Regeneration

Ending the climate crisis in one generation

Paul Hawken

Contents

We accumulated thousands of references, citations, and sources in the process of researching and writing Regeneration. *Although they are too numerous to be published in the book, they may be found at www.regeneration.org/references.*

About the Author

Paul Hawken is an environmentalist, entrepreneur and author. His books have been published in thirty languages in more than fifty countries and have sold more than two million copies. Hawken is a renowned speaker who has led workshops on the impact of commerce on the environment and has consulted with governments and corporations throughout the world.

PHOTOGRAPHY CREDITS

GEORGE STEINMETZ: p. 22 (George Steinmetz), p. 48 (George Steinmetz), pp. 72–73 (George Steinmetz), p. 180 (George Steinmetz), p. 186 (George Steinmetz), pp. 194–195 (George Steinmetz), p. 201 (George Steinmetz), p. 216 (George Steinmetz), p. 218 (George Steinmetz), p. 236 (George Steinmetz)

AMI VITALE: p. 11 (Ami Vitale), p. 90 (Ami Vitale), p. 120 (Ami Vitale), p. 136 (Ami Vitale)

NATURE PICTURE LIBRARY: p. 5 (Guy Edwardes), p. 9 (Sven Zacek), p. 13 (Felis Images), pp. 18–19 (Doug Perrine), p. 25 (Alex Mustard), pp. 26–27 (Tim Laman), p. 33 (Claudio Contreras), p. 38 (Danny Green), p. 40 (David Allemand), p. 41 (Ashley Cooper), p. 46 (Nick Garbutt), p. 49 (Tim Laman), p. 60 (Jack Dykinga), p. 64 (Sumio Harada), p. 66 (Alfo), p. 67 (Klein & Hubert), p. 79 (Klein and Hubert), pp. 80–81 (Heather Angel), p. 82 (Wim van den Heever), p. 83 (Robert Thompson), p. 84 (Mark Hamblin), p. 108 (Gerrit Vyn), p. 114 (Bence Mate), p. 116 (Pete Oxford), p. 116 (Eric Baccega), p. 116 (Eric Baccega), p. 116 (Pete Oxford), p. 116 (Eric Baccega), p. 116 (Enrique López–Tapia), p. 117 (Bernard Castelein), p. 117 (Eric Baccega), p. 117 (Pete Oxford), p. 117 (Pete Oxford), p. 117 (Laurent Geslin), p. 117 (Pete Oxford), p. 147 (Tony Heald), p. 184 (Oliver Wright), p. 204 (Paul D. Stewart), p. 205 (Guy Edwardes), p. 223 (Ashley Cooper), p. 224 (Ashley Cooper)

GETTY IMAGES: p. 110 (Ricky Carioti/The Washington Post), p. 112 (Jeff Hutchins), p. 146 (Carl de Souza), p. 148 (Hufton+Crow/View Pictures/Universal Images Group), p. 162 (Stefano Montesi), p. 172 (CgWink), p. 199 (Roslan Rahman), p. 214 (Zhang Zhaojiu), p. 220 (Kate Geraghty/The Sydney Morning Herald), p. 226 (Stocktrek), p. 228

(STR/AFP), p. 229 (Lalage Snow), p. 231 (Ester Meerman), p. 232 (Burak Akbulut/Anadolu Agency), p. 233 (Storyplus), p. 238 (Jason South/The Age), pp. 240–241 (Prashanth Vishwanathan/Bloomberg), p. 242 (Kevin Frayer/Stringer)

ALAMY STOCK PHOTO: p. 44 (Jacob Lund), p. 104 (Derek Yamashita), pp. 106–107 (Farmlore Films), p. 119 (Romie Miller), p. 144 (Joanna B. Pinneo), p. 150 (Robert Harding), p. 160 (Mauritius Images), p. 164 (Greg Balfour Evans), p. 167 (DPA Picture Alliance), p. 169 (dpa Picture Alliance), p. 174 (Westend61), p. 174 (Ian Shaw), p. 174 (Buiten–Beeld), p. 174 (Phloen), p. 209 (Radu Sebastian), p. 239 (Paulo Oliveira)

NATIONAL GEOGRAPHIC: pp. 36–37 (Mike Nichols), pp. 42–43 (Frans Lanting), p. 62 (Peter R. Houlihan), pp. 68–69 (Alex Saberi), p. 92 (Klaus Nigge), pp. 94–95 (Erlend Haarberg), p. 170 (Jim Richardson)

OTHER: p. 6 (Stuart Clarke), p. 7 (Fernando Tumo), pp. 14–15 (Chris Jordan), p. 17 (Ines Álverez Fdez), p. 21 (Chris Newbert), pp. 28–29 (Neils Kooyman), p. 30 (Jay Fleming), p. 34 (Chris Jordan), p. 45. (Greenfleet/E O'Connor), p. 47 (NASA), p. 50 (Ute EisenLohr), p. 52 (Ute EisenLohr), p. 54 (Kilili Yuyan), p. 56 (Nathaniel Merz), p. 58 (Julianne Skai Arbor), pp. 70–71 (Louise Johns), pp. 74–75 (Charlie Burrell), p. 77 (Charlie Burrell), p. 86–87 (Jillian), p. 88–89 (Chris), p. 96 (NCRS Photo), p. 98 (Catherine Ulitsky), p. 99 (Frances Benjamin Johnson), p. 100 (Kim Wade), p. 102 (Russell Ord), p. 113 (Theo Schoo), p. 118 (Kilili Yuyan), p. 122 (Jerónimo Zúñiga), p. 123 (Mitch Anderson), p. 124 (Jonathan Nguyen), p. 127 (Lubos Chlubny), p. 128 (Philipp Kauffmann), p. 131 (Soul Fire Farm), p. 133 (Soul Fire Farm), p. 134 (Relief International Gyapa™ Project), p. 139 (Mary Reynolds), p. 140 (Mary Reynolds), p. 141 (Mary Reynolds), p. 143 (Mimi Casteel), p. 152 (Jason McLennan), p. 155 (Ronald Tilleman), pp. 156–157 (Michelle and Chris Gerard), p. 159 (Stefano Boeri), p. 166 (Michael Baumgartner), p. 176 (Dave Chapman), p. 177 (The Ron Finley Project), p. 178 (Dave Chapman), p. 179 (Eugene Cash), p. 182 (Courtesy of Pixy), p. 188 (Olga Kravchuk), pp. 190–191 (Rasica), p. 192 (Rainee Colacurcio), p. 196 (Ted Finch), p.

198 (Jaime Stilling), p. 202 (Courtesy of Raoul Cooijmans/Lightyear), p. 207 (Tzu Chen Photography), p. 210 (Jamie Stilling), p. 212 (Photonworks), p. 222 (Ton Keone), p. 234 (Courtesy of Suay), p. 244 (Joseph Wasilewski), p. 247 (Andrea Pistoles), p. 255 (Chris Jordan)

Thakgil Canyon near Vik in the south of Iceland is surrounded by glaciers, rivers, ice caves, black sand beaches, and some of the country's best hiking trails.

Their response and needs were clear. They wanted to grow more food and have better health and education. With a small grant from the European Union, we helped them restore fertility to the land without the use of chemicals. We worked with the local Tanzanian government to improve existing schools and improve or create village clinics. We introduced water-management programs, agroforestry, and permaculture. Utilizing geographic information systems and satellite imagery, we enabled villagers to make land use management plans. Volunteers learned to use smartphones to record the health of their village forest reserves. Scholarships enabled girls to go into secondary education, and microcredit programs enabled villagers—especially women—to start their own sustainable businesses. Family planning information is eagerly received as parents want to educate their children, but schools are expensive. In this way, TACARE advances both environmental and social well-being.

Orphans Kudia and Ultimo hug each other at the JGI Tchimpounga Chimpanzee Rehabilitation Center in the Republic of Congo. One hundred sixty chimpanzees are cared for, for life, at the sanctuary.

There are close to 7.9 billion of us on the planet now. In many parts of the world our finite natural resources are diminishing faster than nature can replenish them. By 2050, it is estimated there may be as many as 10 billion of us. Livestock numbers are also increasing, using up ever more land and water and producing vast amounts of methane gas. Moreover, as people rise out of poverty, they understandably seek to emulate the unsustainable standard of living that we know we must change. If we carry on with business as usual, the future looks, well … grim is hardly a strong enough word.

We must develop a new relationship with nature and ensure that our children are equipped to deal with the problems we have created. There are many programs that promote environmental education and others that discuss social justice. I began Roots & Shoots, an environmental and humanitarian movement for youth, in 1991. It now has thousands of groups, preschool through university, in sixty-eight countries. To help them understand that social and environmental problems are connected, each group is required to choose and participate in projects in three areas—people, animals, and the environment. By taking action, the members realize their ability to effect change. It is empowering and is giving hope to thousands of young people who are working together on issues as diverse as wildlife trafficking, homelessness, women's rights, animal rights, and discrimination.

I have three reasons for hope: the energy and commitment of youth; the resilience of nature (the forest has returned around Gombe) and the way animal and plant species can be rescued from extinction; and the human intellect, which is focusing on how we can live in greater harmony with nature.

Paul, in his usual inimitable way, describes the most important solutions to the environmental and social problems we have brought upon ourselves, and shows how they are inseparably linked. *Regeneration* is honest and informative, a rebuttal to doomsayers who believe it is too late. He echoes my sincere belief that we have a window of time, that there are practical solutions, and that we and all our institutions can initiate and implement them in order to restore life climatic stability and on Earth. Let us work to live up to our scientific name: *Homo sapiens*, the wise ape. •

Aerial view of a small forest lake in Karula National Park, Valgamaa County, Southern Estonia.

communities. Planetary regeneration creates livelihoods—occupations that bring life to people and people to life, work that links us to one another's well-being. It offers path out of poverty that provides people with meaning, worthy involvement with their community, a living wage, and a future of dignity and respect.

In December 2020, Dr. Joeri Rogelj of the Grantham Institute in London and a lead author of the Sixth Assessment of the Intergovernmental Panel on Climate Change made a remarkable statement: "It is our best understanding that, if we bring carbon dioxide [emissions] down to net zero, the warming will level off. The climate will stabilize within a decade or two. There will be very little to no additional warming. Our best estimate is zero." This was a remarkable change in scientific consensus. For decades it was assumed that if we were able to stop our carbon emissions, the momentum of warming would continue for centuries. That was mistaken. Climate science now indicates that global warming would begin to recede after we achieve zero carbon emissions.

This is a watershed moment in history. The heating planet is our commons. It holds us all. To address and reverse the climate crisis requires connection and reciprocity. It calls for moving out of our comfort zones to find a depth of courage we may never have known. It doesn't mean being right in a way that makes others wrong; it means listening intently and respectfully, stitching together the broken strands that separate us from life and one another. It means neither hope nor despair; it is action that is courageous and fearless. We have created an astonishing moment of truth. The climate crisis is not a science problem. It is a human problem. The ultimate power to change the world does not reside in technologies. It relies on reverence, respect, and compassion—for ourselves, for all people, and for all life. This is regeneration.

Agency

The climate crisis is not the warming of the planet. What unnerves scientists is what warming will do to life *on* the planet. Changes in atmospheric temperature, ocean currents, and melting polar ice could trigger runaway disruption on multiple fronts in rapidly succeeding tipping points. Losses could include more frequent droughts in the tropics that would convert the world's rainforests into fire-prone savannas. Changes in ocean circulation would dramatically alter worldwide weather and agriculture. The rapid increase in fires and pests could lead to the collapse of our northern forests. Ocean heating and acidification could cause the death of every coral reef in the world. The accelerating melting of the Thwaites Glacier in Antarctica would cause a three-foot rise in sea levels. The melting of Arctic permafrost would release massive amounts of ancient stored carbon dioxide and methane. It is difficult, if not incomprehensible, to imagine how these events would affect families, cities, economies, companies, food, politics, and children in more temperate climates. However, it is not difficult for more than two dozen Arctic cultures who are experiencing the impact of the melting Arctic directly and quickly: the Inuit, Yupik, Chukchi, Aleuts, Saami, Nenets, Athabaskan, Gwich'in, and Kalaallit, cultures that have occupied their lands for up to ten thousand years.

Accurate as they may be, climate predictions can obscure another set of tipping points, the numerous small changes and crucially important outcomes and that lead to people's involvement and participation, rather than passivity and fear. These are actions that slow, forestall, and transform the climate crisis. Ending the climate crisis means creating a society that is going in the right direction at the right speed by 2030, a rate of change that will lead to zero net emissions before 2050. That means halving emissions by 2030 and then halving again by 2040. Tens of thousands of organizations, teachers, companies, architects, farmers, Indigenous cultures, and native leaders know what to do and are active in implementation. The current growth of the climate movement is magnificent, but it remains a small fraction of the world. Hundreds of millions of people need to realize that they have agency, that they can take action, and that collectively it is possible to prevent runaway global warming.

The agent who can head off the climate crisis is reading this sentence. Logically, this seems like nonsense—surely individuals are powerless to counter the global drivers and momentum of global warming. That's a fair conclusion if we assume that yesterday's institutions should or will do it for us. There is a debate as to whether individual behavior or government policy is the key to solving the climate crisis. There shouldn't be. We need the involvement of every sector of society, top to bottom, and everything between.

It is engaging and fascinating to calculate one's own carbon footprint, but *Regeneration* takes a different and wider tack, because there is no such thing as a single individual. *Thinking* you are an individual is self-identity. *Being* an individual is an ongoing, functional, and intimate connection to the human and living world. When we look at our networks, each of us is multitudes. We have different skills and potential, including sharing, electing, demonstrating, teaching, conserving, and diverse means of helping leaders, cities, companies, neighbors, co-workers and governments become aware and able to act.

Worried that you are not an expert? Almost no one is. But we understand enough. We know how greenhouse gases function and warm the planet; we are seeing greater climate volatility and extreme weather; and we know the primary sources of carbon emissions. We want a stable climate, food security, pure water, clean air, and an enduring future that we can become ancestors to. Cultures, families, communities, lands, professions, and skills vary with every person. The situations we find ourselves in differ. Who better to know what to do at this time, in this place, with your knowledge, than you?

Nevertheless, solving the climate crisis is an unnatural act, one that human beings are ill-equipped to do. Our minds just don't work that way. The idea of a future existential threat is abstract and conceptual. War metaphors about fighting, battling, and combating climate change don't connect either. Who wakes up in the morning excited about mitigating or getting to "net zero" in thirty years? Most people ignore climate headlines, and for good reason. The overwhelming majority focus on current dilemmas, not distant ones, obstacles that impact one's life now, not in 2050. On the other hand, humans are notably brilliant at joining together to solve problems. Give us immediate threats like an impending cyclone, flood, or hurricane, and we are all over it. If we are going to engage the bulk of humanity to end the climate crisis, the way to do it is counterintuitive: to reverse global warming, we need to address current human needs, not an imagined dystopian future.

If we want to get the attention of humanity, humanity needs to feel it is getting attention. If we are going to save the world from the threat of global warming, we need to create a world worth saving. If we are not serving our children, the poor, and the excluded, we are not addressing the climate crisis. If fundamental human rights and material needs are not met, efforts to stem the crisis will fail. If there are not timely and cumulative benefits for an individual or family, they will focus elsewhere. The needs of people and living systems are often presented as conflicting priorities—biodiversity versus poverty, or forests versus hunger—when in fact the destinies of human society and the natural world are inseparably intertwined, if not identical. Social justice is not a sideshow to the emergency. Injustice is the cause. Giving every young child an education; providing renewable energy to all; erasing food waste and hunger; ensuring gender equity, economic justice, and shared opportunity; recognizing our responsibility and making amends to myriad communities of the world for past injustices—these and more are at the very heart of what can turn the tide for all of humanity, rich and poor, and everyone between. Reversing the climate crisis is an outcome. Regenerating human health, security and well-being, the living world, and justice is the purpose.

This requires a worldwide, collective, committed effort. Collectives do not emerge from the tops of institutions. They begin with one person and then another, the invisible social space where commitment and action join and come together to become a dyad, a group, a team, a movement. To put it simply: no one is coming to help. There is not a brain trust that is going to work out the problems while we ponder and wait. The most complex, radical climate technologies on earth are the human heart, head, and mind, not a solar panel. Just as we stand at the abyss of a climatic emergency, we stand at another remarkable threshold. The rate of understanding and awakening about climate change is increasing exponentially, even skyrocketing. Climate change is becoming experiential rather than conceptual. As weather becomes ever more disruptive, and awareness and concern increase, the movement to reverse the

How to Use This Book

The purpose of *Regeneration* is to end the climate crisis in one generation. Ending the crisis does not complete the challenge of global warming. That is a century-long commitment. Ending the crisis means that by 2030, collective action by humanity will have reduced total greenhouse gas emissions by 45 to 50 percent. At this writing, we are going backward and increasing emissions.

The book and its companion website plot a pathway to achieve goals outlined by the special report, "Global Warming of 1.5°C," published by the Intergovernmental Panel on Climate Change (IPCC) in October 2018. The report calls for 45 to 50 percent reductions from 2010 levels in global greenhouse gas emissions in each of the next two decades in order to avoid exceeding a 1.5°C (2.7°F) rise in global temperatures. The most common question about the crisis is "What should I do?" How can a person or entity create the greatest impact on the climate emergency in the shortest time? Most people do not know what to do, or may believe the things they can do are insufficient. We think otherwise.

Our approach to reversing climate change differs from other proposals. It is based on the idea of regeneration. We do not oppose other strategies and plans. To the contrary, we praise and are grateful for all approaches. Our concern is simple: most people in the world remain disengaged, and we need a way forward that engages the majority of humanity. Regeneration is an inclusive and effective strategy compared to combating, fighting, or mitigating climate change. Regeneration creates, builds, and heals. Regeneration is what life has always done; we are life, and that is our focus. It includes how we live and what we do—everywhere.

We conclude the book with Action + Connection. There, we show that the solutions detailed here, scaling and growing, meet the goals established by climate scientists and the IPPC. All of the solutions described are doable and realistic. They require one thing: broad participation. You are welcome to read the end of the book first if that is helpful.

Frameworks. The following are six basic frameworks for action to solve the climate crisis. They overlap in many ways; however, each category holds multiple levels of discovery, innovation, and breakthrough. The Action + Connection section links to the imaginative and effective ways people, communities, companies, neighbors, counties, schools, corporations, and countries can make a difference. What is holding us back today is not lack of solutions. It is the lack of imagination of what is possible. If you are feeling pessimistic or defeatist, read some or all of the book, and then turn to the end. It may change your mind.

Equity. This comes first because it encompasses everything. All that needs to be done must be infused by equity. Fairness is about social systems—how we treat one another, how we treat ourselves, and how we treat the living world. The planet has been transformed in a blink of an eye. If we are to transform the climate crisis, we need to transform ourselves, and we had best not blink. Time is of the essence. Social systems require the same level of care, attention, and kindness as ecosystems. They are incomparable yet inseparable. The state of the environment accurately reflects the violence, injustice, disrespect, and harm we do to people of different cultures, beliefs, and skin color. As Jane Goodall points out in her foreword, you save forests and species by helping to create better lives for people.

Reduce. The primary method of reversing global greenhouse gas emissions is simple: stop putting them into the atmosphere. It is also the most difficult, while being the greatest economic opportunity. The amount of carbon-emitting fossil fuel consumed is astonishing. Every day, the world burns 100 million barrels of oil, 47 billion pounds of coal, and 10 billion cubic meters of natural gas, which together emit 34 billion tons of carbon dioxide every year. Replacing the coal, gas, and oil we currently depend on is a formidable undertaking. *Reduce* includes the carbon and methane emissions from agriculture, food systems, deforestation, desertification, and destruction of ecosystems. The implementation of renewable energy from wind, solar, energy storage, and microgrids are critical, and well on their way. Less discussed but equally important is the reduction of energy and material use. *Reduce* solutions include electric vehicles, micro-mobility, carbon-positive buildings, walkable cities, carbon architecture, electrified buildings, minimized food waste, and the next category: *Protect*.

Protect. This is synonymous with preserving, securing, and honoring. You will find essays about pollinators, wildlife corridors, beavers, habitats, bioregions, seagrasses, wildlife migration, and grazing ecology, subjects not normally associated with solving the climate crisis. How could these be some of the most important solutions to the climate crisis? Because they are essential and critical to the living systems we need to defend and strengthen. Terrestrial systems hold 3.3 trillion tons of carbon in and above ground. That is about four times more carbon than is in the atmosphere. The carbon is contained in forestlands, peatlands, wetlands, grasslands, mangroves, tidal salt marshes, farmland, and rangeland, and we need it to stay here on earth. Each year, some portion of each of these ecosystems is degraded, developed, converted, or lost. It is a relatively small percentage, but it adds up. When living systems break down or are destroyed, the plants and organisms below and above ground die, resulting in carbon dioxide emissions. If we lose 10 percent of the earth's terrestrial systems, those emissions could increase carbon dioxide in the atmosphere by as much as 100 parts per million. *Protect* maintains the healthy function of living systems, resulting in the sequestration and storage of more carbon rather than less. When we lose an ecosystem, the birds, reptiles, rodents, mammals, insects, and creatures that dwell there lose their homes, the primary cause of the extinction crisis. Conversely, if we lose the species that occupy our forests, wetlands, or grasslands, those systems fall apart. Hummingbirds, hawk moths, and sharks may seem irrelevant to climate change, but it is the other way around. Biodiversity, humankind, the land, cultures, the oceans, and climate are inseparable.

A group of juvenile spotted owlets (*Athene brama*) in Tamil Nadu, India.

Sequester. There is a natural carbon cycle that has been functioning for hundreds of millions of years. Carbon moves in and out of the atmosphere. Forests, plants, and phytoplankton take in carbon dioxide and convert it to oxygen and carbohydrates. Roughly 25 percent of our carbon emissions are absorbed by oceans and transformed into fish, kelp, whales, shells, seals, and bones, but most of it is converted to carbonic acid, which is slowly killing sea life and is leading to a dead ocean. The primary way human beings can sequester is through regenerative agriculture, managed grazing, proforestation, afforestation, degraded land restoration, replanting mangroves, bringing back wetlands, and protecting existing ecosystems. The oft-used term ***net-zero emissions*** is not the goal. It is the threshold where the world begins to reduce atmospheric carbon levels back to preindustrial levels.

atmosphere. In 1856, American physicist Eunice Newton Foote determined that carbon dioxide had the greatest warming potential of atmospheric gases. Irish physicist John Tyndall's studies in 1859 are credited with establishing the greenhouse effect. In 1896, Swedish scientist Svante Arrhenius showed that increases in carbon dioxide were coming primarily from industry and that a 50 percent increase would raise global temperatures 5° to 6°C. Were it not for greenhouse gases, the earth would be a frozen, icy rock, and life as we know it would not exist. As carbon dioxide levels increase far beyond what human civilizations have ever experienced, they are in effect double-glazing the planet—more heat is trapped and less escapes into space.

How much carbon dioxide and other greenhouse gases are in the atmosphere?

The amount of carbon dioxide in the atmosphere is 419 parts per million, a 50 percent increase since the beginning of the Industrial Age. However, there are other greenhouse gases, including methane, nitrous oxide, and refrigerant gases—methane foremost due to its ubiquity and impact. They are measured according to their global-warming potential as compared with carbon dioxide. In this book, we describe these other greenhouse gases by their global-warming potential compared with carbon dioxide over a hundred years, a unit we call "carbon dioxide equivalent." If we include these gases, the equivalent level of carbon dioxide in the atmosphere is 500 ppm, the highest parts per million this planet has seen in more than 20 million years.

What is the difference between carbon and carbon dioxide?

Carbon is an element. It becomes a gas—carbon dioxide—when combined with two molecules of oxygen. In the atmosphere, carbon levels are measured as carbon dioxide. In soil and plants, it is measured as carbon only. One ton of carbon converts to 3.67 tons of carbon dioxide.

How much carbon exists on earth?

There are approximately 121 million gigatons of carbon on or near the surface. About two-thirds, 78 million gigatons, is in the form of limestone, sediments, and fossil fuels. Of the remaining carbon, 41 million gigatons is in the deep and near ocean, 3,300 gigatons is held on the land, and only 885 gigatons is in the atmosphere in gaseous form as carbon dioxide.

How big is a gigaton of carbon dioxide?

A gigaton is one billion metric tons. A one-gigaton ice cube would be about one kilometer high, long, and wide. The world burns 17 trillion pounds of coal per year, and each pound emits an average of 1.87 pounds of carbon dioxide, creating 14.5 gigatons of carbon dioxide.

What can be done to reverse warming?

There are three things we can do about planetary heating. We need to reduce and cease net carbon dioxide emissions over time. We need to protect and restore the enormous stores of carbon contained in our forests, wetlands, grasslands, salt marshes, oceans, and soils. And we need to bring carbon from the atmosphere back to earth by sequestering carbon dioxide.

What is sequestration?

Sequestration removes carbon dioxide from the atmosphere through photosynthesis, some of which is stored in soil, plants, or trees. When carbon dioxide is captured by a plant, it releases oxygen into the air and combines carbon and water into sugars that feed the plant, the roots, and underlying soil organisms. Virtually all ecosystems, including grasslands, ocean algae, mangroves, forests, and peatlands, are actively sequestering carbon. There are artificial methods being developed to sequester carbon, such as direct air capture, but it is still too early to determine whether these techniques will prove to be practical and affordable at scale.

What is the Paris Agreement?

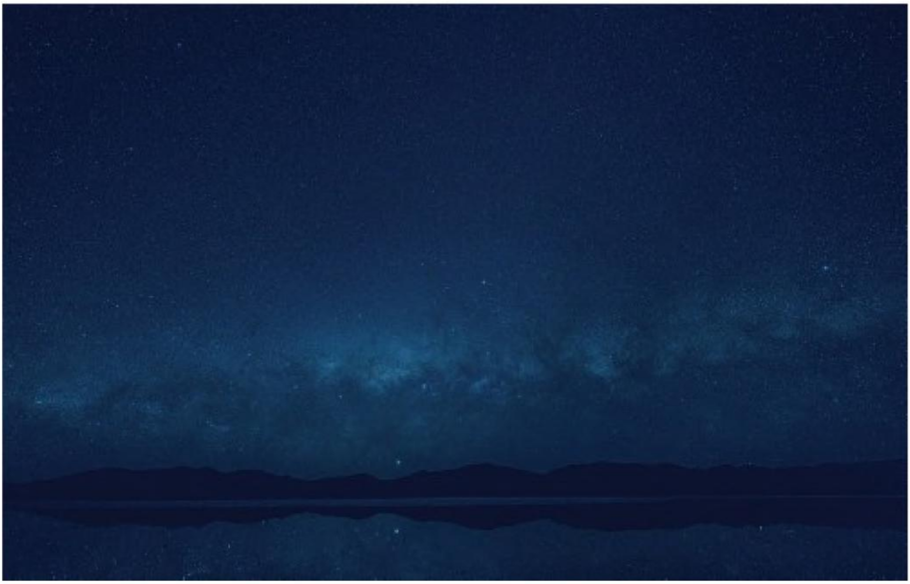
Actions to prevent runaway global warming have been discussed at the UN-sponsored Conference of the Parties (COP), held annually in capital cities around the world. In 2016, a year after COP 21 in Paris, an accord was reached that committed 191 parties to reduce emissions in order to keep global warming under 1.5°C; this is called the Paris Agreement.

Where does the world stand right now with respect to the Paris Agreement?

Of the 191 signatory states, only eight of the country pledges were in alignment with the original 2°C goal and only two countries have targets consistent with the 1.5°C limit—Morocco and Gambia. No G7 country—the United States, Canada, France, Germany, Italy, Japan, or the United Kingdom—has come close to setting targets in alignment with the Paris Agreement.

What units are we using?

Every number is reported in the imperial system of units unless explicitly defined. The notable exception is that all tons are metric tons for consistency with common measurements (e.g., gigatons of carbon dioxide are always reported in metric tons).




Oceans

Marine animals play an essential role in cycling carbon through the oceans by building up carbon in their bodies and releasing it when they breathe, defecate, and die. Some species, like whales, accumulate large amounts of carbon in their bodies that eventually sink to the ocean depths upon their deaths. Additionally, when these immense animals defecate, the nutrients and carbon feed phytoplankton and other small animals at the base of the food chain, encouraging further carbon removal from the water and atmosphere and expanding the cycle of life in the oceans.

Most of the attention being paid to oceans is about protection—how to prevent the degradation, pollution, and acidification that are increasing yearly. In this section, we explore the means of protecting and regenerating oceans that also meet human needs. Because oceans cover 70 percent of the planet, the possibilities are both extensive and global. An important step is to cease using the ocean as a dump.

The second step is the creation of marine protected areas—expanses of ocean that exclude fishing, mining, drilling, and other forms of exploitation. When key areas of the ocean are set aside, fisheries rebound, not only within the protected areas but in the waters surrounding and beyond them. By doing less, we ultimately enable the presence of more fish, kelp, phytoplankton, and shellfish, because the innate regenerative capacity of oceans is allowed to operate unhindered. There is also a burgeoning movement to return to the sea as cultivator, farmer, and steward, interacting with ocean systems regeneratively, methods that not only sequester carbon but that feed billions of people while restoring coastal waters. •

Marine Protected Areas

Hawaiian green sea turtles (*Chelonia mydas*) crowded into a small seaside cavern to bask at sunset. Resting on shore is a rare behavior for sea turtles, except in Hawaii and the Galápagos Islands, Ecuador.

For many thousands of years, Indigenous peoples lived with and relied on a thriving ocean. Cultures across the Pacific Islands depended on healthy reef fish populations, the Chumash people in the Channel Islands ate abundant abalone, and the Aleut people lived off marine mammals in the Bering Sea. When Spanish colonists first reached the Caribbean, so many swimming sea turtles hit the wooden hulls of their ships that the captains recorded the thunking as a danger in their logs. "It seemed the ships would run aground on them and were as if bathing in them," wrote Andrés Bernáldez of Columbus's second voyage in 1494. When the Venetian explorer John Cabot fished off what became the Grand Banks of Canada in 1497, sailors dropped wicker baskets weighted with stones overboard; when they pulled them up, they were wriggling with cod. Massive reefs of oysters protected New York when the Dutch first arrived. Until the early twentieth century, oysters filtered and cleaned all of the Chesapeake Bay in a week. Now, with the oysters mostly gone and the waters polluted by fertilizer runoff and pig waste, the Chesapeake Bay is toxic. Salt marshes held back hurricanes south of New Orleans. Mangroves broke the rush of tsunamis throughout South Asia, and castles of alabaster coral created robust ecosystems of shallow cities from Lizard Island, off the coast of Queensland, to the isle of Bonaire, in the southern Caribbean. Today, the turtles, cod, and coral are gone, damaged, or disappearing. For an excited child on holiday with a mask and a snorkel, the underwater world she finds still seem marvelous, and it is, but it is nothing next to what it once was. This phenomenon has a name, "shifting baselines." What looks alive and wondrous today cannot compare to what colonizers witnessed in stunned shock and what Indigenous peoples knew, enjoyed, and sustainably harvested. This is applies to our perceptions of what a "normal" climate is as well.

Marine protected areas (MPAs) preserve glorious expanses of wilderness areas in the planet's oceans and coasts. They also regenerate degraded, overfished, and over-shelled areas, be they open ocean or coastal. MPAs enhance and recover biodiversity, that lush mix of species and ecosystems, from sharks to seagrass. When well designed and enforced, they serve to protect human cities from storm surge, hurricanes, and sea-level rise, and the ocean itself from further acidification. Perhaps most important in our current situation, the plants and animals within them serve to draw down carbon and bury it for hundreds of years.

Not all MPAs are created equal. Some are designed to increase fish populations outside their boundaries, what is called spillover, and some, usually coastal, serve to keep carbon bound up and buried. There is a difference between protected zones in nearshore coastal areas—what is known as green ocean—and those created in the open or blue ocean areas. Through extensive experimentation, scientists have concluded that if 30 percent of the planet's seas can be protected by 2030—what is called the 30 by 30 approach—there will be more fish, not fewer, carbon dioxide will be drawn down and sequestered, and oxygen levels from phytoplankton will increase for us terrestrial creatures. (One of every two breaths we take originated in our imperiled seas.)

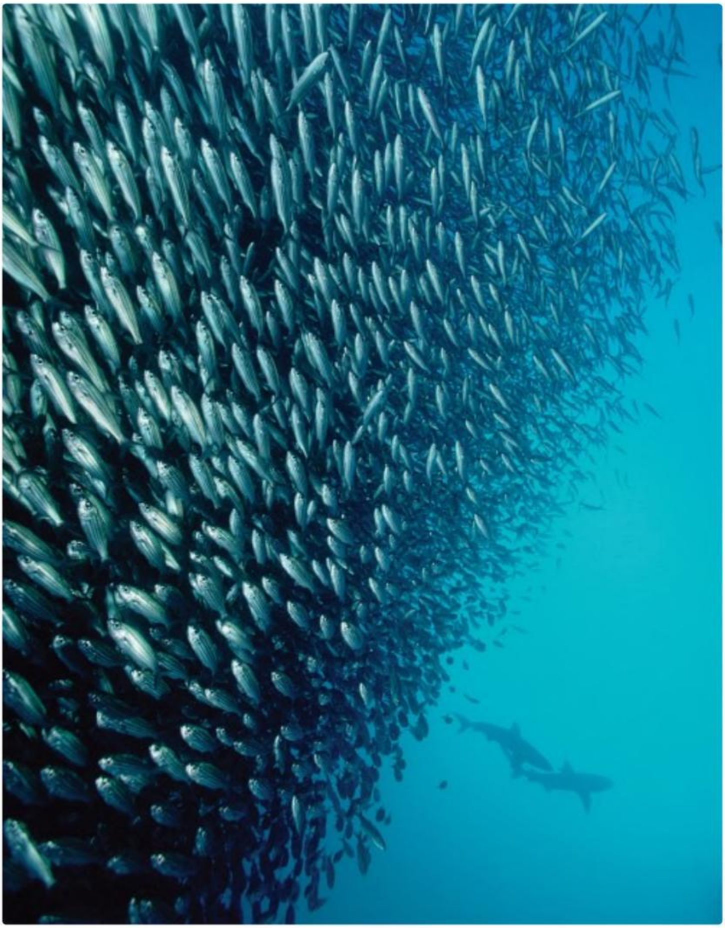
The idea of parks in the ocean or coastal waterways got off to a slow start. Not until 1966 did a movement coalesce to protect marine waters. Indigenous peoples have been practicing community-based management of local marine resources for centuries, if not millennia. Restrictions, called ***kapu*** in Hawaii and ***bul*** in Palau for example, were placed on the harvest of certain fish during certain seasons to support healthy fish populations that would sustain the community. However, by the early twenty-first century, some 90 percent of large predatory fish had disappeared from the world's oceans, and 30 percent of fish stocks were overfished to biologically unsustainable levels. The idea that marine no-take zones—meaning no fishing, shelling, or industrial use, such as kelp cropping or sand mining, would be permitted—was simple, bold, and wildly controversial. But it worked. It didn't bring back abalone or California sardines, because ecosystem baselines had shifted out of reach. But for other species, the eggs, larvae, and fingerlings prospered in MPAs on both coasts, and to the wonder of fishermen, almost all of whom had opposed protected areas, fishing improved outside the reserves, often dramatically. Similar improvements came from addressing indiscriminate fishing techniques directly by outlawing practices such as gillnetting and longlining outside of reserves as well as inside a nation's territorial waters.

What makes a successful marine reserve? First, protection: absolute no-take zones. If fishing or extraction is allowed, the system weakens, even collapses. Protecting keystone species like sharks and otter helps to establish balance and order. Currently, the open ocean is a lawless commons fished by those who have the resources to do so, primarily Chinese industrial fishing fleets. At the same time, unless rigorously protected, nearshore reserves are fair game for poachers. The big fleets need to be reduced and watched, with best practices strictly enforced. Reserves in wealthier nations tend to be easier to protect due to access to funds and stronger governance. In nations where much of a village's or region's protein is overfished, developing alternate sources of income can help to restore sustainability. In the small Cabo Pulmo reserve, on Mexico's Pacific coast, for instance, local fishermen petitioned the government to create a no-take zone, which became spectacularly successful. The number of fish inside the reserve increased over four times by weight, fishing greatly improved outside the reserve, and many citizens found employment in patrolling and maintaining the reserve and the shore as well—not so different from park rangers in Africa. Tourism jumped. Such local buy-in and stakeholder engagement is crucial in regions from the Philippines to Gabon.

Second, size is crucial: a successful protected area is defined as one larger than forty square miles, since fish, fingerlings, and larvae tend to migrate too easily outside the kinds of tiny reserves often set up for show and politics. If surrounded by deep water or sand, all the better.

Third, recovery takes time. Ten years is the most cited repair period. Marine reserves help create and expand ocean alkalinity, which counters the effect of acidification, caused primarily by conservation goals. The biomass of fish and marine life inside a fully protected reserve is one of the measures used to evaluate effectiveness.

MPAs are a low-tech, cost-effective strategy that sequesters carbon and helps protect and enhance the coastlines of the world. The world's 372,000 miles of coastline are populated by one-third of humanity. The goal of protecting 30 percent of the oceans by 2030 is a triple win: more wild fish to feed a growing population; restored biodiversity, which brings resilience to climate change; and secured carbon. •



Black-striped salema (*Xenocys jessiae*) group schooling, and two Galápagos sharks (*Carcharhinus galapagensis*) fifty feet deep, Galápagos Islands, Ecuador.

Seaforestation

The Great Barrier Reef, the only living structure visible from outer space. It is home to fifteen hundred species of fish, four thousand mollusks, and five hundred types of seaweed, making it one of the most biologically diverse environments on earth. It is dying due to acidification and warming. A massive infusion of marine kelp platforms could reverse its demise.

Strap on some scuba gear and plunge into the rocky coastal waters of Monterey Bay. The light dims just a few feet down. You are already in the shade of frondlike seaweed blades that soften the ocean current with their languid undulations. These marine leaves branch off hundred-foot-long stalks, the stipes of giant kelp—the aqueous equivalent of tree trunks. Through your mask they look like frayed rope tying the seafloor to the sky.

The seas can turn carbon into forests at a rate exceeding that of the lushest parts of the Amazon. Giant kelp is a type of brown forest-forming "macroalgae," a designation that encompasses 14,000 species of brown algae but also red and green algae such as the nori of sushi fame and the wakame of seaweed salads. Every year, a single square foot of healthy macroalgae forest can draw down more than two pounds of carbon dioxide from the atmosphere. In a single day, the giant kelp of Monterey Bay can grow over two feet in length.

But there's more. There's a key difference between the carbon fixed by marine forests and the carbon stored in their terrestrial counterparts. On land, much of the carbon is eventually returned to the atmosphere via the decomposition of leaves and wood. Marine forests shed small particles of organic carbon and dissolved organic carbon just as humans shed skin. Consequently, marine forests can be likened to "carbon conveyor belts," exporting carbon that ends up plummeting down into the ocean depths, where it won't be able to contribute to the greenhouse effect for centuries or millennia (if not longer). The upshot is that efforts to increase the coverage of marine forests may restore this natural process regionally and have a larger potential to draw down carbon than growing plants on land.

The starting point is marine reforestation, bringing back kelp forests where they used to occur but are currently absent. In many parts of the West Coast of the United States, humanity has witnessed two sequential decimations of kelp forests over the past decades. The first occurred during the rollout of industrialized farming practices in the first half of the twentieth century. U.S. Geodetic Survey maps from the 1850s to the 1900s show the first decimation of kelp coincided with the rise of industrial agriculture increasing siltation and runoff to the sea, preventing juvenile kelps from growing in deeper waters. The second occurred just in the last decade of warmer oceans, as a big, warm blob of seawater from Alaska stifled the California Current upwelling, followed by the biggest El Niño on record in 2015–16. This stifling of upwelling deprives kelp of its nutrient supply. The warm waters also rev up the metabolism of the sea urchins. The combined effects have turned major portions of the kelp forests from Northern California to Santa Barbara into sea urchin barrens. The habitats earned their name because the spiny creatures act as marine lumberjacks, chewing away the holdfasts of kelp, un-anchoring them from the seafloor and setting them adrift, where they will ultimately die. Decades of ecological studies show that the disappearance of urchin-consuming sea otters also contributed to the loss of kelp.

Sea otters are the cutest member of the weasel family, but to their detriment, they have the thickest and silkiest pelt in the animal kingdom—nearly one million hairs per square inch. Those pelts, so valuable they were referred to as soft gold, were greedily sought in what is known as the Great Hunt, from 1741 until 1911. Hundreds of thousands of otters were killed and sold by Russian, Spanish, and Native American hunters. Hunting expeditions scoured the Pacific Coast from the Aleutian Islands, off Alaska, to the final southern stronghold, near Santa Barbara, California, reducing the sea otter population to less than two thousand globally. Absent otters, the magnificent kelp forests of the Pacific Northwest were decimated by the exploding sea urchin population whose appetites and metabolisms were upregulated by climate warming and marine heatwaves.

While ensuring the recovery of sea otters and restoring lost kelp forests should be a major conservation and climate change priority, there are only so many potential locations for marine reforestation. Kelp requires shallow, rocky bottoms and cool, nutrient-rich waters. The larger potential role for marine forests in our quest for a better climate future comes from seeding kelp in nearby waters where they could not grow on their own, no matter how few urchins. This process was recently termed seaforestation, a portmanteau of "sea afforestation." Just as afforestation on land means growing forests

In aggregate, cattle burps are thus one of the biggest sources of agricultural methane we have. However, by replacing just .5 to 5 percent of a cow's diet with *Asparagopsis*, researchers have found methane reductions of 50 to 99 percent of the methane created by their digestive gases, while facilitating weight gain. Other seaweeds can help as well, supplementing the natural diet of wild deer in New Zealand, reindeer in Svalbard, and sheep in the Orkney Islands over the past 5,000 years.

Seaforestation includes the cultivation of macroalgae like *Asparagopsis*, nori (the seaweed used to wrap your sushi roll), and sea lettuce—these are miniature sea forests and are already becoming widespread. They have given purpose and employment to coastal people from Alaska to Tasmania. According to the World Bank, the seaweed oil industry could expand to support around 100 million jobs worldwide. These farms mostly grow edible macroalgae for food, but it may be possible for sea forests growing macroalgae for other uses to also be profitable. Indeed, investors have already begun to speculate that they could meet billions of dollars of need for a diverse array of natural compounds in the cosmetics, agricultural, and nutraceuticals industries. Many of the natural oils in kelp and other seaweeds already find their way into vitamins and skin creams, for example. Macroalgae foliar biostimulants can promote budding, higher yields, and stress resilience of most flowering crops. Seaweed soil amendments also promote root growth.

Huge, varied, and lucrative markets for seaweed derivatives have led marine afforestation aficionados at the Climate Foundation to adopt the unofficial motto "The First Gigaton's on Us." In essence, they are suggesting that they can cover the costs of drawing down an entire gigaton of carbon dioxide from the atmosphere simply through sales of kelp and red algae products, making early seaforestation efforts a cost-negative climate solution, even without subsidies, tax credits, or a price on carbon. But as the saying also implies, their vision does not end with just one gigaton of carbon drawdown. As independent validators confirm the ecological merits of seaforests, the potential scale of seaforestation grows far larger, even though there is only so much demand for skin creams and plant stimulants. With a modest price on carbon funding their seaforestation activities, some researchers believe that the Climate Foundation's seaforestation development could help draw down atmospheric carbon while feeding the planet and providing kelp forest and coral reef ecosystem life support.

Natural marine forests cast an estimated 11 percent of their carbon into cold storage in the ocean depths. But that is because only a small fraction of dead kelps end up washed off the edge of the shallow seas where they grow and into the abyssal depths of the ocean. Through seaforestation, up to 90 percent of the carbon from harvested kelps could be deliberately sunk into the deep ocean, where it would remain locked away from the atmosphere for centuries to millennia. Seaforestation is thus a climate solution as massive in potential as the ocean is vast. Just imagine how much carbon could be drawn down if oceans were available to grow new forests.

There is one major obstacle to sinking enough kelp or other seaweeds to restore our atmosphere's chemistry to preindustrial levels: kelp won't grow in a desert.

To the untrained eye, the oceans may look uniform. However, in terms of biological activity, sailing a hundred miles can be the equivalent of trekking from the Sahara to the Congo. Most of the ocean's surface is relatively empty. That's particularly true of the large subtropical areas hovering above the deep ocean where carbon can be stored in the form of sunken seaweed. For seaforestation to work on a grand scale, it needs to provide the seaforest with the four conditions they need to thrive: anchoring sites, sunlight, cool water, and lots of nutrients. The underwater platforms solve the first two problems, but how could cool, nutrient-rich water find its way to a marine desert without a massive, complex infrastructure?

According to the Climate Foundation, the answer is right beneath our fins.

On land, deserts occur where there is a lack of water, which is quite emphatically not a limiting factor for life at sea. Instead, offshore subtropical oceanic surface is mostly empty because it is depleted of key nutrients, which are constantly sinking down from the surface in the form of dead plankton, animals, or even fecal matter. But not far below the surface, just past the reach of sunlight, you can find almost unlimited cool, nutrient-rich water. It rarely mixes with the surface waters—and thereby replenishes its depleted nutrients—for the simple reason that cooler water is denser than warmer water. Most scuba divers are well aware of just how stark the layering of the ocean can be, having regularly descended through a shimmering transition point, or "thermocline," where the water abruptly transitions from a sun-heated, freely mixing layer at the surface to a much cooler layer below. The shimmer is a result of the different densities of the two layers of water, which refract light at slightly different angles. Marine stratification gets stronger with higher ocean surface temperatures. In fact, one pernicious consequence of global heating is an increase in marine stratification and an attendant loss in ocean productivity, as profoundly occurred during the Permian Mass Extinction.

Some seaforesters, even those who imagine drawing down many gigatons of carbon, see their main job as drawing up cold, nutrient-rich deep water to the surface using renewable energy. They aim to create oceanic oases in vast expanses of empty ocean by using renewable energy to restore natural upwelling. As it turns out, the key to using seaforestation to pump gigatons of carbon safely ***down*** into the deep is to restore natural upwelling to the surface. The Climate Foundation calls this process ***irrigation***.

As absurd as watering the ocean may sound, they've taken the first steps to show that irrigation works in practice through proof-of-concept projects from the Philippines to Tasmania. Ultimately, they envision many one-kilometer-square platforms submerged just deep enough that their kelp and red algae forests barely touch the ocean's surface and ships can pass over them. They believe that with each platform, they can harvest kelp four times a year, each drawing down thousands of tons of carbon out of the atmosphere and storing it safely in the deep sea. The exact number remains to be proven, but the Climate Foundation anticipates as much as three thousand tons per platform per year.

As if regenerating a healthy climate in a generation, making livestock production more sustainable, and preventing toxic algal blooms were not enough on their own, seaforestation may actually be able to help us achieve even more. Seaforestation via irrigation has some pretty spectacular perks, even beyond those of regular seaweed farming.

For example, it could restore the Great Barrier Reef, off Australia. Networks of submerged seaforestation platforms could potentially pump up enough cold water to blunt marine heatwaves that have already negatively affected more than half of all corals globally and killed almost a third on the Great Barrier Reef.

Sea forests could boost declining fish stocks as well. Some scientists have projected that the protein and energy needs of ten billion humans could be met by seaforesting anywhere between 4 and 9 percent of the ocean's surface. It turns out that in the open ocean, fish need shelter to hide from predators, a major reason why healthy kelp forests are associated with strong commercial fish harvests. A smaller distributed area would be enough to sink and store gigatons of atmospheric carbon dioxide, helping humanity reach drawdown.

A million square kilometers of submerged, storm-tolerant seaforests are easier to summon up in a spreadsheet than in reality, of course. It would take an enormous, civilization-defining effort to achieve such a large transformation, not to mention additional improvements to the many technological milestones already achieved in seaforestation development. But most of the technical hurdles are being addressed to sustainably grow and harvest seaforests at scale.

Much like the swaying kelp forests of Monterey Bay, it is an alluring vision—one worth trying our hardest to achieve. •

Harbor seal (*Phoca vitulina*) in the kelp forest (*Macrocystis pyrifera*), Santa Barbara Island in the Channel Islands, Santa Barbara, California.

areas. Mangrove forests also have important recreational value, earning income from nature-based tourism while also playing an important role in traditional customs and modern cultural practices.

Mangrove ecosystems play a vital role in addressing climate change. They are long-term carbon sinks, storing carbon in the trees themselves as well as soils underwater (where reduced oxygen levels slow the rate of carbon dioxide release). Mangrove forests remove up to four times more carbon from the atmosphere per acre than terrestrial forests and can store almost twice as much carbon. Mangrove ecosystems currently hold between 5.6 and 6.1 billion tons of carbon worldwide, mostly in the submerged soils. Although the total area occupied by marine vegetation, which includes mangroves, seagrasses, and salt marshes, is relatively small—less than 1 percent of the planet's terrestrial surface—they account for 50 percent of all carbon sequestered in marine sediments. This is one reason why researchers, conservationists, and policy-makers frequently refer to marine vegetation as ***blue carbon***, a term coined in 2009 to distinguish it from green carbon, which is associated with plants and trees farther inland. The term has proven to be a handy concept for use in the protection, restoration, and management of these important marine habitats.

There is a sense of urgency for blue carbon ecosystems. The world has lost nearly 50 percent of mangrove forests since 1980, with most of that loss occurring in Southeast Asia due to landscape conversion as a result of aquaculture projects, illegal logging, and industrial and urban coastal development. These impacts are expected to continue and be exacerbated by climate change and population growth. Other major losses have also been reported in Central America and Africa, making mangroves one of the world's most threatened ecosystems. When mangroves are degraded or destroyed, carbon stores that took millennia to accumulate are released in a matter of years, flipping an important carbon sink into a significant carbon source. In Indonesia, 618,000 acres of abandoned shrimp aquaculture ponds that were once pristine mangroves now emit up to 7 million tons of carbon dioxide per year. Restoring these abandoned ponds back to mangrove habitat would not only halt these greenhouse gas emissions but also absorb as much as 32 million tons of carbon dioxide annually. Taken together, the restoration of mangroves could result in 3 billion tons of removed or avoided greenhouse gas emissions by 2030.

By halting ongoing mangrove loss and restoring mangrove forests globally, we have a significant opportunity to combat climate change ***and*** help millions of people adapt to its impacts. It is critical to mobilize governments, institutions, communities, and individuals to protect this "super" ecosystem. Under the historic 2015 Paris climate agreement, many countries included mangroves in their commitments to reducing greenhouse gas emissions. While this is an important start, we now must turn these commitments into action for one of the earth's most important ecosystems. •

Tidal Salt Marshes

Reeds and mudflats on the North Sea in Holland.

The ebb and flow of tidal waters inside the salt marsh carry life in and sweep it back out again. Raccoons that take advantage of low tide to fill their bellies with crabs and mussels are forced to beat a hasty retreat across the mudflats as the tide comes in. Minute by minute, the waters creep up through the low marsh, where the *Spartina alterniflora*, or smooth cordgrass, grows tallest—up to seven feet high—and the ribbed mussel, with whom it has a symbiotic relationship, burrows below, enhancing nutrients in the nearby soil. These helpful bivalves also provide a habitat for fiddler crabs, which take advantage of mussel mounds for their burrows. As the water rises into the high marsh, the cordgrass gradually gives way to glasswort, sea lavender, spike grass, black grass, and marsh elder.

Here the shy saltmarsh sparrow feasts on insects to feed her chicks, hidden from sight in a nest built of woven marsh grass, just barely above the high tide mark. As the tide climbs still higher, it laps against the upland border, where marsh elder, switchgrass, and reeds grow.

Below the surface, plants decompose slowly in the largely anaerobic, salty conditions, and the regular influx of saltwater prevents the formation of methane. Meanwhile, the nutrients washed up in the tidal waters leave deposits, forming a thick layer of marsh peat that continuously grows with each tidal cycle. For this reason, scientists believe saltwater marshes store more carbon per acre than tropical forests. Globally, that amounts to nearly a ton of carbon sequestered per acre annually.

Tidal marshes become carbon dioxide sources when they are converted into roads, houses, or agricultural land. Almost two million acres of coastal wetlands disappear annually around the world, contributing about 500 million tons of carbon dioxide to the atmosphere. In the United States, more than half of tidal wetlands have been drained and converted into farmland, dissected by highways, or cut off from tidal waters by seawalls and levees. However, rising sea levels and an increase in the frequency and severity of hurricanes have been forcing people, especially those in coastal communities, to recognize the critical role of tidal marshlands.

According to satellite data from the National Oceanic and Atmospheric Administration, sea level is currently rising by one-fourth of an inch annually. As a result, in 2019 global sea level was 3.4 inches above its average height in 1993. Higher sea levels cause more damage as stormwater advances farther inland, but they are also problematic for tidal salt marshes.

Over the course of a year, as sediment from the incoming tide gets deposited and as root materials pile up on the marsh floor, the marsh gains up to one-third of an inch of elevation, with surface sediments alone holding between 10 and 15 percent carbon. Until recently, most tidal marshes have been able to grow fast enough to keep pace with sea-level rise. For those that have not, restoration methods include manually increasing the marsh's elevation by spreading a fine layer of sediment over the entire area. Another problem caused by a combination of sea-level rise and seawalls or levees is the inability for tidal salt marshes to migrate inland as needed for survival. By identifying areas where barriers can be removed or altered to accommodate marshland, we create an opportunity to save these tidal wetlands and allow them to regenerate in order to continue to capture carbon and protect coastlines.

Regenerating salt marshland requires a focus on re-creating historical tidal patterns in a given area. If there is too much water from sea-level rise and blockage from coastal development, the marshland is reclaimed by the ocean and "drowns." When there is insufficient water, invasive species take root, forcing the native plants out and dramatically altering the ecosystem upon which fish and birds rely. Restoring a marshland's connection to life-giving tides requires a number of techniques, from dredging to removal of man-made drains to modifications of water-control structures like tide gates. Many tidal marshlands are able to recover once tidal flows are brought back.

One of the marvels of tidal salt marshes is how its inhabitants have adapted to thrive in difficult conditions. Inundated by salt water one moment and drying in the scorching sun the next, the species that call it home are hardy. A reflection of its inhabitants, the marsh is also hardy. Up until this point, tidal marshlands have survived

Seagrasses

Seagrasses include many varieties of grasses, lilies, and palms, a group of plant species that can live entirely immersed in seawater. Like their terrestrial relatives, seagrasses have leaves and roots and produce blossoms and seeds—the flowering plants of the sea.

Seagrasses have been called the forgotten ecosystem, perhaps because they seem so tame when compared with richly endowed mangroves and spectacular coral reefs. They cover the shallow slopes of coastlines from the tropics to the Arctic. Like grasses found on land, seagrasses can form dense underwater meadows, some large enough to be seen from space. These immense areas provide habitat to millions of animals, from tiny shrimp and seahorses to large fish, crabs, clams, turtles, manta rays, and marine mammals such as dugongs and sea otters. Sea grass meadows are essential to fisheries, coastal protection, and maintaining water quality. However, the most unknown quality of seagrasses may be their most important. While sea grass meadows occupy less than 0.1 percent of the ocean area, they provide nurseries for 20 percent of the largest fisheries on the planet, and 10 percent of the carbon buried in ocean sediment each year.

There are seventy-two known species of seagrass with a great diversity of sizes, shapes, and habitats, ranging from eelgrass, with its long, ribbon-like leaves, to spoon grass, with paddle-shaped leaves that form lush, low meadows. The tallest seagrass species—*Zostera caulescens*—has been found to reach thirty-five feet tall in Japan. Like all plants, seagrasses depend on light for photosynthesis; hence, they are most common in shallow depths where sunlight is brightest, but deep-growing seagrass has been found at depths up to 190 feet.

Seagrasses have been used by humans for more than ten thousand years. People fertilize fields, insulate houses, weave furniture, and thatch roofs with seagrasses. By providing critical habitat, they support fisheries and biodiversity. They also trap and stabilize sediment, which not only maintains water quality but also reduces erosion and buffers coastlines against storms. These benefits make seagrasses one of the most valuable ecosystems in the world.

Despite their critical importance, seagrasses are highly endangered. While the current global area of seagrasses is between 45 and 150 million acres, more than 12 million acres of seagrass meadows have been lost in the past century. The rates of loss have increased over that time, from 1 percent per year prior to 1940 to 7 percent per year since 1980. Globally, 24 percent of seagrass species are now classified as threatened or near threatened on the International Union for Conservation of Nature Red List. While seagrasses are impacted by coastal development, poorly managed fisheries, and aquaculture, the greatest threats to seagrasses are coastal pollution and poor water quality. Seagrass loss is occurring at rates similar to tropical rainforests, coral reefs, and mangroves.

The accelerating loss of seagrasses globally is a significant contributor to climate change. Seagrass meadows are natural carbon sinks and can be more effective at sequestering carbon than forests. They absorb carbon from the water and then bury it in the sediment below for up to millennia. The world's oldest living organism is a patch of Mediterranean seagrass, *Posidonia oceanica*, which is estimated to be 200,000 years old and still absorbs and deposits carbon into the thirty-six feet of carbon-rich soil on which it grows. On average, every acre of seagrass buries 0.5 tons of carbon per year (which adds up to 80 million tons per year of carbon captured by seagrasses and kept out of the oceans and atmosphere). Ongoing loss of seagrasses is not only reducing their capacity to remove carbon from the atmosphere; the carbon stored in the soil below the seagrasses can be released once the plants that were holding it in place are degraded or removed. Current rates of seagrass loss are potentially releasing 300 million tons of carbon into the oceans and the atmosphere every year.

Seagrass meadows in Virginia were wiped out by an ocean-borne pandemic and hurricane in the 1930s and never recovered. Over the past two decades, in four coastal bays, 74 million eelgrass seeds have been broadcast into 536 restoration plots that had been barren for nearly a half a century. The grasses have spread to nine thousand acres and have become the largest eelgrass habitat between Long Island and North Carolina. Once established, the grasses clear the water and moderate the waves, providing seafloor stability and sufficient light for the plants to thrive and reseed naturally. The areas seeded are part of the forty-thousand-acre Volgenau Virginia Coast Reserve, protected from boat anchors, propellers, and pollution. What the reserve cannot do is protect seagrasses from rising ocean temperatures. Halting ongoing losses and conserving the world's seagrasses must be a priority for addressing climate change. If we can ensure their future, these remarkable and ancient plants will continue to absorb carbon while also protecting and nurturing the people and rich biodiversity of the world's coasts.

One seed of hope is the scallop, a saltwater clam once ubiquitous along the eastern shores of the United States. In the Volgenau Virginia Coast Reserve, scallops have been found twenty miles from the closest spawning cages, an indication that scallop larvae drifted down the coast into the reserve and began a process of regeneration that was neither predicted or expected. Marine ecologist Mark Luckenbach compares the advent of a harvestable bay scallop population to the introduction of the gray wolves into Yellowstone. It's the beginning of regeneration. •

Azolla Fern

Nearly 50 million years ago, atmospheric carbon dioxide levels were at least double, if not triple, current levels. However, carbon dioxide levels quickly declined to what they are today. There may be many explanations for this transition, including changes in the position of the continents. One partial explanation is that rapid blooms of a diminutive fresh-water fern helped lower carbon dioxide levels. This small fern, *Azolla arctica*, is related to modern azolla species, *Azolla filiculoides*, which have a huge potential to sequester carbon dioxide while replacing fossil fuel–intensive fertilizers, providing animal feed, and/or creating feedstock for biofuel.

In 49-million-year-old sediment cores from the Arctic Ocean, scientists found layers rich in azolla spores and organic matter from the surrounding shores. At the time, the Arctic ocean was mostly land-locked, and many freshwater rivers flowed into it. This allowed azolla to bloom, and this tiny fern contributed to substantial amounts of organic carbon burial over the span of about 800,000 years that its spores are still visible in the ancient Arctic sediments. This carbon burial likely contributed to at least part of the carbon dioxide drawdown and global cooling in that era.

Azolla, also called water velvet or fairy moss, is not your typical fern. Unlike its larger, frond-producing cousins, azolla grows as a coin-size rosette, lying almost flat on the surface of freshwater. Its delicate roots dangle, making no effort to find the soil, even when floating in an inch of water. It places its microscopic seed in an air bag that floats away. It has more protein than soybeans. Azolla contains a special kind of bacteria, held in tiny, oxygen-free pockets called heterocysts. Called *Anabaena azollae*, the species is unique to the azolla fern and has become completely dependent upon it for its survival, having transferred some of its genes to the fern. *Anabaena* is a type of blue-green cyanobacteria that sequesters inert nitrogen from the air, which allows azolla to self-fertilize. And because of that, it can grow at blazing speeds, doubling its coverage on the surface of a water body in as little as 1.9 days.

Azolla could once more play an important role in sequestering carbon dioxide from the atmosphere through the deliberate actions of humans. Recent research outlines multiple potential impacts for azolla, including regenerative agriculture, green fuel, clean water, and, most of all, a livable climate. More than a thousand years of agricultural practice have witnessed azolla's promising role in rice cultivation. The earliest written account of the use of azolla to increase rice production dates back to AD 540, when Chinese scholar Jia Si Xue described how rice farmers inoculated their paddies with azolla in the book *The Art of Feeding the People*. What Jia could not have known, though, was how azolla accomplished its job.

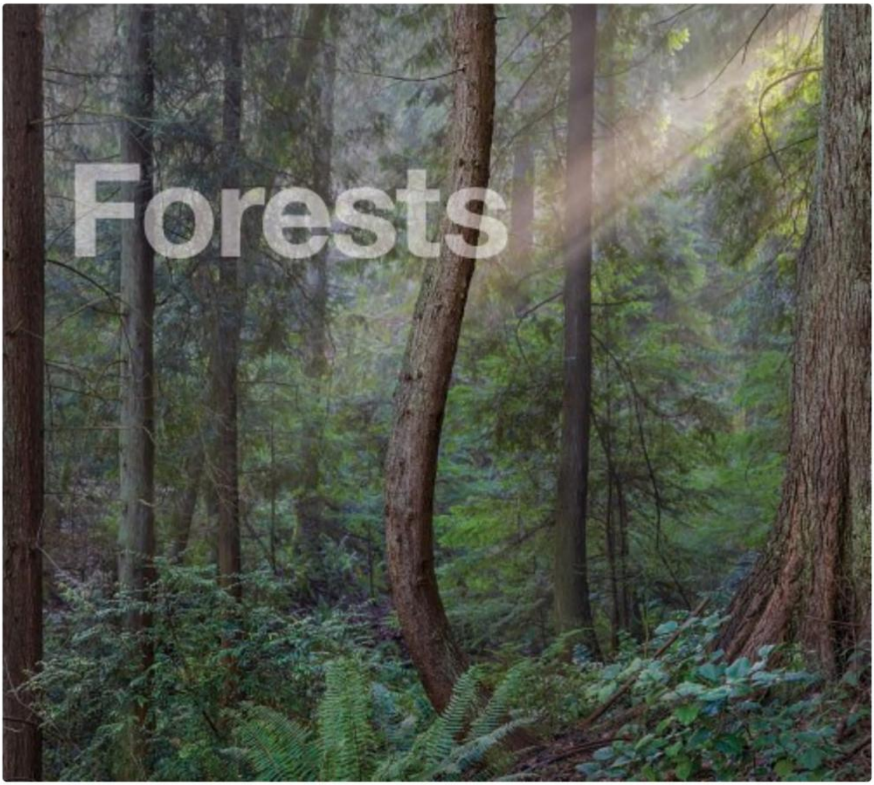
Azolla acts as a "biofertilizer," a living organism that provides critical nutrients to its surroundings. To some extent, azolla is able to transmit nitrogen directly into the water it grows in and makes bigger contributions when bits of it die and get incorporated into the soil where rice plants are rooted. By draining azolla-filled rice paddies at the right time, farmers create a significant pulse of nitrogen as well as a full complement of nutrients that maturing rice plants need in order to maximize their output. By growing azolla alongside rice, farmers in settings where fertilizers are scarce or expensive can increase yields of their paddies by 50 to 200 percent. In more affluent rice-growing regions, azolla can dramatically reduce or entirely eliminate the need for chemical fertilizers.

Boosting yields and displacing energy-intensive chemicals are not the only ways azolla can help with climate change. It draws down current biofuel crops grown at the same latitudes. Early trials suggest that one acre of azolla could concurrently produce nearly as much ethanol as an acre of corn and as much biodiesel as an acre of palm oil. Azolla wouldn't require energy-intensive nitrogen fertilizer as do those other crops, thanks to *Anabaena*. If azolla were grown for the use of its proteins and carbohydrates as animal feeds, its omega-3 fatty acids EPA and DHA would improve the nutrient content of the foods made from these feeds, while other oils could be fractioned off for use as a carbon-neutral fuel for the tractors, trucks, and machinery involved in animal husbandry.

Great care would need to be taken if azolla were introduced into settings where it is currently absent, whether in the name of growing biofuel feedstocks or otherwise. Some species of azolla have become invasive when introduced outside of their native ranges. But there is nothing preventing the sustainable harvest of the fast-growing fern from its existing habitats or from artificial ponds in controlled agricultural settings. When azolla freezes, it usually dies, so that presents one way to manage its proliferation.

Less controversial is azolla's potential for phytoremediation, a term that refers to the use of plants for environmental cleanup. Its ability to soak up phosphorus and even excess nitrogen from waterways is clear, reducing eutrophication of waterways. Not only that, but azolla has a remarkable affinity for all manner of pollutants, including heavy metals like lead, nickel, zinc, copper, cadmium, and chromium, as well as certain pharmaceuticals, and even for the salt ions that cause salinization of some agricultural lands. By concentrating these elements and compounds in its tissues, azolla can be used to clean up mine tailings and fly ash, or even as a way to clean wastewater so it can be used for irrigation. Depending on the type of cleanup operation, the azolla could potentially be harvested for use as green manure or used for biofuel production.

Azolla has already had a positive impact on the earth's geological history and Asian agriculture. With more research and financing, it may once again change the world. •



Douglas fir in the Cascade Range, whose woodlands contain the greatest amount of biomass of any forest on the planet.

Forests are crucial to our well-being. They are watersheds, habitat, and refuge. They cleanse the air, cool the air, and create the air. Forests cover nearly 30 percent of the earth's terrestrial surface—some 10.8 million square miles (reduced from approximately 23 million square miles at the end of the last Ice Age). There are 60,065 known tree species. Brazil, Colombia, and Indonesia have the greatest number, with more than 5,000 species each. There are thousands of different forests, and all store significant amounts of carbon, amplified where there are carbon-rich soils such as peatlands and wetlands. Forestlands contain most of the planet's terrestrial plant and animal species, with tropical forests by themselves containing at least two-thirds of species diversity, possibly as much as 90 percent. Forests are critical to freshwater supplies, as they help regulate and maintain the aquatic environmental conditions and related habitat resources their ecological communities require.

In the past two decades, thanks to scientists such as Suzanne Simard of the University of British Columbia, our understanding of forests has transformed. Just as research on the human microbiome revolutionized our understanding of health and disease, the biological interactions among trees, fungal networks, microorganisms, and unrelated plant species paint a new picture of forests and what occurs within them. Our old image of trees competing for water, sun, and nutrients has been replaced by research showing how primary or intact native forests are social creatures, interacting, sharing knowledge, and taking care of their community. Trees learn—they visually sense animals near them (including us)—retain memory, and accurately anticipate future weather. Trees in a forest behave like a living organism rather than a collection of parts. The forest community includes bacteria, viruses, algae, archaea, protozoa, springtails, mites, earthworms, and nematodes, collectively numbering in the trillions in a single handful of soil.

However, trees are a commodity. Tree trunks and forest acreage are totaled up like a purchase order. This is misguided. While some forest products, such as timber, are useful, the wanton deforestation that usually comes with tree harvesting is both short-sighted and dangerous. It imperils the critical role forests play in regulating our climate. An estimated 2,200 billion tons of carbon are stored in forests, distributed among the three major forest biomes: approximately 54 percent occurs in tropical forests, 32 percent in boreal forests, and 14 percent in temperate forests. Boreal forest ecosystems have the highest carbon densities, and more recent estimates for boreal forests suggest that the total ecosystem stock of carbon, including biomass and soil carbon, is larger than the carbon stock in tropical and temperate forests combined. Any diminishment, including "sustainable" logging, reduces the amount of stored carbon in a forest while raising the risk of wildfire.

To solve the climate crisis, forests are crucial. Our top priority is protecting primary forests, sometimes called old-growth, from destruction. They are the largest, most resilient, most carbon-rich forests on earth. Letting them continue to grow, and to sequester additional carbon, is one of the most effective strategies we have to reverse climate change. Another priority is reforesting land that has been cleared or degraded by human use. But it must be done in the right way. Many climate schemes propose bioenergy projects that would plant and combust more than a hundred million acres of fast-growing trees in the global South, capture the carbon emissions from the incinerators, and bury it. These tree "crops" would be machine-harvested and burned to provide so-called clean energy.

Scientists calculate that planting a trillion trees will help attain timely carbon goals. It sounds logical. Tree-planting targets are a

Proforestation

Scientists measuring the health and caliper of the largest trees on earth, the giant Sequoia of Sequoia National Forest in Tulare County, California. The larger trees are over 250 feet high and up to 102 feet in circumference at the base, more than the distance between home plate and second base in a baseball field.

Environmental scientist William Moomaw coined the term *proforestation* when he realized that protecting intact forests as well as letting degraded forests recover and mature would have a greater impact on global emissions than any other land-based solution. A 2021 University of West Virginia research project that studied changes since 1901 showed that as carbon dioxide levels in the atmosphere rise, the capacity of trees to take up more carbon dioxide increases, though eventually this capacity plateaus. This reversed a long-standing belief that the stomata, the minute pores in the epidermis of the tree leaves that allow movement of gases in and out, became more constricted in the presence of additional carbon dioxide. It turns out to be the opposite: even more carbon is being taken up by the trees than was conventionally understood, which is confirmed by Moomaw's studies.

Forestation is rightly promoted as a prominent drawdown solution for climate change, but practices differ. *Afforestation* is planting trees where none grew before; *reforestation* replaces trees where they were previously grown. Both are activities implemented by humans that result in the sequestration of carbon over the lifetime of the trees. However, the contribution of a newly planted tree to carbon removal is limited during the first decades of its life as it grows to maturity. To meet 1.5°C climate goals, afforestation and reforestation would require 3.7 million square miles of land, an area greater than the landmass of China.

Proforestation is different—the required land is already forested, whether as intact, old-growth forest or as degraded forest that needs simply to recover and grow. The world's total yearly emissions of carbon are about 11 billion tons. However, the net annual increase in elemental carbon in the atmosphere is about 5.4 billion tons, because 5.8 billion tons are sequestered by land, plants, and oceans. Of the three, forests are the greatest remover of carbon dioxide on the planet, and primary, mature forests are responsible for the majority of that sequestration. Until recently, the scientific community assumed that older trees sequestered carbon marginally, if at all. Now we know trees accumulate significant amounts of carbon to almost the end of their long lives. Proforestation would have a forty times greater impact between now and 2100 than newly planted forests.

Intact forest landscapes (over 50,000 hectares in size) where there is no habitat fragmentation and that contain diverse populations of native species are the top priority for protection. They exist throughout the world, from Russia to Gabon to Suriname to Canada.