Review

What we know and don't know about Earth's missing biodiversity

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Estimates of non-microbial diversity on Earth range from 2 million to over 50 million species, with great uncertainties in numbers of insects, fungi, nematodes, and deep-sea organisms. We summarize estimates for major taxa, the methods used to obtain them, and prospects for further discoveries. Major challenges include frequent synonymy, the difficulty of discriminating certain species by morphology alone, and the fact that many undiscovered species are small, difficult to find, or have small geographic ranges. Cryptic species could be numerous in some taxa. Novel techniques, such as DNA barcoding, new databases, and crowd-sourcing, could greatly accelerate the rate of species discovery. Such advances are timely. Most missing species probably live in biodiversity hotspots, where habitat destruction is rife, and so current estimates of extinction rates from known species are too low.

How many species are there?

This deceptively simple question has a rich pedigree. In 1833, Westwood [1] speculated 'On the probable number of species of insects in the Creation'. Over recent decades, many have grappled with the question, reaching widely varying conclusions [2–6]. Clearly, far more species exist than taxonomists have named; most are missing from the taxonomic catalog. Alas, taxonomists have complicated matters by inadvertently giving multiple names to many known species. Chapman's recent, thorough compilation of estimates [7], plus new studies embracing novel methods of estimation, motivate our synthesis of recent progress.

Here, we highlight previous work and ask: How many missing species are left to discover? Where do these species live? What ecological traits might they possess? And, how can unresolved challenges in documenting diversity be best approached? We do not, however, conjecture about the total number of species on Earth. For some taxa, the numbers and their uncertainties are well known. For others, including insects and fungi, the estimates vary so widely as to overwhelm any simple attempt to estimate a grand total for all species.

Human activities currently drive species to extinction at 100–1000 times their natural rate [8]. It is likely that biologists will not discover many missing species before they vanish and so will underestimate the magnitude of the contemporary biodiversity crisis [3,8,9]. The need to discover and describe species has never been more urgent [8,10]. Optimizing where to focus conservation interventions requires, in part, counting species accurately and knowing where they live [3]. Unfortunately, current conservation efforts work from an incomplete biodiversity catalog [11].

Today, describing the unknown animal species might cost US$263 billion [12] and require centuries to complete. Given such obvious impracticalities, there is little choice but to rely on current estimates of total species numbers and their probable geographic distribution, using the best available information [2,3,13–15].

How many species are known?

Known species counts

Table 1 simplifies Chapman's [7] compilation of species numbers. We add additional data to illustrate key debates. As have others, we restrict our analyses to metazoans (fungi, plants, and animals) because for viruses, bacteria, and other microorganisms, the definition of 'species' is unclear. The column 'Currently Catalogued' counts known species within various taxonomic groupings, and represents the work of many thousands of taxonomists across hundreds of years. Despite this massive undertaking, simply adding up the numbers of 'known' species, even for well-studied groups such as birds, is itself not straightforward. (See 'Described Species Range', which shows the range of variability for different groups). Synonymy is the problem.

The problem of synonymy

A range of estimates arises because taxonomists have described some species many times. This is not surprising. The descriptions of species come from different taxonomists on different continents in different generations. Fixing this problem requires considerable effort. For flowering plants, for example, the highest estimate of known species is twice that of the lowest; synonymy is suspected to be upwards of 60–78% for many plant groups [16]. Because estimates of missing species use the number of known species as their basis, these uncertainties are fundamental.

Taxonomists recognize the seriousness of synonyms. Major botanic gardens now collaborate to produce the

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Table 1. Chapman's (2009) estimates of species numbers [7], with other noteworthy estimates discussed in the main text

Kingdom	Phylum/Division	Within Phylum	Major division	Data from Chapman [7] and sources therein		Estimated	Other Refs
				Currently catalogued	Described species range		
Fungi				98 998	45 173–300 000	1.5 M	
						611 000	[6]
						9.9 M	[38]
						3.5–5.1 M	[39]
						1.62 M	[35]
Plants				310 129		~390 800	
				215 644		298 000	[6]
	Vascular plants	Magnoliophyta		(~268 600)	223 300–315 903	(~352 000)	
			Monocots and selected non-monocots			352 000 + 15%	[9,13]
		Gymnosperms		(~1021)	846–1021	(~1050)	
		Ferns and allies		(~12 000)	10 000–15 000	(~15 000)	
	Bryophyta			16 236	13 370–23 000	~22 750	
	Algae			12 272	12 205–12 272	NA	
Animals	All terrestrial			1 233 500		8 740 000	[6]
	All marine			193 756		2 210 000	[6]
	Porifera			~6000	5500–10 000	~18 000	
	Cnidaria			9795	9000–11 000	N/A	
	Mollusca			~85 000	50 000–120 000	~200 000	
	Annelida			16 763	120,00–16,763	~30 000	
	Anthropoda	Tropical arthropods				3.6–11.4 M	[33]
		Arachnida		102 248	60 000–102 248	~600 000	
		Myriapoda		16 072	8160–17 923	~90 000	
		Insecta		~1 M	720 000–>1 M	5 M	
			Coleoptera	360 000–400 000		1.1 M	
			Diptera	152 956		240 000	
			Hemiptera	80 000–88 000			
			Hymenoptera	115 000		>300 000	
			Lepidoptera	174 250		300 000–500 000	
		Crustacea		47 000	25 000–68 171	150 000	
				20 000	20 000–25 000	(~80 000)	
	Platyhelminthes			<25 000	12 000–80 000	~500 000	
	Nematoda					>1 M	[22]
				7003	6100–7003	~14 000	
	Echinodermata			12 673	N/A	~20 000	
	Other invertebrates			64 788		~80 500	
	Chordata		Mammals	5487	4300–5487	~5500	
			Birds	9990	9000–9990	>10 000	
				10 052			[a]
			Reptiles	8734	6300–8734	~10 000	
			Amphibians	6515	4950–6515	~15 000	
			Fishes	31 269	25 000–31 269	~40 000	

[a] http://www.birdlife.org/datazone/info/taxonomy.

unique and continuously updated *World Checklist of Selected Plant Families* [17], which has largely resolved the problem of synonymy for approximately 110 000 species (all monocots, plus selected non-monocot families). Other rigorous attempts to confront synonymy include the 2011 symposium to eliminate separate names for asexual and sexual stages of certain fungi [18]. An estimated 66% of fungal names are synonymous [19].

How many species are unknown?

The completeness of global inventories varies greatly (see 'Estimated' in Table 1). Completeness ranges from approximately 97% for mammals, 80–90% for flowering plants, 79% for fish, 67% for amphibians, roughly 30% for arthropods and <4% for nematodes [11,13,20–22] (Table 1). Across these groups, levels of completeness decline with the currently known numbers of species. Taxonomic effort is distributed approximately evenly among vertebrates, plants, and invertebrates, yet plants have approximately ten times, and invertebrates 100 times, more known species than do vertebrates [23,24].

Global inventories (Table 1 'Estimated') come from various methods, including the expert opinions of taxonomists specialized on the various taxa. Differing methods result in widely varying estimates; for instance, estimates for fungi vary nearly 20-fold. Methods fall into three basic