1 Biodiversity discovery and its importance to conservation

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During the eighteenth, nineteenth, and early twentieth centuries, scientific inventories of biodiversity flourished as naturalists participated in expeditions throughout different geographic regions of the world (Köhler et al. 2005). These expeditions and the various journals produced by many prominent naturalists provided materials for extensive scientific collections as well as accounts of the habits and habitats of both plant and animal species. Charles Darwin and Alfred Russel Wallace were part of this tradition, and both were students of biodiversity. They chronicled their adventures in South America, the Malay Archipelago, the Galapagos Islands, New Zealand, and Australia as they discovered new species, described geology, and encountered various cultures (Darwin 1845; Wallace 1869). These adventures honed their observational skills, and their experiences culminated in their parallel proposals of the theory of biological evolution by means of natural selection. The biodiversity and natural environments encountered by Darwin and Wallace have been altered, and both habitats and species described in their journals have and are being impacted at a drastic rate. The yellow-bridled finch (*Melanodera xanthogramma*), noted by Darwin as "common" in the Falkland Islands, is now gone, and, as predicted by Darwin, the Falkland Islands fox or warrah (*Dusicyon australis*) went extinct in 1876 (Armstrong 1994). The Borneo forest harbors fewer *Mias* or orangutans, and it is unlikely that one would be allowed to collect specimens like Wallace describes (Wallace 1869). Even "pristine" regions, such as those seen by Darwin in Patagonia and the southwest Atlantic coast of Argentina, are still poorly understood, yet they are threatened by numerous human activities (Bortolus & Schwindt 2007).

Owing primarily to the fact that the probability of massive species extinction is inevitable, interest in an all-species inventory and the derivation of a Tree of Life has increased over the last two decades. In 1992, the systematics community in the United States, through funding by the National Science Foundation, organized a meeting to set an agenda for the upcoming millennium. As a consequence, Systematics Agenda 2000 (1994) established three major goals: 1) to conduct a worldwide survey and inventory of all species and the taxonomic description of new species; 2) to derive a phylogeny or Tree of Life for all species that would serve as the basis for a classification as well as a framework for other researchers in the life sciences; and 3) to develop an information retrieval system for managing data on biodiversity.

Although our knowledge of biodiversity on planet Earth has increased as a consequence of the endeavors of early naturalists and these new initiatives, we are still far from a complete census of all species, and many will go extinct before their discovery. Such an inventory is essential because it provides a baseline for understanding the stability of ecosystems and the impact of anthropogenic processes that may eventually result in our own demise.

This chapter relates specifically to the inventory of biodiversity as an important step for its conservation. The first section provides a general overview of the importance of biodiversity to society, presents a survey of its global distribution, and identifies groups and geographic regions threatened by human activities. The second section reviews our current knowledge of worldwide biodiversity in terms of its discovery and description and identifies groups that are poorly known. The third section discusses the future of inventorying biodiversity and reviews how molecular approaches and phylogenetic methods provide means for accelerating the overall processes of species discovery and the construction of the Tree of Life. Finally, we emphasize the importance of an information retrieval system that makes data on biodiversity accessible to the entire scientific community.

BIODIVERSITY

Why is biodiversity important?

Biodiversity is defined as "the variability among living organisms from all sources including, inter alia, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems" (Glowka et al. 1994). The importance of biodiversity and the need for its conservation worldwide cannot be overemphasized. Not only are diverse forms of organisms responsible for sustaining human populations, they also serve important roles in the maintenance of ecosystems.

Advances in human medicine have benefited directly from biodiversity (Bernstein & Ludwig 2008; Harvey 2008). For instance, species of bacteria discovered over the last forty years have helped minimize transplant rejection, provided antibiotics and antifungal drugs that help combat infections from harmful pathogens, and revolutionized molecular biology by providing thermostable DNA polymerases used in polymerase chain reaction (PCR), a procedure employed broadly in medical diagnostics. Other plant and animal species provide drugs useful for treating cancer and serve as model organisms for studying molecular processes associated with disease and neurological disorders. Approximately 50% of the most broadly used drugs were derived from natural resources (Bernstein & Ludwig 2008), and biodiversity continues to serve as an important resource for the development of clinically important pharmaceuticals and other health-related products (Harvey 2008).

Aside from medicine, humans receive both direct and indirect benefits from biodiversity through the provision of food, fuel, clean water, and fertile soil that enhances agriculture. According to Wilson (1985), more than seven thousand species of plants have been used for food, and twenty species are essential as worldwide food sources. Related species to those currently used for food are genetic reservoirs containing genes that may serve as sources of resistance to pathogens and pests as well as to potential climatic changes. In fact, enhancing both genetic diversity and crop diversity to create more complex "agroecosystems" may provide a more natural means of not only increasing production but also reducing the need for excessive use of pesticides and other chemicals (Altieri 2004). Biodiversity also provides a host of benefits and services to ecosystems. Processes associated with the recycling of nutrients, carbon and nitrogen cycling, formation of soils, climate stabilization, plant pollination, and decomposition of pollutants are influenced by biodiversity, and many of these processes are important to worldwide economies (Pimentel et al. 1997).

How is biodiversity distributed?

Biodiversity is not randomly distributed worldwide. Comparisons across biogeographic regions reveal areas that differ significantly in terms of species diversity and levels of endemism (Gaston 2000). Two major patterns associated with differences in biodiversity are considered relevant to conservation issues. First, species richness varies over a latitudinal gradient, with more species occurring in the tropics than in more temperate regions (Gaston 1996). This general pattern appears to hold for many different taxa, such as plants, mammals, and birds, yet there are exceptions. Although amphibians are more diverse in the tropics, their general pattern of diversity is not completely correlated with latitude in that they do show local exceptions, such as their high diversity in the mountains of the eastern United States relative to other areas of North America and Europe (Buckley & Jetz 2007). This latitudinal gradient associated with species richness also appears to be asymmetrical, with the gradient stronger in the northern than in the southern hemisphere (Chown et al. 2004). As indicated by several authors (Gaston 2000; Hawkins 2001; Ricklefs 2004; Buckley & Jetz 2007; Dyer et al. 2007), the mechanisms responsible for the latitudinal gradient are widely debated but probably relate to several different factors including ecological (e.g., species interactions), environmental (e.g., habitat quality, energy, and degree of stability), and historical processes (e.g., degree of isolation, rates of extinction, migration, and speciation). Second, species richness increases with size of area, and, like latitudinal gradients, species-area curves are a pattern observed for plants, animals, and bacteria (Rosenzweig 1995; Horner-Devine et al. 2004). According to Rosenzweig (1992), latitudinal gradients and species-area curves occur at different temporal and spatial scales, with the latter occurring recently and at a more local or regional scale. In terms of predicting species diversity, this area effect probably relates to habitat heterogeneity (Rosenzweig 1992). For instance, Horner-Devine and colleagues (2004) observed an increase in bacterial species diversity with an increase in area that appeared related to an increase in overall habitat heterogeneity as the distance between sites in a salt marsh increased, and Báldi (2008) found that arthropod diversity on several reserves varied in response to habitat heterogeneity rather than to area.

Regardless of the mechanisms for latitudinal gradients and species-area curves, both of these general observations have been used to establish priorities for maximizing the conservation of biodiversity through the identification of regions (termed "biodiversity hotspots") that should receive high conservation priority (Myers 1988). Two criteria are commonly used to identify biodiversity hotspots. First, the number of endemic species (i.e., species that cannot be replaced if lost from a region) is considered a more important indicator than species richness, which is potentially biased toward broadly distributed species. Second, areas with high levels of endemism and under threat of habitat loss receive the highest conservation priority. The overall establishment of biodiversity hotspots is based on an extrapolation of better-known species, especially those that are indicators of habitats. As such, plant diversity is a common means of ranking hotspots. For instance, some of the first hotspots (e.g., ten sites in tropical rainforests) were recognized based on plant diversity (Myers 1988). Similarly, Mittermeier and colleagues (1998) identified twenty-four biodiversity hotspots on the basis of plant species endemism and the degree to which vegetation cover was being removed (some as high as 98%). These original twenty-four hotspots represented approximately 2% of land surface and approximately 46% of endemic plant species (Mittermeier et al. 1998). Currently, Myers and colleagues (2000) recognize twenty-five terrestrial hotspots, encompassing 1.4% of the world's land area and representing a large percentage of plant and vertebrate species. As before, the primary indicator of these biodiversity hotspots is percentage of endemic plant species and secondarily the percentage of endemic species of mammals, birds, reptiles, and amphibians.

There is an inherent assumption that uniqueness of (primarily) plants and (secondarily) vertebrates, as indicators of hotspots, can be extrapolated to lesser-known taxa such as invertebrates. The establishment of global priorities of conservation based on this assumption is somewhat problematic. For instance, Grenyer and colleagues (2006) examined the distribution of three vertebrate groups (birds, mammals, and amphibians) and found similar species richness among regions, yet little congruence in terms of the identification of hotspots based on the distribution of rare and vulnerable species associated with each group. This finding suggests that setting global priorities on the basis of surrogate taxa may be inappropriate, especially when identifying smaller, regional areas for conservation activities (Reid 1998). The finding also implies that broader taxonomic coverage is required for the identification of hotspots that encompass the majority of rare and endemic species.

Is the extinction of biodiversity a problem?

> Those living today will either win the race against extinction or lose it, the latter for all time. They will earn either everlasting honor or everlasting contempt.
>
> (E. O. Wilson 2006, p. 99)

Extant species represent approximately 1–2% of the Earth's historical biodiversity (May et al. 1995). Therefore, *extinction*, the loss of a lineage with no replacement, is a natural process that appears nonrandom, relative to the species that go extinct, and "episodic" in the fossil record (Raup 1986, 1994). This pattern of extinction implies that the average life span for most species is short, between one and ten million years (May et al. 1995). Theoretically, the Tree of Life can withstand random and "vigorous pruning" and recover from major extinction events (Nee & May 1997). Therefore, if extinction is a natural process and the Tree of Life is capable of responding to large extinction events, why is extinction a major concern of persons and groups interested in the conservation of biodiversity? The answers are twofold. The first is from a selfish point of view: The composition of communities that will appear subsequent to such pruning is likely to be different. The loss of important ecosystem services necessary for human survival implies that *Homo sapiens* might be a casualty of rapid and random extinction processes. Even if biodiversity loss does not cause extinction of our species, it is sure to have profound negative impacts on our society. The second answer, of more immediate importance, is the estimated rate at which biodiversity is currently going extinct. Based on the fossil record, Earth has experienced five mass extinctions, each resulting in a net loss of 75–95% of species (Raup 1994). Although difficult to quantify, most evidence suggests that current rates of extinction may be approaching those experienced during mass extinctions. On the basis of annual loss from deforestation and International Union for Conservation of Nature (IUCN) listings, May and colleagues (1995) calculated a range of 200–500 years for the current life span of a species. In a separate study, the current rate of extinction was estimated to be 100–1,000 times faster than the rate estimated prior to humans (Pimm et al. 1995).

According to IUCN's Red List assessment (Baillie et al. 2004), the rate of extinction for birds, amphibians, and mammals over the last century is 50–500 times higher than background extinction. Since the 1500s, 884 extinctions (784 total extinctions and 60 extinctions in the wild) of all species assessed by IUCN have been verified (Baillie et al. 2004). The rate of extinction for amphibians, reptiles, and mammals has increased since the beginning of the twentieth century, whereas extinction of birds started increasing in the eighteenth century, especially on Oceanic islands (Nilsson 2005; Fig. 1–1).

Extinction is an ongoing process, and although many currently recognized species are not extinct, a large number are increasing in vulnerability to extinction. For instance, of the 44,838 species assessed by IUCN (2008), 38% are threatened with extinction, and, except for birds and mammals, the other vertebrate groups show an increased rate of addition to the threatened list between the years 1996 and 2008, owing primarily to an increase in the number of species assessed for these groups (Fig. 1–2). Nearly complete assessments of mammals, birds, and amphibians were performed, and a summary of results is shown in Table 1–1.

Most species of birds, mammals, and amphibians have been evaluated by IUCN, and, among these three groups of vertebrates, amphibians worldwide show the highest risk of extinction. As of January 2010, 6,603 living species have been described (AmphibiaWeb 2010). Table 1–1 shows the number of species considered by IUCN in 2008; approximately 32% are threatened with extinction (Wake & Vredenburg 2008), which represents a potential rate of extinction that may approach 45,000 times the background rate. In comparison to birds and

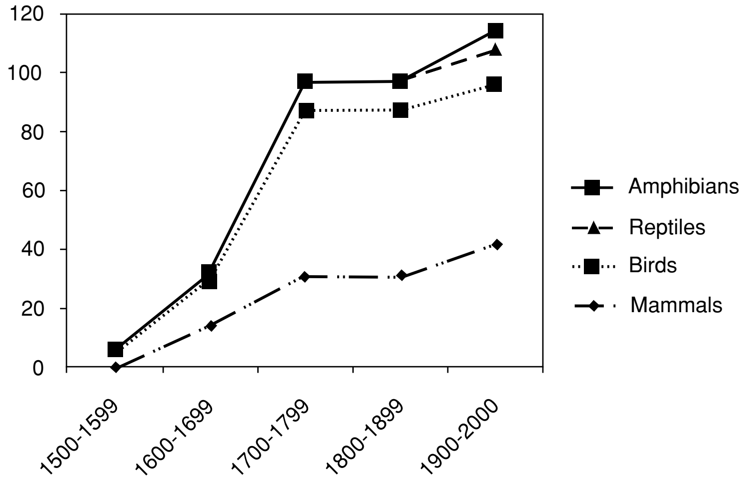

Figure 1–1: Extinction of vertebrate species between 1500 and 2000 (modified from Nilsson 2005).

mammals, twice as many species of amphibians are listed as critically endangered, and nearly one-third of the extinctions of amphibians have occurred in the last thirty years (Stuart et al. 2004). The current rate of amphibian decline has been referred to as "enigmatic" (Stuart et al. 2004) in that the processes responsible are complex, being caused by a host of potential culprits including fungal pathogens, loss of habitat, and changes in climate. The declines are not random. Amphibian communities in the neotropics, especially those in streams, are highly threatened (Dudgeon et al. 2006). In addition, of the 220 species of amphibians in Madagascar, 55 are threatened (Andreone et al. 2005).

A quarter of mammalian species (both marine and terrestrial forms) are vulnerable to extinction, and a high percentage of species show evidence of ongoing

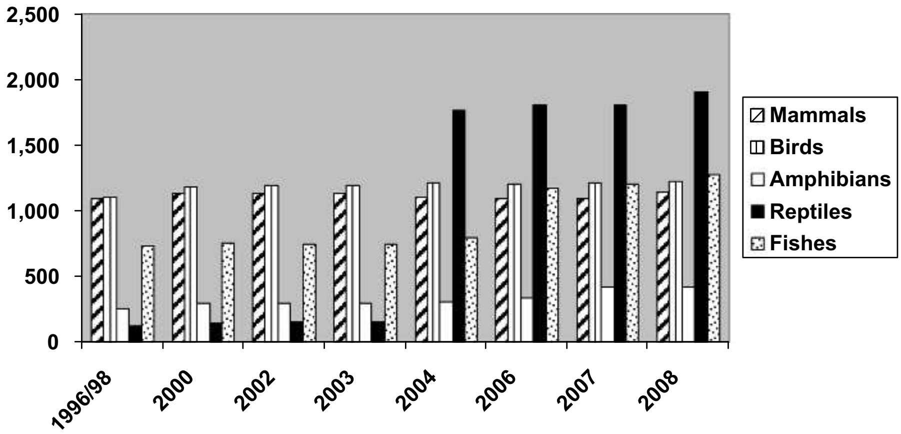

Figure 1–2: Changes in numbers of species of vertebrates in the threatened categories (critical, endangered, vulnerable) from 1996 through 2008 (derived from IUCN's Red List of Threatened Species^{TM} 2008).

Table 1–1. Statistics on threatened species compiled from Table 1 of IUCN's Red List of Threatened Species™ (2008)

	Described species	Evaluated by IUCN 2008	Threatened	% Threatened based on number evaluated
Vertebrates	61,259	26,604	5,966	22
Mammals	5,488	5,488	1,141	21
Birds	9,990	9,990	1,222	12
Reptiles	8,734	1,385	423	31
Amphibians	6,341	6,260	1,905	30
Fish	30,700	3,481	1,275	37
Invertebrates	1,232,384	6,161	2,496	41
Insects	950,000	1,259	626	50
Molluscs	81,000	2,212	978	44
Crustaceans	40,000	1,735	1,735	35
Corals	2,175	856	235	27
Arachnids	98,000	32	18	56
Others	61,209	67	33	49
Plants	298,506	12,055	8,457	70
Lichens, Mushrooms, Brown Algae	50,040	18	9	50
Total	1,642,189	44,838	16,929	38

population decline (Schipper et al. 2008). The trend in mammalian declines is not random in that some regions and groups of species are at greater risk. For instance, nearly 80% of all species of primates from Southeast Asia are threatened (Schipper et al. 2008), and larger mammals in general are more at risk, especially those that have been or are being overexploited by humans, such as the African elephant and many carnivores. Populations of many species of great whales were reduced to near extinction by commercial whaling. Some species have recovered to some degree, but others, including the Atlantic right whale, the Spitsbergen and Okhotsk Sea stocks of bowhead whales, and the western Pacific population of gray whales, are critically endangered and have not recovered despite the cessation of commercial whaling (IWC 2007). There are multiple causes for the demise of mammalian diversity including loss of habitat such as tropical deforestation, overharvesting and bycatch, pollution, and climate change. The Yangtze River dolphin or baiji (*Lipotes vexillifer*) has been declared as extinct, and its extinction represents the first mega-vertebrate extinction in fifty years and the first human-caused extinction of a cetacean. Moreover, it is the fourth mammalian family to become extinct in 500 years (Turvey et al. 2007).

Relative to the total number of species, birds (at 14%) are the least threatened. Extinctions are better documented for birds than probably any other group, however, and the patterns and processes of avian extinctions merit discussion. Some of the more vulnerable regions for birds are islands where, historically, most avian extinctions have occurred. Today, nearly 40% of avian species listed as threatened occur on islands (Johnson & Stattersfield 2008) and have an extremely high probability of extinction relative to mainland species (Trevino et al. 2007). The causes of both extinction and increased vulnerability of island birds include loss of habitat, overexploitation by humans, and the introduction of invasive species

(Johnson & Stattersfield 2008). On some islands, bird diversity has been severely depleted as a result of one or more of these causes. For instance, on Guam, ten of the thirteen species of forest birds are now extinct as a result of the brown tree snake, a species accidentally introduced after World War II (Fritts & Rodda 1998). A large percentage of threatened birds, however, occur in forested mainland habitats, many of which are subject to deforestation and fragmentation (Brooks et al. 1999) that together are accelerating the probability of avian extinctions. One particular region that has experienced considerable loss of habitat is the Atlantic Forest of Brazil and Argentina. According to Ribon and colleagues (2003), approximately 60% of the bird species in this region are either extinct or vulnerable to extinction.

Thorough assessments of both reptiles and fishes are lacking, but both are threatened as a result of overharvesting and loss of habitat. For reptiles, the percentages of threatened chelonians (turtles and tortoises) and crocodilians are 42% and 43%, respectively (Baillie et al. 2004). Although fish diversity is poorly known relative to that of other groups of vertebrates, freshwater ecosystems in general are extremely threatened, and, according to Lundberg and colleagues (2000), approximately 40% (10,000) of all described species of fish occupy freshwater, which makes up 0.01% of the world's water. As indicated by Dudgeon and coworkers (2006), freshwater systems represent the "ultimate conservation challenge" as a result of increased use of this resource worldwide. This increased use threatens not only fish but also other vertebrates, invertebrates, and microbes that rely on freshwater habitats, and extinction rates may be five times higher than predicted for terrestrial ecosystems, reaching nearly 50% in North America (Ricciardi & Rasmussen 1999).

ENUMERATION OF BIODIVERSITY

> We need an expedition to planet Earth, where probably fewer than 10 percent of the life forms are known to science, and fewer than 1 percent of those have been studied beyond a simple anatomical description and a few notes on natural history.
>
> (Wilson 2006, p. 116)

Status of species discovery and description

Species represent the basic units by which biodiversity is measured, and, as such, the first goal of Systematics Agenda 2000 is critical. Accuracy in the estimation of extinction rates, the establishment of conservation priorities based on biodiversity hotspots, and the designation of lineages that are essential for ecosystem function and the long-term survival of biodiversity require knowledge of the approximate number of species currently inhabiting the Earth.

How far have we progressed in our discovery and description of species since Linnaeus? According to Mayr (1969), Linnaeus's *Systema Naturae* lists 4,162 species, and since Linnaeus's time, the enumeration of total species has shown progress, with the current number of discovered species being between 1.5 million and 1.9 million (May 1988, 1990, 1992). Species discovery for birds (Mayr 1946; Monroe and Sibley 1990; Peterson 1998; MacKinnon 2000), mammals (May 1988; Wilson & Reeder 1993, 2005; Patterson 2001; IUCN Red List of Threatened Species 2008), amphibians (Glaw & Köhler 1998; Köhler et al. 2005; Frost 2006; AmphibiaWeb 2010), and turtles (Bickham et al. 2007) is reasonably well documented, and all these groups show an increase in species discovery since Linnaeus, with most species of birds described early in the last century (Fig. 1–3).

The overall rate of species discovery is clearly increasing. For instance, in 2006 (State of Observed Species 2008), 16,969 new species of plants and animals were discovered, with the majority represented by vascular plants and invertebrates (Fig. 1–4). The rate of discovery of amphibian species increased by approximately 26% between 1992 and 2003, and in some geographic regions (e.g., Madagascar) the increase was 42% (Köhler et al. 2005). Mammalian species continue to be discovered. According to Patterson (2000), the rate of discovery of mammalian species in the neotropics is ten times that seen for birds. This rate of discovery is especially high for smaller mammals, such as rodents and bats (Patterson 2001), and in some cases species were rediscovered from existing collections and more recent genetic studies (Patterson 2000).

Although microbial diversity is essential to ecosystem function (Woese 1994), only approximately 5,000 species have been described (Pace 1997). In the past, this lack of species discovery was hindered by the fact that approximately 99% of microbes cannot be cultured (Amann et al. 1995). Most knowledge of bacterial species diversity comes from nucleotide sequences of ribosomal ribonucleic acid (rRNA) (Pace et al. 1986), and molecular markers are now being used to survey microbial diversity in a variety of habitats including soil (Schloss & Handelsman 2006), air (Brodie et al. 2007), marine communities (Sogin et al. 2006; Frias-Lopez et al. 2008), and extreme environments (Huber et al. 2007).

Despite the overall increase in the rate of species discovery, the tally of all species is incomplete and varies greatly across groups. Previous estimates of the potential number of species range between 5 million and 50 million, and the most current estimates are between 15.6 million and 19 million species (Erwin 1982; May 1988, 1992, 1998; Hammond 1992; Stork 1993; Ødegaard 2000; Novotny et al. 2007). Therefore, based on these numbers, our knowledge is limited to about 10% of the Earth's biodiversity (Fig. 1–5). Even for some groups of vertebrates, an all-species inventory is far from complete. For instance, with the exception of turtles, which are reasonably well known and assessed (Baillie et al. 2004; Bickham et al. 2007), the conservation status of many species of reptiles and fishes is less well known, partially as a consequence of the lack of an all-species inventory for these two groups (Table 1–1).

The most species-rich groups of organisms are even less well known than reptiles and fishes (Fig. 1–5 and Table 1–1). Approximately 59% of all described species are insects and 75% of all described species are invertebrates, yet the conservation status for most of these species has not been evaluated (IUCN 2008; Table 1–1). Even more disturbing is the fact that 80–95% of insect species have not been discovered (Stork 2007), and the number of arthropod species may range between five million and thirty million (Erwin 1982; Ødegaard 2000). On the basis of molecular markers, we are far from determining the number of microbial

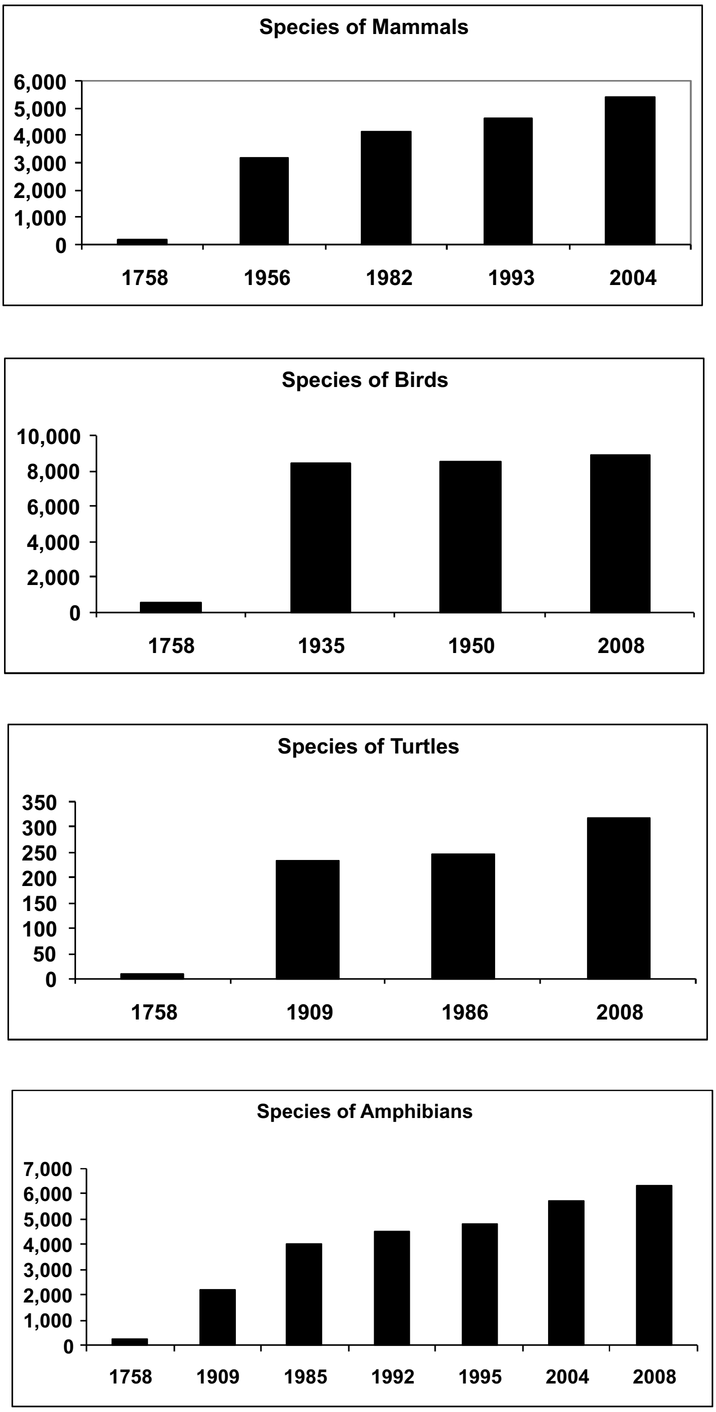

Figure 1–3: Species of vertebrates discovered since Linnaeus.