

THREATENED BIODIVERSITY: UNDERSTANDING, PREDICTING, TAKING ACTION

MARINO GATTO & RENATO CASAGRANDE

1. *What is Biodiversity?*

The history of biodiversity is actually the history of life itself, which originated quite likely 3.7 billion years ago, certainly in the water, perhaps in deep sea vents (see Fig. 1, page 207). We must not forget that the Earth's crust and atmosphere, as we know them, have been shaped by the evolution of diverse organisms.

Life originated in anoxic environments (originally there was no oxygen in water and the atmosphere). The appearance of organisms with the ability to photosynthesize allowed the build-up of oxygen and the development of an atmosphere like the one we experience today.

In his book *What is Life?* the famous Nobel prize for physics Erwin Schrödinger (1944) predicted that the most essential part of a living cell is an aperiodic crystal. His prophecy, which somehow inspired James Watson (according to his statements, 2003), was confirmed by the discovery of the structure of DNA and other nucleic acids a few years later. Schrödinger pointed out that the genome must be on one side very stable – after all, one of the main characteristics of organisms is that they can make copies of themselves – but on the other side quite flexible, that is, capable of development, evolution, and ramification, in other words of diversification. In fact, the structure of DNA possesses exactly these remarkable features. Without knowing anything about genetics or molecular biology, one of the giants of modern scientific thinking, Charles Darwin, had already understood the main mechanisms of this incredible ramification (Darwin, 1859). Life diversification is driven by mutation, but if mutation, that is randomness, were the unique cause of diversification we would not see patterns and organization in the Earth's bios-

phere. Instead, life organization is shaped by the process of natural selection. First of all, mutation is anyway quite infrequent, because of genome stability, and many mutations are deleterious. Of the nondeleterious ones just a few can pass through the sieve of natural selection, which favors those mutants that have a demographic advantage. Selection is very severe, but the sieve acts continuously on myriads of organisms, so it is very effective in the long term and produces organisms adapted to their environment. In small populations neutral mutations can establish, due to a random process called genetic drift (this was pointed out more recently by Kimura and Crow, 1964). In addition, we must not forget that, during the course of life ramification, the evolution of the various organisms has been constrained by the presence of other organisms ecologically interacting with them: therefore evolution is actually co-evolution and adaptation is co-adaptation.

Each organism is unique as it is identified by its genetic code, but one can easily recognize groups of organisms, clusters of genotypes that are very similar. It is the well-known concept of species. The definition is quite clear for sexual beings, for which we refer to a species as to a set of individuals that interbreed freely with one another to produce fertile offspring. In the case of asexual species, it is much more difficult to group organisms and the choice can be to some extent arbitrary, because it is based on their 'characters'. More and more frequently, however, this classification is based on genetic differences. For instance, in the case of the ubiquitous cyanobacterium *Prochlorococcus* (perhaps the most important oxygenic photosynthesizer of the world's oceans), only the analysis of the genome can distinguish between two different strains (*Prochlorococcus marinus* MED4 and *Prochlorococcus marinus* MIT9313) that actually turn out to play significantly different ecological roles (Rocap *et al.*, 2003).

But genetics or taxonomy do not tell us the whole story. We can actually distinguish hierarchies of biodiversity. There is diversity of genomes inside each species, diversity of species and other taxonomic classes inside an ecosystem and diversity of ecosystems inside the landscape of a region. Traditionally, species diversity is the one most commonly used but there is a growing consensus among biologists that diversity of species functions within an ecosystem and diversity of habitats within a landscape play a very important role and deserve much more attention than that devoted to them up to now. If we consider a single ecosystem, we can for instance pay attention to its trophic structure distinguishing primary producers (e.g., plants), herbivores, carnivores, secondary carnivores and

decomposers. Very often, it is reasonable to study species diversity inside each trophic level or guild (group of organisms playing a similar ecological role in the community). But the overall picture of ecosystem diversity can be obtained only by coupling these studies with the study of the food web structure and the flow of energy and materials within the web.

2. *Patterns of Biodiversity*

The most basic question one can ask is how much we do know about the biodiversity of our planet in simple descriptive terms. Actually, very little: we do not even know how many species are hosted by our mother Earth. At present, about 1.75 million species (Purvis and Hector, 2000) have been classified, but many more are still waiting for us to recognize their sheer presence (so much the less for describing their physiology or ecology). The best estimate is that there might be 10 million species, but the uncertainty of the estimate is very high (between 3 and 30 million). Also, the knowledge of world biodiversity is not the same across the taxonomic groups (see Fig. 2, page 208). It is very good for birds and mammals and very bad for bacteria. Insects are the dominators of our earth, because they have ramified into an incredible number of species.

Biodiversity is not spread evenly across the earth. There are a few regions that contain a high number of species, which are in many cases endemic, namely specific to that particular site. These regions (see Fig. 3, page 209) have been called hotspots by Norman Myers and colleagues in a keystone article (Myers *et al.*, 2000). Of course, hotspots are very important because they need a special attention when we want to design global policies that aim at preserving biodiversity on our planet.

From the available, though insufficient, data it is possible to recognize some precise geographic patterns of species diversity on our Earth. This empirical knowledge is preliminary to understanding the mechanisms that determine species diversity. First, there is a clear latitudinal gradient of biodiversity from the poles toward the equator (see Rohde, 1992). For any kind of guild or taxonomic group, be it butterflies or lizards or birds, we can say that there is an increasing number of species as we travel from the poles to the tropics. Second, there is a remarkable area effect. This is specially apparent in archipelagos, where there is a clear power law relating the number of species S to the area A of each island: $S = cA^z$.

Surprisingly, the exponent z is about 0.3 for a great variety of taxa and geographical locations (Preston, 1962). But the species-area power law

operates even in the habitats that constitute islands inside the mainland, like lakes or caves or forest fragments. Third, there is a relationship between species diversity and climatic indicators (Gaston, 2000). For instance, summer temperature is a main determinant of bird diversity in Britain and sea temperature is a key factor for gastropod diversity in the Pacific. Evapotranspiration is not only the main explanatory variable for tree diversity, but is a main determinant of animal diversity, although the relationship for higher trophic levels is saturating.

Describing biodiversity only in terms of the number of species is too simplistic, since the concept of diversity is actually multidimensional and hierarchical as we already pointed out. In particular, species can be more or less abundant. Ecological communities with one or two species that are very abundant and dominate the landscape are intrinsically less diverse than communities in which all the species have more or less the same abundance. So, observed species-abundance relationships are crucial to properly describing biodiversity. Also, size, color, shape, physiological and genetic traits are yet other important components of diversity.

Can we explain the underlying causes of the various diversity patterns? The word ‘explaining’ here means formulating scientific theories that are validated by data and can make correct predictions. There are a lot of theories, and reviewing all of them goes well beyond the scope of this article. To give the flavor of how complex the problem is, we just provide a few ideas about how to approach this kind of questions.

The modern theory on what shapes the distribution of species within the same trophic level (for instance, herbivores) is due to one of the most brilliant ecologists of the past century, Robert H. MacArthur. He developed a clear methodological approach to the problem of competition for common resources and precisely defined the concept of ecological niche by means of his utilization functions (MacArthur, 1958). These are defined as the probability that different resources be utilized by each species. In general, similar species occupy the resource dimensions with niches that overlap, but not too much (limiting similarity). It was shown by May and MacArthur (1972) that species can coexist if approximately the niche width (measured, for instance, by the standard deviation of the utilization function in one-dimensional resource spaces) is smaller than the distance between niches. To what extent the principle of limiting similarity can be generalized is an open question, debated from the early 1970s to date (e.g., Meszena *et al.*, 2006)

MacArthur’s approach (1957) allows the prediction of several species-abundance relationships that might result from different competition rules.

If there is resource pre-emption with the arrival of a first species that utilizes a proportion k of the resources, then of a second species utilizing the same proportion k of the remaining $1-k$ and so on, the resulting abundance distribution is a geometric series. If the species arrivals are random, the distribution is a log-series. By contrast, suppose that all the competing species occupy the resource space simultaneously, but the allocation of resources among species is just random. Then the process is similar to taking a chocolate bar and dividing it at random. The species that gets a bigger chunk will have greater abundance. This paradigm is aptly called the *broken-stick model*. Finally, there might be many random factors and resources that are important for competition and act in succession. The central limit theorem would predict a log-normal distribution for this case.

When we look at the data we discover that, depending on the circumstances, they can actually match one or the other of the 4 models (or even a combination of two models as in the case of Bristol Channel fish shown in Fig. 4) or none of the models described above. This is not discouraging. It simply means that the problem of explaining biodiversity is complicated. There can be concurrent phenomena acting together, but accurate analysis of data and ecological theory can unravel, if not the totality, at least part of the underlying causes of the observed diversity patterns.

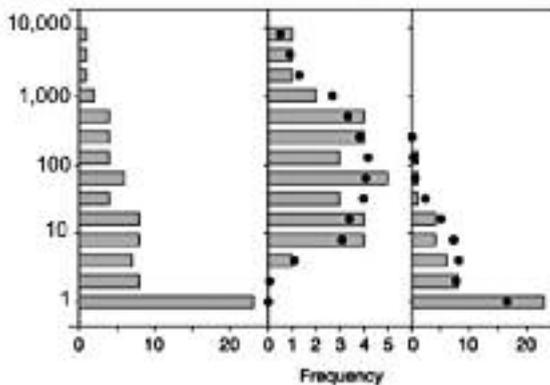


Figure 4. Reprinted with permission from Magurran and Henderson (2003). The data for a fish community in the Bristol Channel, UK. The abundance distribution for all species (left histogram) can be seen as the sum of the abundance distribution of the core species (central histogram) and the abundance distribution of the occasional species (right histogram). The black dots in the central and right panels represent a log-normal fit and a log series fit respectively.

However, biodiversity should not be understood only within a trophic level, but also across the food chains of the whole ecosystem. For instance, if we lose species from the ecosystem food web, how much is the ecosystem functioning (suitably defined) compromised? Given the present loss of species richness at the global level, this is not only a theoretical question but has important practical implications. It is generally recognized, from both data and theories, that fortunately there is some kind of redundancy. In other words ecosystem functioning does not linearly increase with species richness, but is saturating. There are several ways to quantitatively describe ecosystem functioning. One is productivity (for instance, net primary production or standing biomass per unit area). The experimental and theoretical work (especially important the analysis of grasslands by Tilman and colleagues, 2001, see Fig. 5, page 210) confirms that ecosystem productivity increases with species richness according to a nonlinear concave relationship.

A second way to describe ecosystem functioning is stability. Here the problem is much more complicated. The traditional viewpoint, which goes back to the 1950s and the work of Charles Elton (1958), is that more diverse systems, such as tropical forests, are intrinsically more stable than species-poor communities. The celebrated experiments by Robert Paine (1966) with the manipulation of rocky tidal communities seem to confirm this viewpoint. When Paine eliminated the top predator (the starfish) from the community, the ecosystem collapsed with mussels becoming the dominant species. However, the Elton-Paine viewpoint was challenged by the theoretical analysis conducted by Robert May (1973). He showed that in general more complex dynamical ecosystems are less stable. In fact May's condition for community stability in randomly assembled food webs is:

$$SC < i^2$$

where S stays for the number of species in the community, C represents the probability that any pair of species will in fact interact (food web connectance) and i is the average interaction strength.

By assuming that both web connectance and species interaction strength are more or less independent of the species number, May obtained that the likelihood of having all the eigenvalues of the community equilibrium with negative real parts, which implies community stabili-

ty, is higher when the number of species is smaller. Robert May's provocation stimulated a lot of work (reviewed by McCann, 2000). Many authors pointed out the weakness of May's assumption that (1) food webs are randomly assembled, (2) the interaction strength is constant, (3) stability is defined à la Lyapunov (internal stability of equilibria). These conditions are unrealistic because: first, food webs are not random, rather the result of coevolution; second, the links between different ecosystem components can be extremely strong or weak and variable in time; and third, community diversity can be maintained by external disturbance. In extreme synthesis, after a long debate it is now widely believed that both data and theory support the original Elton-Paine intuition that more diverse ecosystems are more stable or resilient or resistant to perturbation.

3. *The Loss of Biodiversity*

The problem of present and future biodiversity loss is confused by some people with the 'natural' ebbs and falls of diversity at the evolutionary timescale. Our Earth has always been experiencing biodiversity loss since the origin of life. More precisely, there have been five periods of mass extinctions followed by subsequent radiation. The causes of these extinctions are not very well-known. In contrast, the cause of the forthcoming sixth extinction is very well-known and it is man. That's why Paul Crutzen (2002) has termed the present era the *Anthropocene*.

When the skeptics say that species have always become extinct and we should not worry, they make a very common mistake: they pay no attention to the time and space scale. The problem is that the geological lifetime of species was of the order of millions of years, while it is now estimated to be of the order of tens of thousands of years. In particular, birds and mammals (Fig. 6, see over) are very much endangered, because their species lifetime is reduced to hundreds of years (Lawton and May, 1995). Islands are specially vulnerable, because of the species-area relationship we cited above. Of the many bird species presently inhabiting the Hawaii, few are indigenous because the majority of them have become extinct or are on the verge of extinction. Of the current 272 bird species found in the Hawaii, 54 are alien, 50 are native resident species, 155 are nonbreeding visitors and 13 breeding visitors. It is estimated that before man's arrival (about 2000 years ago) there were at least 128 species of native breeding birds (American Ornithologists Union, 1983).

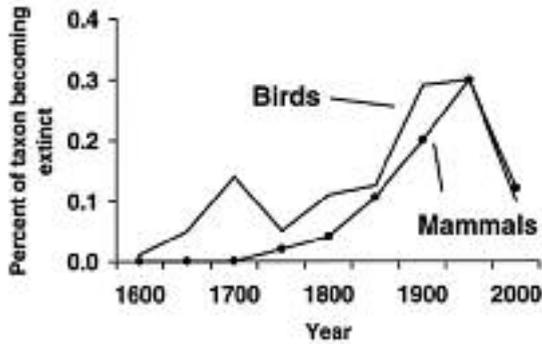


Figure 6. Reprinted with permission after Primack (1998). Changes in extinction rates over time in mammals and birds as estimated by Smith *et al.* (1993).

What are the main factors leading species to extinction? Statistics have been made. The most important one is the destruction and degradation of habitat, followed by the introduction of exotic species, by pollution and by overexploitation. There are many examples of habitat degradation, the most impressive being probably the daily destruction of tropical forests at unbelievable rates. While the forests of Europe have been destroyed and fragmented on a time scale of centuries, and with the aim of building villages and towns that originated our present culture, the Amazon forest is being destroyed on a much shorter time scale (just a few decades) and mainly to produce resources for what we call the developed countries. Often fragmentation is linked to road construction as in the example of Brazil rain forest. Sometimes, like in the example of Bolivian forests shown in Fig. 7 (see over), the land use is being converted to soy-bean cultivation for export, mostly funded by foreign loans. Destruction is unfortunately very fast and creates an unnatural mosaic of patches at different spatial scales.

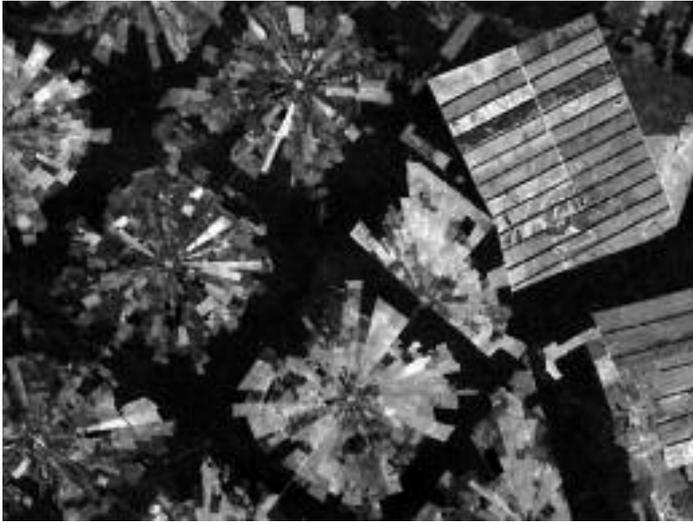


Figure 7. A Landsat7 image dated august 2000 showing the new agricultural settlements east of Santa Cruz de la Sierra, Bolivia in an area of tropical dry forest. (Credit Landsat image courtesy USGS EROS Data Center and Landsat7 science team. Photographs courtesy Compton Tucker, NASA GSFC).

Many modelling efforts are currently made to understand and predict the loss of biodiversity due to habitat fragmentation. First of all, it is important to remark that even unperturbed populations are in many cases fragmented. The butterflies *Melitaea cinxia* in the Ålan Island (Hanski *et al.*, 1995) and *Euphidra editha* in California (Harrison *et al.*, 1988) are just two famous examples. The first species lives in a landscape composed by hundreds of vegetation patches located in many islands while the second requires a particular habitat (serpentine grasslands) which is patchily distributed in California. The famous ecologist Richard Levins (1970) was the first who used the term metapopulations (namely 'populations of populations') to indicate a set of local populations in which local extinctions can be balanced by dispersal from other occupied patches. Metapopulation is now the current paradigm not only for populations inhabiting naturally inhomogeneous landscapes but also for populations endangered by habitat fragmentation. The key points are two: (1) local populations can become extinct, because they are small and subject to random effects, but (2) dispersal from occupied patches can lead to recolonization of empty habitat

patches thus salvaging the global metapopulation. There are several models for studying the process of extinction in fragmented populations (see Hanski and Gaggiotti, 2004). The fundamental parameters that describe every metapopulation are the landscape structure (number and average size of fragments and distance among patches), the ability of the species to disperse and colonize empty fragments, the demographic potential of the species inside each habitat fragment. One of the fundamental points for appropriately evaluating the risk of extinction is that each fragment hosts very few individuals. So an appropriate model is one that considers individuals as discrete entities subject to demographic stochasticity (Casagrandi and Gatto, 1999; Casagrandi and Gatto, 2006).

Using a Markov model and assuming initially no space structure (i.e., an infinite number of equal and equally connected patches), we have shown that metapopulation persistence requires a sufficiently high rate of demographic increase (and this is somehow obvious) and an intermediate dispersal rate (this is less obvious). Therefore, species that are most at risk are those moving too little, because empty fragments cannot be effectively recolonized, or moving too much, because dispersing individuals can end up in unsuitable habitat without being able to reach suitable habitat patches. But the really interesting result is the one we obtain when we consider realistic, space-explicit metapopulations in which we have a finite, small number of patches, each hosting a local population with a discrete number of individuals that can disperse only to contiguous patches. The principle of intermediate dispersal is still valid. Obviously the likelihood of species extinction is higher than that in a very large network of patches connected at any space scale. We can actually quantify the proportion of species that are lost because only a few habitat fragments are left. There is a power law relating this proportion to the number of patches (Fig. 8, see over). The result is theoretical, but has some implication for applied problems too. For instance we can estimate that the cost of losing a habitat fragment when there are 5 patches left (each hosting at most 10 individuals) is the loss of a further 4% of the species living in the fragments. So, theoretical work can lead to important predictions on the loss of biodiversity we may expect in the future decades.

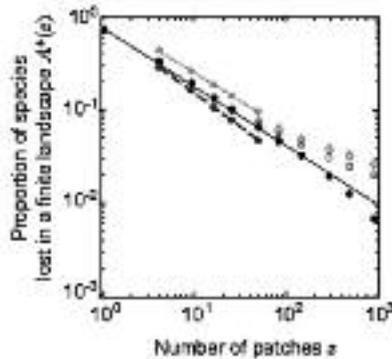


Figure 8. Reprinted with permission from Casagrandi and Gatto (2006). The proportion of species $A^*(z)$ that are lost in a fragmented landscape composed by less than infinite fragments is plotted against the number of patches z . As it is evident, there is a power law indicating that it is at least roughly possible to estimate the number of species lost by destroying a patch.

In addition to habitat fragmentation and destruction, there is now another major threat to future biodiversity loss and this is Global Climate Change (GCC). The golden toad (*Bufo periglenes*) of the mountains of Costa Rica is probably the first species that was officially declared extinct because of climate change. An estimated 67% of the 110 or so species of harlequin frogs (*Atelopus sp.*), which are endemic to the American tropics, have met the same fate (Pounds *et al.*, 2006). Other species escape from climate change by moving. Others, with possible effects on man's health, such as malaria carrying mosquitoes, thrive in the warming environments. In the oceans, coral reefs are the ecosystems hosting the most of diversity. They are very sensitive to temperature, because they can survive only inside a restricted range of water temperature. There have already been several episodes of coral bleaching and this is certainly related to increasing sea surface temperatures, as documented by the NOAA-NESDIS (National Oceanic and Atmospheric Administration, National Environmental Satellite Data and Information Service) and by the UNEP-WCMC (United Nations Environment Program – World Conservation Monitoring Centre).

A lot of modelling work is now being done to forecast the loss of biodiversity due to global climate change. Before discussing this matter, let

us point out that organisms are among the best indicators of global warming. The ecological fingerprints of GCC, as they have been called, are clear. The shift in plant and animal phenology (namely the time of flowering or reproduction) is apparent. In the recent decades there has been a mean shift of 5 days per decade with birds being the most sensitive to the climatic signal (Root *et al.*, 2003). Poleward shift of indicator species like butterflies is also being discovered (Parmesan *et al.*, 1999). Very clear is the elevational shift too. For instance the response of Alpine vegetation (the beautiful flowers of European Alps) to warming is of a few meters per decade (Grabherr *et al.*, 1994).

Studying the effects of GCC on our planet biodiversity is not an easy task. The web of impacts is very intricate and there are a lot of pathways one should account for (Hughes, 2000). Different time scales are involved (physiological, demographic, behavioral and even genetic if we consider adaptation); different trophic levels and species interactions must be considered, at least in principle.

We can make a classification of models that can be used to predict the response to global climate change. First, models can be static or dynamic. Static models assume that we observe populations only at equilibrium (which is sometimes a reasonable approximation for short-lived species) and that species' distribution and abundance are related to exogenous factors, including climate, through a simple function. In practice, one assumes that species can track the climatic change without any delay. In dynamic models the response of species to the global warming trend is not instantaneous and time lags are considered. For instance models of this kind try to predict the shift of treeline. Second, models can consider species as isolated or describe the response of the whole ecological community. Clearly, it would be necessary to consider species interactions, but this is rarely done in practice, because it complicates the problem awfully. As of now, the most common approach is to use individualistic responses of the different species and simply make a collection of a great number of them. Finally, conceptually different models must be used for different spatial scales. For instance, the vegetation distribution at a broad scale (tens of kilometers) is mostly governed by the climatic tolerance of species physiology, while at a finer scale the soil composition and topography play an important role. Of course, regional governments would like to know what the global change will imply at a reasonably detailed local scale. '*Think globally and act locally*' is an often abused statement, which is however very sensible. A lot of effort is now being devoted-

ed to this point but there is an important problem: that of downscaling global climate models. Even the most recent coupled atmosphere-ocean general circulation models have a resolution of a few hundred of kilometers. Regional models with a resolution of 50 km are being developed for limited areas via suitable downscaling techniques. So, the problem is not solved at the climatic level yet, much the less at the ecological level.

Probably the most used models to predict the impacts of GCC on ecosystems are the so-called envelope models. Usually they are based on describing the climate or environment encompassing the current distribution of a species or ecosystem (the environmental envelope or climatic envelope), then mapping the location of this same envelope under a climate change scenario. The various envelope models of a great many species can be put together to produce predictions of changing biodiversity. Fig. 9 (see page 211) shows the results of this kind of simulation for Europe in 2100. Mediterranean countries and the Balkans will be most affected in the future. It must be remarked that habitat fragmentation and GCC can have a synergistic effect. Species would like to move to avoid global warming, but that might be impossible because there are barriers and few or no corridors left to escape. A recent projection for the world biodiversity by Thomas and colleagues (2004) indicates that 25% of the species might become extinct by 2050 (mid-range scenario). Even if this prediction were wrong by an order of magnitude the loss would be anyway devastating.

4. *The Value of Biodiversity*

A question that is frequently asked is why we should preserve biodiversity. Is it really so 'valuable'? Isn't it a waste of money, a luxury that only rich countries can afford? Clearly this question involves not only science, but also ethical considerations. Social scientists make a distinction among direct value (what we can extract from organisms, namely food, fiber, etc.), indirect value (the free services provided by ecosystems) and intrinsic value (aesthetic, spiritual, etc.). We will not discuss this third kind of value, which is in a way evident but in another way more debatable.

Let us first give a very clear example of ecosystem services. During the tsunami that hit the shores of East Asia in December 2004, in the areas of Sri Lanka where the coral was still intact, the wave travelled just 50 meters inland without causing any death. Unfortunately, this did not happen a few kilometers away where coral reefs had been illegally destroyed

(Fernando, 2005). Ecosystem services are indeed uncountable. The following list of benefits provided by ecosystems is certainly incomplete:

- moderate weather extremes, thus contributing to climate stability
- mitigate drought and flood impacts
- protect stream and river channels and coastal shores from erosion
- protect people from the sun's harmful ultraviolet ray
- cycle and move nutrients
- purify the air and water
- detoxify and decompose wastes
- control agricultural pests
- regulate disease carrying organisms
- disperse seeds, pollinate crops and natural vegetation
- generate and preserve soils and renew their fertility

While at the beginning of the 1970s there was a growing awareness that environmental evaluation and assessment is as necessary as economic evaluation (just think of the legislation on EIA – Environmental Impact Assessment – that was passed in North America and Europe), in more recent years the old logic that economic evaluation should prevail on any other consideration has gained new strength. This led Robert Costanza and colleagues (1997) to conduct a purely monetary evaluation of the resources and services that are provided to us by biodiversity. They estimated that these services were worth US\$ 33 trillion (global GNP being US\$ 18 trillion). Although that approach has been criticized (Gatto and De Leo, 2000), we must admit that its results should convince even the most skeptical economist. In other words, preserving biodiversity does pay off. Ecosystem services are worth at least twice the global GNP. Any time we lose a species, we may lose the potential remedy for a disrupting disease affecting humanity. In fact 80% of the world's population relies upon natural medicinal products. Of the top 150 prescription drugs used in the U.S., 118 originate from natural sources: 74% from plants, 18% from fungi, 5% from bacteria, and 3% from one vertebrate (snake species). Nine of the top 10 drugs originate from natural plant products. Over 100,000 different animal species – including bats, bees, flies, moths, beetles, birds, and butterflies – provide free pollination services. One third of human food comes from plants pollinated by wild pollinators. The value of pollination services from wild pollinators in the U.S. alone is estimated at four to six billion dollars per year.

Benefit-cost analyses can be conducted and they show that it is not true that preserving biodiversity is too expensive for developing countries. Actually, the cost of preservation is largely outweighed by the benefits (see Balmford *et al.*, 2002, 2003).

5. *Preserving Biodiversity*

An extremely difficult, but urgent, question we can make at this point is about what we should do, as humanity, to preserve biodiversity. A couple of ecologists alone, as the authors of this chapter, cannot face such a huge question in a serious way, of course. However, we can try to introduce the problem by hinting at the main discussion that is taking place right now: Where should the efforts at a global level be directed? Financial and other resources that can be devoted to preserving biodiversity are limited. So there is a problem of optimal allocation of money, time, labor, etc. Where should our dollars or euros go? To preserving the Mediterranean flora or the Australian fauna? As mentioned at the beginning of this chapter, Norman Myers and colleagues (2000) identified 25 hotspots of biodiversity in the world using species endemism and degree of threat. That work sparked a very useful debate. Obviously, the optimal allocation is really a multicriteria problem. The answer depends on the criterion being used. Recently, Orme and coauthors (2005) have performed a very interesting analysis on bird biodiversity (avian fauna is very well known) considering 3 different criteria: species richness, species threat, and endemic species richness. The resulting hotspots do not coincide, as you can see from the 3 maps overlaid in different colors in Fig. 10 (see page 212). However, there is some overlap among the areas identified by the 3 criteria. Endemic species richness is apparently the criterion that is most representative, in the sense that it includes areas and species that are also included by the other criteria. The hottest hotspot is Tropical Andes which is pinpointed by all 3 criteria. It is interesting to remark that the hotspots are mainly located in highlands and archipelagos.

This viewpoint is partially contradicted by another analysis which considers a different indicator of ecological diversity. It is true that the species is the key concept of diversity and the basic unit of life evolution. However, we already mentioned that ecosystem functioning is another important goal. And even the goal of preserving species might be better achieved by aiming at preserving not each species but rather the habitat where species live (Hoekstra *et al.*, 2005). So another possible target of conservation is that of preserving habitats and biomes that are fast disappearing, like the Mediterranean vegetation. It is interesting to note that, for instance, in Hoekstra *et al.*'s (2005) map Tropical Andes are no longer present. They have a very high endemic species richness, but the habitat as a whole is not currently critically endangered. Also, consider that some

ecosystems hosting little biodiversity, like the vast tracts of boreal forests from Russia to Canada, provide important ecosystem services such as the uptake of carbon from atmosphere, which is fundamental for the mitigation of global warming. These ecosystems were not classified by Myers *et al.* (2000) as hotspots of biodiversity, yet they deserve conservation. So the debate is very much open.

An important issue for global conservation is that of gap species. In September 2003 it was announced that the global network of protected areas now covers 11.5% of the planet's land surface (at least formally). This seems a very good achievement, actually beyond the target set a decade ago. However, the protected areas are not designed in such a way as to really protect the necessary amount of biodiversity. In particular there are many species that are officially declared as endangered by IUCN (International Union for Conservation of Nature) and are not inside any protected area (Rodrigues *et al.*, 2004). Overall, 20% of all threatened species analysed were identified as gap species. In particular, amphibians are given little protection. By the way, from this analysis it turns out that Tropical Andes has a lot of gap species!

So what should we do? Personally, we think that the preservation of ecosystem functioning must be given special attention, more than it is currently given. The regulation of the climate of our earth is of paramount importance. For instance, no effort should be spared to conserve soils which are the most important terrestrial sink of carbon.

6. Conclusions

Understanding and protecting biodiversity is of paramount importance for humanity. As pointed out by Simon Levin (1999) our Earth is an incredibly complex yet fragile dominion. For millennia man has taken for granted that its functioning is very resilient and that human disturbance is small and can be absorbed by the surrounding environment. This is no longer true. The scale of human perturbation has become global. In 16,000 years the human population has expanded more than a thousand-fold in numbers, from a few million to over six billion by the turn of the 21st century; fish stocks are now depleted all over the oceans (Watson and Pauly, 2001); the combustion of fossil fuels has driven the concentration of carbon dioxide to levels unprecedented in the past 650,000 years (Siegenthaler *et al.*, 2005), and tropical forests which are the most diverse biomes on our planet are being destroyed at very high rates (The Food

and Agriculture Organization, FAO, estimates that 53,000 square miles of tropical forests – rain forest and other – were destroyed each year during the 1980s). As a consequence the bank of world biodiversity, an astonishing array of genotypes playing the most different roles in the wonderful theatre of life, is being disposed of day after day.

In the chapters of Bible describing the deluge and Noah's ark we can find the verses:

The Lord then said to Noah, 'Go into the ark, you and your whole family, because I have found you righteous in this generation. Take with you seven of every kind of clean animal, a male and its mate, and two of every kind of unclean animal, a male and its mate, and also seven of every kind of bird, male and female, to keep their various kinds alive throughout the earth' (*Gen. 7:1-3*).

It is interesting to notice that God said to Noah he should bring with him any sort of animals, both clean and unclean. In this chapter we have shown that there exist compelling scientific and economic reasons for protecting our biosphere, but we think it is also a moral obligation for us to preserve biodiversity in its totality, from the beautiful giant pandas to the humble earthworms. They are all necessary to the well-being of our living planet.

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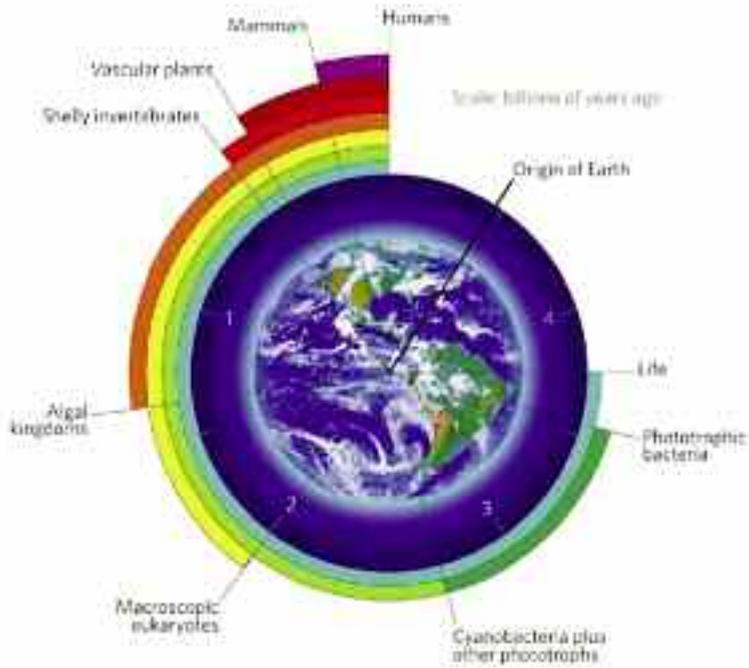


Figure 1. Reprinted with permission from Des Marais (2005). A diagrammatic clock sketching the ages of life on Earth.

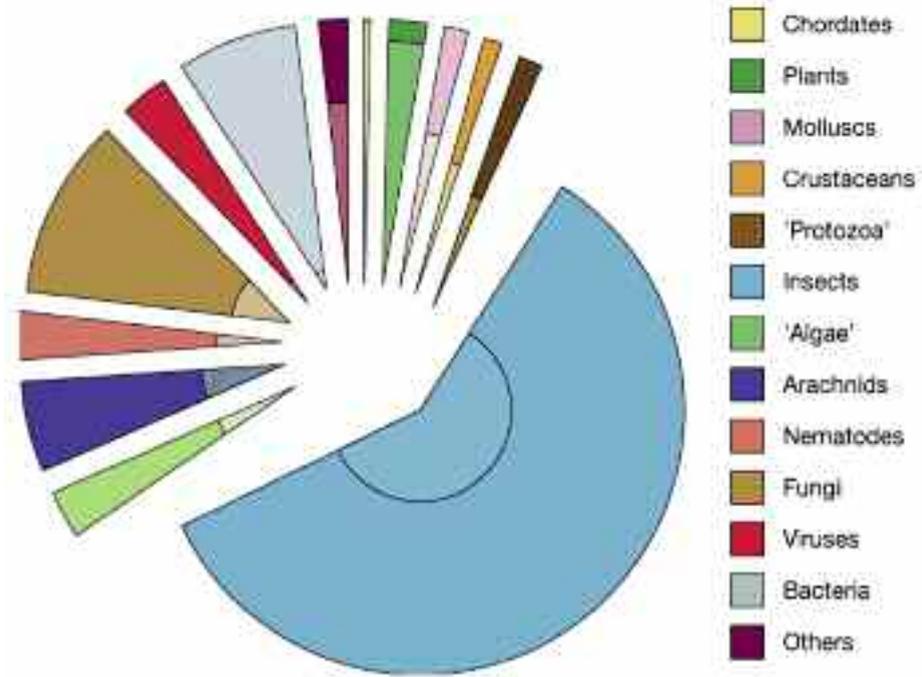


Figure 2. Reprinted with permission from Purvis and Hector (2000). How the world biodiversity is probably subdivided across different taxonomic groups. The area of each slice of the pie represents the number of species estimated to exist in each group; the inner sectors show the proportion that have been formally described.

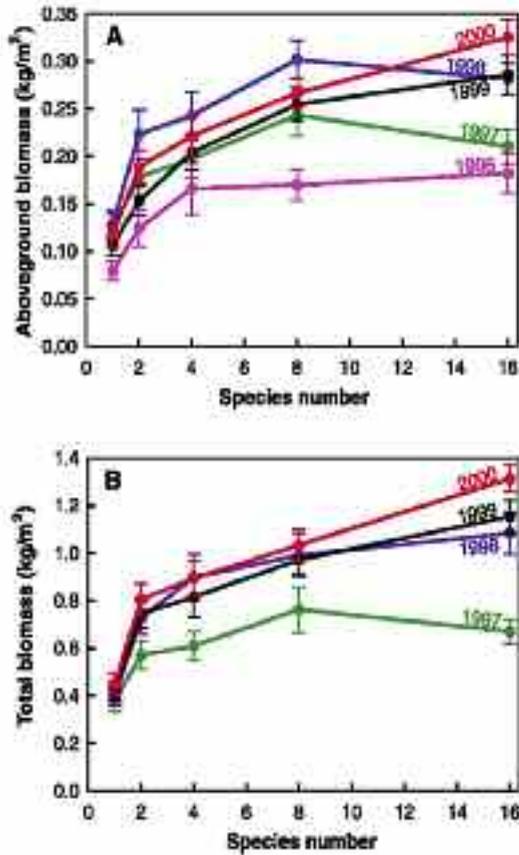


Figure 5. Reprinted with permission after Tilman *et al.* (2001). Results of experiments in a north-American grassland (A) The plant aboveground biomass and (B) the total biomass, i.e., aboveground plus belowground living plant mass, as functions of the number of planted species. Data are shown as the mean \pm SE.

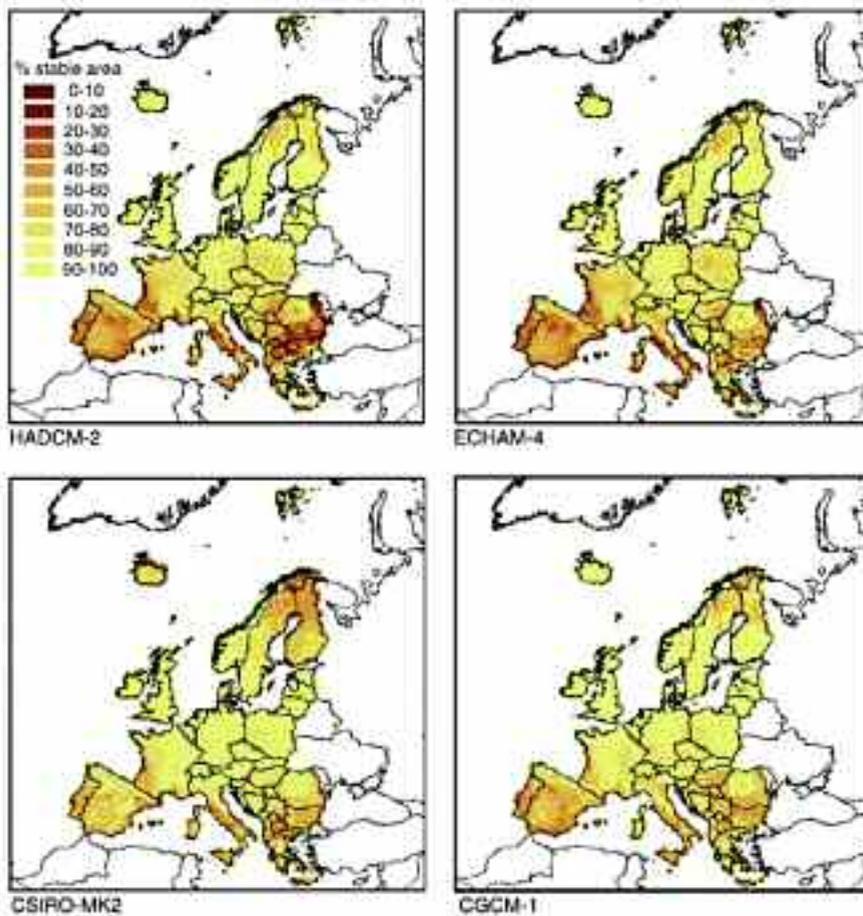


Figure 9. Reprinted with permission after Bakkens *et al.* (2006). Biodiversity changes in Europe by 2100 in the baseline climate scenario (namely with business as usual emissions, Van Vuuren *et al.*, 2003) according to four different Global Circulation Models. For each grid cell, % stable area is defined as the percentage of vascular plant species for which the cell will remain suitable with respect to 1995.



Figure 10. Hotspots of species richness (in green), hotspots of threatened species (in yellow) and hotspots of endemic species (in red). Modified after Orme *et al.* (2005).