (Table 1). The reason for this is likely that these microtaxa can be superabundant; can disperse without any energy cost by air, water, and attaching to drifting materials and other species; and can survive until they find suitable conditions to grow (8, 11–13). Thus, they are relatively more widespread than larger taxa. Their wide geographic dispersal mitigates against speciation and extinction. There is no evidence that rates of species description

Table 1. The number of species per higher taxonomic group. Data from <http://species.asu.edu/files/SOS2010.pdf> (27). Higher taxa are classified into those generally large (mega, >10 cm), small (macro, >1 mm), and microscopic (micro, <1 mm) when at reproductive age.

Higher taxonomic group	Described living species
<i>Mega</i>	
Pisces: fishes	31,658
Aves: birds	9,997
Reptilia: snakes, lizards, turtles	8,863
Amphibia: frogs, toads, salamanders	6,644
Mammalia	5,528
Other chordates	149
Subtotal	62,839
<i>Macro</i>	
Insecta	1,013,692
Plantae: vascular, including flowering	283,701
Arachnida: spiders, mites	103,568
Mollusca: snails, slugs, bivalves, squid, octopus	85,880
Crustacea: crabs, shrimp, krill	48,014
Platyhelminthes: flat worms	20,225
Annelida: segmented worms	16,897
Algae	12,304
Cnidaria: corals, jellyfish	9,926
Echinodermata: sea urchins, starfish, sea cucumbers	7,037
Porifera: sponges	6,057
Tunicata: sea squirts	2,808
Hemichordata: acorn worms	110
Other invertebrates	40,575
Subtotal	1,650,794
<i>Micro</i>	
Fungi: yeasts, molds, mushrooms	100,342
Protozoa: protists, nucleated algae	29,104
Nematoda: round worms	25,205
Prokaryota: bacteria, archaea	8,216
Others, e.g., micro-Chromista, Bryophyta	46,210
Subtotal	209,077
Total	1,922,710

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are getting relatively higher for these micro-taxa, because they are generally proportional to the number of known species in higher taxa (Fig. 1). Thus, insects make up about half of all species and continue to provide the most new species. It is true that some of the microscopic taxa have high local species richness, but this does not necessarily translate to high global species richness because the species may be more widespread than sampling indicates, although it may have narrow habitat requirements (14, 15). Species' distributions are underestimated by limited geographic sampling, which can overestimate habitat and host specificity and endemism.

A key finding in our Review (1) was that we now have better estimates of how many species may be on Earth than of extinction rates. We concurred with recent studies that recent extinction rates have not been as severe as may have been expected, in large part because species survive in secondary habitats, the success of conservation efforts, and a so-far unquantified extinction debt. Human-mediated species extinctions have been mostly due to hunting and introduced predators on islands, whereas current rates may be more due to habitat loss and future rates due to climate change. Laurance (2) agreed with us that present rates are in the range 0.01 to 1.0% per decade. However, Mora *et al.* (3) proposed that the average of extinction estimates given in Stork (16) should be used. This is a simplistic and flawed approach, first because many of these estimates are based on a range of untested assumptions and also because it assumes that estimates would be normally distributed around the true mean. Early estimates of species extinctions of 10 to 30% loss of species per decade were based on a flawed species-area model (17) and clearly have not eventuated; otherwise, we should already have seen the loss of 50% or more of all species. As Pereira *et al.* (18) indicated, some of the models using habitat loss measures were predicting the numbers of "species

committed to extinction," but the lag time for this extinction debt may be centuries or millennia, and habitat changes during that period of time can be considerable. We favor a more carefully deliberated weighting of the evidence and arguments for the estimates. While agreeing with us that the current record of species extinction is "very low," Mora *et al.* (3) attributed this to the limited number of species whose extinction risk has been assessed. However, the species first assessed tend to be groups where extinction rates are highest (e.g., amphibians), whereas other taxa (e.g., fish) have much lower recent extinction rates per number of known species. Nevertheless, we emphasize that the global loss of any species is a tragic event and the rapid movement of many species up the scale of threat toward extinction, as shown in the International Union for Conservation of Nature List of Threatened Species (19), is of great concern.

A series of studies on fossils, regional and global fauna and flora, all marine species, and all algae have shown that several times as many people have been describing species as ever before (9, 20, 21). Critics may counter that this reflects a new fashion to put more people's names against a new species (the "*et al.*" effect) and that there is a greater proportion of people describing new species part-time. However, the "*et al.*" effect only appeared in the 1980s when this trend was already under way, and two independent analyses showed it did not significantly alter the trend (8, 22). Moreover, the data show no indications of relatively more "part-timers," whether measured as the proportion of authors who described one or more species per decade for the past century, the average duration of authors' publication lives, or the skewness of the relative number of species per author over time [reviewed in (21)]. The number of authors of new species has increased most in Asia and South America and represents a younger generation employed in universities (23). Thus, the relative average effort per taxonomist does not appear to have

changed over time. Until recently, estimates of global species richness had not considered the size of the taxonomic workforce or assumed it was declining.

In recent years, species descriptions may take more time to prepare because of higher expectations of journals and the need to account for more literature than before. On the other hand, there are technological efficiencies in communication, access to literature, laboratory methods, photography, paper preparation, and the publication process (24). One metric of taxonomic productivity is the number of publications and new species described. The last decade saw a record number of new marine species named (9). The rate of marine species descriptions has been relatively higher than for terrestrial since the 1950s, reflecting the new capabilities to explore the ocean. It has generally taken twice as many authors to name marine species compared with terrestrial species over time (21). However, the greatest period of terrestrial and overall species discovery was 100 years ago (9), and there has been a significant decline in the number of species described new to science overall per author since then (21). This fact has not previously been considered in estimates of global species richness and indicates that it has been getting relatively harder to discover new species because most have been found (8, 21).

Mora *et al.* (3) suggested that if 0.5 million species remained to be described in collections, this indicates that it is not hard to find new species. However, there has always been a backlog of species to describe because no institution has experts in all taxa; the specimens may not be of sufficient number or quality to confidently describe as new species; the specimens may have gone unnoticed due to having been originally mislabeled based on the more limited knowledge at the time; and it can sometimes be easier to collect new species than to describe them. It takes on average 21 to 25 years from their date of collection for species to be described (25, 26). Hence, recommendations for greater online access to information on what taxa occur in what collections and for collaboration between institutions and experts to address this backlog (21, 25).

Considering the size of the workforce and its current productivity, we may expect that taxonomy at a global level is in a healthier state than some have believed. The number of new species described in recent years would be a reasonable measure of current effort. This is most commonly estimated from the Index of Organism Names, which encompasses the Zoological Record and tracks a wide range of literature for studies that name new species, subspecies, and higher taxa (27). Since the late 1970s, the process has been digitized, appears accurate, and has been used in several studies [e.g., (23, 28–30)]. However, Mora *et al.* (3) dispute this data, and their analysis could only confirm the validity of 45% of the species described since 2000, and they alleged that a further 46% were synonyms

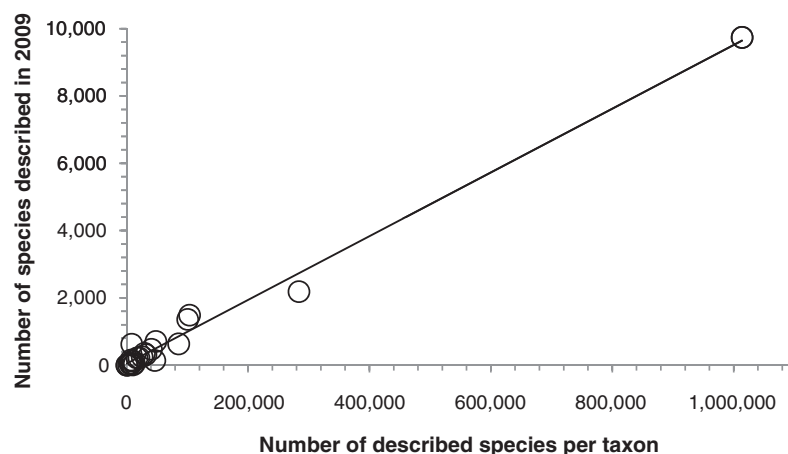


Fig. 1. New species named in 2009 versus already named species. The number of species for higher taxonomic groups described in a typical year compared with the number already described ($r^2 = 0.99$). The trend is similar if the insects ($r^2 = 0.85$) and plants ($r^2 = 0.80$) are omitted. [Data from (27)]

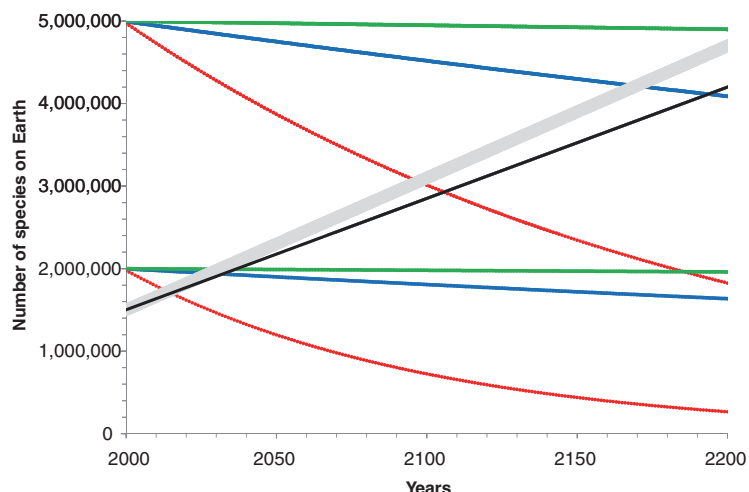


Fig. 2. Predicted species extinction and description rates in future years. The number of species described per year (gray line) in Costello *et al.* (1) and adjusted to 13,500 per decade (black line) to exclude new fossil species and subspecies. Colored lines show species remaining based on whether there are 5 or 2 million species on Earth and whether extinction rates are 1% (red line), 0.1% (blue line) or 0.01% (green line) per decade.

or invalid names. It is not clear exactly how they derived these figures because they did not cite the data sources as their licenses required (31, 32), and these databases will change in quality and quantity over time. It would be extraordinary that about two-thirds of all recently named species have already been found to be synonyms or otherwise invalid. Their analysis of three databases, including the World Register of Marine Species (WoRMS) (31), indicated that about 8000 new species were described from 1990 to 2000. This analysis was clearly wrong because WoRMS alone contained at least 17,286 accepted species that had been named in those years, and it was incomplete (9, 33). If this represents about 15% of all species (the proportion that marine species are of all species on Earth), then more than 115,000 species would have been named in that decade, which is 14 times the figure calculated by Mora *et al.* (3). From 1990 to 2012, the Index to Organism Names reported an average of 16,500 new species of animals per year, and more than 17,000 from 2006 to 2010, to which should be added new species of plants and fungi. In our Review, we used a conservative figure of 16,000

new species per year but did not take account of the fact that about 19% of these were fossils and 6% were subspecies (27). We do so here, but this has negligible effect on the general trends in species discovery versus extinction rates (Fig. 2). Of course, some of these species will be found to be synonyms, as will future named species. In our Review, we emphasized the importance of the need to revise species descriptions and re-examine type specimens to resolve synonyms. The important point is that we proposed practical recommendations to accelerate this pace, which have not been criticized. Following these recommendations will improve data and understanding of species' biogeography and how habitat change may affect species extinctions, provide more accurate estimates of global species richness and extinction rates, and enable the discovery of most species before they go extinct.

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