THE NATURE OF NATURE

Why We Need the Wild

ENRIC SALA

NATIONAL GEOGRAPHIC
Washington, D.C.

Published by National Geographic Partners, LLC
1145 17th Street NW Washington, DC 20036

COVER AND CHAPTER OPENER ILLUSTRATIONS: Spring Stories, Life in the Tropics, Tropical Desire, and Inhabitants of the Sea patterns © Piñata/www.youworkforthem.com.

PHOTO INSERT: 1, Jim Richardson/National Geographic Image Collection (NGIC); 2 (UP), Enric Sala; 2 (LO), Michael Nichols/NGIC; 3 (UP), Aleksander Bolbot/Shutterstock; 3 (LO), Fraser Hall/robertharding/NGIC; 4, Thomas P. Peschak/NGIC; 5 (BOTH), Octavio Aburto; 6-7, Science Source; 8 (UP), Mattias Klum/NGIC; 8 (LO), Konrad Wothe/Minden Pictures; 9 (UP), Norbert Rosing/NGIC; 9 (LO), Cagan H. Sekercioglu/NGIC; 10 (UP), NASA Goddard Space Flight Center Image by Reto Stôkli (land surface, shallow water, clouds). Enhancements by Robert Simmon (ocean color, compositing, 3D globes, animation). Data and technical support: MODIS Land Group; MODIS Science Data Support Team; MODIS Atmosphere Group; MODIS Ocean Group Additional data: USGS EROS Data Center (topography); USGS Terrestrial Remote Sensing Flagstaff Field Center (Antarctica); Defense Meteorological Satellite Program (city lights); 10 (LO), Brian Skerry/NGIC; 11 (UP), Xose Manuel Casal Luis/Alamy Stock Photo; 11 (LO), Cyril Ruoso/Minden Pictures; 12-13, Art: Beau Daniels. Sources: Suzanne Simard and Camille Defrenne, University of British Columbia; Kevin Beiler, Eberswalde University for Sustainable Development; 14 (UP), C.R. Burrell; 14 (LO), Tom Murphy/NGIC; 15, Colin Monteath/age fotostock; 16, Enric Sala.

ISBN 9781426221019
Ebook ISBN 9781426221026

Financially supported by the National Geographic Society.

Since 1888, the National Geographic Society has funded more than 13,000 research, exploration, and preservation projects around the

CONTENTS

Index

To all those who dedicate their lives to preserve the diversity and abundance of life on Earth

CLARENCE HOUSE

During the last forty years, I have had an opportunity to visit some of the most stunning places on Earth and seen the devastation caused by our over-exploitation of the natural world. We are in the midst of an existential crisis, not only affecting the survival of our very society, but also about our place in the world. Global warming, climate change and the destruction of biodiversity worldwide, caused by human activities, are the most dangerous threats that humanity has ever faced. At the same time, as we have replaced the wild with the domesticated, we have distanced ourselves from Nature. Long ago, we unilaterally decided to place ourselves *above* Nature, instead of acknowledging that we exist *within* Nature.

There is indeed a deep mutual interdependence within our natural world which is active at all levels, sustaining individual species so that the great diversity of life can flourish within the natural limits of the whole. We do not truly know how many species there are – we can only guess – and we still know less about what species do. But what we know is the greatest wonder we ever encountered. Plants and bacteria give us the oxygen we breathe, insects pollinate our crops and forests filter the water we drink, among many other critical services. Millions of species work together to produce a harmony that we cannot explain, but which works to sustain our world – and to keep ourselves alive and prosperous.

In the modern era, the sense of awe and wonder in the face of the works of Nature has been abandoned in favour of monetary value. Therefore, being able to show the economic value of Nature, of healthy ecosystems, is paramount. Economists have shown that the value provided in services by the natural world for free is larger than the global gross domestic product. Yet, at this moment, we have a hugely important opportunity to reimagine the world through the lens of a new global market and a new way to measure prosperity, with clear benefits to people and planet at the heart of value creation. This is why, in September 2019, in collaboration with the World Economic Forum, I created the Sustainable Markets Council with the goal of fostering the development of a new type of market: green, inclusive, equitable and profitable. I would like to emphasize that profitability in our new world ought to mean obtaining net benefits while restoring the natural world that is the foundation of our wealth.

But valuing the natural world through an economic lens is not enough. I also believe that we need to abandon our purely mechanistic and utilitarian approach to life and adopt a humbler attitude – in other words, to restore a sense of the sacred. Human prosperity and empathy and respect for all living creatures are not mutually exclusive; they can go hand in hand. In fact, that may be the key to our survival.

The good news is that we know what the solutions to the environmental crisis are. If we were to choose three main solutions, we need to phase out fossil fuels, change the way we produce food and protect more of Nature. For example, on the Duchy of Cornwall's Home Farm in Gloucestershire, I have been able to shift from chemically-dependent farming to organic, agro-ecological production methods, where fertility is sustained by plants, animals and careful management that includes rotation of the land. Instead of an exploitative relationship with Nature, the farm works in partnership with Nature. Scaling such efforts globally could restore the fertility of the soil, produce healthier food, and in turn absorb huge amounts of our carbon pollution.

I am delighted to be able to contribute this foreword for Dr.

Enric Sala's *The Nature of Nature* because his book touches on all these points. Enric's book tells stories of discovery of key ecological principles that go beyond facts and data. There is fascination and love in the discovery of how Nature works. A deep appreciation of natural history is a kind of poetry, which should instil a sense of wonder. And that leads to love of the world of which we are an intrinsic part, with a profound respect for the existence of other creatures. The only way forward is to reconnect with Nature and restore vital eco-systems so that our life support system – and the engine of the human economy – can continue supporting us and the rest of life on the planet.

Charles

INTRODUCTION

IN THIS COMPELLING NEW BOOK, *The Nature of Nature —Why We Need the Wild,* Enric Sala takes us on a guided tour of Earth's marine environment, this time not only its aesthetic power but also the life-giving products of Earth's majority living cover. The health of the sea, no less than the health of the land, is ultimately responsible for every morsel we put in our mouths, every breath of air we take. We cannot create the land and sea, but we can destroy them.

It is fortunate that we humans can fully appreciate nature, even though through science we have only begun to understand her. What exactly is she, this Mother Nature, that we should give her almost divine status? I have devoted a large part of my life as an ecologist to the scientific study of nature, yet a definition of it in words still escapes me and most others I challenge. Nature evokes a feeling as much as a physical image. So let me try a definition that is more poetry than science.

Nature, sometimes called Mother Nature, is the metaphorical goddess of everything in the universe beyond human control, from the sweet descent of her sunsets to the tantrums of her thunderstorms; from the explosive brilliance of her ecosystems to the black void of her empty space.

Sala's approach to marine biology, aside from the beauty of his photographs, lies in the clarity of his vision of marine ecology as a scientific vision comparable to that achieved by studies of terrestrial ecology. The convergence is especially striking in the origin and evolution of ecosystems to land habitats such as forest and grassland on the one hand and coral reefs and other marine habitats on the other. Ecosystems, with their enormous origami-like relationships, are among the most complex of all natural constructions. To understand the patterns and laws of their common origins is one of the most important challenges of science in the present century. *The Nature of Nature* can help us in that quest.

—Edward O. Wilson

CHAPTER ONE

RE-CREATING NATURE

ON SEPTEMBER 26, 1991, eight people (four men and four women) were locked in a closed facility the size of two soccer fields in Oracle, Arizona. The project was called Biosphere 2, and its goal was to conduct an experiment to test whether we can build a viable self-sustaining human colony. The real biosphere—what one could call Biosphere 1—is the self-sustaining web of life that forms the thin living skin of our planet and makes our life possible. If Biosphere 2 succeeded, it would pave our way to colonizing other planets.

The plan was to create a simplified model of our biosphere that could sustain the lives of eight humans. Within a futuristic-looking glass and stainless steel structure, developers re-created a rainforest, a fog desert, a thorn-scrub, a savanna, a marsh, a mangrove, and a coral reef—together with an agricultural area where the participants could grow their food. These habitats were hermetically isolated from the world outside and designed based on the best ecological knowledge. But things started to go wrong rather quickly.

After 16 months, the oxygen concentration in Biosphere 2 had dropped from the healthy 21 percent in our atmosphere to a low 14 percent—low enough that some "biospherians" showed symptoms of altitude sickness. The soils imported into the enclosure were very rich in organic matter, selected with the goal of producing enough nutrients for vegetation to grow over time. As it turned out, though, microbes in the soil processed that organic matter, sucking up oxygen and building up carbon dioxide (CO_2). At the same time, the plants being grown were not large enough to produce enough oxygen to compensate or to absorb that extra CO_2. In addition, that extra CO_2 reacted with the concrete in the structure, forming calcium carbonate, which meant that carbon and oxygen were not available to the living beings in the enclosure anymore. In the long run, oxygen had to be pumped into the experiment to keep the system and its inhabitants alive.

One of the biggest problems within the enclosure was the rise in CO_2—a prophetic consequence, since rising levels of CO_2 represent one of the major threats to human civilization on the planet today. But not only the atmosphere failed in Biosphere 2—the wildlife did too. Species became extinct faster than anticipated, and few of the introduced animals survived the experiment. The ecological designers had brought in bees, moths, butterflies, and hummingbirds as pollinators. They had also included snakes, skinks, lizards, turtles, and bats, among other vertebrates. But the bees and hummingbirds died off, meaning that plants could no longer reproduce by themselves. Meanwhile, other species boomed, including crazy ants, cockroaches, and morning glories, which managed to overgrow every other plant. Thus, the biospherians had to spend over half of their time just tending to their crops. Only six out of 25 small vertebrate species survived by the end of the experiment.

The first mission of Biosphere 2 ended two years after it started. A second mission in 1994 only lasted six months, mostly because of human conflict: Some biospherians insisted on opening up air locks, and a bitter dispute between the main financer of the project and the in-site management team resulted in federal marshals ousting the team by serving a restraining order.

What did we learn from Biosphere 2? Some biospherians say that the experiment was a success because it taught them to become self-sufficient and to solve unexpected problems. There is some truth to that. Given more time, maybe the enclosed habitat could have become self-sustaining—likely different from what the designers of Biosphere 2 envisioned, but a functioning ecosystem nonetheless. The fact is, in the two years of the first mission, Biosphere 2 did not turn into slime.

Moreover, this is the way science advances. We experiment, fail, learn from it, and try new things using the knowledge we acquire. We tend to learn more from our failures than from our successes. Biosphere 2 was a bold, innovative experiment that taught us very bluntly how difficult it is to maintain a relatively simple ecosystem and a healthy atmosphere. It failed to replicate the viability of Earth for human life. The experiment was a testament to our ignorance of how life on our planet works—and our inability to re-create it.

In essence, what it did show is that our planet is a miracle. It does not matter whether you believe Earth was created by an omniscient God, or grown by physical forces from cosmic dust circling around a nascent star, or generated as a computer simulation (yes, there is a group of theoretical physicists who believe so). We're traveling in a spaceship 107,800 kilometers an hour (67,000 mph) around a star that is in turn traveling 69,200 kilometers an hour (43,000 mph) in the suburban part of our galaxy. There are 400 billion planets in our galaxy alone, orbiting around at least 100 billion stars. What makes Earth truly unique is life. Life on Earth and its mind-blowing, intertwining complexity is the greatest miracle humanity has known.

But if we had to make a catalog of all that we know about the living creatures on Earth, 99 percent of the pages would be blank. To date, scientists have described fewer than two million species of multicellular organisms—the plants and animals we can see. We know the birds pretty well. We also know the mammals, fish, corals, and flowering plants well, even though every year we add a total of 6,000 new species to our catalog. But scientists estimate that the total number of species is probably around nine million. This does not include single-cell organisms, the microbes such as bacteria and archaea, found everywhere from our guts to the clouds above us to two miles underground. These could add up to a trillion species to the census, yet we have come to know only a fraction of them.

But one thing we know with absolute certainty is that everything we need to survive—every morsel of food we put in our mouths, the oxygen in every breath we take, the clean water we drink—is the product of work done by other species. They give us so much, and how do we repay them? We ignore, undo, and destroy them.

We are erasing species from existence at a rate a thousand times faster than the natural extinction rate. A 2019 United Nations report warned that human activities will drive the extinction of one million species of plants and animals (one in nine) in the next few decades. And we're filling the void—actually, creating that void—by replacing that lost diversity of life with our food sources. Today, 96 percent of the mass of mammals on the land is us and our domesticated livestock. Only 4 percent is everything else, from elephants to bison to panda bears. As a matter of fact, we have lost 60 percent of the terrestrial wildlife since 1970 and 90 percent of the large fish in the ocean (sharks, tuna, cod) in the last century. Seventy percent of the birds on Earth are our domesticated poultry—mostly chickens—and only 30 percent are wild.

Not only are we replacing thousands of species of wildlife with a few species of farm animals, but we're also transforming the land at a scale second only to the forces of plate tectonics. Presently, more than half of the inhabitable land surface is farmed or pastured—gone are the former forests and grasslands that used to enrich those soils—and almost 80 percent of that agricultural land is used to raise or feed livestock.

If we continue our ways, soon the only large animals left on the planet will be us, our domesticated food, and our pets, and the largest plant communities won't be the magnificent tropical and boreal forests, but monocultures like the vast industrial croplands that now make up the American Midwest. Is this a viable future for humanity? Can we survive on a planet without wild places? If worse comes to worst, will we be able to build viable colonies on other planets that can support a self-sustaining human society?

Biosphere 2 was carried out 25 years ago. Our science and technology has improved phenomenally since then. In fact, as of November 2000, humans did become the long-term residents of a space colony: the International Space Station (ISS). The ISS is a miracle of engineering that orbits Earth at an average altitude of 409 kilometers (254 mi). It is the only existing human colony in space—but still attached to our planet by its gravitational pull, like the infant who does not dare to wander too far from mother. It takes an extremely complex international cooperation, with control centers in the United States, Canada, France, Germany, Russia, and Japan, to keep between two and eight astronauts alive up there. In addition to its initial price tag of a hundred billion dollars, it costs NASA alone three billion dollars every year to cover its share of running the ISS. That means ensuring that those few people have, at the very least, a stable supply of oxygen to breathe, water to drink, and food to eat—plus a protective shield against cosmic radiation and the lethal void. In space, everything is trying to kill you. If we learned one thing from Biosphere 2, or from the daily work necessary to keep humans in the ISS alive, it is that we should worship our actual biosphere that keeps us alive.

Here on Earth, we don't have to worry about cosmic radiation. (Have you ever met anyone who does?) We don't have to worry about—or pay anything for—the oxygen we breathe. Until recently, many of us did not have to pay anything for the water we drink—it fell from the sky or arose from eternal springs. In addition, we underpay for our food, because we are not charged for the sunlight that keeps plants going or for the bees that pollinate our orchards—or, until recently, for the environmental costs created by our industrial food production processes.

If it's so difficult to keep even small ecosystems stable enough to sustain the life of a handful of humans, how do nine million species of plants and animals and a trillion species of microbes coexist and allow for our survival? How does this Biosphere 1 manage to keep everything alive and in balance? In what way do we depend on all those other species for our own survival?

This book aims to answer these questions.

I HAVE SPENT the last 30 years studying natural ecosystems, mostly those in the ocean. These questions have been in my mind since I began studying biology in college in 1986, and I have dedicated a great part of my life to try to make sense of the overwhelming miracle of life on Earth.

I started my forays into marine biology as an undergraduate, studying the marine algae that grew on the rocky shores of the Costa Brava in Catalonia, Spain. First, I had to identify them—that is, I needed to know which species was which, in the same way that any botanist should be able to distinguish an oak from a pine. On the coast of Catalonia alone there are more than 500 different species of algae, so this was no easy task. Before the internet, the only source of identification were monographs published in specialized journals that were available either at the university library or, more often, in the private libraries of a handful of professors who were students of algae. Fortunately for me, one of them, Lluís Polo, became my professor of botany during my second year of biology studies at the University of Girona, in my hometown.

During the summer months I worked the night shift at my uncle's restaurant on the beach. After the latest diners left (and in the Mediterranean summer, that meant after midnight), I had to reconcile the receipts and reload the bar fridges. When all my co-workers had gone back home or were partying at one of the local discotheques, I was carrying cases of sodas, beer, and sparkling water from the pantry in the back of the restaurant to the bar near the entrance. I typically closed the doors of the restaurant after 1 a.m. and went to bed, exhausted. But I never slept well because of the excitement I felt about the coming day. I knew I needed to wake up early to get to the water before the hordes of summer tourists colonized the coves nearby.

Shortly after 8 a.m., I walked by closed restaurants, yet-to-be-opened stores selling beach accessories and perfumes, and open yet sleepy newspaper stands. I carried a mesh bag containing my mask, snorkel, fins, a blunt kitchen knife, an old pair of pantyhose, and a beach towel. Walking down steps cut into the rock, I meandered among curvy orange and pinkish rocks crowned by green pines that curled toward the Mediterranean, as though they were bowing to the sea. At the base of the steps were little sandy coves, hugged by the rocky promontories. The small waves of the calm morning sea kissed the beach with a hush of such regularity that, had I lain on the sand for a minute, they would have put me to sleep. But instead I jumped into the clear turquoise waters with the knife and the pantyhose, on my quest for algae, as many different types as possible, always looking for those I had never seen before. That was my little paradise.

Two days a week I would take the 8 a.m. bus to Girona, 36 kilometers (22 mi) from the beach, to visit Polo at his laboratory. He was the one who introduced me to the wonderful world of algae. First I learned to divide the algae between three evident groups: brown, red, and green. But some algae that looked brown actually belonged with the red algae. Scratching my head, I started to realize that things might not be so evident in nature as one might think. The diversity of species was astounding: brown algae that looked like foot-long Christmas trees, green algae like little lettuce only two cells thick, and minute red algae no thicker than a human hair that, under the microscope, revealed branches that divided in perfect symmetry with alternating bands of red and transparent cells. In its algae, the Mediterranean was as diverse as any exotic coral reef, only at a miniature scale. Another local expert who later became my mentor and one of my closest friends, Enric (Kike) Ballesteros, once took a sample at 40 meters (131 ft) deep and identified 149 different types of algae in an area the size of a cafeteria tray.

Very quickly I realized that these algae were not found just anywhere. Each kind had its own favored location. Some algae grew on top of each other, sometimes with algae growing on algae growing on algae. And the algae at the base might grow on a rock or over a barnacle or mussel. There was a regularity: Different species—and the distinct “communities” they formed—were found at different depths, at different exposures to waves, and at different exposures to light (for example, on top of an underwater boulder versus at the edge of a rock overhang). Polo and Ballesteros taught me that these algal communities form distinct belts found at predictable depths. Some algae—the little Christmas trees—were only present at the interface between the rocks and the sea, in rough areas exposed to the waves, because that was the only place where they escaped from the schools of voracious salema porgies, a species of sea bream with an oblong silver body with golden stripes (which, by the way, can cause hallucinations when eaten). Other algae grew abundantly on top of underwater boulders. They didn’t need the protection of rough waves or rocky overhangs because they produced chemical compounds that made them unpalatable to the fish.

As I sorted algae in the lab, I discovered thousands of little creatures living among their branches—crabs, shrimplike amphipods, wood lice, worms, snails, sea slugs, and many more. Some of these species were eating the algae, some were eating each other, and all were hiding from the fish within the algal canopy. The more I learned, the more new worlds appeared in front of my eyes. My mind was ever hungry, and marine biology became my life and my passion.

FAST-FORWARD 10 YEARS. After finishing my Ph.D., I moved to the prestigious Scripps Institution of Oceanography in La Jolla, California. As a university professor, my job was to educate the future leaders in the field of marine ecology and conservation, to conduct scientific research, and to publish in scientific journals. But the places that I was studying, places that I loved deeply, were falling under the force of the relentless human sledgehammer. Corals and seagrasses were dying everywhere, and fish were being taken out of the water faster than they could reproduce. What had been lush underwater gardens full of large animals were being turned into dead reefs overgrown by brown algae and murky jellyfish dystopias.

One day I realized that all I was doing was just writing the obituary of ocean life. In fact, many of my colleagues and I were *rewriting* the obituary with more and more precision. I felt like the doctor telling you how you are going to die with excruciating detail, but without offering a cure.

That's when I decided to quit academia and dedicate my life to reversing the degradation of the ocean. Thus, I have spent the last 12 years as a National Geographic explorer-in-residence, helping to protect some of the last wild places in the ocean through our Pristine Seas project. Visiting these places has allowed our team to catch glimpses of intact, fully functioning ecosystems. I have dived, explored, and conducted research in many places around the world, from the polar regions to temperate seas to the tropics. I have seen degraded places, pristine places, and many in between. I have seen the miraculous recovery of overfished places once fishing stopped. I have seen nature thrive in places, and nature wane in others. I have been privileged to witness what few people have, and I understand, from the purely rational to the supremely spiritual level, why we need all these species around us.

It all started with my being able to tell species apart, to know who all my new friends were. Then came observing who lives next to whom, how, and where. Then who eats whom. And, more recently, recognizing the impact of human activity on the natural world.

The Nature of Nature explores how the natural world works, outlines the consequences of its unraveling by our activities, and offers practical solutions—with a description of societal and economic benefits. The next 10 chapters of this book are a step-by-step crash course in ecology—you might call it "ecology for people in a hurry": what species do, how they coexist, and how the natural world self-assembles and works, compared with our human-built environment—with implications on how to run our society and economy more efficiently. What I am offering is a mix of my own first-hand experience and stories of science heroes, some of whom I have been privileged to know and work with. In Chapter 12 I discuss the moral case for the conservation of life on Earth, because utility cannot be the only lens through which we see the world. In other words: Do other creatures have a right to exist, and why? In Chapter 13 I explain why it makes economic sense to protect more of the natural world than to degrade it.

Chapter 14 synthesizes the lessons from the book and proposes practical solutions for safeguarding our biosphere and human society at the same time. I thought this was going to be the last chapter. But after the book had been edited and was ready for printing, the COVID-19 pandemic happened. My editors and I decided to delay the production process so I could write a final section on the novel coronavirus, which has turned out to be the most powerful wake-up call to the world about the enormous risks to human health posed by our broken relationship with nature.

By talking to the brain and the heart, and at the same time reaching into the pocket, I hope to illuminate an inner appreciation for all life on Earth, instill a greater sense of humility, and help us understand why we need a world with wild places.

CHAPTER TWO

WHAT'S AN ECOSYSTEM?

CORSICA, the granite island in the middle of the western Mediterranean, is one of my favorite places on Earth. When I first went to conduct research there as part of my Ph.D. work, in 1993, it was, as my doctoral adviser Charles-François Boudouresque warned me, "like traveling back to the Mediterranean of 500 years ago."

I had spent my childhood summers in coastal towns with crowded beaches and concrete walls. Even my favorite coves, where I did my first observations of marine life, were surrounded by villas, hotels, and apartment blocks. But Corsica was different. It was just before sunrise when the ferry that took me from mainland France approached the shoreline of Ajaccio, in the southwest of the island. I stood on deck, sleepy but in awe. The tall and proud Corsica was wild, with very few signs of human habitation, in contrast with the mainland I was used to, where patches of green poked through concrete and asphalt. As the sun peeked over the mountains, a pocket of warm air delivered an aroma from the island that filled my eyes with tears. I can still remember it: juniper, laurel, rosemary, myrtle, sage, mint, thyme, and lavender—the essence of the wild maquis of Corsica. That was the beginning of a love affair that soon became central to my scientific endeavors.

I am extremely privileged to have been to Corsica many times with a handful of dear friends and colleagues, to conduct scientific research at the Scandola Marine Reserve, on the northwest side of the island. Many people have joined us over the years, but initially we were a tight group of friends, people who also were my mentors and colleagues: Kike Ballesteros, who taught me about algae and natural history; Mikel Zabala, an amazing naturalist and professor of ecology at the University of Barcelona who co-directed my Ph.D. thesis; and Joaquim Garrabou, also working on his Ph.D. at the time, studying how the dynamics of ecological communities change with depth. What brought us together was that we were all fanatic divers fascinated by nature, and all of us were unable to stay idle. We all wore green wet suits for diving and, bouncing off the nickname for the famous U.S. basketball team that won the Olympic title in Barcelona in 1992, we called ourselves the "green team."

Our fieldwork in Corsica typically took place in October, after the few tourists were gone and the reserve manager could dedicate his attention to our work. October in Corsica is a crapshoot. You never know what weather you will get. Some years we had sun and calm seas, but other years we had strong winds or rough seas that prevented us from reaching our diving spots. But we never stood idle, and when the sea did not want us, we explored the old oak forests in search of wild mushrooms—mostly the delicious cèpes, chanterelles, and Caesar's mushrooms. Or we simply walked the elegant pine forests along the desert beaches, or hiked the spectacular granite mountains that stretch up to their summit at Monte Cintu, 2,710 meters (8,891 ft) above sea level.

IF WE PUT TOGETHER all the dives and hikes in one transect from depths to heights, it would reveal a clear distribution of

Corsica's plants and animals. Sixty meters (197 ft) below the surface are forests of white and red sea fans and yellow sponges like organ pipe cactus. At 50 meters (164 ft) they give way to a forest of old brown algae that look like miniature olive trees, with gnarled trunks and a tuft of branches growing from what look like olive pits. As we move toward the surface, a different species of brown alga appears at about 30 meters (98.5 ft) depth, this one with a brown trunk as thick as a thumb, crowned by a palm tree–like canopy. Different algal species become more dominant closer to the surface, forming forests of different height and age. The animals follow similar patterns, with sea fans living deeper and sea urchins closer to the surface. Some fish, such as the salema porgy, move through different depths, but most species are found within a predictable range.

As we exit the water, we climb red volcanic rocks sprinkled with deep-green bushes and the wild aromatic herbs that brought me to tears when I first smelled them—and still fill me with sweet nostalgia every time I recall them. Or we can turn left and walk across a sandy beach bordered with stone pines, cork oak, and evergreen oak, and meet an undammed river, home to freshwater turtles and fringed by a riparian forest. As we climb up, we encounter maritime pine interspersed with mixed forests of downy oak, sessile oak, Italian alder, and sweet chestnut, with a rich diversity of the wild mushrooms that we gathered and enjoyed when the weather was too rough for diving. Higher up on the mountain, these broadleaf deciduous forests are replaced by forests of Corsican pine on the slopes facing south, and silver fir and European beech on the slopes facing north. Above the forest line, at about 2,000 meters (6,560 ft), we find shrublands of green alder, juniper, sycamore, maple, and silver birch. Continuing up, eventually it becomes too cold for large plants, and all you can see are lichens growing stoically on granite. The very top of Monte Cintu is bare rock—and a lot of snow in the winter.

If we drew the borders between the different types of plant and animal associations we saw, they would look like a series of belts, roughly parallel to each other. Each of these unique groupings of plants and animals can also be defined as different ecological systems—or ecosystems.

AN ECOSYSTEM is simply the community of living organisms (microbes, plants, and animals) and the physical environment (the habitat) they occupy. The organisms and their relationships are what ecologists call a “food web”—a collage of overlapping food chains where a predator eats a predator eats a prey, and where species compete for space, light, and other resources. But living beings don’t just occupy their habitat, be it granite or volcanic rock, sandy beaches or inland plains; they can actually create their own habitat (for example, coral reefs) and provide room and food for many creatures. If life on Earth is a miracle, what life does is still an even more wondrous miracle.

Ecosystems grow and shrink and senesce, and parts of them regress to a young state that allows dormant species to have a day in the sun. Ecosystems are never static. They self-regulate through feedback loops within the biological community but also between living organisms and their habitat. They create rain and regulate the weather. They fill the atmosphere with a mix of gases that allows us to breathe and survive. They filter the clean water we drink. They protect us from floods. They have been saving us from catastrophic climate change for more than a century. But few of us have noticed.

Ecosystems have had billions of years to experiment and, through trial and error, self-organize into the most efficient machines in the universe. They are always changing, and until recently they always fluctuated within reasonable bounds, following predictable pathways. We cannot really re-create much of what ecosystems do for us. Yet dead ecosystems have allowed humans to be the masters of life on our planet—and its destroyers too. But we will park all these stories for later.

Not only forests and wetlands and rivers are ecosystems. Our cities are too. For instance, New York City's habitat is primarily a built environment made of asphalt, concrete, glass, and steel, interspersed by some greenery. When thinking of wildlife in New York City, most may think of rats, Central Park squirrels, or the odd peregrine falcon nesting on the roof of an office building and making headlines. But New York is also home to thousands of plant and animal species that coexist with the city's almost nine million people. This wildlife includes coyotes, squirrels, bats, skunks, opossums, red foxes, white-tailed deer, snapping turtles, eastern box turtles, salamanders, and more than 200 species of birds. Strikingly, in the waters surrounding New York City, and in the Hudson River, live 80 species of fish. Even humpback whales and fin whales have been observed. In the most claustrophobic concrete jungle, life hangs on.

If humans suddenly abandoned New York City, the built habitat would collapse. New York City is like Emmentaler cheese belowground, with dozens of tunnels, 245 miles of subway routes, and 6,600 miles of sewer mains and pipes. Without the 290 pump rooms working 24/7 that the city currently uses to drain more than 16,000 gallons per minute of water from the Hudson River, the East River, and the Upper Bay, the metro routes and the tunnels would be flooded. That would turn the holes in the cheese even larger and eventually cause the collapse of buildings. It would not take long for dust to accumulate in holes and crevices on the surface, and for plants to colonize the rubble. Wildlife would start to overtake the ramshackle surroundings.

Life—and the ecosystems it forms—has an extraordinary capacity to regenerate and self-assemble, even in the most unlikely places. Everyone in my generation can remember the explosion of the Chernobyl nuclear reactor in 1986. Despite the heroic efforts of Soviet scientists, soldiers, and miners to contain the radiation, it became so pervasive that people were evacuated from the neighboring town of Pripyat—permanently. Even pets had to be killed to prevent them from spreading radiation. And then nature took over. Now the buildings are crumbling, conquered by shrubs and trees, and the city is the territory of wolves. Apparently the built habitat cannot survive without its builders. In a few thousand years, Pripyat might look like Maya cities in the jungle when first rediscovered under a thick canopy of green.

IF WE ZOOMED OUT from the Corsican forests, we would see the divide between the land and the sea. Zooming farther out, we'd notice that Corsica is an island ecosystem surrounded by the Mediterranean. Zooming farther out still, the Mediterranean itself would appear as a distinct ecosystem with clear boundaries north—the Alps and the Carpathian Mountains—and south—the Sahara. Astronauts on the International Space Station, who have zoomed out even farther, recognize that the entire planet is an ecosystem, with no visible borders except for those between land and sea, desert and vegetation, cities and farms. No wonder. Ecosystem comes from the ancient Greek word *oikos,* meaning "family," and also "house."

Full circle.

But how does this living miracle work and sustain itself? How can nine million species of creatures we can see and a trillion types of microbes we cannot see interact in a way that provides stability to the entire planet? To answer these questions, we need to start from the beginning. Let's put two species together and see what happens.

CHAPTER THREE

THE SMALLEST ECOSYSTEM

IN 1934, a Soviet biologist only 23 years old published a book titled *The Struggle for Existence*. This little book, unknown to most students of biology today, is one of the most important studies in the history of biology, for it provided the first experimental basis for understanding how species compete with each other and how species can destroy each other (and themselves) in a world of limited resources.

Georgyi Frantsevich Gause, that young biologist, was the son of Frants Gause, a professor of architecture, and Galina Gause, an industrial worker at an automotive steel plant. Gause and his family took long summer vacations to the Caucasus, where he developed a love for nature. At 17 he entered the prestigious Moscow State University. The Russian system required a faculty adviser for every student, and in one of those serendipitous moments that randomly shape a life and its influence in history, Gause was assigned to Professor Vladimir Alpatov.

Alpatov was influenced by American research on population growth, which hypothesized that the growth of any population, including humans, tends to slow as its density increases. That suggested that the human population would not grow forever until we exhausted all resources on the planet and died. Instead, the population would grow slowly in the beginning, then increase very fast, and then level off, and population numbers would stabilize. Biologists have observed this pattern of slow growth followed by explosive growth and finally stabilization—called logistic growth—in many a species since, including ourselves. It's the theory behind the prediction that the human population will likely stabilize around nine or 10 billion people by 2050.

In science, after a theory is proposed, it has to be tested with field observations or, ideally, with experiments. Gause thought that fieldwork would never be able to test these logistic growth assumptions properly because species do not live in a vacuum, since they are all interacting in a complex web of relationships. Simply put, there are too many confounding factors in nature to isolate the factors needed to test this hypothesis. But Gause thought that he could conduct experiments in the laboratory by building simplified environments, controlling all factors. Thus he started one of the most significant studies in the history of biology.

GAUSE WAS STRONGLY INFLUENCED by Charles Darwin, who had published his *On the Origin of Species* only a few decades earlier. Darwin assumed that all species compete in the struggle for existence in ways that we do not comprehend because of our ignorance of "the mutual relations of all organic beings." Darwin thought that "each organic being is striving to increase in a geometrical ratio; that each, at some period of its life, during some season of the year, during each generation, or at intervals, has to struggle for life and to suffer great destruction."

The "geometrical" growth (also called exponential growth) that Darwin mentioned means *explosive* growth. A great example to illustrate geometric growth is the tale of a craftsman who presented a chessboard to an Indian king. The king, marveled by the board and the game, offered the man any reward he wanted. The man asked that a single grain of rice be placed on the first square of the chessboard, then two grains in the second square, four in the third, eight in the fourth, and so on and so forth, doubling the number of grains in each new square until all 64 squares had been filled. That was the reward he requested, and the king agreed to it. But there was a little problem: When you double the amount of rice 64 times and add up all the rice grains found on all squares, it equals 210 billion metric tons, enough to bury all of India under one meter of rice.

Put another way, if every species were to increase geometrically—which could seem plausible, if every individual had just two babies—our planet would be filled with an enormous number of individuals of every species. But this is not what we see in our world. Instead, we see that not all species are equally abundant. In the African plains, grasses are more abundant than acacia trees, and wildebeests are more abundant than elephants. Thus Darwin thought that, despite every species' drive to reproduce as much as possible, there must be something that keeps their abundances in check, some kind of "struggle for existence" that limits their growth. Part of that struggle is, of course, how much food is available. Another part of the struggle, Darwin thought, must be the relationship of each species with other species in the ecosystem.

Before Darwin's time, no one really understood how species interact with one another to form ecosystems. Biologists knew that plants compete for light and soil nutrients, and that predators reduce the abundance of their prey, but they did not understand how species abundances stabilize within the web of complex relations. Gause wanted to prove that the complex relationships between organisms are determined by simple processes that could be modeled mathematically. He wrote: "Such an elementary process is that of one species devouring another, or when there is a competition for a common place between a small number of species in a limited microcosm."

A few years earlier, Umberto D'Ancona, an Italian biologist, conducted a statistical study on the numbers of fish sold in three markets in the northern Adriatic Sea. He observed that during World War I the relative numbers of predatory fish—sharks, rays, and skates—had increased relative to the smaller fish they feed on, and then decreased shortly after. He proposed that the drastic decline in fishing during the war had restored “the natural balance” of the marine ecosystem, whereas the intense fishing occurring after war’s end had disturbed it. Unaware of the ecological explanation, D’Ancona asked his uncle, the famous mathematician Vito Volterra (by then retired), if he could come up with a mathematical model explaining his observations. Volterra quickly developed the first models for interactions between species. These models became the basis for understanding the relations between species that compete for a resource and the relations between predators and their prey. Applied to the Adriatic in the early 1900s, the model suggested that the decline in fishing allowed the large fish—the predators—to recover from human exploitation. More numerous predators ate more of their fish prey, hence the observed increase in the relative abundance of the predators. After the war, fishing resumed and predator numbers were depleted once more, which brought prey numbers up again.

Gause knew about D’Ancona’s and Volterra’s work, and he set out to test Volterra’s models with experiments. Laboratories in the early 1900s tended to be quite archaic compared with what university students can enjoy today, but Gause’s creativity compensated for the lack of resources. He created the microcosms he had envisioned using test tubes filled with food (a nutritive medium) and stopped with cotton wool. Within each glass tube was a self-contained ecosystem, isolated from all the confounding factors that one finds in nature.

GAUSE’S FIRST EXPERIMENT was intended to test whether a single species would grow following the logistical law. The species of choice was *Paramecium caudatum,* a single-celled organism the shape of a short cigar whose pointy end has not been cut. Its transparent body is covered with fine hairlike filaments that it uses to move and feed on small organisms such as bacteria and yeast. *Paramecium* is only 200–300 microns in size (a 20th the size of a medium rice grain), and it reproduces rapidly by dividing itself in two daughter cells, without need for sex with other individuals. That makes *Paramecium* an ideal organism for experiments involving multiple generations.

Gause introduced five individual *Paramecium* into small test tubes, each containing 0.5 cubic centimeter of nutritive medium (the equivalent of 10 drops of water). For six days he counted the number of individuals in every tube. The numbers increased rapidly in the beginning and more slowly later, until on the fourth day the *Paramecium* had reached an average abundance of 375 individuals per tube, attaining what Gause called the "saturating population." The growth of *Paramecium* in the microcosms fitted the logistical curve beautifully.

The next step was to complicate that mini-ecosystem one notch, by adding a second species. Gause believed that different species, no matter how closely related they are on the tree of life, do not use the environment in the same way. For instance, they must consume different quantities of food and excrete different quantities of metabolic products. His question was, Would two species living together reach a saturating population equal to the one they reached when living in isolation? Or would one species be victorious over the other—that is, reach a higher abundance?

Gause shifted to two species of yeast that ate the same food to assess the competition between them: *Saccharomyces cerevisiae,* the yeast used for brewing beer, and *Schizosaccharomyces kefir,* the yeast used to produce kefir. Both species can grow with or without oxygen. When yeasts grow without oxygen, fermentation occurs: They create ethanol as a waste product. When oxygen is added to the mix, some fermentation still occurs, but yeast cells divide more rapidly. Both species produce alcoholic fermentation, but the kefir yeast grows very slowly without oxygen.

First Gause grew each species in isolation, to determine their saturating populations. Then he grew them together in the same test tube with a nutritive medium containing 5 percent sugar. He developed 111 separate microcosms for this experiment, and then averaged the results across three treatments: beer yeast growing alone, kefir yeast growing alone, and the two species growing together.

As expected, when growing alone, both species of yeast followed the logistic curve, first growing fast and then slowing down until they saturated. The decline in growth occurred even before all sugar in the medium was consumed, because the accumulation of their waste product—ethanol—killed the young yeast buds. The kefir yeast grew much more slowly, and its saturating population alone totaled less than half that of the beer yeast alone. But the combined amount of yeast in the microcosms containing both species was lower than that of the beer yeast growing alone. What happened?

When growing together, the amount of yeast of each species was lower than the saturating population each would have reached in isolation. Further, the amount of ethanol produced was larger when two species were growing together than when either grew in isolation. Therefore, Gause concluded, the amount of ethanol attained toxic levels earlier in the mixed treatment than it would have from single species.

Gause repeated the experiment, now adding oxygen to the mix by aerating the microcosms in the same way you might aerate a home aquarium. The main results were the same: The saturation population was lower for each yeast species when growing together, even though the kefir yeast grew much faster than without oxygen, and its saturating population more than doubled. What Gause called “the coefficients of the struggle for existence” were predictable under defined environmental conditions, no matter how fast the species grew. That meant that, as he put it, “if we know the properties of two species growing separately...we can calculate theoretically the growth of species and their maximal volumes in a mixed population.” In the case of yeast, the result of the competition between two species was determined by the accumulation of their waste product.

But that finding was still not enough for the brilliant young Soviet scientist.

In a methodic buildup of his analysis of species interactions, Gause then repeated the experiments, using another same-species pair, in this case his old experimental subject, *Paramecium caudatum,* and a similar species, *Paramecium aurelia*. But he added a twist: Now he would keep adding water and food to the microcosm daily, in an attempt to mirror the natural conditions where the energy from the sun is available daily without interruption—as opposed to previous experiments where food was limited and, once it was consumed, there was food no more. Gause's key question now was, "Will one species in these conditions drive the other one out completely, or will a certain equilibrium become established between them?"

Both species grew well separately and attained their saturating population in about 10 days, but the news here was that *P. aurelia* drove *P. caudatum* extinct in about two weeks when growing together—that is, when competing for the same food. Surprisingly, *P. caudatum* started to grow faster than *P. aurelia,* but *P. aurelia* was more resistant to waste products, making it competitively superior in the longer term.

This seminal finding was later named the "competitive exclusion principle," whereby two species that compete for the same resource cannot coexist at constant abundances. When one species has an advantage over the other, even the slightest one, it will dominate in the long term. The comparisons with our own interaction with the rest of species on Earth could not be more chilling.

THE NEXT STEP in Gause's work was to introduce one more level in the food web: a predator. With unplanned prescience, he named that chapter in his book "The Destruction of One Species by Another." The new extended ecosystem was now composed of three levels: bacteria → *Paramecium caudatum* → *Didinium nasutum. Didinium* is a barrel-shaped, single-cell organism that eats mostly *Paramecium,* even though *Didinium* is only half the length of *Paramecium.*

Volterra's mathematical equations (developed independently by his contemporary Alfred Lotka, an American scientist) suggested that in nature, a predator will never drive its prey extinct. This is what biologists believed all along: When the prey abundance decreases because of predation, it will be followed by a decline in predator abundance because of a shortage of food. But when the predators decline, the prey will increase again because of decreased predation, and so on. The Lotka-Volterra theory predicted periodic oscillations in the abundance of predators and prey, and field data supported the theory.

Once again, Gause was in for a surprise. He placed five individuals of *Paramecium* in his microcosms, and two days later added three predator *Didinium.* In his own words: "After the predators are put with the Paramecia, the number of the latter begins to decrease, the predators multiply intensely, devouring all the Paramecia, and thereupon perish themselves." In other words, the predators eat all the prey and subsequently become extinct because of the absence of food. Gause repeated the experiment many times, in vessels of different size, and adding the predators at different times, but the result was always the same: In the end, the predators could not help themselves, and everybody died.

This is not what we observe in the natural world, however, where predators and prey coexist in many different environments. A wonderful example comes from pure observation of an unintended experiment. Records of pelt trading by the Hudson Bay Company in Canada from the mid-1800s up to Gause's days showed an oscillation between the number of lynx (predator) and hare (prey) fur caught by trappers. The numbers of animals caught back then were small relative to the total size of the wild population, so trapping was probably not the main factor in explaining changes in lynx and hare numbers. The assumption was that the success of trapping lynx and hare reflected their abundances in the wild. There were cycles where lynx numbers increased and hare numbers decreased, followed by a decline in lynx numbers and an increase in hare numbers, and so on and so forth. Yet lynx never drove hares extinct. In the same way, lions in the African plains, wolves in temperate forests, or sharks in coral reefs never drive their prey extinct. So what happened differently in Gause's experimental microcosms?

Gause continued by replicating some natural conditions, adding variety in his little microcosms. His test tubes represented a homogeneous ecosystem, which does not exist in the real world. So he added sediment to the test tubes, where *Paramecium* could hide. As expected, *Didinium* ate all *Paramecium* outside of the sediment, while some *Paramecium* were able to escape by taking refuge within the sediment. *Didinium* does not hunt actively for prey—it only ingests whatever comes near it—so the prey in the sediment were safe. But that meant that soon there was no food available for *Didinium,* so the predator went extinct. Without the predator, *Paramecium* resumed growing until it reached its saturating population. Once again, it became hard for Gause to re-create the natural conditions of even the simplest food chain. Spatial refuges prevented the extinction of the prey but resulted in the extinction of the predator, while Lotka-Volterra equations predicted the oscillations in predator-prey numbers. What was missing here?

Gause then added another factor: immigration. He introduced a few *Didinium* predators every three days, and finally was able to re-create the lynx-hare oscillations observed in Canada and predicted by the mathematical models. The coexistence of predator and prey was possible if there were refuges for the prey and if the predator was not confined to a narrow space—a situation that is closer to what we can observe in the natural world.

Gause showed that two species can coexist even when they compete for the same resources, only at different abundances than when living without their competitors, and that the species that has an advantage over the use of resources in their environment is poised to be “dominant”—that is, more abundant than the other. Gause also showed that both a predator and a prey can coexist within the same environment, as long as the prey has some refuges to escape from the predator.

Our planet is home to millions of species, and ecosystems such as coral reefs and tropical forests harbor tens of thousands of species each, living together in what appears to be a miraculous balance. How do we move from two species to tens of thousands? How do species come together and create these magnificent ecosystems? It would take scientists studying natural environments over time and space to start to tackle these questions.

CHAPTER FOUR

SUCCESSION

IN 1970, two marine biologists based in Hawaii, Richard Grigg and James Maragos, wanted to understand how coral reefs develop over time. The longevity of some coral species —some live decades, if not centuries—made it impractical, however, for scientists to study them within their lifetimes. But Grigg and Maragos had an idea.

The island of Hawaii is crowned by the Kilauea volcano, which is still active and produces lava flows periodically. You might have seen footage of the lava flows reaching the ocean, either as a glowing red waterfall or as a crawling blob with the viscosity of tar. When the hot lava meets the Pacific Ocean, it crackles and hisses, boiling the seawater and creating violent explosions of white steam. The largest lava flows continue their path underwater, succumbing to gravity and hugging the bottom until they solidify and become part of the seafloor.

Lava is a destroyer of ecosystems. As lava flows smoothly over the slopes of a volcano, it vaporizes everything in its path and then buries it under a sarcophagus of basalt that hardens once the lava cools down—both above and under the water. At the same time, lava flows are regenerators of life, for by obliterating ecosystems, they provide a virgin substrate for species to colonize.

Grigg and Maragos discovered that accurate dates of lava flows had been recorded since 1801. They measured the diversity and abundance of different types of corals on underwater areas that had been covered by lava flows between 102 years and 1.6 years before their study. The ages of the different lava flows allowed them to substitute space for time in this natural experiment. They did not have to run an experiment for decades. The volcano had already done that for them.

Grigg and Maragos found that not all species of corals arrive at the same time. Some are “pioneers” that settle and grow fast, while others take longer to colonize. In exposed shallow areas, recovery time was 20 years, but in sheltered areas, it might take more than 50 years for the complete recovery of the coral reef.

Their study has several lessons for us. First, the pioneers that arrive first and grow fast might not be those that last long. The pioneers would be like the weeds that grow after a forest has been burned, with the trees taking longer to colonize.

Second, an ecological community in an environment that is more stable over time—a deeper reef, where wave action is less noticeable, for example—will require a longer time to form. That is because deep corals take a longer time to grow. Only a stable environment without major disturbances would allow for old coral colonies to develop. And they can be very old: A recent study showed that some deep coral communities in Hawaii are 15,000 years old. In shallow waters, in contrast, coral reefs are subject to the destructive force of tropical storms, so the only species able to colonize are the pioneers that grow fast.

Finally, the factors that go into forming an ecosystem are many. The lava flow study showed us that species with different traits—growth rates, for example—thrive at different times and places. Gause showed us that even a simple ecosystem with just three species—a prey, a predator, and a top predator—can be complex, and the relationships between species may change depending on changes in the environment. Then how can thousands of species come together and form mature, functioning ecosystems such as tropical forests and coral reefs?

How do ecosystems develop? Are there ecosystem assembly rules, like do-it-yourself furniture instructions?

Let’s think of a house. Nothing can be built until the foundations have been established. Only then we can start building the walls. The plumbing and the electrical system come only after the walls have been built. So do the doors and the roof. Masonry comes after the pipes have been installed. And the furniture should come only after all the hardware is in place. In summary, the assembly of a house has to follow a logical succession of steps. Does a forest, or a coral reef, get assembled the same way, following some type of ecological progression?

Even though species may not have an architectural plan, it turns out that ecosystems do assemble along a process that scientists call “ecological succession.” Succession is driven by a small number of rules regarding how species arrive and in what sequence as they colonize a place—just as the different species of corals did on Hawaii’s lava flows—and the properties emerging from that self-assembly.

IF ECOSYSTEMS in environments exposed to continuous disturbance cannot develop beyond some simple stages, what happens in an environment that is relatively stable for centuries, or millennia? Let’s take a look at forests.

Forests are the most complex ecosystems on the land and contain over half of the different types of plants and animals. What is the ecological succession that leads to a mature forest? How does a forest start?

Picture the ancient forests of Earth, the so-called primary forests that have never been cut. A forest in the California Sierras, with sequoias as tall as a football field is long, which were already alive when the last great pyramid of Egypt was built. A forest in the eastern part of Poland, with oaks that sprouted from acorns when Columbus reached the Caribbean and are now more than 10 stories tall. The Amazonian forest, with more different species growing on a single Brazil nut tree than all the species than can be found in a hectare of European soil. These forests are at least as old as the oldest tree in them. How did they assemble?

Let's now picture a fire that burns part of the forest to the ground. Where there was a green canopy, now there is black, scorched earth. Soon, however, new life emerges. If you are a European wild mushroom aficionado, you must know that morels and asparagus grow well in burned areas. My dad used to take me foraging when I was a child, when I developed a craving for sautéed mushrooms collected only hours before in pine and oak forests near home (which came in very handy for our nondiving days in Corsica years later). Even if you are not such an aficionado, you still might have seen green grass growing within weeks in an area that was burned. Where do these fungi and weeds come from?

Forest fires commonly only burn the upper part of the ground, leaving the soil underneath the surface intact. Within that soil are seeds of plants that have been waiting for their chance to have their day in the sun, literally. There is not much light under a thick forest canopy, so most plants cannot flourish. But their seeds can survive underground for decades. As an example, in some parts of the Atacama Desert in Chile, it never rains—never, at least, within a human lifetime. Thus the desert is an arid terrain with no conspicuous life. But in 2018 it rained in an area that had not had any rain for a hundred years. A few days later, what had been a barren yellow surface was now a multicolor carpet of wildflowers. These flowers in turn reproduced and produced seeds that ended up on the desert floor, and then they dried up after the miraculous effect of the rain had disappeared. Covered by dust and sand, those new seeds will also wait for their opportunity—their 15 days of fame. Maybe it will take another century. Nature does not rush, but she always gets things done.

Fungi do not produce seeds. They mostly spread through filaments that form massive webs in the soil upon which forests grow. The mushrooms that we all know, with their little hats, are reproductive parts that produce spores that the wind will disperse, spreading the fungus farther. Some fungi are parasites, but others are the glue that binds the soil and the forest together. Many plants, including trees, can only absorb nutrients from the soil thanks to a symbiosis with fungal filaments. Thus, the soil is like the foundation of the house. Without a foundation, there is no house. Without a living soil, with fungi, worms, insects, and microbes, there is no forest.

The weeds will grow using nutrients contained both in the soil and in the ashes of the former forest. By developing shallow roots and spreading, they will stabilize the burned ground and enable the seeds of other plant species, carried to the site by the wind, to germinate and grow. The weeds will attract insects, which will eat their leaves and blades. The insects will attract small birds that will eat them. Then a bird will fly over the patch and drop feces containing the seeds of a bush from elsewhere, which will grow, providing more habitat for other species. These pioneer species facilitate the arrival of others. They provide the enabling conditions for an ecosystem to develop.

Seeds of the dominant trees will eventually make it into the patch from surrounding unburned forests. Not all of them will survive to grow into trees. They will take a longer time, but in the end they will dominate the ecosystem, which now looks like a forest again. In due time, the canopy will be thick again and shade the ground below, thus relegating smaller plants that need abundant light to be patient and wait for another opportunity. Maybe lightning will burn a tree, which will fall and create an opening in the forest. Time for the pioneers again.

IN THE 1950S AND 1960S, Eugene Odum, an American ecologist, and a formidable Catalan ecologist, Ramón Margalef, among others, started to extract patterns from studies in different ecosystems and parts of the world. I have to admit a soft spot for Margalef because I was trained in his school of thought at the University of Barcelona and had the privilege of attending some of his lectures in his late university years. These giants of ecology had an extraordinary ability to identify patterns within masses of information and create wonderful syntheses.

Odum and Margalef realized that ecological succession was a sequence of processes that could be predicted. For instance, over time, a forest will be a puzzle of shrubs, small trees, and large trees of many species. Their abundance and their distribution will depend on many factors, such as whether birds or mammals have spread their seeds, or the slope of the terrain, or the acidity of the soil. Although we cannot predict what exact path ecological succession will take, we do know that grasses will colonize first, followed by shrubs, followed by trees. Some species will need the previous work, so to speak, done by other species to facilitate their arrival. For example, bromeliads are plants of astounding variety, with needle-thin to broad and flat leaves, soft or spiky, green, gold, or brown. Some of them, such as Spanish moss, live on top of other plants, typically trees—they are called epiphytes, a word derived from the Greek meaning "over plants." Tropical bromeliads can grow large and heavy; thus, they need sturdy branches of trees to grow on, and these trees in turn need fungi to provide an underground network that helps them absorb nutrients from the soil. It's facilitation upon facilitation.

What Odum and Margalef realized independently was that some properties emerge along ecological succession, regardless of the type of ecosystem. Some things happen over time that are predictable for coral reefs, wetlands, forests, grasslands, or your garden—if left unattended.

From a plethora of studies, they showed that over time, as the ecosystem matures, the number of species in a given area increases. This is because the abundance of the species that provide the living architecture of the ecosystem (plants in a forest, corals in a reef) also increases, and at the same time there is an increase in the three-dimensional complexity of the ecosystem. Not only the types of creatures increase; their total biomass—their weight—increases over time until it saturates, like the microbes growing in Gause's test tubes. At one point, the laws of physics do not allow larger trees or more leaves per square meter.

The more holes and nooks and cracks and crevices and tall trees and bushes and dead tree trunks, the more micro-habitats exist for different species to colonize. For example, some fungi only grow on dead tree trunks. Some species of fungi extremely rare in the United Kingdom were miraculously rediscovered only after the owners of a private estate let old dead trees follow their natural succession and decompose by natural forces. In the rest of the country, where dead trees are cut up and hauled away for firewood or mulch, those fungi are nowhere to be seen. Dead and dying trees are also preferred by many woodpeckers for nesting, because their wood is softer. In lowland tropical forests, a quarter of all plant species are likely to be epiphytes, like the orchids. Orchids not only show preferences for the species of tree they grow on, but also prefer to grow high on the canopy of tall trees—far from the shadow created by the tree's branches, where, incidentally, some shade-tolerant orchids can actually live. And so on ad infinitum.

The pioneers tend to be generalists—that is, species that can eat and grow whatever and wherever. As ecological succession progresses, the specialists arrive—that is, species that have more narrow requirements for survival, such as the species of hummingbird that only feeds on nectar from the flowers of a single type of tropical plant. Ecosystems advance toward a complexity that Margalef called the "baroque" of nature.

And the work provided by different species—the natural processes they perform—also changes over time. As a forest grows, its amount of wood and leaves increases over time. The productivity of the forest increases until it reaches a limit, and then it saturates. A forest will reach that limit when physically there is no room for more wood. At that point, the trees have created a canopy such that all the sunlight that can be used by the plants in the forest is being used. The trees will have reached such ages and sizes that it is physically impossible for them to grow larger.

During early successional stages, the weeds grow fast: In a week, they can double their biomass—a measure of their abundance in weight, for example, pounds per square meter. But a mature forest dominated by old trees will appear unchanging to human eyes. In other words, the more mature an ecosystem is, the more inhabitants it has, the more connections between them there are, and the slower it changes—the slower its turnover rate.

The growth of a forest is pure magic, a natural alchemy that we take for granted but that is unbelievable when one thinks about it—and an ongoing process that is helping us to avert climate catastrophe around the world. This is the where the magic lies: Plants use sunlight to turn an invisible gas in the air into growth. The invisible gas is carbon dioxide (CO_2), which is found naturally in Earth's atmosphere. Plants use the energy contained in sunlight to break the CO_2 into its constituent parts: carbon (C) and oxygen (O). They use the carbon to make sugars and grow, with the help of water, which brings essential nutrients such as nitrogen and phosphorus from the soil via the roots. They release the oxygen back into the atmosphere. The process of taking carbon out of the air and turning it into plant stuff—leaves, wood, or roots—is called carbon sequestration. The plants on Earth (from the microscopic algae in the open ocean to the giant sequoias in the American West) remove about half of our carbon pollution every year. As the forest matures along ecological succession, it stores more and more carbon—in wood but also in the soil. More magic tricks.

The more leaves are produced, the more dead leaves on the forest floor; that's nature's waste. But if the forest floor is its landfill, why don't we find a carpet of dead leaves several meters deep on the ground under a deciduous forest, like our own trash that we see accumulating everywhere? Because leaves are truly organic, biodegradable, and fully recyclable: They are the quintessential compost. In an older forest, there are plenty of insects, fungi, and bacteria that will eat and decompose the dead leaves into basic nutrients, which in turn will be reincorporated into the forest's food web, moving into the trees' roots with water. The natural world is a true circular economy, where there is no waste, but everything is reused to produce something else. Ironically, the more mature the ecosystem, the more detritus (waste) it produces, but the more important detritus is for regenerating nutrients, which keep the forest thriving.

There is more. We all have heard that the forests are the lungs of our planet, but actually most of the oxygen in the atmosphere has been produced by bacteria and microscopic algae in the ocean. In fact, much of the oxygen produced in a forest could be respired (literally, burned up for use as energy) by the activity of all the animals that live within, which use that oxygen to process the consumption of all the plant material produced by the forest. Instead, forests are the sweat glands of the planet. Trees pull water from the soil, move it up to their branches, and release it mostly as water vapor through their leaves. This process, equivalent to our own sweating, is called evapotranspiration—evaporation of water makes plants move water from the soil to their leaves, which will transpire, or give off that water as vapor into the surrounding air. The evaporation of our sweating cools our bodies down; evapotranspiration cools entire forests down.

At the end point of succession, the ecosystem reaches what is called its "climax"—the culmination of the growth process, where the ecosystem is at its most baroque and yet most efficient. But just how long do a particular ecosystem and its climax last?

MY FRIEND AND COLLEAGUE John Pandolfi is a paleontologist: He studies fossils to understand how life on Earth has evolved in the recent geologic past. John has studied Caribbean coral reefs in ancient terraces that emerged after the last glacial era, going back 115,000 years. He found that two species of fast-growing corals of the *Acropora* type dominate the fossil record on shallow reefs: the staghorn coral, with cylindrical branches that branch like the antlers of a deer, and the elkhorn coral, with fat, flat branches resembling the antlers of a moose. (Maybe it should be renamed "moose coral.") These are pioneers, weedy corals that grow fast. All Caribbean reefs get hammered by hurricanes every decade or so, their shallow corals broken every single time, but they manage to come back because the *Acropora* are able to grow fast and recolonize the reefs in between hurricanes.

Because damaging hurricanes and wave action are relatively frequent, the ecological succession of a typical shallow coral reef has never advanced beyond communities composed almost exclusively of elkhorn coral (shallower) and staghorn coral (just a little deeper). The cycle has been hurricane, coral rubble, *Acropora* reef, hurricane, rubble, *Acropora* reef, and so on and so forth—at least until the second half of the 20th century, when a combination of human activities changed the environment to such an extent that *Acropora* corals began to have a hard time surviving.

It takes a long time—centuries or millennia—for old ecosystems to assemble. Information takes a long time—and a long succession of events—to accumulate. But losing it all tends to happen catastrophically. A fire will destroy thousands of years of forest growth; a lava flow will destroy a centuries-old coral reef; building a shrimp farm can mean cutting down a centuries-old mangrove forest in days.

Natural disturbances like forest fires, lightning, or lava flows will reset the successional clock in parts of the ecosystems. It's the lightning that fells a large tree, opening a hole in a tropical forest canopy, or large herbivores rummaging about the temperate forest floor that will allow for succession to restart. Thus, an old forest won't necessarily be a full canopy of ancient trees, but a mosaic of patches at different successional stages: here old canopy, a patch of forest at its climax, there a just opened clearing, a younger canopy in a clearing that opened up a few decades ago somewhere else, and so on. A healthy mature ecosystem is not like a picture of a single color, but a multicolor quilt that evolves and responds to changes in the environment, and to changes within itself.

Our built environment also follows successional principles. China can now produce a massive city relatively quickly, but in the past, cities grew organically. When the first Dutch settlers started building in Manhattan, there were wooden shacks, a few basic jobs, and few public services. It took more than 200 years to grow from a few hundred people to more than eight million people with thousands of different jobs (the city equivalent of the different species' roles in a nonhuman ecosystem), from garbage pickers and doctors to canine hairdressers, speaking hundreds of languages. Today, New York City conserves none of the original dwellings, but it exhibits an exuberant variety of brick, steel, and glass buildings, from one story to 541 meters (1,775 ft) high, from pre-20th century to under construction, with and without doorman, with and without elevators. The growth rate of New York City has also slowed down over time: The size of the initial settlement may have doubled within a year, but presently the annual changes in the city are minuscule relative to its size and complexity. Only patches where buildings are torn down allow for regrowth, like clearings in a forest.

Despite these similarities, there is an inherent tension between ecosystem development and human progress. Humans want quantity over quality, growth over development, production over protection—usually realized in the most inefficient of ways. Natural ecosystems self-organize with an increase of species richness, size and age of organisms, biomass, productivity, efficiency in the recycling of organic matter, three-dimensional structure created by living organisms, and stability, among many other properties. But humans latch on to one idea and blindly focus on it. We turn mature ecosystems into monocultures—cultures of single species—which are the simplest of ecosystems. With our blinders on, we prioritize just one species, selected to grow fast —like cornfields in Iowa or salmon farms in the Chilean fjords— and we focus all our efforts on it to the detriment of any surrounding species. Although these monocultures are intended to feed us, ironically, they are the closest thing to a barren landscape when it comes to ecosystem maturity—the anti-climax. Our built environments are misguided attempts at re-creating the assembly and the productivity of natural ecosystems, designed to satisfy our needs.

We are abruptly interrupting and most often reversing ecological succession across the biosphere, turning complex ecosystems into simple, homogenous systems with fast turnover rates: That is, we are accelerating and fragmenting the biosphere. Does that mean that we are isolating ourselves from nature? Or are we immersing ourselves into nature more deeply than she can handle? These are questions worth asking as we try to learn from the ways of nature, and a way to answer these questions is to look at the boundaries between ecosystems.

CHAPTER FIVE

BOUNDARIES

ONCE A YEAR, a miracle occurs off the coast of South Africa. A seasonal wind running parallel to the coast displaces surface water alongside the shore. The water that moves away is replaced by water coming from the deep. The upwelling of deep water rich in nutrients creates a bloom of microscopic algae—phytoplankton—that thrives as it exploits the fertilizer brought up from the deep and the abundant sunlight. These algae blooms can be seen from space: beautiful green patches and eddies, visible in satellite photos.

As deep, nutrient-rich waters make it to the surface, they jump-start a planktonic succession, in the same way that a fallen tree restarts the forest succession. First, very small bacteria that conduct photosynthesis and small phytoplankton develop. They are followed by larger phytoplankton such as diatoms, which create glass skeletons using silica dissolved in seawater. An abundance of prey will inevitably result in greater opportunities for predators. As these large phytoplankton become abundant, small animal predators show up, in turn attracting large predators, building an extraordinary food web with four or five levels. The predators of phytoplankton are also microscopic, mostly shrimplike animals—zooplankton. As the biomass of zooplankton develops, billions of sardines—predators of zooplankton—show up for their annual feast. Sometimes the sardine runs along the South African coast measure up to eight kilometers (5 mi) long.

And then, in a matter of just weeks, one of the most extraordinary food webs in the world assembles. The colossal abundance of sardines attracts large predators: tuna, sharks, seabirds, sea lions, dolphins, and large whales. Perhaps you have seen this feeding frenzy in nature documentaries. A large school of sardines is surrounded by predators. As a defense mechanism, the sardine school packs itself into a tight ball—fatalistically called a bait ball—and starts spinning madly. The fast-moving ball of sardines makes it very difficult for a predator to chase a single individual. For the sardine, there is safety in numbers. But for the predators, there is efficiency in numbers. Tuna and dolphins push the bait ball closer to the surface, reducing the ability of the sardines to escape them. But danger also comes from the sky. Hundreds of birds such as boobies dive into the sea, capturing sardines one by one. Attacked from all angles, the sardine school is helpless, its volume reduced quickly. A final nail in the sardines' coffin may come from whales, taking advantage of the packing of the prey by other predators. In a single swoop, a large whale coming from the deep with mouth agape can ingest tens of thousands of sardines. In the end, all that's left of the sardines is a rain of shiny scales that sink to the seafloor.

What ecological principles can we extract from this wondrous spectacle? And what does this have to do with our exploitation of natural ecosystems?

The boundary between the plankton bloom—and later between the massive sardine run—and surrounding waters is sharp and asymmetrical: Here is a thick soup of plankton and sardines, and a few feet away there is just water. But that boundary is permeable and active because predators come in and out of it. Energy—in the shape of food that organisms need to survive—also moves across the boundary.

Inside the plankton bloom, on one side of the boundary, we can find an ecosystem in early stages of succession: fast-