ENVIRONMENTAL SCIENCES

Accelerated modern human–induced species losses: Entering the sixth mass extinction

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The oft-repeated claim that Earth's biota is entering a sixth "mass extinction" depends on clearly demonstrating that current extinction rates are far above the "background" rates prevailing between the five previous mass extinctions. Earlier estimates of extinction rates have been criticized for using assumptions that might overestimate the severity of the extinction crisis. We assess, using extremely conservative assumptions, whether human activities are causing a mass extinction. First, we use a recent estimate of a background rate of 2 mammal extinctions per 10,000 species per 100 years (that is, 2 E/MSY), which is twice as high as widely used previous estimates. We then compare this rate with the current rate of mammal and vertebrate extinctions. The latter is conservatively low because listing a species as extinct requires meeting stringent criteria. Even under our assumptions, which would tend to minimize evidence of an incipient mass extinction, the average rate of vertebrate species loss over the last century is up to 100 times higher than the background rate. Under the 2 E/MSY background rate, the number of species that have gone extinct in the last century would have taken, depending on the vertebrate taxon, between 800 and 10,000 years to disappear. These estimates reveal an exceptionally rapid loss of biodiversity over the last few centuries, indicating that a sixth mass extinction is already under way. Averting a dramatic decay of biodiversity and the subsequent loss of ecosystem services is still possible through intensified conservation efforts, but that window of opportunity is rapidly closing.

INTRODUCTION

The loss of biodiversity is one of the most critical current environmental problems, threatening valuable ecosystem services and human well-being (*1*–*7*). A growing body of evidence indicates that current species extinction rates are higher than the pre-human background rate (*8*–*15*), with hundreds of anthropogenic vertebrate extinctions documented in prehistoric and historic times (*16*–*23*). For example, in the islands of tropical Oceania, up to 1800 bird species (most described in the last few decades from subfossil remains) are estimated to have gone extinct in the ~2000 years since human colonization (*24*). Written records of extinctions of large mammals, birds, and reptiles date back to the 1600s and include species such as the dodo (*Raphus cucullatus*, extinguished in the 17th century), Steller's sea cow (*Hydrodamalis gigas*, extinguished in the 18th century), and the Rodrigues giant tortoise (*Cylindraspis peltastes*, extinguished in the 19th century). More species extinction records date from the 19th century and include numerous species of mammals and birds. Records of extinction for reptiles, amphibians, freshwater fishes, and other organisms have mainly been documented since the beginning of the 20th century (*14*, *17*). Moreover, even in species that are not currently threatened, the extirpation of populations is frequent and widespread, with losses that far outstrip species-level extinctions (*18*, *25*). Population-level extinction directly threatens ecosystem services and is the prelude to species-level extinction (*18*).

Here, we analyze the modern rates of vertebrate species extinction and compare them with a recently computed background rate for mammals (*7*). We specifically addressed the following questions: (i) Are modern rates of mammal and vertebrate extinctions higher than the highest empirically derived background rates? (ii) How have modern extinction rates in mammals and vertebrates changed through time? (iii) How many years would it have taken for species that went extinct in modern times to have been lost if the background rate had prevailed? These are important issues because the uncertainties about estimates of species loss have led skeptics to question the magnitude of anthropogenic extinctions (*26*) and because understanding the magnitude of the extinction crisis is relevant for conservation, maintenance of ecosystem services, and public policy.

Until recently, most studies of modern extinction rates have been based on indirect estimates derived, for example, on the rates of deforestation and on species-area relationships (*11*, *14*). Problems related to estimating extinction since 1500 AD (that is, modern extinctions) have been widely discussed, and the literature reflects broad agreement among environmental scientists that biases lead to underestimating the number of species that have gone extinct in the past few centuries—the period during which *Homo sapiens* truly became a major force on the biosphere (*1*–*4*, *6*–*8*, *14*, *15*). However, direct evaluation is complicated by uncertainties in estimating the incidence of extinction in historical time and by methodological difficulties in comparing contemporary extinctions with past ones.

Less discussed are assumptions underlying the estimation of background extinction rates. The lower these estimates, the more dramatic current extinction rates will appear by comparison. In nearly all comparisons of modern versus background extinction rates, the background rate has been assumed to be somewhere between 0.1 and 1 species extinction per 10,000 species per 100 years (equal to 0.1 to 1 species extinction per million species per year, a widely used metric known as E/MSY). Those estimates reflect the state of knowledge available from the fossil record in the 1990s (*7*, *9*–*13*). In a recent analysis, which charted the stratigraphic ranges of thousands of mammal species,

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Table 1. Numbers of species used in the Table 2 calculations of "highly conservative" and "conservative" modern extinction rates based on the IUCN Red List (*17*). For the highly conservative rates, only species verified as "extinct" (EX) were included; for the conservative extinction rates, species in the categories "extinct in the wild" (EW) and "possibly extinct" (PE) were also included.

Vertebrate taxon	**No. of species, IUCN 2014.3**				
	Highly conservative rates (EX)		**Conservative rates (EX + EW + PE)**		**No. of species evaluated by IUCN**
	Since 1500	**Since 1900**	**Since 1500**	**Since 1900**	
Vertebrates	338	198	617	477	59% (39,223)
Mammals	77	35	111	69	100% (5,513)
Birds	140	57	163	80	100% (10,425)
Reptiles	21	8	37	24	44% (4,414)
Amphibians	34	32	148	146	88% (6,414)
Fishes	66	66	158	158	38% (12,457)

Table 2. Elevation of "highly conservative" and "conservative" modern vertebrate extinction rates above background rate of 2 E/MSY (see table S2 for calculations). For each assessment category, two periods are shown: extinction rates computed from 1500 to the present, and from 1900 to the present.

Animal group	**Elevation of modern rates with respect to expected rates**			
	Highly conservative		**Conservative**	
	Since 1500	**Since 1900**	**Since 1500**	**Since 1900**
Vertebrates	8	22	15	53
Mammals	14	28	20	55
Birds	13	24	15	34
Reptiles	5	8	8	24
Amphibians	5	22	22	100
Fishes	5	23	12	56

extinction rates were measured over intervals ranging from single years to millions of years, and the mean extinction rate and variance were computed for each span of time (*7*). In this way, the background extinction rate estimated for mammals was estimated at 1.8 E/MSY, here rounded upward conservatively to 2 E/MSY (that is, 2 extinctions per 100 years per 10,000 species). This is double the highest previous rough estimate.

Those previously estimated background rates were primarily derived from marine invertebrate fossils, which are likely to have greater species longevity than vertebrates (*10*, *15*). Data deficiencies make it impossible to conduct empirical analyses (as was done for mammals) for non-mammal terrestrial vertebrates; therefore, we assume the background rates of other vertebrates to be similar to those of mammals. This supposition leads to a more conservative assessment of differences between current and past extinction rates for the vertebrates as a whole, compared with using the very low background extinction rate derived from marine invertebrates.

The analysis we present here avoids using assumptions such as loss of species predicted from species-area relationships, which can suggest very high extinction rates, and which have raised the possibility that scientists are "alarmists" seeking to exaggerate the impact of humans on the biosphere (*26*). Here, we ascertain whether even the lowest estimates of the difference between background and contemporary extinction rates still justify the conclusion that people are precipitating a global spasm of biodiversity loss.

RESULTS

Modern and background rates of vertebrate extinctions

Modern rates of vertebrate extinction were much higher than a background extinction rate of 2 E/MSY. Among the vertebrate taxa evaluated by the International Union of Conservation of Nature (IUCN), 338 extinctions have been documented since 1500 ["extinct" (EX), Table 1]. An additional 279 species have become either "extinct in the wild" (EW) or listed as "possibly extinct" (PE), totaling 617 vertebrate species summed over the three categories. Most extinctions have occurred in the last 114 years (that is, since 1900; Table 1). Our estimated "highly conservative" (that is, using data for EX species only) and "conservative" (that is, by including EX, EW, and PE) modern extinction rates for vertebrates varied from 8 to 100 times higher than the background rate (Table 2). This means, for example, that under the 2 E/MSY background rate, 9 vertebrate extinctions would have been expected since 1900; however, under the conservative rate, 468 more vertebrates have gone extinct than would have if the background rate had persisted across all vertebrates under that period. Specifically, these 468 species include 69 mammal species, 80 bird species, 24 reptiles, 146 amphibians, and 158 fish.

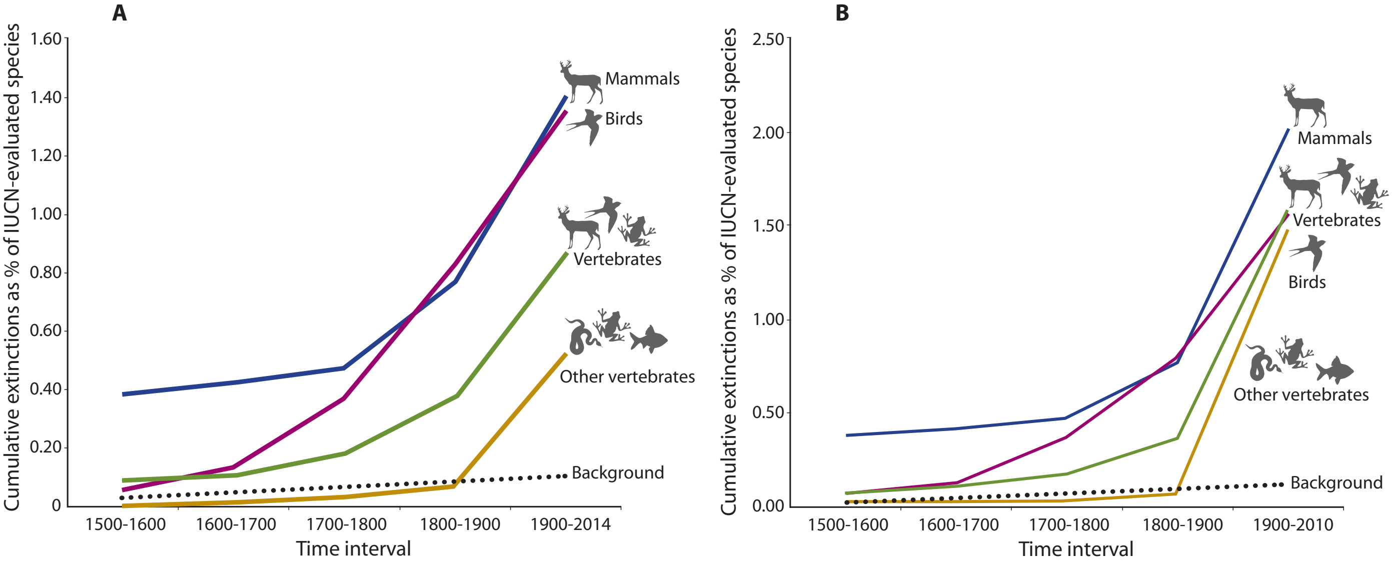

Fig. 1. Cumulative vertebrate species recorded as extinct or extinct in the wild by the IUCN (2012). Graphs show the percentage of the number of species evaluated among mammals (5513; 100% of those described), birds (10,425; 100%), reptiles (4414; 44%), amphibians (6414; 88%), fishes (12,457; 38%), and all vertebrates combined (39,223; 59%). Dashed black curve represents the number of extinctions expected under a constant standard background rate of 2 E/MSY. (**A**) Highly conservative estimate. (**B**) Conservative estimate.

Variation in modern extinction rates through time

Modern extinction rates have increased sharply over the past 200 years (corresponding to the rise of industrial society) and are considerably higher than background rates (Fig. 1). Rates of modern extinctions vary among vertebrate groups (Fig. 1). For example, amphibians, comprising of ~7300 species, show an accelerating rate of extinction: only 34 extinctions have been documented with a high level of certainty since 1500, yet >100 species have likely disappeared since 1980 (*17*, *23*). This may not only reflect real trends but also a shortage of data for groups for which most species are not yet evaluated, such as reptiles and fish (*21*, *22*).

Modern extinctions if background rate had prevailed

Our results indicate that modern vertebrate extinctions that occurred since 1500 and 1900 AD would have taken several millennia to occur if the background rate had prevailed. The total number of vertebrate species that went extinct in the last century would have taken about 800 to 10,000 years to disappear under the background rate of 2 E/MSY (Fig. 2). The particularly high losses in the last several decades accentuate the increasing severity of the modern extinction crisis.

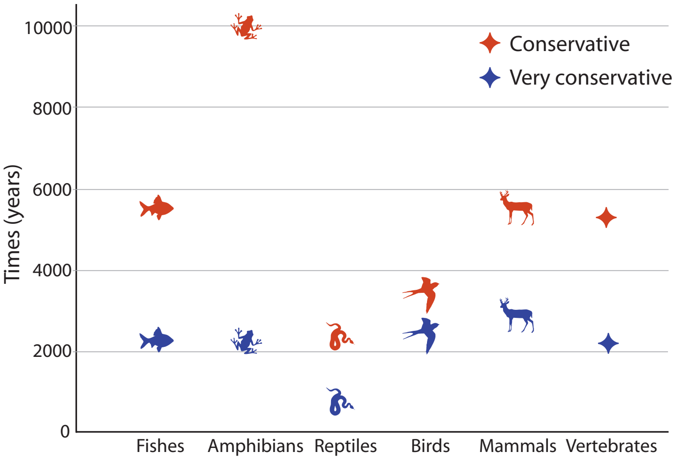

Fig. 2. Number of years that would have been required for the observed vertebrate species extinctions in the last 114 years to occur under a background rate of 2 E/MSY. Red markers, highly conservative scenario; blue markers, conservative scenario. Note that for all vertebrates, the observed extinctions would have taken between 800 to 10,000 years to disappear, assuming 2 E/MSY. Different classes of vertebrates all show qualitatively similar trends.

DISCUSSION

Arguably the most serious aspect of the environmental crisis is the loss of biodiversity—the other living things with which we share Earth. This affects human well-being by interfering with crucial ecosystem services such as crop pollination and water purification and by destroying humanity's beautiful, fascinating, and culturally important living companions (*4*, *5*, *15*, *27*–*30*).

Our analysis shows that current extinction rates vastly exceed natural average background rates, even when (i) the background rate is considered to be double previous estimates and when (ii) data on modern vertebrate extinctions are treated in the most conservative plausible way. We emphasize that our calculations very likely underestimate the severity of the extinction crisis because our aim was to place a realistic "lower bound" on humanity's impact on biodiversity. Therefore, although biologists cannot say precisely how many species there are, or exactly how many have gone extinct in any time interval, we can confidently conclude that modern extinction rates are exceptionally high, that they are increasing, and that they suggest a mass extinction under way—the sixth of its kind in Earth's 4.5 billion years of history.

A final important point is that we focus exclusively on species, ignoring the extirpation of populations—the units relevant to ecological functioning and the delivery of ecosystem services (*4*, *5*, *29*). Population extinction cannot be reliably assessed from the fossil record, precluding any analysis along the lines of that presented here. Also, although it is clear that there are high rates of population extinction (*18*), existing data are much less reliable and far harder to obtain than those for species, which will remain true for the foreseeable future. Likewise, we have not considered animals other than vertebrates because of data deficiencies.

The evidence is incontrovertible that recent extinction rates are unprecedented in human history and highly unusual in Earth's history. Our analysis emphasizes that our global society has started to destroy species of other organisms at an accelerating rate, initiating a mass extinction episode unparalleled for 65 million years. If the currently elevated extinction pace is allowed to continue, humans will soon (in as little as three human lifetimes) be deprived of many biodiversity benefits. On human time scales, this loss would be effectively permanent because in the aftermath of past mass extinctions, the living world took hundreds of thousands to millions of years to rediversify. Avoiding a true sixth mass extinction will require rapid, greatly intensified efforts to conserve already threatened species and to alleviate pressures on their populations—notably habitat loss, overexploitation for economic gain, and climate change (*31*–*33*). All of these are related to human population size and growth, which increases consumption (especially among the rich), and economic inequity (*6*). However, the window of opportunity is rapidly closing.

MATERIALS AND METHODS

To estimate modern extinction rates, we compiled data on the total number of described species and the number of extinct and possibly extinct vertebrate species from the 2014 IUCN Red List (*17*). In the IUCN's list, extinct species can be viewed as the minimum number of actual extinctions during recent human history (that is, since 1500) because it lists species known to be extinct (EX), extinct in the wild (EW), and possibly extinct (PE, a subcategory within "critically endangered" reserved for species thought to be extinct, but not confirmed) (*17*) (table S1). We used the IUCN data to calculate modern extinction rates in two ways: (i) we estimate a "highly conservative modern extinction rate" by using the data exclusively on species listed as EX, and (ii) we calculate a "conservative extinction rate" by including also both EW and PE species (table S2). Including these latter two categories recognizes that there is only a slim chance that most of the species in those categories can reestablish viable populations in their native habitats. In terms of biological impact and the provision of ecosystem services, we consider EW and PE species to be functionally equivalent to EX species: even if some individuals still exist, their abundances are not sufficient to have a substantial influence on ecological function and processes.

The IUCN's list is considered the authoritative, albeit likely conservative, assessment of the conservation status of plant and animal species. About 1.8 million species have been described since 1758 (when the current nomenclature system was developed), of which 1.3 million are animals (*3*, *17*). Of these animal species, about 39,223 (of the currently counted 66,178) vertebrate species have been formally assessed and reported in the 2014 IUCN Red List (*17*). In the IUCN sample, mammals, birds, and amphibians have had between 88 and 100% of their known species evaluated, whereas only 44% of reptiles and 38% of fish species have been assessed (Table 1). We focus our comparisons on vertebrates because they are the group for which the most reliable data exist, both fossil and modern.

To produce conservative comparisons with modern extinctions, we assumed a background extinction rate of 2 E/MSY as the highest likely baseline average background extinction rate (*7*); that is, we should expect 2 extinctions per 10,000 vertebrate species per 100 years. That background extinction rate was empirically determined using the exceptionally good fossil records of mammals, combining extinction counts from paleontological databases and published literature on the fossil, subfossil, and historical records (*7*). Using the resulting high background extinction rate provides a stringent test for assessing whether current modern extinction rates indicate that a mass extinction event is under way. Previous estimates of background extinction rates for other taxa are invariably lower than the mammal-derived estimate of 2 E/MSY used here.

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/1/5/e1400253/DC1

Table S1. Definitions of IUCN categories (*17*) used to assess modern extinction rates.

Table S2. Estimation of modern extinction rates since 1500 and 1900.

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