Earth 2020: Science, society, and sustainability in the Anthropocene

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April 22, 2020, marks the 50th anniversary of Earth Day and the birth of the modern environmental movement. As we look back over the past half century, we can gain significant insights into the evolving human imprint on Earth's biophysical systems, and the role of science and scientists in driving societal transitions toward greater sustainability. Science is a foundation for such transitions, but it is not enough. Rather, it is through wide collaborations across fields, including law, economics, and politics, and through direct engagement with civil society, that science can illuminate a better path forward. This is illustrated through a number of case studies highlighting the role of scientists in leading positive societal change, often in the face of strong oppositional forces. The past five decades reveal significant triumphs of environmental protection, but also notable failures, which have led to the continuing deterioration of Earth's natural systems. Today, more than ever, these historical lessons loom large as we face increasingly complex and pernicious environmental problems.

climate change | sustainability | Earth Day | social engagement | communication

On April 22, 1970, millions of people took to the streets in cities and towns across the United States, giving voice to an emerging consciousness of humanity's impact on planet Earth. This first Earth Day was the brainchild of US Senator Gaylord Nelson, and organized by a grass roots movement coordinated by Denis Hayes, a 25-y-old Harvard student. The events included demonstrations, teach-ins, and community cleanups ("Trash Wednesday") in over 2,000 communities across the country. Protesters shut down Fifth Avenue in New York City, while students in Boston staged a "die-in" at Logan Airport, lying in coffins to raise awareness about airplane-related pollution. The protesters were mostly white, middle-class, and young, but their message also reached some in the older generation. Walter Cronkite, by then widely seen as the most trusted man in America, hosted a half-hour Earth Day special on the *CBS Evening News*. He had become increasingly concerned about "the fouled skies, the filthy waters, and the littered earth," as he put it, and he concluded the program with a call for the public to heed "the unanimous voice of the scientists warning that halfway measures and business as usual cannot possibly pull us back from the edge of the precipice."

Today, half a century later, Cronkite's words are eerily familiar. Since the first Earth Day, we have, no doubt, made significant progress in addressing many acute environmental problems, like acid rain and the ozone hole. However, other, more pernicious, threats have emerged, from climate change to global biodiversity loss; the warnings seem louder, and the edge of the precipice ever closer, as growing scientific evidence demonstrates planetary-scale human perturbations of the Earth system. In the face of these challenges, a look to the past can provide some important lessons.

Back in 1971, John Harte and Robert Socolow published their now-classic book, *Patient Earth* (1), which addressed a range of topics in the nascent field of environmental science, including human population growth, resource scarcity, and nuclear contamination. A year later, Donella Meadows and her team at the Massachusetts Institute of Technology released the results of a landmark study entitled *The Limits to Growth* (2), which used an early computer simulation to examine

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Author contributions: P.D.T. wrote the paper.

The author declares no competing interest.

This article is a PNAS Direct Submission.

Data deposition: Earth system data from the past 50 y have been compiled at https://purl.stanford.edu/mg458wc3389.

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future potential limits to growth from population increase, resource depletion, and pollution. As we mark the 50th anniversary of Earth Day and move ever deeper into the Anthropocene, a new geologic era of human dominance over planet Earth, it is instructive to revisit some of the ideas first addressed by these two classic works. This is the challenge I took up with a new edited collection of essays, *Earth 2020: An Insider's Guide to a Rapidly Changing Planet* (3), which brings together some of the world's leading thinkers to understand how planet Earth has evolved over the past 50 y, and what the future might yet hold. The answers to these questions, seen from a wide variety of disciplines and perspectives, provide a deeper understanding of how science and society have coevolved in the age of the Anthropocene, and how humanity might live in greater harmony with Earth's natural systems.

The Road to Earth Day

Looking back through the mists (or smog) of time, the arc of events leading up to the first Earth Day are clear enough. Nearly a decade before the 1970 event, Rachel Carson, a naturalist, writer, and biologist at the US Fish and Wildlife Service, published her book *Silent Spring* (4), a stark warning about the devastating ecological impacts of pesticides and other synthetic chemicals. *Silent Spring* brought widespread attention to an issue first raised by unionized farm workers in California, led by Dolores Huerta and Cesar Chavez. In Carson's telling, the fruits of human ingenuity, miracle compounds of the postwar industrial age, had come back to haunt us as poisons embedded in our food and our bodies. It became a deeply personal issue for Carson; beyond her own health struggles (recurring battles with cancer, from which she died 2 y after the publication of *Silent Spring*), her work required enormous personal sacrifice. She was fiercely criticized by industry lobby groups, who tried to discredit her as a hysterical communist. This was to be expected. After all, Carson's message not only threatened the profits of some of the most powerful companies in the world, it also undermined a growing faith in the power of science to promote a better, healthier, and more prosperous future, where humans would, at last, triumph over nature. Before *Silent Spring*, the pesticide dichlorodiphenyltrichloroethane (DDT) had been championed as one of the great scientific discoveries of World War II, credited with saving the lives of countless soldiers from malaria and other insect-borne diseases (5). Even some of Carson's colleagues felt that her outspoken public stand was an irresponsible breach of scientific objectivity. As a federal employee, she challenged government regulatory practices and testified before Congress, in 1963, arguing for new policies to protect human health and ecosystem integrity. Within a year of her congressional testimony, and 1 mo after Carson's death, US President Lyndon B. Johnson signed the Pesticides Control Bill.

Rachel Carson was able to mobilize public opinion and policy by combining scientific rigor with a compelling and accessible message. Before her foray into environmental politics, she was widely known as one of the nation's great natural history writers, with popular books including *Under the Sea Wind* (6) and *The Sea Around Us* (7). Through her lyrical prose, grounded in science, Carson inspired public audiences about the wonder and beauty of the living world, and addressed what she saw as a growing separation between humans and nature. She also displayed great courage in the face of significant adversity, and came to understand that she could not remain detached from the broader societal implications of science.

Rachel Carson's experiences provided an important lesson for subsequent generations of environmental scientists. Her example was also not lost on some scientists of her own era. In the mid-1960s, Caltech geochemist Clair Patterson began a crusade to draw public attention to environmental lead contamination. Earlier in his career, Patterson had developed ultraclean analytical methods to precisely determine the age of Earth based on lead isotopic signatures (8). Over the course of this work, he observed elevated lead concentrations in supposedly pristine regions around the globe (and in modern human tissues, which he compared to Egyptian mummies), resulting from the widespread use of tetra-ethyl lead as a gasoline additive. A decade earlier, Patterson's Caltech colleague, the geochemist Arie Jan Haagen-Smit, had linked Los Angeles' developing smog problem to the photochemical reactions of ozone with unburned hydrocarbons and nitrogen oxides in automobile exhaust (9). Like Rachel Carson, Patterson and Haagen-Smit were attacked by powerful companies who felt threatened by their work. Eventually, they would prevail. As chairman of the California Air Resources Board, appointed by then Governor Ronald Reagan, Haagen-Smit oversaw the deployment of vehicle emissions controls to begin addressing the smog problem. And, over the following decades, leaded gasoline was phased out in virtually every country around the world. These societal changes were driven by science, but also by scientists who advocated publicly and vigorously for much-needed reforms.

In 1968, as Patterson was ramping up his anti-lead crusade, Stanford biologist Paul Ehrlich published a short book entitled *The Population Bomb* (10), addressing the dire potential consequences of global overpopulation. At the time, the world was undergoing a strong demographic transition, resulting from increased human longevity that was not matched by declining birth rates. Ehrlich advocated for immediate action to limit population growth, balancing the birth and death rates through greater access to reproductive control technologies. Initially, the book's message had little impact. That changed 2 y later, following Ehrlich's appearance on *The Tonight Show Starring Johnny Carson* in February 1970. Ehrlich's charisma, wit, and bluntness won over Carson, and he was invited back on the show, shortly before Earth Day, to deliver a stark warning about the dangers of human overpopulation to a live audience of millions. The message was clear, but not without controversy. Critics argued that the book made false prophecies and underestimated the problem of growing resource consumption in wealthy societies. However, there can be no doubt that Ehrlich's powerful and accessible voice mobilized public opinion and increased awareness of the planet's finite resources.

Another event transpired in 1968 that would have a major impact on the nascent environmental movement. On December 24 of that year, NASA astronaut William Anders captured an image from the window of the Apollo 8 spacecraft of Earth rising above the moon's surface. In the Earthrise picture (NASA image AS08-14-2383), the planet is seen as a beautiful blue orb suspended against the "inky black void" of space, as Anders called it. The image offered a profoundly new global perspective that transcended national boundaries. As American poet Archibald MacLeish put it in a Christmas day letter to *The New York Times*, "To see the Earth as it truly is, small and blue and beautiful in that eternal silence where it floats, is to see ourselves as riders on the Earth together, brothers on that bright loveliness in the eternal cold." The Earthrise image caused an immediate sensation, appearing in newspapers and television sets across the globe (11).

After he had left office, in 1969, US President Lyndon Johnson sent copies of the picture to leaders around the world. Walter Cronkite kept a framed copy above his desk.

As the turbulent 1960s came to a close, the "bright loveliness" of MacLeish's poem was threatened by dark clouds. The world remained gripped in the midst of the Cold War and had verged on the brink of nuclear confrontation during the Cuban Missile Crisis just a few years earlier. The conflict in Vietnam was rapidly escalating, and antiwar sentiment ran at a fever pitch across much of the United States and beyond. Growing social unrest began to spill over into the fledgling environmental movement. In cities across the developed world, cars belched out noxious leaded fumes that choked the air in blankets of smog, while rampant industrial pollution created acid rain, and turned some rivers and lakes into flammable toxic sludge. In the United States, the catalytic moment came with the Santa Barbara oil spill in January 1969, when more than 100,000 barrels of oil were released onto the seafloor and beaches along the California coast, creating a surface slick that would eventually kill thousands of marine birds, fish, and mammals (12). At the time, it was the largest environmental disaster in US history, and it captured widespread attention. Senator Gaylord Nelson, inspired by the burgeoning antiwar movement, sought to channel public outrage into a rallying cry for environmental action. So, as a new decade dawned, the stage was set for the first Earth Day in 1970.

First Steps

To many observers at the time, the first Earth Day was a mixed success. Some rallies and demonstrations were bigger than expected, but others were small, with limited participation across wide swaths of the population, including those who felt that the Vietnam War, poverty, and civil rights were more pressing issues. Others questioned the motivation of the Earth Day organizers. As luck would have it, the event occurred on the 100th anniversary of Lenin's birth, prompting some to wonder whether the entire thing was a subversive communist plot (13).

However, the legacy of the first Earth Day would soon prove to be significant. By the end of 1970, the US government would create the Environmental Protection Agency, and major environmental legislation soon followed, including sweeping amendments to the Clean Air and Clean Water Acts, and the introduction of an Endangered Species Act. The pesticide DDT and many other toxic chemicals were rapidly phased out across the United States (although DDT production continued in Mexico well into the 1990s). Other industrialized countries followed suit, marking a new era of legislative environmental stewardship, and a shift in the political landscape. In 1972, the Swiss Popular Movement for the Environment (PME) became the world's first environmentally focused political party. Before the end of the decade, Daniel Brélaz, a mathematician, would become the first PME member of the Swiss national parliament.

By the end of the 1970s, new environmental legislation led to rapid improvements in air and water quality in many industrialized countries. Firm limits were placed on contaminant levels in water and air, and enforcement mechanisms were created to ensure compliance. Progress was stimulated by technological advancement, including new waste water treatment facilities and gas scrubbers. However, economics also played a critical role. As early as the 1920s, British economist Arthur Pigou had suggested that governments could impose a tax per unit of pollution (14) (known today as a Pigouvian tax). However, Pigou's ideas were well ahead of their time, and they gained little traction in the decades that followed. That began to change, however, by the late 1960s, due in large part to a *Science* article published by Garrett Hardin (15). Hardin, a biologist, argued that unregulated use of a shared resource—cattle grazing on an open pasture, for example—could lead to unsustainable exploitation and environmental degradation, as individuals competed for access and profit, with little regard for the broader public good. The ensuing "tragedy of the commons" would, Hardin suggested, result in the extinction of species and the large-scale degradation of natural habitats. Subsequent work by Elinor Ostrom (the first female Nobel Laureate in economics) showed that appropriate collective management of public resources could avert such ecological tragedy (16). However, in the industrialized nations of the early 1970s, examples of such collective management seemed few and far between.

Hardin's article set off a flurry of intellectual activity, which led to the founding of the *Journal of Environmental Economics and Management* in 1974. Early pioneers of this field, like Herman Daly, sought to situate economics in the context of Earth's biophysical systems (17), and to address the failure of private markets to provide public goods, like clean air and water, which are available to everyone whether or not they pay. Moreover, environmental economics sought to measure the unequal distribution of net costs and benefits for any proposed pollution mitigation measure, designing policies that achieved the greatest pollution reduction for a given expenditure. In 1968, Canadian economist John Harkness Dales (18) proposed a new approach to maximize the cost efficiency of environmental protection, based on government-issued caps on pollution levels, with emissions permits that could be traded in the market. This approach encouraged innovative new solutions by allowing individual emitters to deploy their own pollution mitigation strategies rather than adopting government-mandated technologies. Permit trading also enabled firms with limited pollution control options to pay other companies to offset their emissions, through a so-called "cap-and-trade" approach. Decades later, such economic approaches would come to play a critical role in global efforts to reduce greenhouse gas emissions. More generally, these innovations demonstrated how natural science and engineering could interface with other disciplines (economics, in this case) to develop meaningful societal tools for environmental protection.

By the end of the 1970s, it seemed that industrialized nations were moving toward addressing many of the environmental problems that had motivated the organizers of the first Earth Day. Under widespread public pressure, political will had been mobilized, and legal, technological, and economic forces, guided by science, were deployed to combat the most urgent environmental threats facing these nations. Progress was rapid, and visible improvements in local water and air quality soon followed. Importantly, these environmental challenges were largely addressed within national contexts, where the attribution of responsibility and liability was generally clear, and where individual countries (or cities, states, or provinces) had undisputed legislative authority. By comparison, there was much less awareness of global-scale environmental impacts; solving these problems would soon turn out to be significantly more challenging.

A Global Perspective

As the 1970s marched on, scientific advances provided new ways of observing Earth's biophysical systems on previously unimaginable scales. The early seeds for this were planted with the International Geophysical Year (IGY) (1957 to 1958), when scientists from more than 60 countries came together to address a range of research questions, attempting to bridge the growing isolationism of the Cold War (19). Their efforts were aided by rapid developments in space technology (Sputnik 1 was launched in 1957), radar, and computing power, and by the understanding that unfettered international collaboration was necessary to address the biggest challenges facing humanity. The IGY created internationally coordinated observational networks, and mandated that all data be freely available to scientists around the world. The World Data Center was established, in April 1957, to manage all data collected during the program, mostly in the form of computer punch cards and magnetic tape drives.

Among the most important legacies of the IGY was an atmospheric monitoring program initiated by Roger Revelle and Charles Keeling at the Mauna Loa Observatory in Hawaii. The observatory, perched atop a remote volcano far removed from local pollution sources, provided an ideal location to examine large-scale trends in atmospheric CO_2 concentrations. The observations soon revealed a detectable interannual CO_2 increase (superimposed on the pronounced seasonal cycle) that was attributed to fossil fuel burning (20). Rising atmospheric CO_2 levels had first been predicted by the 19th-century Swedish chemist and Nobel Laureate Svante Arrhenius (21), who used a simple model to calculate a global temperature rise of several degrees for a doubling of CO_2 (which he expected would occur over the next millennium). The Mauna Loa measurements, and subsequent observations from a global network of stations, were significant in providing direct evidence for a human impact on global-scale atmospheric chemistry. The observed atmospheric CO_2 increase, combined with information on total anthropogenic CO_2 emissions, also yielded important insights into the size of global terrestrial and oceanic CO_2 sinks (22), which proved to be significantly larger than expected by Revelle and others.

Another critical scientific advance occurred in the mid-1970s, when Mario Molina and F. Sherwood Rowland (23) first demonstrated that chlorofluorocarbons (CFCs) would break down under UV exposure in the stratosphere, releasing free radicals that catalyzed ozone destruction. The pair would go on to share the 1995 Nobel Prize in Chemistry with Paul Crutzen (24), who discovered that nitrogen oxides had a similarly destructive effect on ozone. Molina and Rowland's landmark study was published in *Nature* in 1974, but it would be nearly a decade before concrete evidence emerged of CFC-related ozone destruction on a globally significant scale. In 1985, a team led by British scientist Joseph Farman (25) used novel satellite measurements to demonstrate the presence of a large seasonal thinning of the ozone layer over Antarctica. These observations were not unprecedented—earlier land-based measurements from Dobson spectrometers deployed by the British Antarctic Survey had shown a similar trend of decreasing ozone levels (26). However, the satellite data provided a new type of compelling visual imagery that captivated public attention. The ozone hole, visible from outer space, appeared as a gaping wound in Earth's protective shield, increasing the amount of cancer-causing UVB radiation (280- to 320-nm wavelength) reaching the planet's surface. The fundamental science mattered, but so too did the visually arresting way in which it had been presented to the public.

The story of CFCs was reminiscent of the battle over DDT two decades earlier. Like DDT, CFCs were seen as miracle compounds, supposedly inert and harmless molecules with many useful industrial applications. These compounds (invented by Thomas Midgley, the father of leaded gasoline) had made home refrigerators and air conditioning safe and reliable, enabled the production of foam products for cushions, food packaging, and insulation, and increased the efficiency of aerosol spray cans (including those delivering DDT). However, careful science revealed unexpected chemical reactivity of these molecules under the high UV conditions of the stratosphere, while satellite observations yielded compelling visual evidence of their impact on Earth's atmosphere. Compelling as it was, however, good science was almost not enough. Despite early progress in the late 1970s to restrict CFC production, US President Ronald Reagan was slow to take bolder action. Lawmakers were likely influenced by significant industry lobbying efforts, most notably from the chemical giant DuPont, the world's largest manufacturer of CFCs. In the face of significant opposition, and criticism over scientific uncertainty, Molina and Roland became leading public voices in the global effort to ban CFCs. They gave public lectures and interviews, and pushed for legislation and political action. In the end, their efforts paid off, in 1987, with the signing of the Montreal Protocol. The protocol, ratified by every single nation on Earth, charted a path to phase out the production and consumption of ozone-depleting substances. To this day, it is widely seen as a monumental success of international cooperation, and global policy motivated by robust science.

For all of its success, the Montreal Protocol almost did not come to pass. The CFC problem was seen as an issue to be dealt with by the rich nations of the world, and negotiations were difficult and protracted. Developing countries had contributed very little to the accumulation of atmospheric CFCs, and had legitimate needs to expand their use of these compounds for much-needed refrigeration. To address this divide, the authors of the Montreal Protocol adopted a novel principle of "common but differentiated responsibilities," which recognized the unequal burdens of responsibility between industrialized and developing countries; wealthy industrialized nations would immediately begin reducing CFC use to 50%, while developing countries could increase their use by 15%. Critically, all signatories agreed to base their actions on science and to enforce the targets through trade sanctions (27).

The same year that the Montreal Protocol was signed, the World Commission on Environment and Development released a major environmental report, entitled "Our Common Future," also known as the Brundtland Report (28) after the group's chair, Norwegian Prime Minister Gro Harlem Brundtland. The report represented a major global effort to address the pollution versus poverty argument, and defined a new concept of "sustainable development." The Brundtland Commission followed in the wake of the 1972 Stockholm "Declaration of the United Nations Conference on the Human Environment" (the "Stockholm Declaration"), which had acknowledged the power of "man" to "transform his environment in countless ways and on an unprecedented scale," and had asserted an explicit human right to a healthy environment. Despite its aspirational language, the Stockholm Declaration had a limited impact; the meeting was boycotted by many of the world's developing nations who felt that the problems being discussed were largely attributable to the actions of wealthy industrialized countries. In contrast, the Brundtland Report took a more holistic view, recognizing unequal responsibilities and burdens across different countries and generations. Its definition of sustainable development changed the nature of global environmental regulation, and emphasized, for the first time, the importance of indigenous peoples and knowledge systems.

Other important developments occurred during the closing years of the 1980s. In 1988, the Intergovernmental Panel on Climate Change (IPCC) was established as a definitive international advisory body on the state of Earth's evolving climate. Over the next three decades, this group would come to exert a profound influence over the global discourse on climate change, representing a strong consensus among scientists around the world, and creating a platform for science on the international stage (the group was awarded a Nobel Peace Prize in 2007). By 1989, the United Nations (UN) General Assembly voted to hold a major Earth Summit in June 1992. That same year, the Berlin Wall fell, initiating a rapid end to the Cold War, and a global geopolitical shift. Many hoped for a "peace dividend" that would redirect massive resources from military expenditures toward environmental protection. With the formation of the IPCC, the release of the Brundtland Report, and signing of the Montreal Protocol just a year earlier, it seemed that environmental issues had finally broken through to the highest level of international diplomacy. In addition, the global media was paying attention. By the end of 1988, *Time* magazine featured "Endangered Earth" on its cover as Person of the Year. Earth was sexy.

As a new decade dawned, Earth Day 1990 went truly global, mobilizing over 200 million people in more than 100 countries around the world. Two years later, the movement for global environmental stewardship culminated at the 1992 Rio Earth Summit. By all accounts, the meeting was a major success, resulting in a suite of new treaties aimed at protecting the environment, while simultaneously addressing poverty and development issues in the Global South. The Rio commitments to preserve biodiversity and mitigate climate change were subject to legally binding treaties (the Biodiversity Convention, and the UN Framework Convention on Climate Change [UNFCCC]). Some treaties, including the Biodiversity convention (ratified by all UN member nations except the United States), formally recognized the long historical relationships of indigenous peoples to their lands, and the wealth of traditional ecological knowledge. However, for all of the success and publicity of the Rio Earth Summit, the resulting treaties, although legally binding, lacked concrete enforcement mechanisms (unlike the Montreal Protocol). Ultimately, this would prove to be a critical limitation. Over the next two decades, the promise of Rio never fully materialized, as the world's aspirations for sustainable development became challenged by powerful global forces.

Two Steps Back

The early signs of trouble came swiftly. A few weeks after the Rio Earth Summit, a select group of world leaders met again under very different circumstances. At the 1992 G7 Summit in Munich, leaders of the most powerful industrialized nations convened to discuss multilateral trade negotiations and economic growth. The resulting G7 communiqué referenced the Earth Summit, but the Rio commitments to the developing world were largely ignored. Rather, the focus of G7 discussions was on the development of the World Trade Organization (WTO) as a replacement to the 1948 General Agreement on Tariffs and Trade. The WTO came into being in 1995, rapidly ushering in a new world economic regime. Within a short time frame, the organization greatly expanded the scope of international trade, helping to support economic growth in many of the world's developing nations. At the same time, the WTO shifted the framework to increased corporate rights in trade agreements, with significant environmental impacts. The North American Free Trade Agreement (NAFTA), which was established during this period, provides a case in point. On one hand, it supported economic development in Mexico, helping to lift many people out of poverty; on the other hand, the agreement greatly strengthened corporate leverage over trade between Canada, the United States, and Mexico, impacting the rights of national governments for environmental protection and other social benefits. Under NAFTA chapter 11, foreign corporations could seek damages against governments that introduced laws, policies, or regulations (environmental or otherwise) that reduced the profitability of their investments (29). The potential for chapter 11 claims, sometimes in the billions of dollars, put a chill on governments considering environmental protection policies that might threaten corporate profits.

Another significant factor in stalling environmental progress was the influence of industry-funded lobby groups who promoted pseudoscience, and exploited legitimate scientific uncertainty to delay or block environmental protection policies (30). By the mid-1990s, when the IPCC had already issued its first two (of now six) Assessment Reports, with increasingly strong warnings of anthropogenic climate impacts, multinational oil and gas companies were spending hundreds of millions of dollars supporting think tanks with beguiling names, such as the Global Climate Coalition, to argue for personal, short-term interests over science. In many cases, these efforts involved the same groups (and perhaps people) who had previously challenged the science of Rachel Carson, Clair Patterson, and others. The industry consultants were well-seasoned, well-funded, and extremely effective. They were also supported by a few powerful voices from within the scientific establishment, including Frederick Seitz, a retired physicist and former president of the US National Academy of Sciences. Through his activities at the George C. Marshall Institute, Seitz wrote influential reports questioning not only anthropogenic climate change (31), but also the importance of CFCs in ozone depletion and the dangers of secondhand tobacco smoke. At the same time, other expert voices, including James Hansen and Susan Solomon, emerged from the scientific community to present clear evidence for human impacts on global climate and atmospheric chemistry. Hansen became one of the public faces for scientific advocacy on climate change mitigation, combining impeccable scientific credentials with clear and accessible communication (in media interviews and congressional testimony) to raise broad public awareness about the dangers of continued greenhouse gas emissions. These individual efforts were supported by collective statements from the international scientific community warning of impending environmental threats (32).

Unfortunately, the message of scientists was increasingly being drowned in a crowded media landscape. By the mid-1990s, weekly science columns were becoming increasingly rare among major US newspapers, and many science stories were being presented with a focus on health and technology (33). Moreover, in an attempt to maintain objectivity and balanced coverage, reporting increasingly covered "all sides" of a story, giving equal weight, for example, to both climate scientists and skeptics, even when the weight of evidence was balanced overwhelmingly on the side of science (34). In addition, the scientists, themselves, felt bound by restraint and a desire to avoid "oversensationalizing" or, worse still, crossing the line into advocacy. The result was a growing public disengagement with climate science and other environmental issues. This disconnect was exacerbated by shifting geopolitical concerns, which began to dominate headlines around the world, from the rise of global terrorism and renewed threats of nuclear confrontation, to catastrophic refugee crises and the emergence of China as a new economic and political superpower.

The shifting economic, political, and media landscape would soon take a significant toll on efforts to address climate change. The most public casualty was the 1997 Kyoto Protocol, which was signed 5 y after the establishment of the UNFCCC, as a first step toward regulating global emissions of greenhouse gases. Using the principle of "common but differentiated responsibilities" that had been successfully used in the Montreal Protocol a decade earlier, the Kyoto Accord set different emissions reductions targets for developed and developing countries, although, importantly, it did not articulate a specific time frame to close the allowable emissions gap. Kyoto also employed "flexibility mechanisms," including international emissions trading that were inspired by the economic innovations of the early 1970s. On the face of it, the Kyoto Accord should have been a success story. However, the agreement soon fell victim to the circumstances of its time; within a few years, US President George W. Bush announced that his country would not ratify its Kyoto commitments, and other countries soon followed. This signaled the end of a decade of promise and progress initiated by the Brundtland Report and Montreal Protocol. A lot had changed in the short time since George W. Bush's father, President George H. W. Bush, had led the American delegation at the Rio Earth Summit.

Impatient Earth

Fast forward about 25 y to the year 2020. As we have failed to achieve the aspirations of Rio and Kyoto, evidence for profound anthropogenic shifts in the Earth system has become increasingly clear. Large scientific advances in many fields, from computer modeling and remote sensing to geochemistry and genomics have ushered in a new era of Earth observation and insight. We now have the ability to observe and model the coupled terrestrial–ocean–atmosphere system with unprecedented resolution, while also unraveling the molecular diversity of microbial communities from mountaintops to deep ocean trenches. These tools have provided new ways of witnessing the rapid planetary-scale changes unfolding across different components of the Earth system, and predicting possible future scenarios. As humanity has been locked into a "business-as-usual" world, things are anything but usual for planet Earth.

Over the three decades between 1990 and 2020, global fossil fuel consumption has grown by ∼30% (35), and atmospheric CO_2 concentrations have increased [from 350 to 410 ppm (36)], more than they did over the entire period between 1700 and 1950. At the same time, global average temperature has increased by more than 0.5 °C since 1990, with significantly more warming (in excess of 2 °C) over some polar regions (37). These perturbations have reverberated throughout the Earth system, and will continue to do so well into the foreseeable future.

The warming atmosphere has influenced global wind and precipitation patterns, and increased the intensity of extreme weather (38). Catastrophic fires across Australia, driven by a decade-long drought, are just one visible recent expression of this change. Atmospheric chemistry also continues to be impacted by human activities; despite significant reductions in atmospheric CFCs and Pb concentrations, there has been a sharp rise in airborne particulate matter in some regions (39), most notably in the developing world.

In the oceans, rising CO_2 concentrations have led to noticeable acidification, with surface H^+ concentrations in the waters at Station ALOHA near Hawaii decreasing by more than 10% over the past 30 y (40). At the same time, warming surface waters may have already begun altering ocean circulation patterns (41), influencing the distribution of nutrients and oxygen, and the uptake of atmospheric heat and CO_2. Meanwhile, melting land-based ice sheets and glaciers have contributed to a 10-cm rise in global sea level since 1990 (42), while the annual minimum extent of Arctic sea ice has decreased by about 20% (∼2 million square kilometers) since 1970 (37). Warming and acidified oceans have led to coral bleaching (43), enhanced dissolution of planktonic and coralline calcium carbon skeletons (44), and contraction of cold-water habitats (45). Direct human pressures on marine food resources have also become increasingly evident. In 1996, the global fisheries catch began to decline for the first time since the Second World War, despite increasing fishing effort (46). Smaller forage fish, such as sardines and anchovies, now make up a larger proportion of total catches, as large predatory fish, including swordfish and tuna, become increasingly scarce in the high seas (47).

Big changes have also occurred across Earth's terrestrial systems. Since 1970, as the global human population has doubled, deforestation has increased by 3 million square kilometers (48), an area roughly comparable to the size of India. This recent clearing has mostly occurred in tropical regions, with nearly 20% of Amazonian forests lost over the past half century, and half of world's tropical forests lost globally (48). Much of this deforestation is attributable to the conversion of lands for agriculture, driven by global commodity markets supplying beef, soy, palm oil, and sugar to wealthy countries. At the same time, increasingly hot, dry summers and mild winters have made forests more susceptible to fires and insect outbreaks (49), converting some boreal forests from net sinks to net sources of greenhouse gases (50).

"Green Revolution" technologies of the postwar years have intensified the use of existing agricultural soils. The development of high-yielding plant varieties, coupled with increased use (and overuse) of fertilizers and irrigation, has resulted in a per capita cereal production increase of 30% over the last 50 y (51), helping to avoid some of the dire consequences predicted by *The Population Bomb*. By 2013, the world was producing an average of 2,884 daily kcal per person, which is more than sufficient to meet the basic requirements of every person. However, these calories are not equally distributed across the globe, with hundreds of millions of people undernourished and suffering nutrient deficiencies (51). At the same time, wealthy nations are currently experiencing an obesity epidemic, resulting from a range complex social and economic factors driving unhealthy lifestyles and diets (52). Today, just three plant species—rice, maize, and wheat—contribute nearly 60% of the world's plant-based food supply. This is symptomatic of a large-scale global decline in agrobiodiversity, with more than 90% of crop genetic diversity lost to agriculture over the 20th century (51).

Land use changes over the past half century have significantly impacted ecosystems, biogeochemical cycles, biodiversity, and climate. The global area equipped for irrigation has doubled since the 1960s, and agriculture now represents 70% of fresh water withdrawals around the world (51). Over this same period, global fertilizer use quadrupled (51), leading to increased nutrient runoff into inland waters and coastal seas, driving coastal eutrophication and exacerbating the ongoing problem of ocean deoxygenation (53). At the same time, the clearing of forests and grasslands accounted for nearly a quarter of anthropogenic greenhouse gas emissions between 2007 and 2016 (54), while also contributing to a global biodiversity crisis (55). Present day species extinction rates are estimated to be 1,000 to 10,000 times higher than natural (pre-Anthropocene) levels (56), and about 60% of wild vertebrate populations appear to be in decline (57). In North America, the total number of birds has dropped by about 30% since 1970, a reduction of about 3 billion individuals (58). A recent UN report concluded that up to 1 million species globally are now at risk for extinction (59).

The humanity activities that deplete Earth's nonrenewable resources have also led to the accumulation of vast quantities of long-lived synthetic wastes. Since 1970, global production of plastics (derived from fossil fuels) has increased more than 10-fold, to nearly half a billion metric tons per year (60). In just the last 13 y, we have doubled the total quantity of plastic ever made. This production far outstrips our ability to recycle and recover wastes, leading to the accumulation of plastic across the entire Earth system, from mountain glaciers and remote oceanic waters to the tissues of organisms across the entire food web. Plastics also leach dissolved chemicals, such as phthalates, that act as endocrine disruptors in a variety of organisms, including humans (61). Our trash pile extends well beyond the planet's surface, with an ever-increasing amount of space junk circling high above us. At present, there are well over 10,000 pieces of space debris larger than 10 centimeters in Earth's orbit, and many millions of smaller fragments and particles (62), posing a significant potential threat to satellite-based technologies that support our increasingly digital lives. The accumulation of these wastes, on land, in water and in the sky, is the most visible manifestation of the human impact on planet Earth; it is, perhaps, the defining geological signature of the Anthropocene.

Silver Linings

The news is not good, but we can find at least some solace in the scientific advances of the past half century. As our Earth-observing capabilities improve, so do our abilities to make future projections, enabling us to act with greater foresight. Better climate models provide resources to support long-range planning, while improved forecasting has led to more effective early warning systems (63) for extreme weather, and improved tracking of storm trajectories. This will help diminish the loss of human life associated with these extreme events, even as their frequency and intensity increases on a warming planet. Longer-range seasonal forecasting, once seen as the stuff of science fiction, is now becoming a reality, facilitating better planning and resilience against future droughts, crop failures, and other new realities of our changing climate (64).

Human societies have begun to adapt and innovate (although too slowly), seeking approaches to mitigate the worst possible environmental and social outcomes. Economic incentives have stimulated research and investments that have reduced the costs of renewable energy, contributing to a rapid global growth of low carbon energy production. Over the past 5 y, global annual investment in renewable energy, including solar and wind power, has topped $300 billion (about 0.5% of global gross domestic product), while new energy installations have become increasingly dominated by renewables and lower carbon natural gas sources (65). New regulatory approaches, sometimes developed at local levels, have also come into play, and some major corporations have taken a global leadership role in addressing climate change and other environmental threats, through the development of innovative technologies and more sustainable commodity supply chains. Carbon markets and pricing have emerged as an important mechanism to limit CO_2 emissions, building on the pioneering environmental economics of the 1970s. However, these measures, we now know, may not be sufficient to limit the accumulation of atmospheric CO_2 below a threshold that could lead to serious negative climate impacts. Even if the world sticks to the most recent targets of the 2016 Paris Agreement (which appears unlikely), it is still uncertain that global temperature rise can be limited to less than 2 °C. This has stimulated research and public debate on geoengineering approaches, including carbon capture from the atmosphere and solar engineering through enhanced aerosol-based reflectance of incoming radiation (66). There are still critical unresolved scientific questions around these approaches, such as the impacts of artificial aerosols on atmospheric chemistry (interactions with ozone, for example), or the potential to alter regional precipitation patterns through aerosol effects on cloud nucleation. There are also many societal implications that must be addressed through a range of voices and perspectives, including ethics, global geopolitics, and economics.

Other technological innovations are underway, including electric vehicles, smart irrigation systems, and biodegradable alternatives to plastics, to name a few. However, the global uptake of these innovations remains limited. New approaches are also being developed to better manage forests and agricultural lands, while promoting biological conservation and habitat protection through economic incentives that support sustainable development. Increasingly, solutions to many environmental problems have drawn on local and indigenous knowledge (67), inspired by Winona LaDuke and others to develop regionally adapted approaches that respect traditional relationships with the land. These developments, combined with changing diets in wealthy countries (a shift toward eating lower on the food chain), would also significantly reduce greenhouse gas emissions.

Over the past few decades since the Brundlandt Report, there has been an increased focused on balancing environmental protection with sustainable development. In this respect, the UN Sustainable Development Goals (SDGs) provide a rallying cry to unite the nations of the world in addressing intertwined social and environmental problems, taking inspiration from activists like Wangari Maathai, a Nobel Peace Prize Laureate and founder of the Green Belt Movement for sustainable development in East Africa. The SDGs recognize, first, that poverty, inequality, and injustice can be drivers of environmental degradation, and, second, that the human impacts of this degradation fall disproportionately on the poorest citizens of the world. We have also come to more fully recognize the historical legacies, including colonialism, which have shaped the uneven distribution of resources around the world. These are important threads running through any meaningful attempts to address global environmental problems. Perhaps a new global consciousness is emerging, harking back to that first 1968 Earthrise image.

The Road Ahead

Looking back over the past half century, we have come to better understand the limits and resiliency of Earth's biophysical systems, and the evolving human societies that are a primary agent of planetary change. With increasingly dire and urgent messages, we may be, once again, at a pivotal moment for action. Just as young people led the charge in 1970 (school strikes were part of the first Earth Day activities), they are also doing so today. The global climate youth movement, inspired by Swedish teen activist Greta Thunberg, has been a strong rallying cry. However, that is not enough; the adults must also come to the table. Now is the time to deploy the tools we have developed over the past 50 y—new technologies, and legal, political, and economic levers to drive the needed change toward more sustainable societies.

Just as science played a critical role in the lead-up to the first Earth Day, scientists must still be front and center. We must continue to develop and implement new tools for understanding our rapidly evolving planet, and for monitoring the impacts of any proposed environmental mitigation. However, we will do so in a very different context than the one that existed in 1970. For one thing, science now competes for public attention with a flood of news and (mis)information constantly pouring out from a myriad of digital devices. In addition, we must also contend with strong oppositional forces and economic interests who continue to deny science in favor of corporate profits. In the face of these strong headwinds, science and scientists must continue to conduct careful, rigorous, and objective work. However, following on the example of Rachel Carson, Clair Patterson, and others, we must also engage with broad public audiences and civil society through compelling and clear narratives. In this respect, a new generation of top scientists, including Kate Marvel and Katherine Hayhoe, are leading the way in bringing scientific complexity and nuance into the public domain through accessible and widely distributed formats. Importantly, the value of this scientific engagement must be explicitly recognized within the context of academic promotion and merit considerations. We must, once and for all, move beyond the "Sagan effect" (68), named for the astrophysicist Carl Sagan whose celebrity status as a popular science writer and television personality was viewed by some in the scientific community as evidence of substandard scientific achievement. [Despite publishing hundreds of peer-reviewed articles, including a number of landmark studies (69, 70), Sagan was denied tenure at Harvard and never inducted into the US National Academy of Sciences.]

The accessibility of science not only requires new models for open source data archiving and publication, but also innovative approaches to translate the outputs of science into relevant products that inform public debate. Increasingly, this requires science to embrace interdisciplinary approaches across domains, including social sciences and humanities. At the same time, science must engage with other worldviews, including indigenous perspectives of Mother Earth, which can help us reimagine ways of living within, as opposed to outside or above, nature. In addition, by embracing the disruptive power of the creative and performing arts, science can reach new audiences, engaging both rationally and emotionally to move beyond paralyzing anxiety, bringing new perspectives to long-standing questions.

The lessons of the past 50 y loom large as we reflect on the daunting environmental challenges we face today. History has provided many examples of our own failures as stewards of planet Earth, but there have also been some remarkable successes. Where there is will and motivation, there is no doubt that we can take bold and concrete actions to tackle grand societal challenges, informed by robust science. As Greta Thunberg said in a 2019 address to the US Congress, "You must unite behind the science. You must take action. You must do the impossible. Because giving up can never ever be an option." As scientists, we must each recognize our own opportunities and responsibilities to help lead the way toward transformative societal change.

Data Availability. All of the results discussed in this article are derived from previous studies, and the reader is referred to the literature and web pages cited in the text for primary data sources. As a companion to this Perspectives article, a number of Earth system data from the past 50 y have been compiled at https://purl.stanford.edu/mg458wc3389 for use in an Earth Symphony project, a musical representation of Earth system evolution since 1970. For an example of atmospheric CO$_2$ and sea level data converted into musical tones, see https://www.openbookpublishers.com/esources/9781783748457/co2-seaLevel.mp3.

Acknowledgments

I wish to thank all the authors who contributed chapters to Earth 2020: An Insider's Guide to a Rapidly Changing Planet. Their insights have helped shape the narrative presented here. Dianne Newman (Caltech), Matthew Long (US National Center for Atmospheric Research), John Harte (UC Berkeley), Rob Socolow (Princeton University), David Archer (University of Chicago), Paul Ehrlich (Stanford University), U. Rashid Sumaila, Hannah Wittman, Mark Jellinek, Maria Maldonado and Kate Schuler (University of British Columbia), and one anonymous reviewer provided helpful comments on the manuscript.

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