Plants make our existence possible

All of the articles featured in this special issue, including this one, were first presented at a National Geographic Society symposium entitled "A World of Plants" 29–30 October 2019, in Washington, DC, USA. The presented topics were selected to provide a wide range of information on plants and concentrated on areas for which we considered that extra effort would likely yield interesting results, especially those useful for conservation. We emphasized plant diversity and evolution, as well as their ecology and key role in ecosystems. We offer our thanks to the National Geographic Society for supporting the symposium and the preparation of these articles. We hope that the collection will stimulate further thought and action in a time of rapid population growth and continued, radical disturbance of natural habitats. Few organizations have as much power as the National Geographic Society to help us understand the way plants are essential to our survival, and thus to encourage us to save them from mass extinction while there is still time to do so.

Although all of humankind depends on plants for survival, we have often been slow to recognize and act on their importance for us. This article presents information about plant evolution and details the enormous diversity of plants and their roles in the global biosphere. Owing to the breadth of the subjects covered here, the papers in two recent review volumes will be taken as general background and their extensive citations not repeated in detail (Dasgupta et al., 2019; von Braun et al., 2020). These works also emphasize ways in which we can work together to preserve plants for the benefit of those who follow us.

The ways in which plants have built and continue to maintain global sustainability can be understood best against the background of Earth history (Lenton, 2019; Shubin, 2019). Our planet is about 4.57 billion years old, with life originating a few hundred million years later. Some 3 billion years ago, Cyanobacteria, the first photosynthetic organisms, began to generate oxygen, which eventually grew to constitute about 20% of the atmosphere. The oxygen shielded the first organisms that ventured onto land from the mutagenic effects of solar radiation. As successive forms of life evolved, the diversity of terrestrial organisms increased, with flowering plants and placental mammals both originating in the early Cretaceous Period, about 130 million years ago. During the history of life on Earth, four major extinction events occurred before the origin of these groups, all causing massive losses in the species that existed at those times. Halfway through the history of placental mammals and flowering plants (Angiosperms) on Earth, the most recent major extinction event occurred, about 66 million years ago at the Cretaceous–Paleogene boundary. The last of the dinosaurs and some other archaic organisms went extinct, opening up new habitats within which plants, terrestrial vertebrates, insects, and other kinds of organisms evolved, gradually forming the ecosystems and biogeographical patterns that we recognize today.

By the time of the most recent mass extinction, Angiosperms had risen to dominant roles in most of the world’s ecosystems and remained dominant, but with changes in composition, as extinction proceeded. A number of the families familiar to us, including Fabaceae, Myrtaceae, Fabaceae, and Onagraceae had appeared before the end of the Cretaceous Period and continued to spread and multiply. Others, such as Asteraceae—a very large family today—originated subsequently. All of these families continued to differentiate and evolve in the many habitats that already existed or appeared from the end of the Cretaceous Period until the present.

The first 10 million years of the Cenozoic Era were characterized by moderate, equable climates that gradually became warmed during the Eocene Period (56–34 mya) and subsequently (Lenton, 2019; Shubin, 2019). The differentiation between the ecosystems of lower and higher latitudes, so familiar to us, had not yet become nearly as obvious as it is today. Ecosystems dominated by drought-resistant trees and shrubs began to appear in regions where precipitation was lower, such as in the Rocky Mountains of North America; grasslands appeared and spread from the late Eocene onward. During the Miocene Period (23–5 mya), glaciers formed in Polar Regions and grew larger, accompanied by an increase in widespread aridity about 15 mya. Over the same years, colder Polar climates, with their extensive taiga and tundra ecosystems, on the one hand, and warmer Equatorial climates, dominated by tropical lowland rainforest, on the other, came to resemble those of today. The frigid Polar Regions were the origin of cold currents that rotated clockwise in the Northern Hemisphere and counter-clockwise in the Southern Hemisphere. Where the prevailing westerlies blow across the cold water onto warm land during summer, Mediterranean (summer-dry) climates are formed, evolving their own unique vegetation separately on five continents over a period of several million years.

For land plants, evolutionary radiation into these diverse ecosystems has led over time to the origin of perhaps 450,000 species, some 380,000 of which have been recognized and assigned scientific names (Joppa et al., 2010). Unfortunately, however, we have learned...
relatively little about most of the species we have named, often only a few of their characteristics and a bit about the areas where they grow. In other articles in this collection, the authors will discuss patterns of distribution and abundance in more detail (see Brummitt et al., 2020; Pimm, 2020; Vorontsova et al., 2020). Overall, as for most groups of organisms, about two thirds of plant species occur in the tropics, the remainder in temperate regions.

The existing species of vascular plants are a small enough group and well enough known that we can reasonably hope to get an objective measure of their diversity before a large proportion of them become extinct. There are relatively few other groups of organisms, including terrestrial vertebrates, with perhaps 35,000 species; butterflies, with some 20,000 species; and mosquitoes, with about 3,500 species, for which we will be able to gain a relatively complete, overall picture while they still exist. For groups such as mites (45,000 named species), nematodes (15,000 named species), and fungi (120,000 named species), where millions of species are estimated to exist, we will unlikely be able to have a relatively complete account of all species (Raven & Miller, 2020; Raven et al., 2020). By using our ingenuity, however, we can certainly get some idea of the overall picture of their ecological roles and distribution patterns. In a few places in the tropics, such as La Selva in Costa Rica, the Danum Valley in Borneo, and Barro Colorado Island in Panama, we can gain a solid understanding of all groups and the interrelationships between them if we focus our efforts sufficiently. The same is true of a number of places in the Earth's temperate and arid areas. For most groups of organisms, a race to name all the species that exist while so many of them are slipping through our fingers seems to me to have relatively little potential for understanding (Raven, 1980; Raven & Wilson, 1992). However, barcoding as many species as possible does afford a scaffolding on which knowledge can be accumulated, and will reveal a fair amount about the patterns of distribution and abundance that exist.

As mentioned earlier, placental mammals evolved along with plants, with Primates appearing near the very end of the Cretaceous Era and hominids, the evolutionary branch to which we as humans and our relatives belong, diverged from a common ancestor with African apes some 6–8 million years ago. This line radiated in Africa and partly in Eurasia also. Eventually, one of its members, Homo sapiens, migrated out of Africa at least 60,000 years ago, spreading rapidly throughout Eurasia and to Australia, and ultimately reaching the Americas no less than 15,000 years ago. All of their migration took place during the recent glacial maximum, a cool period that lasted from 110,000 to 10,000 years ago. Some 11,000 years ago, hunter-gatherers developed crop agriculture and the domestication of grazing mammals, probably initially in Western Asia. As this process got underway, there were only about 1 million of us, but our population soon began to swell around the villages, towns, and cities that agriculture made possible. With some 200 million people at the time of Christ and 500 million at the start of the Renaissance (1,500 AD), we first reached a total of 1 billion people in Napoleonic times. From that point onwards, our numbers spurred by the Industrial Revolution grew rapidly to the nearly 7.8 billion of us living today, with an additional 2.1 billion projected to be added during the next 30 years (Population Reference Bureau, 2020).

Turning now to our complete dependency on plants, it has many dimensions. In the course of deep history, plants, with other photosynthetic organisms, created the air that we breathe and set up the qualities of the soil on which we grow our crops. Today, in addition to maintaining those functions, they regulate the flow of water and the extent of erosion worldwide, thus, forming the backbone for all ecosystem functions. Our existing ecosystems have formed over millions of years, their continued functioning depending on the maintenance of their structure. That structure in turn depends on the interactions between thousands or tens of thousands of species of organisms, depending on the particular ecosystem. Trees are of fundamental importance in creating and supporting the structure of ecosystems, and yet we are only in the early stages of learning deeply about them and their world (Lowman, 2020). In any case, we clearly do not know how many species can be subtracted from a given ecosystem before it collapses. Some of the interactions in ecosystems are active, others historical and deeply rooted (Raguso, 2020). We must understand these complex interactions if we are to manage ecosystems properly and preserve as much of the rich life within them as possible. Without plants and their interactions, no life would be possible anywhere.

All living beings, including humans, depend on plants directly or indirectly for all of their food. Globally, a majority of people also depend on plants for their medicine; at least a quarter of those sold at drugstores were derived originally or are still derived today from plants. Plants also provide building materials, biofuels, chemicals, and other products that we use. Moreover, they are endlessly beautiful, inspiring us every day we live.

Despite the essential benefits we receive from them, we are not treating plants well. In the course of destroying them, we are threatening our own continued existence and that of all animals and other organisms on Earth. Our impact on global ecosystems has become overwhelmingly negative. Agriculture occupies some 40% of the Earth’s land surface, with humans affecting virtually every square centimeter of our planet’s surface. Global warming, driven in large part by human activities, has led to a 1°C increase in world temperatures over the past century, to a point at which they are warmer than they have been for millions of years. With an increase of 1.5°C (projected to occur by 2030), scientists anticipate that the effects of climate change will be disastrous; yet our efforts to form a global alliance to hold back climate change have not yet been effective. Sea level has risen about 2 mm per year for the past century, the rise totaling about 20 cm by now, and will continue to rise to some unknown future level that depends on when and what we decide to do about the problem of climate change. Plants amount to more than four fifths of the total living biomass on Earth, playing a huge role in absorbing carbon and, thus, slowing global warming (Bar-On et al., 2018).

We can measure our global impact by our consumption of total sustainable productivity, which has increased from an estimated 70% in 1970 to some 175% currently (Global Footprint Network, 2020).
By August 22, 2020, we had used up all that the Earth’s ecosystems could regenerate for 2020, and have been living on unsustainable depletion since (Earth Overshoot Day, 2020). The date for 2020 falls some 3 weeks later than those for the immediately preceding years because of the global slowdown attributable to COVID-19. Nations consume this productivity very unequally, with the U.S. and Western Europe at the top and many nations essentially without any remaining sustainable resources whatever—stuck in extreme poverty (Wackernagel et al., 2019). Globally, stark inequality also prevails for individuals, with the British charity Oxfam estimating that 5 years ago the eight richest people possessed as much wealth as the 3.6 billion poorest (Hardoon, 2017). Half the people on Earth lack sufficient quantities of at least one essential nutrient and many survive on US $2 per day or less. At the same time, some 821 million of us do not receive enough food to lead a normal active life (World Food Programme, 2019).

Implementing strategies for finding and if possible preserving plant species is of critical importance for the future well-being of life on Earth, and certainly for the effective continuation of human civilization. As has been pointed out (Pimm et al., 2014), the species most likely to become extinct are by definition the rare ones, and most undescibed species are relatively rare. Many species of both plants and animals must have disappeared since human beings began to practice agriculture. In this context, one can only imagine how many species must have gone extinct during the spread of agriculture in regions such as the intensively cultivated Mediterranean of western Eurasia and North Africa. At the same time, invasive species of animals and plants, pests, and pathogens are spreading around the world in ever-increasing numbers, often outcompeting or killing others in the new regions they reach. On top of this, we are not yet controlling global climate change, despite the fact that it threatens to affect the productivity, even the habitability, of major sections of the Earth, and certainly so if individual and national greed prevails over our common interest. In any case, we need to continue to develop detailed and accessible knowledge of the distribution of plants in order to be able to do an effective job of conserving them (Brummitt et al., 2020).

Probably, a majority of endangered plant species grow in “hotspots,” originally defined by Myers et al. (2000) as areas that were 70% disturbed by human activities and having at least 2,000 endemic vascular plant species; clearly, much of our conservation attention ought to be concentrated in these areas to achieve the best possible results.

Doing so would be an extremely effective way of conserving plants and many other groups of organisms, a necessary approach that must accompany our attempts to preserve large stretches of forests and the other relatively undisturbed habitats that remain. It is likely that biodiversity hotspots house most plant species that are yet to be discovered by science (Joppa et al., 2011), making them especially important areas for investigation.

What about the tropics were an estimated two thirds of all plant species occur? We have destroyed about a quarter of their lowland forests in the 27 years since the 1993 ratification of the Convention on Biological Diversity—hardly a mark of great conservation success. In a similar vein, I can attest personally that most living botanists who have collected plants anywhere in the tropics in the past find virtually every of their localities destroyed by now. Tropical forests are the most poorly known of all regions biologically, and the home of at least two thirds of the world’s species of vascular plants, perhaps as many as 300,000 species overall, probably half of them in Latin America (P. H. Raven, unpublished data). These forests are also some of the most poorly known areas on Earth, with limited representation of their species in botanical gardens and seed banks. Areas such as S.E. Asia, the Central Andes, and Madagascar urgently need more attention if we are ever to have a reasonably complete picture of their plants (e.g., Vorontsova et al., 2020). Some details were presented about individual countries in a collection of essays, “Voices from the Tropics” (Sodhi et al., 2013), showing that most of the forests of some of the richest and most poorly known areas, such as New Guinea, are likely to be gone by mid-21st century or soon after. As if that were not bad enough news, the destruction of these forests will likely increase the rate of warming everywhere on our planet, and in turn is likely to make the destruction of all types of ecosystems even more rapid. Relationships of this kind present us with a real sense of urgency, since there will be only so much we can learn during the time we have remaining, and suggests that those in a position to do something about the matter ought to develop some joint goals and pursue them vigorously. Unfortunately, there will be no second chances.

The extensive studies of Tetsukazu Yahara of Kyushu University provide a telling demonstration of how little we actually know about tropical trees (e.g., Binh et al., 2018). Using molecular comparisons, Yahara and colleagues have discovered many dozens of previously undetected species of Southeast Asian trees and shrubs, species which when detected usually exhibit clear morphological differences. Especially in groups such as oaks and families like Lauraceae, whose inconspicuous, usually yellowish-green flowers last only a few weeks, the discoveries have been impressive, indicating that far more species exist in the tropics that we have yet identified. In an even more general sense, the application of genomics to the relationships between species of plants and other organisms is opening an enormous cornucopia of new information about their histories and their identity (Soltis & Soltis, 2020). The amount of genomics information available is rapidly increasing, which holds great promise for effective plant conservation.

Outside of the tropics, the very numerous species of Mediterranean climates are directly at risk in the age of climate change. As the ocean warms, the Prevailing Westerlies will be warm when they reach land and, with rain in the summer as well as in winter, the characteristic climate of these regions will cease to exist. In addition, the Westerlies are responsible for the moist, foggy conditions that have thus far enabled the survival of relict species like the Coast redwood (Sequoia sempervirens), which now exists in only a tiny corner of its former continental range. When we disrupt their underlying climate, the conditions under which their thousands of
endemic plants and unique animals cease to exist—and massive extinc-
tion is sure to follow. As we shall see, we can save the seeds and living tissues of as many species as we can obtain, but a very large number of others are likely to disappear in the wild unless we take effective action soon. Species that occur near the polar ends of continents, such as the very rich floras of Australia and South Africa, will have no place to go as the climate warms. Species living at higher elevations on mountains will also face a growing risk of extinction as the climate warms, progressively eliminated their habitats. Climate change overall poses an increasingly serious problem for species of all kinds (Lovejoy & Hannah, 2019). It is of critical importance, in the face of those challenges, to save as many of the threatened species as possible while we still have an opportunity to do so.

As the present century unfolds, our population is continuing to grow explosively, our agricultural lands are being expanded, climate change is intensifying, and our demand for ever-higher levels of con-
sumption seems unrelenting. In the face of these trends, we seem destined to lose many natural habitats and millions of species during the remainder of the 21st century. What new rates of extinction can we expect? Over the past 66 million years, we have lost about 0.1 species per million per year in those hard-bodied groups that we can sample adequately (essentially terrestrial vertebrates and mollusks). By comparison, we estimate that current extinction rates have already reached about 1,000 times the historical ones (De Vos et al., 2014; Pimm et al., 2014). Taking the evaluations of individual species by con-
servation groups such as the International Union for Conservation of Nature (IUCN) into account, perhaps a fifth of all species might disappear within the next few decades, with twice that proportion or more by the end of the century (Kew, 2016; Pimm & Raven, 2017; Pimm et al., 2014; Raven, 2020). Beyond the direct loss of species, the rates of population extinction overall are alarming. For example, Ceballos et al. (2015) have shown that some 60% of the populations of Mexican vertebrates have disappeared since 1950. The situation for plants is doubtlessly similar, indicating that extinction is actually proceeding far more rapidly than we generally assume. For the biologically richest habitats, the tropics, the situation is especially dire.

How, then, can we be most effective in our attempts to save as many plant species as possible from extinction? In one respect, plant conservation is much simpler than it is for almost any other kind of or-
ganism. The reason is that we have developed the ability to preserve viable plant seeds and tissue cultures at low temperatures, as well as living plants in botanical gardens and other institutions (e.g., Heywood et al., 2017; Walters & Pence, 2020). With plants, unlike most animals, we can regenerate tissue cultures relatively easily to produce whole, complete individuals. In addition, there are more than 115,000 species of plants, over a quarter of the total number, currently in cultivation in botanical gardens (Mounce et al., 2017; P. Smith, personal communi-
cation). Notably, Botanic Gardens Conservation International, together with its regional and national partners, is prioritizing the collection and conservation of rare and threatened plant species by employing a cost effective, rational sharing of responsibilities, skills, and knowledge (Smith, 2016; Westwood et al., 2020). In particular, Kew’s Millennium Seed Bank has gathered seed samples representing nearly 40,000 species of vascular plants, with the number increasing steadily. There are notable large seed banks based in Canberra, Australia, and Kunming, China, with others being found across the Northern Hemisphere. P. Smith(personal communication) estimates that about 42% of the IUCN-
denominated threatened species of plants have already been preserved in seed banks. Overall, those seed banks and related tissue culture cen-
ters include more than 60,000 species of vascular plants, but clearly not all of them maintain optimal conditions for the long term. This still represents only about an eighth of the world’s plant species, and we should certainly do what we can to increase both the number of spe-
cies represented and the dependability of their storage conditions. For some biologically very rich areas, including tropical Asia and the central Andes, the representation of plants in seed banks is particularly poor.

Although difficult in a time of rapid climate change, we must do our very best to re-establish plant species in nature to ensure their long-term survival without further human interference. Sergei Volis, who presented at the National Geography Society symposium "A World of Plants", has been an effective exponent of what these oppor-
tunities could mean for us (Volis, 2019). However, successful our current efforts may be, we still must find ways to establish viable ecosystems in the world that we continue to alter so profoundly.

The future of tropical forests is unfortunately unclear, although there are many plans and suggestions for how we might successfully conserve some of them. The major differences in wealth and the con-
sumption of sustainable productivity between nations means that, with no change, saving very much of these biologically rich forests will be exceedingly difficult. An increasing number of the countries where they occur have already fallen or are falling into what we have defined as an "Ecological Poverty Trap" (Wackernagel et al., 2019). At such a point, the countries have very little to consume, falling incomes, and a declining biocapacity per person. Overseas interests often take what is left, with little thought to the fate of the people living in such countries. These countries will not be able to pursue schemes for the conservation of their biological riches by following plans and suggestions developed by the wealthy unless those of us who have greater opportunities can find more effective ways to re-
verse our natural selfishness, recognize the worth of all people, and cooperate with them fully to help us all attain a sustainable planet.

Overall, the flood of extinction has already begun. Its pace has increased to the point at which many biologists have concluded—not-
tably Ceballos et al. (2017)—that we have already started the world’s Sixth Major Extinction Event, the first one since the end of the Cretaceous Period 66 million years ago. At that time, the character of life on Earth was altered permanently. Many of us have concluded that a similar irrevocable trend is underway at present. In any event, it is of great importance that we address the problem of mass extinc-
tion directly, using all the tools at our disposal while we still can do so (Pimm, 2020).

Everything about our situation now calls for collaboration, with the development and pursuit of appropriate collective goals, ultimately demanding recognition by our governments of the mad-
ness of maintaining their selfishness in the face of the disasters we are facing together. Anything less would not result in saving the
biological richness with which our world has been endowed, and indeed would not be worthy of us all. As our colleague, Dan Janzen, stated at a recent meeting, “If we don’t save it now, we can’t save it later.” It is time to get even busier, more focused, and collective in our thoughts. If we do not decide to study, understand, and save the plants that make up the backbone of all of our natural systems, there will not be room for anything else, and ultimately perhaps not even for us. This represents a tremendous challenge, but one of vital importance for the future.

**KEYWORDS**
conservation, ecosystems, evolution, plant history, plants, usefulness

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