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# THE ECONOMIC CASE FOR PROTECTING BIODIVERSITY

Geoffrey Heal

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**ABSTRACT**

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A data appendix is available at http://www.nber.org/data-appendix/w27963

# The Economic Case for Protecting Biodiversity

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**Abstract**

This paper summarizes in non-technical terms the economic case for conserving biodiversity, and explains why we cannot rely on market forces to do this task. It reviews the policy interventions that could help in biodiversity conservation.

*Introduction*

Conserving biodiversity, the range of species on the planet, is crucial to human survival and prosperity. We are a part of biodiversity, and if biodiversity is destroyed, we may be a part of what is lost. Biodiversity is crucial to human well-being: we evolved in concert with it and are dependent on it in myriad ways, some obvious and some subtle.

A powerful illustration of the importance of biodiversity comes from a review of the habitability of Earth compared with our immediate neighbors in the solar system, Venus and Mars. Neither is remotely habitable: Venus way too hot, Mars too cold, Venus with a poisonous atmosphere and Mars with none. Why does Earth have a temperature which is just right for animals like us, and an atmosphere that allows us to live? Because, unlike Venus and Mars, Earth is surrounded by the biosphere, the thin layer of atmosphere, oceans and plant and animal life that extends from the surface of Earth to about ten thousand meters above it. The gaseous composition of the atmosphere ensures that Earth is at a temperature at which we can thrive, and also provides the oxygen we need to function. This atmospheric composition arose as a result of the evolution of blue-green algae, and then much later plants, which by photosynthesis removed carbon dioxide from the atmosphere and replaced it by oxygen, thereby both making our lives possible and stabilizing earth's temperature. Without the natural world that surrounds us we would not and indeed could not exist: it brought us into existence. Biodiversity is a key element of this natural world.

The importance of the natural world, the biosphere, is also emphasized by the extraordinary story of Biosphere 2. Looking like a collection of alien spaceships amidst the sand and cacti of the Sonoran Desert in Arizona, Biosphere 2 is a set of sealed glass buildings enclosing a 3.15-acre ecosystem. Built at great expense and with the latest technologies, its two-year mission was to investigate the possibility of supporting human life in a totally self-contained system. Eight "biospherians" inhabited this complex, together with pollinating insects, and were to grow all their own food in a system with a fixed volume of air and water, both of which were to be recycled and reused. Biosphere 2 was to replicate the functioning of the original biosphere in miniature.

Simply put, it failed: after eighteen months the oxygen level fell from 21 percent to 14 percent, a level normal at 17,500 feet and barely sufficient for humans to function. All of the insect pollinators died, meaning that people had to transfer pollen with Q-tips from flower to flower in the hope of eventually

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getting a zucchini. Had they continued in Biosphere 2, the humans would not have been able to breath or eat. The bottom line is that, sophisticated though we may be, we can't replicate what the natural world provides for us, and so can't survive without it.

*Economic Framework*

Economists recognize the importance of the natural world to the functioning of our societies, and think of this in terms of capital stocks. A capital stock is an asset that provides a flow of services over time. An investment in equities provides a flow of dividends; an investment in a house provides a flow of accommodation services; an investment in a computer provides a flow of digital services. These are examples of the most commonly-recognized types of capital, financial capital (equities) and built capital (houses, computers). Other categories of assets also provide a flow of services over time: knowledge is one of the most important. If you train as a lawyer or accountant or a computer programmer, you can use the knowledge acquired to generate a flow of income over time. We call this human capital, capital embedded in human beings.

For present purposes, another category, natural capital, is important. Natural capital refers to lands, waters and the diversity of life that provide human societies with a flow of services over time. Norway has great lakes that provide huge amounts of electricity via hydro-electric power stations: these lakes and the hydrological systems that replenish them are natural capital. Upstream forests control the waterflow into the lakes and reduce soil erosion, which would otherwise fill the lakes and reduce waterflow. They are clearly equivalent in many ways to conventional power stations, so the designation as capital seems very appropriate. Switzerland's mountains and alpine pastures are beautiful, and also provide excellent conditions for skiing. As a result, many tourists visit Switzerland, adding to the income of those who live there. These geographic features are a form of natural capital. The islands of the Caribbean provide a similar example: their climate and beaches mean that millions of North Americans visit during the winter, adding to the income of the islanders. Climate and geography again combine to form an asset with great value to the local population. The fertile soil of the American Midwest, together with its temperate climate and adequate water supplies, make it a remarkably productive area for growing a range of important food crops, so again a range of geographic and climatic conditions combine to provide a flow of services – food production – that have great economic value. Until only a few decades ago, the North Atlantic teemed with fish such as salmon and cod, providing food and a living for coastal communities, a valuable natural capital stock that has been sadly depleted in the last few decades.

The services that natural capital provides – food production in the cases of the American Midwest and North Atlantic – are called ecosystem services: natural capital is the machinery of nature, the infrastructure on which ecosystems run. So, we now have a picture of natural capital as an asset that supports a variety of ecosystems and together they generate a flow of services which we refer to as ecosystem services.[2]

Although articulated fully only in the last few decades, this perspective is not new: it can be traced back at least to President Theodore Roosevelt, who remarked to the US Congress in 1907 that "*The conservation of our natural resources and their proper use constitutes the fundamental problem which underlies almost every other problem of our national life*" and then went on to remark that "*The nation*

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[2] For an extensive discussion of how to measure and model natural capital and use the idea in conservation projects see the Natural Capital Project at naturalcapitalproject.stanford.edu

*behaves well if it treats the natural resources as assets which it must turn over to the next generation increased and not impaired in value.*" Here is a clear precedent for seeing the living world around us as an asset that is integral to our wellbeing and that repays conservation. An important aspect of this environment-as-natural-capital paradigm is that societies invest in capital: they willingly cut back current consumption to enhance their capital stock. It may therefor make economic sense to invest in the environment: the future returns from an enhanced environment may more than compensate for the loss of current consumption.

In the financial sector, assets are generally valued at the expected present value of the services that they will provide. We can value natural capital in this way too, though valuing the services that it will provide is more challenging than valuing the dividends of an equity. There are often no markets for the services that natural capital provides, and so no prices to provide estimates of value. Nevertheless, researchers have developed techniques that can give answers and provide estimates of economic value.

Biodiversity is an integral part of natural capital, the living part. We generally take the word biodiversity to refer to the total variety of living organisms on the planet, from single celled organisms to great apes. It is the total range of living things together with their genetic, cellular and other biological characteristics that make them unique and different from each other, and enable them to function in their diverse environments.

*Biodiversity's Contributions*

*Soil*

Soil repays closer study. Soil is clearly an asset, particularly productive soils such as those of the American Midwest or of the Punjab in the Indian sub-continent. Both regions are often referred to as the breadbaskets of their countries. Soil is not just a collection of inorganic chemicals: it is a living community populated by a vast range of micro-organisms. Even a handful may contain billions of living creatures. These are an important part of what makes the soil valuable. They interact with the roots of plants growing in the soil and support the chemical processes that make them grow. They are a living (but invisible) component of natural capital and a part of biodiversity. Frequent tilling of soil, and intensive use of fertilizers and pesticides, can kill these micro-organisms and diminish the fertility of the soil. Soil, then, is natural capital with both living and non-living components, and though the living component is the less visible of the two it is arguably the more important. This is an iconic example of biodiversity: an element of the natural world that brings us our essential food, yet is invisible to most of us. Markets recognize the value of productive soils, and farmland in such regions trades for prices greatly in excess of those of less productive areas. In this case markets are recognizing the value of biodiversity, though in most cases biodiversity's value is hard to capture in market transactions.

*Crop Pollination*

Pollinators are another example of a category of biodiversity that is crucial for us, and is only slightly more visible than soil microbes. Plants generally need to be pollinated if they are to bear fruit, although some of the most widely used crop plants are wind-pollinated or have been bred to be self-pollinating. These includes wheat, corn, rice and soybeans.  Other crops, however, need pollinators – fruit, nuts and vegetables typically need an insect or small animal to transfer pollen from one flower to another. In fact, about one third of the food that we eat (by weight), the tastiest and most nutritious third, would not be available without pollinators, generally bees and bats, with birds also important, particularly hummingbirds and sunbirds.  The last few decades have seen a sharp decline in populations of these pollinators world-wide, particularly of insects and bats. Many newspapers and TV programs have reported on the evolving "insect apocalypse", and also on the US's loss of about three billion birds over the same period. One driver of this loss is habitat destruction: clearing natural habitats for farming and residences. Another is the extensive use of pesticides: most plant pests are insects, so pesticides are insecticides and kill pollinating insects too. Bat populations have been reduced to a fraction of their former levels by white nose syndrome, a fungal disease that is spreading around the world. It is one of the worst wildlife diseases of modern time and threatens the continued existence of bats in many regions. In some places, they have also been decimated by wind farms, as the blades of the turbines hit and kill bats. There also seems to have been a collapse of bee populations beyond what could be attributed to habitat destruction and pesticide use, perhaps due to the global spread of mites that infest and kill bees. While the cause remains a mystery, this precipitate drop in pollinator populations has spelled trouble for farmers, and initially led to sharp drops in fruit and vegetable yields.

This collapse of natural populations has led to the emergence of a rental market in pollinators: beekeepers rent hives of bees to farmers whose crops need pollination. The largest managed pollination event in the world is in Californian almond orchards, where nearly half (about one million hives) of the US honey bees are trucked to the almond orchards each spring. New York's apple crop requires about 30,000 hives; Maine's blueberry crop uses about 50,000 hives each year. Some of the domesticated rental bees have been affected by the infections that are killing bee populations, so even this commercial form of pollination does not have an assured future. The market here has replaced natural biodiversity by managed biodiversity.

What's the value of pollination services provided by biodiversity? To think about this, suppose we lost the pollinating insects, bird and bats that currently bring us about one third of our food. There are two questions we can ask: What would be the cost of replacing them? And, if we didn't replace them, what would be the value of the food that we lost?

It's not clear that we could replace them. To date, in many places we have replaced wild pollinators by domesticated ones, bees bred for the purpose, and we are at some risk of losing these as well as the wild insect pollinators due to colony collapse disorder and pesticide use. If we did lose these vital resources, it's not clear that we could replace them, so if we lost pollinators we would probably lose food output too. How much food? German and French researchers recently estimated that worldwide the loss of all pollinators would lead to a drop in annual agricultural output of about $217 billion, a truly huge sum.[3]

But vast as it is, this again may be an underestimate of the value of pollinators. They pollinate wild plants as well as crops, so their absence would have an impact on wild ecosystems, which in turn could have economic consequences. A subtler point is that even if we were to lose $217 billion dollars of food from the absence of pollinators, that missing food might actually be worth a lot more to us than its market value. Suppose for example that we lost an apple crop for which we currently pay $1 million, and other fruits – peaches, grapes, oranges, lemons etc. – worth another $5 million. Is the total value of our loss $6 million? Probably not, because it's likely that even though we actually paid $6 million for what we lost, we would in fact have been willing to pay more for it. Demand for apples doesn't drop to zero if the price rises; people continue to buy them, though perhaps on a reduced scale. The economic value of the apples we have lost is not what we actually paid for them but the maximum we would have been

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[3] Helmholtz Association of German Research Centres (2008, September 15). Economic Value Of Insect Pollination Worldwide Estimated At U.S. $217 Billion. *ScienceDaily*. Retrieved March 1, 2011, from http://www.sciencedaily.com /releases/2008/09/080915122725.htm. See also Smith M.R. et al., Effects of decrease of animal pollinators on human nutrition and global health: a modeling analysis, *The Lancet*, Vol 386, Nov 14 2015. This paper assesses the nutritional impact of the loss of pollinators.

willing to pay, which for foods is generally quite a lot more. There are many goods you might go without if their prices rise even a little, but food is not one of them. In fact, the French and German study cited above takes this point into account, and estimates that the total willingness to pay for the food that we would lose were the pollinators to vanish, would be over $500 billion annually. Using standard financial valuation techniques shows that an asset that produces a stream of services this great has a capital value of about $14 trillion, about 75% of the value of US national income. Think of this as a low estimate of the value of only a part of the Earth's insect population.

Insects also pollinate non-food crops – in fact they pollinate mostly non-food crops. In the US about 80% of the total value of pollination services derive from the pollination of forage crops such as alfalfa, which is fed to cattle and used to produce beef and dairy products. Absent pollinators, some of the beef and dairy products would be lost too. So even this huge number, $500 billion, is on the low side. The bottom line is that pollinators may be very small insects but they loom very large in terms of economic value.

A recent study confirmed the economic importance of bats in the US.[4] In the last decade, white nose syndrome has laid waste to bat populations in parts of the north eastern US. The eliminations of bats from some counties but not all acted like a controlled experiment and enabled researchers to prove that in counties where this has occurred, farmers have significantly increased their purchases of insecticides, showing that bats were making a real contribution to agriculture. The need to pay for insecticides reduces farm profits, and the increase in their use further harms pollinators and also lead to a statistically significant uptick in infant mortality. The conclusion – bats contribute to our welfare along many dimensions.

*Forests*

We have spoken of soil and of pollinators as examples of biodiversity and the contributions it makes to human wellbeing. Forests are another powerful illustration of the importance to us of living organisms. Forests, like watersheds, birds and insects, are mundane but nevertheless play a fundamental role in managing the climate, both locally and globally. Trees manage the balance between carbon dioxide and oxygen in the atmosphere, regulating the amount of the principal greenhouse gas and ensuring that we can breathe. Not for nothing are they often referred to as the lungs of the earth. Using sunlight to generate electric currents, i.e. using solar power, they split water molecules into hydrogen and oxygen and combine the hydrogen with carbon dioxide from the air to produce carbohydrates. Oxygen, which we and all other animals breathe, is a by-product released into the air. Forests and the soil beneath them absorb about a quarter of all emissions of carbon dioxide. This reinforces a point that we noted above - that vegetation is responsible for the earth being habitable by animals like us. In fact, preserving and growing forests is one of the most cost-effective ways of reducing the concentration of greenhouse gases in the atmosphere. Forests, incidentally, are not just collections of trees. Tropical forests, which are the most effective on the planet at capturing and storing CO2, rely on species such as monkeys and birds for regeneration: these species eat the fruits of the trees and pass the seeds, spreading them around the forest and leading to the next generation of trees. And the tropical soils, as we noted before, are alive with millions of micro-organisms.

Trees also affect the climate locally by evapotranspiration, a process by which they release water into the atmosphere. This is one of the reasons why rainforests have rain. A large forest releases so much water that it affects the climate locally and generates rain. We have known for a long time that clearing

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[4] See Eyal Frank, *The Effects of Bat Population Losses on Infant Mortality through Pesticide Use in the U.S.* Available at http://www.eyalfrank.com/research/

forests reduces humidity and rainfall, and a major concern in a country like Brazil with huge forests and also vast agricultural areas is that deforestation will reduce rainfall and hence the productivity of the agricultural areas. In fact, some scientists believe that deforestation of the Amazon region would dry the climate as far north as the US. This is not a small point, as there is evidence that the survival of the Amazon as a rainforest is at risk: rainforest ecosystems can only survive if they operate on a large enough scale, and deforestation may be pushing the Amazon to a point where it no longer has the size needed to be viable.

The climate-stabilizing role of forests has a readily measurable value. Forests capture and store carbon dioxide from the atmosphere – they carry out carbon capture and storage, generally abbreviated to CCS. CCS is the Holy Grail of climate policy: it provides a way to offset the emissions of greenhouse gases from the use of fossil fuels. Many research groups are spending hundreds of millions of dollars trying to develop technologies for CCS, yet trees provide an efficient and proven one available at zero cost. The social cost of carbon is an estimate of the present value of the damages resulting from the release of one extra ton of CO2 into the atmosphere: there is a range of estimates of this number, from about $40 to several hundred. If we value the removal of a ton of CO2 from the atmosphere at the social cost of carbon and very conservatively take this to be at least $35 per ton, then the CCS services of the world's forest are worth roughly $262 billion per year, giving forests viewed as CCS assets a value of about $9.5 trillion. This is a very conservative estimate: it would be easy to argue for a social cost of carbon considerably in excess of $35. Recent research has argued for as much as $600 per ton CO2,[5] which would imply a value for forests in their CCS role of well over $100 trillion.

*Watersheds*

Most of New York City's drinking water comes from a watershed in the Catskill mountains, a range of hills about three thousand feet high and about one hundred miles north and west of the city. This watershed provides a well-documented example of natural systems as critical infrastructure. Watersheds don't just collect water and channel it in a particular direction: at their best they add two further services. They smooth out the waterflow, and they purify the water. Rain, of course, falls unevenly, but rainwater has to be matched to a relatively constant demand for water. Soil in the watershed smooths out the flow of water, absorbing water at times of heavy rainfall and releasing this slowly over time. Soil not only acts to smooth the waterflow from highly variable rainfall, but it also acts as a highly effective filter, removing many fine particles and other contaminants. Most large cities in the developed world have to pass their drinking water through a filtration plant so that it can be consumed safely: New York doesn't. It has a special exemption from the US Environmental Protection Agency (EPA). The reason is simply that the Catskill watershed does an amazing job of cleaning the water as it flows through the soil. Back in the late 1990s, the quality of New York's water began to fall, and the EPA warned the city that unless this trend was reversed it would have to build a filtration plant, at a cost of eight billion dollars (1995 dollars). Research showed that the reason the water quality was falling was that the Catskills watershed was being polluted by economic development in the area: sewage systems from summer homes for New York residents were leaking and fertilizers and pesticides from arable farms were running into the watershed, as were animal wastes from livestock farms. All of these were reducing the effectiveness of the watershed soil as a filter. The city calculated that it would be less expensive to restore the functioning of the watershed than to build a filtration plant, and so tackled this by paying crop-growers in the area to use organic agriculture (no pesticides or fertilizers), paying livestock farmers to keep their animals back from the streams so that they would not pollute the water,

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[5] Umberto Llavador, John Romer and Joaquim Silvestre, *Sustainability for a Warming World*, Harvard University Press, 2015.

improving the local sewage systems and buying up undeveloped land or buying conservation easements on it. The city has to date invested around $1.5 billion, a fraction of the anticipated cost of a new treatment plant. This investment in ecosystem restoration has worked well. Again, soil and the micro-organisms in it turns out to be critically important.[6]

*Genetic Resources: Food*

Genetic variability provides a very different example of the economic importance of biodiversity. This variability exists both between species and within species. The genes of mice differ from those of men, an example of inter-species genetic variation. The genes of Vladimir Putin also differ from those of Donald Trump, a case of intra-specific variation. Indeed, all individuals have different genomes, so that we can use the genome as a unique personal identification device. Although all humans have different genomes, there are certain aspects of the genome we all have in common and that are different from those that all mice have in common.

This genetic variation has economic value. Slight variations in the genomes of early grasses allowed our ancestors to selectively breed grasses to produce grains such as wheat: had the genomes of grasses been homogeneous this would not have been possible. Similarly, slight variations in the genomes of aurochs (the predecessors of cattle) allowed early farmers to breed cattle. Again, this involved taking advantage of naturally-occurring variations in the genetic details of aurochs and selectively breeding for desirable characteristics. Had the aurochs and grasses of antiquity been genetically homogeneous, we would today be much worse off. It's fair to say that most of our food comes to us courtesy of historical intra-specific genetic variation, which allowed our predecessors to breed the productive food animals and plants on which we depend today.

Today's within-species genetic variability has value too. It provides insurance against pests and diseases. The grassy stunt virus is a powerful illustration of this point. This virus is transmitted by an insect, the brown planthopper, which is common in south east Asia, and infection by the virus can lead to the loss of as much as fifty percent of a susceptible crop. Until the 1980s there was no known cure for grassy stunt infections of rice crops, and some Asian countries were losing as much as one third of their crops to the virus. The problem was eventually solved by the use of biodiversity. The International Rice Research Institute (IRRI) in the Philippines maintains a living library of rice strains and rice relatives, and found that an early relative of current commercial rice varieties was resistant to the virus. Selective breeding allowed this resistance to be transferred to today's commercial varieties, some of which were then immune to the virus. Genetic diversity, a dimension of biodiversity, provided protection against a serious and growing threat to food supplies in a populous part of the world.

*Genetic Resources: Medicines*

It's not just our food supplies that depend on genetic diversity: many of our medicines come from this source too. Perhaps the most significant example is aspirin. We all know it as a very effective painkiller with few side effects: it can also reduce the risk of heart attacks and cancer. It is effective, easy to produce and inexpensive – a rarity in today's pharmaceutical world. It's not a modern discovery: aspirin comes from the bark of willow trees, and the medicinal properties of willow bark have been known for centuries. Indeed, gorillas have been seen to eat willow bark when sick, showing that knowledge of aspirin's effectiveness crosses species boundaries. The German pharmaceutical company Bayer was the first to commercialize aspirin, and to find a way of synthesizing the active ingredient so that willow bark

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[6] For more details see Geoffrey Heal, *Nature and the Marketplace: Capturing the Value of Ecosystem Services*, Island Press, 2000.

was no longer needed. But without the willow bark we probably would not have discovered this simple and safe painkiller.

Subsequently many more modern medicines have been derived from natural sources: in fact, according to some estimates as many as one third of the drugs in use today were originally found in plants or insects or other animals, or were derived from substances occurring naturally in these. Bayer has another important drug derived from natural organisms: glucobay, a treatment for high blood glucose levels, which has generated over $4 billion in revenue for Bayer. Glucobay was initially derived from bacteria found in a lake in Kenya. Discoveries like this have led to the growth of "bioprospecting," searching for pharmacologically active molecules in natural settings. Through evolution and natural selection, plants and animals have come to contain pharmacologically active substances as defenses against their predators. These pharmacologically active molecules can in some cases be used as the basis for new drugs: in these cases, we are standing on the shoulders of evolution and natural selection, and taking advantage of the centuries of work that they have done in refining molecular specifications. Most bioprospecting occurs in the tropics, as these are the regions where many differing species interact closely and the chances of predation and so the needs for defenses are greatest. So-called biodiversity hotspots, regions where there are unusually large densities of different species of plants, insects and birds, are seen as the most promising locations for bioprospecting. If such a region contained only one substance as valuable as aspirin or glucobay, its value as a source of knowledge would vastly exceed its values in other possible uses, such as felling the trees for lumber or clearing the land and using it for farming. It is perfectly possible that a biodiversity hotspot could contain the raw materials for several new pharmaceuticals, all as valuable as aspirin. The rosy periwinkle, a pretty flower occurring in Madagascar, was the source of two important drugs, vinblastine and vincristine. The former is used to treat childhood leukemia, and the latter to treat Hodgkin's Disease. The loss of biodiversity means the loss of opportunities to discover new molecules of great value to humanity.

The famous Harvard biologist Ed Wilson suggest that we think of biodiversity as a library, as a vast source of information. In support of this vision he makes the following interesting observation:[7]

> "*In a purely technical sense, each species of higher organism is richer in information than a Caravaggio painting, Bach fugue, or any other great work of art. Consider the typical case of the house mouse, Mus musculus. Each of its cells contains four strings of DNA, each of which comprises about a billion nucleotide pairs organized into a hundred thousand structural genes. If stretched out fully, the DNA would be roughly one meter long. But this molecule is invisible to the naked eye because it is only 20 angstroms in diameter. If we magnified it until its width equaled that of a wrapping string to make it plainly visible, the fully extended molecule would be 600 miles long. As we traveled along its length, we would encounter some 20 nucleotide pairs to the inch. The full information contained therein, if translated into ordinary-sized printed letters, would just about fill all 15 editions of the Encyclopedia Britannica published since 1768.*"

It is information of this type and on this scale that we are destroying when we lose biodiversity.

The recent outbreak of a novel coronavirus in China gives another topical illustration of the costs of biodiversity loss. This new disease is zoonotic – it has jumped from wild animals to humans, who have

[7] Edward O. Wilson, *The Biological Diversity Crisis*, Bioscience, vol. 35 no. 11, pp 700-706.

no established immunity to the virus. SARS, the corona virus that circulated in China in 2003, is also zoonotic, as are Ebola, an extremely dangerous hemorrhagic disease now threatening populations in west Africa, and HIV, which has spread from Africa around the world. These diseases, which have probably been endemic in the wild animal populations for centuries or more, spread to humans as a result of increasingly close contact between humans and their wild carriers, largely through hunting and consumption, which brings highly stressed or dead animals, exuding fluids, into close contact with each other and with their human consumers. A recent paper in Nature reviews the impact of biodiversity loss on the emergence and transmission of infectious diseases, and comments that "… in recent years, a consistent picture has emerged—biodiversity loss tends to increase pathogen transmission and disease incidence, " suggesting that the growth we are seeing in new diseases is connected to the loss of biodiversity.8

Here is one more example of the value of genetic diversity. A key element of modern biotechnology is the polymerase chain reaction (PCR for short) which is used to amplify DNA specimens. This reaction is fundamental to many modern biotechnology processes and it is fair to say that much of the modern biotech industry would not exists without it. This reaction requires an enzyme that is resistant to high temperatures, and no such enzyme was known until the bacterium Thermus aquaticus was discovered in the Lower Geyser Basin of Yellowstone National Park. Again, we see a relatively rare naturally-occurring micro-organism playing a key role in an evolving modern technology. In fact the polymerase chain reaction is central to the test currently being used for Covid-19,[9] so without an obscure bacterium from Yellowstone we would be severely handicapped in dealing with one of the worst pandemics of the last hundred years.

What all these examples establish is that biodiversity is a crucially important element in the natural infrastructure, the natural capital, that underpins our prosperity. Without biodiversity we cannot flourish. Our food comes from biodiversity. The plants and animals we eat owe their productive forms to genetic diversity that existed many years ago, the plants are pollinated by birds and insects, and current genetic diversity provides insurance against devastating infestations and infections. Much of this biodiversity is now threatened.

*Biodiversity as an Asset*

Biodiversity is an asset which provides a flow of services that are crucially important. Some of these services can be valued at least partly, as in the case of the carbon capture and storage services of forests, or the plant pollination service of insects, birds and bats, or the bioprospecting services of biodiversity hotspots, or the insurance role of plant biodiversity. The numbers are approximations and are also very partial estimates of biodiversity's economic contribution, because for every contribution that can be measured and converted into a dollar value, there are many that cannot. But there is no

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[8] See Felicia Keesing et al., Impacts of biodiversity on the emergence and transmission of infectious diseases, Nature 2 DECEMBER 2010, VOL 468, NATURE, pp 647 -652

[9] See the Centers for Disease Control web site at https://www.cdc.gov/coronavirus/2019-ncov/lab/testing-laboratories.html

doubt from the few valuations we can conduct that biodiversity is a vastly important asset. We have a lower bound on its value which is measured in tens of trillions of dollars.

It is also worth noting that biodiversity is an asset that doesn't depreciate. Built capital does, as does human capital: natural capital generally doesn't. A river that provides hydroelectric power today will still do so centuries from now: by then a conventional power station would have been replaced many times. Biodiversity will continue to provide all of its services as long as we need them – and as long as we allow it to by maintaining it intact.

One more really important point about biodiversity is that its loss is often irreversible. Once a species is extinct, we can't recreate it, and everything associated with it, all the information implicit in as described so graphically by E.O. Wilson, is gone forever. Forest loss can also be irreversible: one might think that a cleared forest can be replanted or allowed to regenerate, and that is true within limits, but if a large fraction of a tropical rainforest is destroyed this leads to permanent changes in the soil and in the local weather patterns, and reforestation is no longer possible. Most assets can be replaced if lost or damaged, so this is a distinctive characteristic of biodiversity. It has ramifications: it is commonplace in economics that choices leading to irreversible changes need to meet higher standards of justification than others.[10] So a decision to destroy biodiversity, which we are making every day, needs to meet stricter cost-benefit standards than conventional economic decisions. In particular such choices should not occur by default.

*The Economic Value of Biodiversity*

The earlier sections provide illustrations of cases in which we can assign at least a partial value to biodiversity. Pollinators as an asset are worth at least $14 trillion, and tropical forests in their CCS role at least $9.5 trillion, probably a great deal more. These numbers are strictly lower bounds: we have calculated them by valuing only some of the services these assets provide. Hence the "at least" before the dollar values. The total values may be a large multiple of these numbers. There are estimates of the value of other aspects of biodiversity, again all partial in nature, all lower bounds.[11] Several researchers have attempted to estimate the value of the genetic resources in biodiversity hot spots to pharmaceutical companies as bioprospecting resources, with a wide range of outcomes. Others have looked at the insurance role of biodiversity and asked what an insurance company would charge for such risk mitigation. All the resulting numbers are large, confirming that biodiversity has immense economic value, though all are partial and all have a large margin of error around them.

A crucial point that emerges from looking at cost-benefit studies of biodiversity conservation is that it is easy to underestimate the benefits, as they are often unknown or estimated only with very large uncertainly. Because of the uncertainty about the exact value of the benefits of biodiversity conservation, studies sometimes omit them. But this is equivalent to setting them to zero, and whatever the benefits are, they are not zero. It is important to have some estimate of the value of conservation, even a rough one. The correct approach is to work out the possible range of values, from minimum to maximum values, and then evaluate conservation projects using all the values in the range and seeing how sensitive the overall picture is to the value assumed.

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[10] Avinash Dixit and Robert Pindyck, *Investment Under Uncertainty*, Princeton University Press, 1994.
[11] See Geoffrey Heal, *Endangered Economies: How the Neglect of Nature Threatens our Prosperity*, Columbia University Press, 2018.

We have seen that a part of the value of biodiversity is in the tens of trillions of dollars, with the total value probably far higher than the numbers suggested in the cases reviewed above. The total value of biodiversity as an asset, and so the cost of biodiversity loss, is highly uncertain. It is also possible that there are costs to biodiversity loss of which we are currently unaware. For example, until the onset of HIV in the early 1980s, we were unaware of the potential for zoonotic diseases, yet we are now aware that these pose a major public health threat and that their emergence is related to biodiversity loss. There clearly could be other consequences of biodiversity loss that will loom large in the future but are as yet unknown.

In summary, there are costs to biodiversity loss that we can describe but about whose magnitude we are highly uncertain (although we have lower bounds), and there are potentially other costs about which we currently know nothing – there are partly known unknowns, and completely unknown unknowns. This makes any formal cost-benefit analysis particularly challenging. We have some ideas about the costs of conserving biodiversity – the costs of parks, protected areas, etc. – but much more imprecise ideas about the benefits. In such a situation there is always a danger that the apparently-robust and well-understood costs will outweigh the much less precise benefits. Such an outcome would be in violation of an emerging consensus amongst decision-theorists on how to make decisions when some of the outcomes cannot be described even in probabilistic terms.[12] An element in this consensus is that in such situations it is rational to focus on the worst outcomes that could occur, and place heavy emphasis on these. In the current context, this would mean developing detailed worst-case scenarios that could be associated with loss of biodiversity and then basing a cost-benefit analysis on these. If the cost of biodiversity loss is unknown then rather putting a zero in the cost-benefit equation, use a number based on a worst-case scenario.

The World Bank has for more than a decade run an initiative called WAVES, standing for Wealth Accounting and Valuation of Ecosystem Services.[13] The central idea is that developing countries should incorporate the value of natural capital and ecosystem services into their development planning. The Bank, in partnership with a number of client countries, has developed and mainstreamed techniques for valuing certain types of natural capital and the services it provides so that these can be incorporated into national income accounts and their contributions to the national well-being considered in strategic economic decisions. This is an important development and one that should be encouraged in all countries and not just those in the WAVES partnership.

*Markets Failures and Biodiversity*

A natural question is: given the immense value of biodiversity to human societies, why do we allow it to be destroyed? Why do institutions such as the market not capture the value of biodiversity? Markets do a good job of valuing many things that are clearly much less important to us than biodiversity, so why don't they do this with biodiversity too?

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[12] See Itzhak Gilboa, Andrew Postlethwaite and David Schmeidler, *Probability and Uncertainty in Economic Modeling*, Journal of Economic Perspectives, Volume 22, Number 3—Summer 2008 —Pages 173–188

[13] See https://www.wavespartnership.org . See also the Natural Capital Project, cited in footnote 1.

Unfortunately, there are several quite compelling reasons why markets and other economic institutions fail to reflect the value of biodiversity. The key economic concept here is market failure: markets generally do a reasonable job of allocating value to resources, but there are certain cases, rehearsed in all standard economics texts,[14] where they fail dismally. Biodiversity occurs at the intersection of several of these market failures.

A good place to start in understanding this is with the idea of public goods: most goods are private goods and their consumption by one person prevents their being consumed by anyone else. Public goods instead can be consumed simultaneously by many people: if they are provided for one, they are provided for all in a certain group. Cleaner air is a good example: if New York City cleans its air, then this is a good provided for all New Yorkers, and not just for a specific few. Markets can't handle the efficient provision of public goods because you can't exclude from receiving them those who didn't pay for them, meaning that markets under-provide public goods relative to what is needed for economic efficiency. Many of the benefits of biodiversity are public goods. Pollination services are available for everyone – bees don't check whether the owner of an orchard has paid for their services. Forests suck CO2 out of the atmosphere and in so doing benefit everyone, whether they paid for the forest or not. Drugs produced by bioprospecting can benefit everyone, whether they paid for the conservation of biodiversity or not. Knowledge is a classic public good, and as E.O. Wilson so sagely observed, knowledge is what in many cases we get from biodiversity.

Another way of thinking about this is in terms external costs and benefits. Sometimes a transaction between a buyer and seller produces costs or benefits for a third party who is not directly involved in the transaction. Burning fossil fuels as a result of a transaction between an airline and an oil company leads to the emission of pollutants and greenhouse gases, which impose costs on many others not parties to the transaction. These are called external costs or benefits – costs in this case – and are another standard cause of market failure. Markets lead to inefficient outcomes when there are external costs or benefits. Biodiversity conservation leads to external benefits: conserving tropical forests leads to benefits that accrue to many people who are not involved in the conservation – in fact, to everyone in the world. As a result, the economic incentives to conserve these forests are far too small and markets do not allocate enough resources to their conservation. Economically the situation is dire: in general, the owner of a tropical forest can generate a return from it only by destroying it, either selling it for lumber or using the cleared land for farming. In either case the biodiversity is destroyed. The forest owner cannot monetize the carbon capture and storage carried out by her forest, nor generally can she capture the value that its biodiversity may have in bioprospecting. There failures are not inevitable: the global community could decide to compensate forest owners for the CCS services that their forests provide to us all, and indeed the 2015 Paris COP's endorsement of REDD+ in Article 5 set the scene for doing this. The Convention on Biological Diversity is also trying to make it easier to monetize the values of genetic diversity in a forest. As of yet, neither is sufficiently operational to provide a return to forest conservation and overcome the basic market failure. The same is true of conserving pollinator habitat.

A third dimension of market failure relevant to biodiversity is the lack of well-defined property rights: markets can only manage the purchase and sale of goods and services efficiently if the ownership of those commodities is clear, so that when there is a sale, there is no ambiguity about who sells and who

[14] *Anatomy of Market Failure*, Francis Bator, Quarterly Journal of Economics, Vol. 72, No. 3 (Aug., 1958), pp. 351-379. See also Geoffrey Heal, *Endangered Economies: How the Neglect of Nature Threatens our Prosperity*, Columbia University Press, 2018.

buys, about who pays and who receives. For many environmental goods and services this is not the case: no-one owns the atmosphere or the birds that fly in it or the oceans or the fish swimming in them. Indeed, most biodiversity is no-one's property, so no one has any financial interest in conserving it or in ensuring that it is allocated to its highest-value use.

*Policy Interventions to Benefit Biodiversity*

The economic conclusion is that because biodiversity provides benefits that are sometimes public goods and sometimes external benefits, and because the ownership of biodiversity is generally unclear, the market will undervalue and underprovide biodiversity. We cannot rely on market forces to solve the problem of biodiversity loss, making policy intervention essential. This may take many forms, but all in essence have to overcome the underlying market failures linked to biodiversity.

The simplest forms of intervention are the establishment of protected areas, such as national parks, in which biodiversity is protected. In the oceans the equivalent is the marine protected area (MPA). There is abundant evidence that if established on a sufficient scale and if well-managed, parks and MPAs can stabilize biodiversity and indeed reverse losses that have occurred. Both have costs: there is a political cost to declaring an area off limits to economic activity, and a financial cost to managing the conserved area and ensuring that the habitat is in fact protected. In the U.S., the current system of national parks was of course established by Teddy Roosevelt, whose prescient comments about natural resources we noted above. There is evidence that MPAs will pay for themselves after somewhere between five and ten years,[15] because they lead to large increases in fish populations and eventually these increased populations leak out of the MPA into the surrounding fishing grounds, increasing yields, so that in the long run the local fishers gain from the existence of the MPA. Similarly, in some cases it is possible to generate a cash return from the biodiversity conserved by a park through ecotourism. Conservation of charismatic animals in southern Africa has certainly led to an increase in tourism there, and this has provided close to commercial levels of returns on the investments in conservation,[16] but Africa's charismatic megafauna are unique in terms of their drawing power. On a smaller scale Costa Rica and Panama have developed ornithological tourism based on the conservation of their tropical bird populations, providing some return to the costs of conservation.

Protected areas are an important weapon in the conservationist's armory, but they have limitations. They isolate populations, leading to inbreeding, and make it impossible for species to move in response to changing climate. Ideally, they should be connected by corridors along which species can migrate and through which genetic exchange can occur.

Ecotourism based on charismatic fauna is an example of a more general approach to monetizing a public good like biodiversity, namely bundling it with private goods whose value it enhances. In the case of ecotourism, what is being sold is not of course the biodiversity on display, but hotel rooms, camp sites, and guiding services. No one would pay $1000 per night to camp in the Okavango Delta were it not for the lions, cheetahs, leopards, elephants, hippos, sitatunga, and many other species to be seen there. Biodiversity increases visitors' willingness to pay for spending time in the Okavango, and safari camp operators make their profits from this. This exemplifies a more general proposition, which is that the provision of a public good (which cannot profitably be sold) may increase what consumers are willing to pay for a private good if its consumption is made more enjoyable or productive by the presence of the

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[15] James Rising and Geoffrey Heal, Global Benefits of Marine Protected Areas, December 2001.
[16] See *Nature and the Marketplace: Capturing the Value of Ecosystem Services*, Geoffrey Heal, Island Press, 2000.

public good. Sellers of the private good therefore have an incentive to provide the public good too: they are able to sell it indirectly via its impact on the price of the private goods they sell. Under certain conditions this incentive is strong enough that the public good is provided at an economically efficient level.[17]

An example very different from ecotourism is provided by housing development on Spring Island, a barrier island off South Carolina coast.[18] Zoned for development, it was auctioned 1990. The State, which hoped to conserve the island, was outbid by a developer. But the developer, instead of constructing the 5,500 homes permitted by the zoning, built 500 high-value homes and deeded the balance of the land to a conservation trust. This was not, he explained, charity: being embedded in a nature reserve increased the value of the 500 homes to the point where this was the more profitable strategy. The nature reserve, a public good, was enhancing the value of the private homes he was selling. A similar case occurred with a group of Montana Hunters who had traditional hunted on an area of land and grew concerned that its development would end their ability to hunt. They borrowed money to buy the land and finance construction of small number luxury homes, and placed a conservation easement on remainder of land, giving themselves the right to hunt. After this they sold houses they had built for more than cost of buying the land and building the houses. Again, being embedded in a conserved area of great beauty enhanced the value of the homes. In all of these cases a public good is being sold with – bundled with – a private good and is enhancing the private good's value so much that the seller has a real incentive to enhance the provision of the public good.

A less comprehensive form of bundling occurs when a company takes the trouble to have its products certified as in some way biodiversity-friendly. Examples are lumber that is certified by the Forest Stewardship Council or fish certified by the Marine Stewardship Council. A recent development in this field is the Roundtable on Sustainable Palm Oil: palm oil is widely used in processed foods, is grown largely in south east Asia, and virgin tropical forest is frequently cleared to make space for oil plantations, at a great cost in terms of biodiversity loss. The roundtable results from pressure by western consumer and environmental groups on companies like Nestlé, Procter and Gamble and Unilever to stop using palm oil from growers who destroy rainforests.

A company whose products are certified as "sustainable" in one of these categories is telling consumers that it is contributing to biodiversity conservation, generally in the expectation that consumers will react positively to this and will therefore be predisposed to buy this product rather than a competitor.[19]

In the U.S., one of the most powerful regulatory tools for biodiversity conservation has been the Endangered Species Act (ESA), passed by Congress in 1973. Once a species is listed as "endangered," which requires a complex administrative process, the ESA makes it illegal to take any actions that reduce its survival chances. Wolves, eagles, the red cockaded woodpecker and many other less charismatic

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[17] For more details see Geoffrey Heal, Bundling Biodiversity, *Journal of the European Economic Association*, April-May 2003, 1, 553-560. See also Matthew Kotchen, Voluntary and Information-Based Approaches to Environmental Management: A Public Economics Approach, *Review of Environmental Economic and Policy*, Vol. 7, Issue 2, 276-295.

[18] See https://www.springisland.com and also https://www.nytimes.com/1992/06/28/realestate/focus-spring-island-sc-development-with-an-environmental-bent.html

[19] Matthew Kotchen develops a theory of certification in: Voluntary and Information-Based Approaches to Environmental Management: A Public Economics Approach, *Review of Environmental Economic and Policy*, Vol. 7, Issue 2, 276-295.

species, survive in the U.S. largely because of the ESA. Introduced by President Nixon, it has been systematically weakened by subsequent Republican presidents, but still provides a valuable tool for support of biodiversity. In its original form it prohibited any actions that threatened the survival of a listed species: it has been amended to allow such actions provided that the actor takes makes other provisions that more than compensate, which has led into complex and sometimes controversial territory but has also led to the evolution of mitigation banking, a market-oriented approach to biodiversity conservation.[20]

Other forms of policy intervention tackle more directly the market failures associated with biodiversity. Recall that one of these is the presence of external costs: many economic activities, such as farming and property development, have the side effect of destroying biodiversity habitat. A classic economic solution would be to discourage them by placing a tax on them. Put a "biodiversity conservation tax" on any activities that harm biodiversity, such as land clearance for development or for agriculture.[21] Conversely, give a subsidy to those that help biodiversity. These would be directly addressing the external effects that are so often associated with biodiversity conservation or destruction.

A natural extension of the idea of subsidizing biodiversity conservation, is the idea of payment for ecosystem services. The key point here is that owners of natural capital – in general landowners – should be compensated for ecosystem services that originate on their land but benefit others. To give a concrete example, owners of land in the Catskills that is part of New York City's watershed would be compensated for the provision of clean drinkable water to the City: in effect the City would buy such water from them. This would clearly give them an incentive to maintain the ecological functions of the watershed. In the same way, owners of land that supports pollinators would be paid the value of the pollination services, and forest owners would be paid for the carbon capture and storage roles of their forests – which, as we have seen, are of great economic value and could provide a healthy return to investments in forests. This is a policy one can imagine going into effect if the regions providing ecosystem services are owned by a single landowner or by a small number, but which could be difficult to implement if the region is the property of many small landowners, which was the case with the Catskills watershed. In this case the coordination problem could prove overwhelming.

In fact, payment for carbon capture and storage is one of the aims of Reducing Emissions from Deforestation and Degradation (REDD), a system aimed at reducing greenhouse gas emissions from cutting tropical forests by providing financial rewards to countries that reduce deforestation or increase forest cover. Although the explicit aim of this measure is to reduce climate change, if successful it also stabilizes biodiversity by conserving tropical forests. It is an attractive policy because it can tackle two of the world's major environmental problems at the same time. As mentioned, Article 5 of the 2015 Paris Agreement provides a basis for the implementation of REDD and this could also be an important avenue for increasing funding for forest conservation.

None of these policies will directly address the values of genetic diversity - as a source of new variants on existing species, as a source of new medicines, or as insurance against novel pathogens. It is possible that the Convention on Biological Diversity (CBD) could be strengthened to cope with some of these issues: the focus of the Nagoya Protocol to the CBD is bioprospecting and this could provide a basis for a more determined approach to regulating bioprospecting. In the case of rice, the collection and

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[20] See The Endangered Species Act at Thirty, editors D.D. Goble, J.M. Scott and F.W. Davis, Island Press, 2005.

[21] Unfortunately, much of the land clearance that matters for biodiversity loss occurs in developing countries, where the implementation of such a tax is challenging.

conservation of rice relative and predecessors has been managed by the International Rice Research Institute, mentioned in the context of the grassy stunt virus above: the IRRI is funded by the Ford and Rockefeller Foundations and the government of the Philippines. The CGIAR (formerly Consultative Group on International Agricultural Research) also performs some of these functions for a wider range of plants, and is funded mainly by the aid agencies of western countries. All of these entities are clearly useful, but all need to be scaled up if they are to have the resources needed to make an impact on the loss of biodiversity at a global level.

An important move that could greatly help preserve biodiversity is the development of an agricultural system that is less land-intensive and drives deforestation less. A major driver of deforestation is cattle ranching, so moving diets away from beef and towards plant-based foods could be a great gain for biodiversity – and for public health as well.[22] In this context the growth of vegan diets amongst millennials is a source of hope. Indeed, the emergence of companies like Beyond Beef and Impossible Foods suggests that plant-based alternatives to meat are commercially viable and could reduce the pressure to clear land for ranching. Any policies that encourage the growth of plant-based diets could reduce biodiversity loss.

*Conclusion and Next Steps*

Pulling everything together, biodiversity is an asset to humanity. It has been demonstrated to be a hugely valuable asset, providing a wide range of critically important services without which our societies would never have evolved as far as they have, and which still underpins our prosperity in myriad ways. It is an asset that never depreciates and whose loss is irreversible, so it behooves us to be particularly careful about its loss.

In this respect we are failing badly. Even though biodiversity is of critical economic importance, we cannot rely on markets to conserve it; it has characteristics of both public goods and external benefits, which means that much of its value escapes the market, and market-based decisions inherently lead to the destruction and loss of biodiversity. Policy interventions are thus essential if biodiversity is to survive.

Traditional government establishment of parks and protected areas, and the use by government of laws and regulatory systems to protect biodiversity such as the U.S.'s Endangered Species Act, have all been effective in protecting biodiversity but in fairly limited ways. More recent experience with government programs to either pay for or compel private actors to make payments for ecosystem services are showing some potential, although experience with this to date is still limited.

The Convention on Biological Diversity is clearly a framework that could act as a building block in this area, and the approaching COP 15 delineation of both measurable biodiversity targets and a supporting financial resource mobilization framework offers some immediate hope. The financial analysis and associated development of nine financing mechanisms and fiscal policies offered in the next chapters of this report, if taken up by the COP Parties and country signatories, could put in place strong policies and economic measures that when scaled up will have a lasting and measurable effect in protecting the planet's biodiversity.

[22] W. Willett et al., Food in the Anthropocene: the EAT-Lancet Commission on healthy diets from sustainable food systems, The Lancet, published online January 16 2019, http://dx.doi.org/10.1016/S0140-6736(18)33179-9