Biosphere: How Life Alters Climate

People had long speculated that the climate might be altered where forests were cut down, marshes drained or land irrigated. Scientists were skeptical. During the first half of the 20th century, they studied climate as a system of mechanical physics and mineral chemistry, churning along heedless of the planet's thin film of living organisms. Then around 1960, evidence of a rise in carbon dioxide showed that at least one species, humanity, could indeed alter global climate. As scientists looked more deeply into how carbon moved in and out of the atmosphere, they discovered many ways that other organisms could exert powerful influences. Forests in particular were obviously involved in the carbon cycle, and from the 1970s onward, scientists argued over just what deforestation might mean for climate. By the 1980s, it was certain that all the planet's ecosystems from the oceans to arctic tundra were major players in climate change by emitting greenhouse gases, by removing them from the atmosphere, and in other ways. Attention turned to how global warming itself might provoke vicious feedback cycles of increased biological emissions and slower removal. (For emissions from agriculture and animal husbandry—the dominant ecosystems in many regions—see the essay on Other Greenhouse Gases.)

"In our century the biosphere has acquired an entirely new meaning; it is being revealed as a planetary phenomenon of cosmic character." — *W.I. Vernadsky*[1]

There was a rain squall every afternoon when Christopher Columbus anchored at Jamaica in 1494. He remarked that the island's lush carpeting of forests caused these rains, for "he knew from experience that formerly this also occurred in the Canary, Madeira, and Azores islands, but since the removal of forests that once covered those islands, they do not have so much mist and rain as before."[2] Columbus was claiming to see an impact of living creatures on climate—in two senses. In the first place, humans are living creatures, so anything we do is an effect of life. More directly, Columbus thought the climate change was a result of alterations in the forms of life covering the islands, from forest to grassland. Of course a change in climate itself might bring such ecosystem alterations. But nothing altered a region so quickly and dramatically as human civilization.

[1] Vernadsky (1945), p. 4.

[2] Colón (1960), p. 147.

Since the ancient Greeks, scholarly theories and folk beliefs had speculated that chopping down a forest, irrigating a desert, draining marshlands or grazing a prairie to bare dirt might change the temperature and rainfall in the immediate vicinity. Americans in the 19th century argued that settlement of the country had brought a less savage climate. Sodbusters who moved into the Great Plains boasted that “rain follows the plough.” Some European scientists, however, agreed with Columbus that deforestation made for a dryer, not wetter, climate.[1]

By the end of the 19th century, meteorologists had accumulated enough reliable weather records to test whether rain did follow the plough, or perhaps fled from the axe. Both ideas failed the test. Even the transformation of the entire ecosystem of Eastern North America from forest to farmland had apparently made little difference to climate. If the spectacular changes wrought by humankind could not alter a region’s climate, there seemed little reason to consider the impact of other species. Through the first half of the 20th century, scientists who studied climate treated ecosystems as passive. Deserts and forests expanded or shrank in helpless response to climate changes. The cause of these climate changes might be upheavals of mountain ranges, or variations of the Sun’s radiation, or other forces surely far mightier than the meter or so of organic matter that covered some patches of the planet’s surface.

A few scientists thought otherwise. The deepest thinker was the Russian geochemist Vladimir I. Vernadsky. During his work mobilizing industry during the First World War, he recognized that the volume of materials produced by human industry was approaching geological proportions. Analyzing biochemical processes, he concluded that the oxygen, nitrogen, and carbon dioxide gas (CO_2) that make up the Earth’s atmosphere are put there largely by living creatures. More, he insisted that biological processes influenced the chemistry of practically every element in the Earth’s crust. In the 1920s, he published works that described how carbon cycled through living matter. He argued that living organisms were a force for reshaping the planet, comparable to any physical force. Beyond this he saw a new and still greater force coming into play—intelligence. A few scientists began to study how living creatures affected the chemistry of the Earth’s surface, notably in a “Biogeochemical Laboratory” set up in the Soviet Union in 1929. Vernadsky’s visionary pronouncements about humanity as a geological force were not widely read, however. They struck most readers as mere romantic ramblings.[2]

Carbon Dioxide and the Biosphere (1938 - 1950s)

The first barely credible champion of an influence of life on climate was the British engineer G.S. Callendar, who from 1938 on published arguments that human emissions of CO_2 were

[1] Fleming (1990); Fleming (1998), ch.s 2-4; Stehr and von Storch (2000), introduction and chapter 4; the latter is a translation of Brückner (1890b), chapter 1.

[2] Vernadsky’s *Geochemistry* was published in France in 1924 (and in Russia in 1927) and his *Biosphere* in 1929, see Vernadsky (1924), Vernadsky (1929), Vernadsky (1945); Bailes (1990). At least one earlier review of geochemistry, Clarke (1920), ch. 2, included plants along with mineral chemistry as possibly important sources of some gases.

already producing a global warming. A few scientists found this interesting enough to take a closer look at how the gas, and indeed all forms of carbon, moved in and out of the atmosphere. It had long been understood that the bulk of the planet's carbon was locked up in lifeless chemicals. Since the 19th century a few scientists had studied the age-long cycles as the gas was puffed out by volcanoes, absorbed into minerals or the oceans, and deposited in carbonate rocks. It hardly seemed worth mentioning that much of this rock—millions of cubic kilometers of chalk, limestone, and coal—had once been part of living creatures. But now scientists were asking about carbon on the move, over a span of mere centuries. For this they had to look at biology.

Nothing much was known in the 1950s about the slow movements of carbon in and out of the planet's biomass. Measurements of radioactive carbon-14 brought a new source of data that stimulated studies, but for more than a decade the data were too uncertain to tell anything useful. The few people who took up the carbon question had only vague estimates to work with, but that did not stop them from reaching conclusions. They could calculate, in particular, that the amount of carbon bound up in forests, peat bogs, and other products of terrestrial life is several times greater than the amount in the atmosphere (the lowly soils alone store two or three times more CO_2 than the air holds). Since these ecosystems had been fairly stable over geological time, the stock of carbon bound up in organic substances must have remained in rough balance with the atmosphere over millions of years.

The likely cause of stability was a fact demonstrated by experiments in greenhouses and in the field—carbon is an essential nutrient for plants, and they often grow more lushly in air that is "fertilized" with extra CO_2. Thus if gas were added to the atmosphere, plants should rapidly take it up, turning it into wood and soil. Turning the argument backward, in 1954 the biochemist G.E. Hutchinson figured that if atmospheric CO_2 had in fact increased as Callendar claimed, that was probably due to emission from soils that were decaying following the clearing of forests. This was the first time anyone had noticed that deforestation—men with axes—might alter the atmosphere's CO_2. Hutchinson did not see it as a problem. It was a one-time step, for once humanity finished converting the world's forests to farmland, biomass uptake would soon restore a "self-regulating" equilibrium.[1]

However plausible planetary self-regulation might seem, scientists still wanted to check it rigorously. That meant making a numerical model of the carbon system. They drew diagrams with boxes—one box to represent the reservoir of carbon in the atmosphere, other boxes for the oceanic and biological reservoirs—and between the boxes they drew arrows to show the exchanges of carbon. Applying a few equations and plugging in measurements of radioactive carbon isotopes and other data, they made rough estimates about how carbon moved about. (This box-and-arrow scheme has become so common for visualizing the geophysical circulation of

[1] Hutchinson (1954), 389-90; see also Hutchinson (1948). On fertilization in actual greenhouses (a practice that increased "dramatically" from the 1970s) see Megha Poudel and Bruce Dunn, "Greenhouse Carbon Dioxide Supplementation," Oklahoma State University Extension (Sept. 2023), online at https://extension.okstate.edu/fact-sheets/greenhouse-carbon-dioxide-supplementation.html.

chemicals that it seems natural and inevitable, but in fact it became familiar only in the late 1950s.)[1]

Historians usually treat techniques as a stodgy foundation, unseen beneath the more exciting story of scientific ideas. Yet techniques are often crucial, and controversial. A case especially important for biological studies is explored in a short essay on Uses of Radiocarbon Dating.

One of the first attempts to integrate the available data was a model devised by Harmon Craig, an enthusiastic young scientist who was in touch, by visit and letter, with the leading oceanographer Roger Revelle and others who were doing parallel work. Craig's model boxes split the world-ocean into two layers, the surface waters and the deeps. An arrow showed carbon carried in water physically moving between the levels. Another box and arrow showed the chemical exchanges of CO_2 between the surface water and the atmosphere.[2] Meanwhile in Stockholm, two meteorologists devised a model with a single box for the oceans but including separate boxes for the reservoirs of carbon in living plants and in dead organic matter such as forest litter.[3] In the following years several additional models were published, as people added and adjusted boxes—more ocean layers, perhaps, or separate boxes for ocean plankton and terrestrial vegetation—each with its own estimates for the uptake and release of carbon.[4]

The first primitive models suggested that the systems should behave in the manner long assumed. Seawater and especially plants would absorb or emit just enough CO_2 to stabilize the concentration of the gas in the atmosphere. But in fact the diagrams and equations were so oversimplified that they only showed that it was *possible* for the system to be self-regulating. On the other hand, a widely noted model of biosphere absorption, constructed by Erik Eriksson, oscillated all by itself under certain conditions.[5] This was characteristic of many models built from a few simple equations, "as if their self-regulating properties were defective in some way" (as a leading meteorologist put it).[6] Scientists expected that adding more realistic complexity would add to stability. There might be short-term oscillations, but over the long run, surely any extra carbon would be stored away in biomass. Eriksson insisted that "the atmospheric concentration is but little affected" by human input.[7]

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[1] A pioneer carbon cycle diagram, remarking that "a quantitative statement is rarely attempted," was Hutchinson (1948), pp. 222-23; the idea may have been drawn from "compartment" models of biological systems familiar in the 1940s to people who worked with radioactive tracers, see Atkins (1969).

[2] Craig (1957a).

[3] Eriksson and Welander (1956).

[4] Especially important was Oeschger et al. (1975), see p. 191 for applications, and see for references to other models.

[5] Eriksson and Welander (1956).

[6] Rossby (1959), p. 16.

[7] Eriksson and Welander (1956), quote p. 171; the model most used in the next couple of decades was Craig (1957a).

More complex models did not change these views. A modeler would draw up a system of carbon reservoir boxes and write down five or so equations to describe how they interacted. To get anywhere with this, the modeler had to make simplifying assumptions of dubious validity. But with the poor data at hand, there was little point in refinements, and none of the models was pursued far.[1] The biological boxes were by far the most poorly understood components. These early models tended to treat biomass almost like a free parameter that the modeler could adjust, within the very broad limits of what was known, to make the outcome fit the other data. Thus the conclusions about stability relied not just on objective calculations but also on what seemed plausible.

Can People Change Climate?

The scientists were under the sway of a firm belief that natural systems are self-regulating. Biologists and ordinary people alike had long assumed that communities of living creatures always managed somehow to adjust their growth to counter any dangerous departure from equilibrium—the indestructible "balance of nature." When it came to the atmosphere, most geological experts thought that even on a lifeless planet, the atmospheric balance would remain stable. It seemed reasonable that chemical cycles would long ago have settled down into some kind of equilibrium among air, rocks, and seawater. Compared with those titanic kilometer-thick masses of minerals, it hardly seemed necessary to consider the thin scum of bacteria and so forth. Experts continued to calculate how the levels of atmospheric gases, even oxygen, would be maintained by mineral processes that had nothing to do with living creatures. In particular they figured that the level of CO_2 in the atmosphere was locked down over the long run by geological forces—emission from volcanoes balanced by absorption in weathering rocks.

The planet's carbon cycle looked like just another example of the kind of stable system that scientists had studied during their training. Chemistry textbooks taught as an established principle (enunciated in 1888 by Henri Le Chatelier, a French industrial chemist) that a system in equilibrium responds to any stress in a way that tends to restore its equilibrium. Le Chatelier's Principle reliably regulated chemicals in laboratory flasks and in industrial plants. Why not in the Earth's atmosphere as a whole?

In the 1960s, these views were standard, and few scientists imagined that the planet's biology had much to do with its chemistry.[2] There were occasional doubts. A pioneering 1963 report on global warming, noting that human emissions of greenhouse gases were at a rate geologically

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[1] Models were reviewed by Keeling (1973); the only one that went so far as to use stepwise computer integration was Eriksson and Welander (1956).

[2] "Looking back, the papers published in the 1960s... are astonishing to read... The biochemist G.E. Hutchinson was almost alone when he wrote that methane, nitrous oxide, and other gases probably came from bacterial sources." Lovelock (1999), p. 204; for an estimate that most of the air's methane comes from bacteria in animal guts, see Hutchinson (1954), pp. 392-93; carbon dioxide balance: Berner et al. (1983).

unprecedented, warned: "It is not a cause for complacency that nature seems to have lots of checks... There may be processes... which will eventually be alarming." On the other hand, in 1966, when the U.S. National Academy of Sciences arranged a study of possible climate change, the panel mainly considered urban and industrial influences, that is, deliberate human excavation and emission of materials. The experts remarked that changes involving living creatures in the countryside, such as irrigation and deforestation, were "quite small and localized," and set that topic aside without study.[1]

Yet as the panel realized, the planetary environment was certainly affected by human activity. During the 1960s, evidence mounted that such human products as nuclear bombs and chemical pesticides could inflict global harm. The comfortable traditional belief in the automatic stability of biological systems was faltering. These feelings connected with concern for the entire atmosphere when C.D. Keeling published his data on changes in the level of CO_2. His measurements were so precise that from the outset, they showed a seasonal "breathing" of the planet: plants in the northern hemisphere took up carbon from the atmosphere in spring and summer, and returned it to the air when dead leaves and grass rotted away in autumn and winter. One could even use Keeling's data to estimate how many tons of carbon cycled through the plants each season.[2] It was evident that consumption was not keeping up with the quantities of the gas that humans were putting into the atmosphere, for each year the winter peak was ominously higher.

Keeling's curve was just one of many things that raised concern about global biological effects. In the early 1970s, public sensitivity redoubled following a series of climate disasters, especially a drought in the African Sahel. Photographs of starving children, huddled in a barren landscape of scrub, told a terrible story of expanding deserts and changing climates. Was the Sahara desert expanding southward as part of a natural climate cycle that would soon reverse itself, or was something more dangerous at work? For a century, African travelers and geographers had worried that overgrazing could cause changes in the land that would turn the Sahel into a "man-made desert." During periods of drought, missionaries and colonial officials blamed ignorant native practices for the harm (few remarked that if anything would make a permanent change, it would most likely be practices introduced under the colonial regimes). The Sahara was not so much encroaching, one scientist remarked in 1935, as taking advantage of "man's stupidity."[3]

In 1975, veteran climate modeler Jule Charney proposed that climate change was acting as man's accomplice. Noting that satellite pictures showed a widespread destruction of vegetation in the Sahel from overgrazing, he pointed out that the barren clay reflected sunlight more than the grasses had. He figured this increase of albedo (surface reflectivity) would make the surface

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[1] Conservation Foundation, 1963, p. 5; National Academy of Sciences (1966), p. 11.

[2] Keeling (1960); tonnage: e.g., Bolin and Keeling (1963).

[3] Pearce (2002); Stebbing (1935), "seized the opportunity of man's stupidity," Arthur Hill, p. 523.

cooler, and that could change the pattern of winds so as to bring less rain. Then more plants would die, and a self-sustaining feedback would push on to full desertification.[1]

Charney was indulging in speculation, for computer models of the time were too crude to show what a regional change of albedo would actually do to the winds. It would be a few more years before models and observations demonstrated what had long been suspected—surface vegetation is an important factor in the climate. For example, the Amazon rainforest generates much of its own rainfall through evaporation. It would take a still later generation of models to show that Charney's specific mechanism was valid to a degree. It was an influence, but not the only one, in a complex set of interactions involving other factors such as variations in the surface temperature of the Atlantic and Indian Oceans. (In the Sahel, the advance of the desert reversed for a while in the 1990s, showing that overgrazing did not by itself dominate changes. But the question of human influence remained open. Later studies showed that along with overgrazing, human emissions, not only greenhouse gases but especially industrial haze, had caused changes in regional weather patterns that contributed to the disaster.) Despite the confusing details, scientists grasped the truth of Charney's main lesson. Human activity could change vegetation enough to affect albedo, and a change in albedo could interact with other factors to change climate. More generally, the biosphere did not necessarily regulate the atmosphere smoothly through "negative" feedbacks that pulled the system back from any change. It could itself be a source of the kind of "positive" feedbacks that amplified changes. (For biological feedbacks, it was not good to be positive!)[2]

Where Does the Carbon Go? (1971-1980s)

The science of biology was in no condition to answer the questions that climate scientists were starting to bring. A scientist's funding and advancement depended on the publication of conclusive studies that could be completed in a few years. To meet that demand, most biologists concentrated their research projects on one or another particular species if not a single molecule. Even the pioneering scientists who had begun to consider larger systems rarely undertook field studies that lasted as long as five years. That was hardly enough to see how a biological community might respond to climate change. Nevertheless the study of living communities in all their complexity was gradually growing in scale and sophistication, under the newly popular

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[1] Charney (1975); see also Lamb (1977), pp. 14, 671.

[2] E.g., human-caused albedo variations from desertification, and to some extent tropical deforestation, were connected with past global climate changes by Sagan et al. (1979); a pioneering model confirming "the long-held idea that the surface vegetation... is an important factor in the Earth's climate" was Shukla and Mintz (1982); Amazon Basin: Salati and Vose (1984); more recently, see Kutzbach et al. (1996). "It is very likely that sea surface temperature change, natural vegetation [feedback] processes, and land use change have acted synergistically to produce the unusual [Sahel] drought," concluded Zeng (2003). In particular, warming of the Indian Ocean influenced monsoon rains, Giannini et al. (2003). Effects of haze (sulfate aerosols): Hegerl et al. (2007), p. 715.

banner of ecology. The field was attracting researchers who were curious about human impacts on the environment.

By the early 1970s, everyone had grown sensitive to a variety of ways that humans were affecting the planet as a whole. The public was becoming aware, in particular, that slash-and-burn farming was eating its way through entire tropical forests. People realized that only a small and diminishing remnant remained of the great ancient forests of North America, and the same fate threatened the rest of the planet's trees. Concern about the destruction of forests was on the rise, although the concern was for the sake of wildlife, not climate.

Meanwhile a few scientists pointed out that the world's forests were a significant player in global cycles of carbon and water. The conversion of forests to croplands since the early 19th century had made a big early contribution to the global rise of CO_2. (Decades later, scientists realized that deforestation also contributed to cooling—for one thing, snow on exposed soil reflects more winter sunlight than a forest does—so the net effect of deforestation may have helped keep the 19th century cool.) Moreover, as anyone who has walked sweating through a steamy jungle might understand, a forest evaporating moisture can be wetter than an ocean, in the way it affects the air overhead. The ancient ideas about climate change from deforestation looked plausible again. Only now it was not just local weather, but the entire global climate that could be affected. Just what kind of changes would further deforestation bring? As one scientist who pioneered study of the subject remarked, "it is difficult even to guess."[1]

There were a few things that could be measured with confidence. Statistics compiled by governments on the use of fossil fuels told how much CO_2 was going into the atmosphere from industrial production. And Keeling's measurements showed how much of that remained in the air, pushing the curve higher year by year. The two numbers were not equal. Roughly half of the gas from burning fossil fuels was missing. Where was the missing carbon going? There were only two likely suspects. It must wind up either in the oceans or in biomass.

In 1971, the geochemist Wallace Broecker and colleagues developed a model for the movements of carbon in the oceans. They calculated that something like 40% of the CO_2 that humanity was adding to the atmosphere dissolved into the surface layer of seawater, and they figured most of the rest would stay in the atmosphere. While admitting that knowledge of biological interactions was inadequate, they thought it likely that the "biosphere is not an important sink" for swallowing up CO_2.[2] However, more precise calculations indicated that the oceans were not taking up all of the missing CO_2. "It seems impossible that any oceanic model can fully explain" the missing carbon, Keeling wrote. The residue must somehow be taken up by the terrestrial

[1] For precipitation change, one early suggestion was Newell (1971), quote p. 459. Computer simulations "suggest that the relatively cool climate in the second half of the 19th century is largely attributable to cooling from deforestation" according to Bauer et al. (2003).

[2] Broecker et al. (1971), p. 292-93.

biosphere, that is, all organisms on land. Perhaps trees and other plants were growing more lushly, fertilized by the increase of atmospheric CO_2?[1]

It was hard to check whether fertilization was indeed at work. The pioneering carbon box models mostly concentrated on chemistry and did not attempt to calculate whether any organisms might grow more abundantly when CO_2 increased. Some carbon studies that centered on the oceans left out the terrestrial biota altogether. Plant biologists—a type of specialist that had scarcely interacted with climate scientists—had published few solid studies of carbon fertilization. (It was clear enough in greenhouses, but that said little about what would happen amid the complexities of a real forest.) The prevailing view had been established in the 1960s by Eugene Odum, the pioneering author of the dominant ecology textbook. In a mature ecosystem, Odum maintained, gains and losses of carbon precisely balanced one another. “Without much evidence to the contrary,” a reporter noted, “Odum’s paradigm held sway for several decades.” (It was not until the end of the 1990s that field studies showed that forests were indeed gaining mass, presumably thanks to fertilization by the increased CO_2 in the atmosphere, perhaps enhanced by warmer temperatures.)[2]

What was clear in 1973, as Keeling pointed out, was that even with good data on past and present conditions, any calculation of the future fertilizer effect would be unreliable. Every gardener knows that giving a plant more fertilizer will promote growth only up to a certain level (usually the level where a lack of some other nutrient kicks in). Nobody knew where that level was if you gave more CO_2 to the world’s various kinds of plants. “We are thus practically obliged to consider the rate of increase of biota as an unknown,” Keeling warned.[3] As a sign of the uncertainty, some rough calculations suggested that land plants might not currently be a sink for CO_2 at all. As Hutchinson had suggested back in 1954, deforestation and other human works would increase decay in soils, so the land biota could be a major net *source* of the gas.[4]

The uncertainties became painfully obvious in November 1976 at a “Workshop on Global Chemical Cycles and Their Alteration by Man” held in Dahlem, Germany. The respected meteorologist Bert Bolin broke with his earlier view that plants were not a major source of CO_2. He argued that deforestation of the tropics, plus the decay of plant matter in soils damaged by agriculture, was releasing a very large net amount of CO_2 into the atmosphere—somewhere around a quarter of the amount added by fossil fuels. Since the level in the atmosphere was not rising all that fast, it followed that the oceans must be taking up the gas much more effectively

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[1] Keeling (1973), p. 320; similarly, “a surprisingly large fraction of the fossil-fuel CO_2" went into the biosphere in a model of Machta (1973), p. 26.

[2] Odum (1969); “Odum’s paradigm:” Popkin (2015). McMahon et al. (2010).

[3] Keeling (1973), p. 279; Anderson and Malahoff (1977), see p. 22 for overview.

[4] Reiners (1973); Hutchinson (1954).

than anyone had thought. Bolin admitted that "This result is difficult to reconcile with present models of the role of the oceans."[1]

One problem was that the top hundred meters or so of seawater, mixed by storms and waves and warmed by sunlight, floats inertly over the immense volumes of colder water. Oceanographers understood that there are only a few regions where massive currents plunge downwards or bring water up from the abyss. As CO_2, dissolved into the thin surface layer, the stagnant seawater would become steadily more acidic and thus less able to hold additional carbon. To pull carbon from the air and sequester it for centuries, terrestrial vegetation seemed more promising.

George Woodwell, a botanist who had recently joined the Marine Biology Laboratory at Woods Hole to direct their Ecosystems Center, went still further with calculations he had begun independently of Bolin. Woodwell believed that deforestation and agriculture were putting into the air as much CO_2 as the total from burning fossil fuel, or maybe even twice as much. His message was that the attack on forests must be stopped, not just for the sake of preserving trees and wildlife but also to avoid disrupting the climate.[2]

Broecker and other geochemists thought Woodwell was making ridiculous extrapolations from scanty data. Defending their own calculations, the geochemists insisted that the oceans could not possibly be taking up so much carbon. "The subject dominated the Dahlem conference," Woodwell recalled dryly, "stimulating much discussion."[3] The arguments spilled over into general social questions of environmentalism and regulation. People's beliefs about the sources of CO_2 were becoming connected to their beliefs about what actions (if any) governments should take.[4]

Researchers tried to resolve the problem scientifically, attacking it from many directions. In meetings, workshops, and publications the experts met and wrangled, sometimes bitterly but always politely. As occasionally happens in scientific debates, opinions divided largely along disciplinary lines: oceanographers plus geochemists versus biologists. The physical scientists like Broecker pointed out that they could reliably calibrate their models of the oceans with data on how the waters took up radioactive materials (fallout from nuclear weapon tests was especially useful). Woodwell's biology was manifestly trickier. His opponents argued that nobody really knew what was happening in the immense expanses of the Amazon and Siberia. When he invoked field studies carried out in this or that patch of trees, his opponents brought up more ambiguous studies, or just said that studies of a few hectares here and there could scarcely be extrapolated to all the world's forests.

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[1] Stumm (1977); Bolin's new estimate was 10-35% from biota. Bolin (1977), p. 615; his earlier view of plants in equilibrium or a net sink is explained e.g. in Bolin (1970).

[2] Woodwell and Houghton (1977); also Woodwell et al. (1978); Woodwell (1978).

[3] Woodwell (1978), p. 40.

[4] A 1977 workshop thrashed out the issues once again without conclusion: Bolin et al. (1979), see p. xxvii.

Key data came from measurements of carbon in old wood. (This used the fact that new radioactive isotopes cycled through the atmosphere and plants, whereas fossil fuel emissions had long since lost any radioactivity.) In 1978, Minze Stuiver used isotope measurements to estimate that two-thirds of the CO_2 added to the atmosphere up to 1950 had come from cutting down forests. But global industry and population had been multiplying explosively. The situation had changed, and now nearly all the new carbon was coming from fossil fuels. The crude ocean models were roughly correct.

This did not mean that forests were unimportant. The way Keeling's CO_2 curve swung up and down with the seasons showed plainly that the springtime growth and autumn decay of plant matter played a huge role in the atmosphere's carbon budget. But averaged over a year, the gas emitted from decaying or burned plants seemed to be roughly balanced by the amount taken up by other plants. Maybe deforestation was balanced by more vigorous growth due to fertilization by the increased CO_2 in the atmosphere—"a chance compensation of opposed effects."[1]

Woodwell denied this, and through the 1980s, he continued to insist that tropical deforestation and other assaults on the biosphere were contributing about as much net carbon to the air as the burning of fossil fuels. Calling carbon dioxide "a major threat to the present world order," he called not only for a halt to burning forests but for aggressive reforestation to soak up excess carbon. Saving the forests, more for the sake of wildlife than of climate, was a popular idea in the growing environmental movement—a movement in which Woodwell had long been a leader.[2] Other scientists, however, never accepted his numbers, and eventually Woodwell had to concede that deforestation was not adding as much CO_2 to the atmosphere as he had thought.

An important lesson remained. As a team headed by Broecker wrote in 1979, Woodwell's claims that destruction of plants released huge amounts of CO_2 had been a "shock to those of us engaged in global carbon budgeting." The intense reexamination triggered by the claim had called attention to "the potential of the biosphere." Broecker and others concerned with the geochemistry of the oceans were especially frustrated by what they starting to call the "missing sink" of carbon. The only areas so poorly understood that they might hide such a huge feature of the system were biological.[3] From the late 1970s onward, it was clear that nobody could predict the future of global climate with precision until they could say how the planet's living systems affected the level of CO_2.

Taking his own advice, Broecker began to look at seawater as a container not only of chemicals but of life. In a pair of seminal 1982 papers he drew attention to what was later called the "biological carbon pump." The vast clouds of plankton that inhabit the oceans' surface layer use

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[1] The net fluxes "appear to have been negligible over recent decades." Stuiver (1978), p. 258; Broecker et al. (1979), quote p. 417; in writing this section I have benefitted from Elliott (1977-89).

[2] "threat:" Woodwell (1978), p. 43; see Woodwell et al. (1983).

[3] Broecker et al. (1979), pp. 409, 417, "missing sink" on p. 415.

carbon to build their bodies and shells. Their fecal pellets and fragments of their carcasses gradually sink through the water, eventually to be buried in sea floor sediments. This “marine snow” was known since the 19th century, but the wispy particles were too fragile and evanescent to measure easily. Serious research began only in the 1970s, when marine biologists took up scuba diving and saw the “snow” drifting down all around them.

Investigation found that over the course of many millennia, the biological carbon pump could sequester huge amounts of carbon in the seabed, perhaps ending up as carbonate rocks. On a shorter timescale the effect was less straightforward. For example, when creatures make calcium carbonate for their shells, they alter the complex chemistry of seawater, which actually ends up releasing gas into the air. Scientists had much to learn about the many biochemical changes that occur as plankton flourish and disintegrate.[1]

In studying all this, Broecker and his colleagues were not concentrating on what it meant for the contemporary carbon budget. Their chief interest was what the burial of carbon over thousands of years might mean for the swings between ice ages and warm periods. Over the long run, the more carbon was buried, the less there should be in the atmosphere. Could studying changes in the atmosphere’s CO_2 content lead them to the “holy grail” of geochemical research, the mechanism that dominated ice age cycles?[2] Powerful support for this hope came from studies of ancient ice pulled up from boreholes in the Greenland and Antarctic ice caps. It turned out that during past ice ages, the level of CO_2 in the atmosphere had gone through big swings up and down in step with the rise and fall of global temperature. Nobody could think of any physical or chemical effect strong enough to cause this. That left the biosphere, and above all the oceans. Ocean biology might be the key to explaining how global temperatures and CO_2 had shifted together over the millennia.

It was especially noteworthy that plankton could grow only where they got enough trace minerals like iron and phosphorus. Thus the global carbon cycle depended on the upwelling of ocean currents bearing fresh nutrient minerals, and on the winds that blew mineral dust out to sea. The patterns of upwelling, winds, and erosion were not the same during glacial periods as during warm periods like the present. Besides, changes in temperature would obviously affect the growth of plankton directly. It was an outrageously tangled case of interactions between ocean biology and climate.

Scientists now saw these interactions as crucial not just on geological timescales but for our near future. It took millennia for the surface layer to mingle with deeper waters, so it had to be mainly

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[1] Broecker (1982a), crediting G. Brass and N. Niitsuma for preliminary ideas; Broecker (1982b); for a precursor, see Hutchinson (1954), p. 384; the phrase “carbon pump” was defined and three types analyzed in Volk and Hoffert (1985). See Mary Silver, “‘Marine Snow: a Brief Historical Sketch,” *Limnology and Oceanography Bulletin* 24 (February 2015): 5-10 [doi:10.1002/lob.10005]; Silver et al. (1978).

[2] “holy grail”: Sigman and Boyle (2000), p. 859.

the biological pump that removed carbon in the particles of marine snow pulled down by gravity. This came under intense scrutiny around 1989 when a few scientists "challenged well-established paradigms" by asserting that transport into the depths of carbon dissolved in seawater was more important than the sinking particles. A passionate but short-lived controversy quickly confirmed Broecker's insight—the lives and deaths of plankton were indeed responsible for sequestering a substantial fraction of humanity's emissions. (Much later calculations gave a number: without the biological carbon pump, the concentration of CO_2 in the atmosphere would be at least 50% higher, bringing disastrous global heating at a headlong pace.)[1]

Broecker and several other scientists launched into increasingly elaborate calculations of the connections between CO_2 in the atmosphere, the chemistry of the various layers of ocean waters, the plankton inhabiting those layers, and climates past, present, and future. The biology and chemistry had so many complexities and pitfalls that questions multiplied faster than answers, but one thing was clear. In the future, as more and more CO_2 from fossil fuels dissolved into the ocean—with levels already well above anything found in measurements that went back half a million years—there would be serious chemical changes. In particular, the carbonated seawater would more easily dissolve the compounds that make up shells. Whether that would endanger sea creatures, and what would eventually result from all this, nobody could guess.[2]

Biological processes on land were easier to investigate, and progress was steady. For example, in 1983 a pioneering study modeled 69 regional ecosystems separately, and concluded that changes in land use since the 18th century had caused a net release of carbon from soils. That confirmed Stuiver's finding that until around 1960 humanity had released more carbon into the atmosphere by cutting down forests and the like than through burning fossil fuels. The uncertainties were large enough so that if you assumed the lowest reasonable level for some factors and the highest reasonable level for others, it was possible to balance the global carbon budget.[3]

Despite such efforts the argument over the fate of CO_2 remained unresolved. As one pair of authors complained, "from meager statistical information and often ill-documented statements in

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[1] "Challenged:" Hansell et al. (2009). The supposedly transported dissolved chemicals were organic, so biology mattered in any case. Some minor physical effects noted later: currents carrying dissolved material could indeed help sequester carbon in some regions, see Wang et al. (2023); eddy currents in subtropical regions could carry down particulate carbon, Freilich et al. (2024). For a review see Heinze et al. (2015), calculating that "In a world with a lifeless ocean, the atmospheric CO_2 concentration would have been about twice as high as the pre-industrial one. A sudden hypothetical stop of marine life would increase the atmospheric CO_2 concentration by 200–300 ppm" above the current ~400ppm.

[2] Broecker (1982a); also Broecker (1982b); other papers with discussions and a variety of ideas include Anderson and Malahoff (1977); McElroy (1983); Siegenthaler and Wenk (1984); Sarmiento and Toggweiler (1984); Knox and McElroy (1984); for a later example, Boyle (1988a); a review: Sigman and Boyle (2000).

[3] Houghton et al. (1983).

the literature, it is extremely difficult to calculate" what was happening between the biosphere and the atmosphere.[1] Woodwell insisted that if not now, then in the future, global warming would cause vegetation to release overwhelming amounts of CO_2. Debate continued through the 1980s as scientists came up with a wealth of new data and new ideas, doing less to solve the carbon problem than to reveal ever more complications. The complications were not only scientific. Calling yet again for an end to deforestation, Woodwell pointed out that the goal collided with powerful economic forces, not to mention corruption. The necessary changes, he said, "require political advances rather than scientific or technical insights."[2]

The story of the missing carbon is continued below in the "Global Warming Feedbacks" section.

Methane (1979-1980s)

Controversy over the numbers in the planet's carbon budget, linked with growing concern about global warming due to CO_2, goaded scientists to study more closely the biological exchanges of carbon. In 1979 a team reported that the burning of forests put into the atmosphere significant quantities not only of CO_2 but also other greenhouse gases. Methane gas (CH_4) in particular had a significant part to play in the global carbon budget.[3] And scientists had recently realized that methane, molecule for molecule, was many times more effective than CO_2 as a greenhouse gas.

Methane came mainly from living creatures: bacteria lurking everywhere from soil to seawater. Everyone knew that "swamp gas" bubbles out of wetlands in particular. Back in 1974, a German geochemist had calculated that terrestrial bogs, not the oceans, were the largest source of the methane in the atmosphere.[4] These natural emissions were much greater than the amount of methane that escaped as humans extracted and burned fossil gas ("natural gas"). Meanwhile, people were beginning to recognize that the world's wetlands were rapidly changing under human impact. And that was not all.

Studies found that animals could be a significant source of both CO_2 and methane. Methane in particular was produced by bacteria in the guts of cattle and other animals and then burped into the air. The rapid increase in meat and milk production was adding significantly to the rising level of the gas in the atmosphere. (In later decades studies pinned this down, finding that animal husbandry contributed more than a tenth of humanity's greenhouse gas emissions. One component of this was another potent greenhouse gas, nitrous oxide (N_2O), released from fertilizers used in growing fodder.) Rice paddies too had been spreading swiftly, with methane

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[1] Seiler and Crutzen (1980), p. 1980, note the large bibliography.

[2] For a review, see Detweiler and Hall (1988); Woodwell (1991), p. 246.

[3] "Biomass burning has previously been considered unimportant as a global source of atmospheric trace gases—our analysis shows that this is not the case." Crutzen et al. (1979).

[4] Ehhalt (1974).

bubbling up from the mud.[1] Even termites, abundant around the planet wherever dead wood decayed, might be a significant source of methane and CO_2. (Later research showed that termites are indeed a factor, but contribute considerably less than domestic animals or rice paddies.)[2] Human activities would affect these releases and uptakes of gas; the activity of soil bacteria and termites, for example, were largest in areas disturbed by cultivation or burning. And of course such things would also be affected by climate change itself. All these interlocked effects would somehow have to be taken into account.

An especially thought-provoking calculation showed that a huge reservoir of biological carbon was frozen in the deep permafrost layers of peat that underlie northern tundras—perhaps half as much carbon as in all the world's tropical forests and jungles.[3] When global warming reached these peat beds, they might release a huge amount of $CO_{2.}$ Microbes in the soggy tundras, which covered millions of square kilometers and were highly sensitive to temperature change, might meanwhile emit massive quantities of methane.[4] A similar danger turned up in an even more gigantic reservoir of methane, at least partly of biological origin, that was locked up in "clathrate" ices in the muck of deep sea beds. Global warming would probably increase the emission of greenhouse gases from all these sources. That raised an alarming possibility of an amplifying feedback—more greenhouse warming, thus more emission, and so on up.

A strong hint that this was a real concern showed up in the studies of ice from boreholes in the Greenland and Antarctic ice caps. Not only CO_2 but also methane in the atmosphere had swung up and down roughly in tandem with the temperature swings. While for CO_2 this meant mainly looking to marine life and perhaps soils and forests, for methane this pointed to changes in how tundra, wetlands and clathrates took up the gas as climate cooled or released it in a warm period.[5] Reversing the sequence, if the greenhouse gas abundances changed because of something happening in the biosphere (for example, human activities), climate change would follow.

Gaia (1972-1980s)

Geoscientists had originally thought of carbon mainly as something to do with volcanoes and the weathering of rocks, but from the early 1970s forward they understood that biology was a major

[1] For references, see Mooney et al. (1987). More than a tenth (with nitrous oxide about as important as methane), according to the Food and Agriculture Organization of the United Nations: Gerber et al. (2013).

[2] Zimmerman et al. (1982); more recent estimates are summarized in IPCC (2001a), p. 250.

[3] Schneider and Londer (1984), p. 312n (citing a 1980 paper by Gordon MacDonald); for more recent figures, which could be lower or higher depending on how wetlands are classified, see IPCC (2001a), pp. 192, 194.

[4] Harriss et al. (1985); for other references, see Mooney et al. (1987).

[5] E.g., one pioneer paper suggested "marine biospheric activity," Berner et al. (1980), p. 234-35.

player in the global carbon budget by way of CO_2 and methane. Indeed living creatures dominated the game on the human timescale of centuries. As for other chemical elements, for example the cycling of sulfur through the oceans and atmosphere, scientists still felt that simple mineral chemistry must predominate. That changed during a research voyage on the Atlantic Ocean that included James Lovelock, a wide-ranging and exceptionally independent-minded researcher. His Ph.D. was in medicine, but his most notable achievement at this point had been inventing instrumentation for measuring rare gases even at tiny concentrations. On the high seas Lovelock discovered that one such gas, dimethyl sulfide (DMS), was a principal element in the global sulfur cycle. The main source of DMS was ocean plankton.[1]

Lovelock was already convinced that, as he put it, "the atmospheric gases are biological products." His interest was partly stimulated by gases that he found everywhere in the Earth's atmosphere and that were undoubtedly produced by living creatures: pollutants from human industry. But Lovelock based his thinking more deeply on the most fundamental property of biology, the uphill march of life against entropy.[2]

Back in the 1960s, Lovelock had proposed measuring gases in the Martian atmosphere as a way to look for traces of life. In 1965 a pair of scientists had found that the oxygen in Earth's atmosphere comes mainly from photosynthesis in plants. Living creatures, Lovelock explained, could drive their planet's atmosphere into "a state of disequilibrium." Mars lacked the free oxygen of our own planet precisely because Mars was sterile. At this point in Lovelock's thinking, a stable balance gave witness to dead minerals, whereas the system of life plus minerals created a perpetual state of dynamic imbalance.[3]

Lovelock ran into trouble when he tried to publish these ideas in 1966. At the time he simply remarked that the physical sciences habitually ignored the physical effects of life "to the point of blindness." Long afterward, he reflected that "Conventional biology and planetary science held the false assumption that organisms merely adapt to their environment. My ideas for life detection acknowledged that organisms change their environment... Neither my critics nor I were aware of this fundamental difference of viewpoint." Lovelock's difficulties illustrated how hard it was to grasp that living creatures could play a starring role in the geochemistry of their planet.[4]

In 1974, Lovelock put together a grand generalization in collaboration with Lynn Margulis, who had a deep understanding of microbiology (and shared a taste for planet-sized speculation with her former husband, Carl Sagan). Their article was entitled, "Atmospheric homeostasis by and for the biosphere: The Gaia hypothesis." Lovelock and Margulis proposed that the ensemble of

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[1] Lovelock et al. (1972). Lovelock's suggestion that dimethyl sulfide governed cloud production over the oceans has turned out incorrect: Quinn and Bates (2011).

[2] "products:" Lovelock and Margulis (1974), p. 9.

[3] Oxygen: Berkner and Marshall (1965). Hitchcock and Lovelock (1967), "disequilibrium" p. 150, "blindness" p. 158.

[4] "Conventional" Lovelock (2000), p. 235, for Gaia, see ch. 9.

living creatures had taken "control of the planetary environment" in a way that would maintain conditions favorable for life itself. This pushed to the limit the new way of seeing the atmosphere as something susceptible to biological influence. Under the new hypothesis the atmosphere was altogether "a component part of the biosphere," in fact a "contrivance." The rhetoric and the name, after the Greek Earth-goddess, carried an implication of purposeful or even supernatural guidance, which disgusted many scientists. But if you stripped away any implication of conscious purpose, the idea that biology controlled atmospheric content was rationally defensible.[1]

For more than a decade the Gaia hypothesis led nowhere scientifically. Most scientists considered it visionary at best. Then in 1987 Lovelock, working with Robert Charlson and others, argued plausibly that the DMS that ocean plankton emitted could influence climate, much like the smoggy sulfur aerosols produced by human industry. In the clean air over the oceans, particles of DMS were a major source of nuclei for the condensation of the water droplets that would form clouds. This suggested a Gaia-like self-regulation. Perhaps if the oceans got warmer, the plankton would produce more DMS... which would make more clouds and more reflection of sunlight from the atmosphere... which would bring a compensatory cooling back toward normal. Perhaps this biological regulation "has already counteracted the influence of the recent increase in CO_2 and other 'greenhouse' gases." (Studies in later years found that there might indeed be a slight cooling effect, but not enough to counteract the greenhouse warming.)[2] On the other hand, one could also imagine scenarios where global warming killed off plankton, bringing a vicious circle of increasing warmth.

Some people hoped the Gaia hypothesis could put a scientific foundation under the traditional belief in ecological self-regulation, the beneficent "balance of nature." Over the long run, species that damaged their ecosystem were automatically laid low—a troubling thought, given that humankind was such a species. To others, the hypothesis was not science but mysticism. If the Earth's atmosphere had remained favorable for life over the past billion years, most scientists saw no logic or evidence compelling them to think that the stability was due to anything but sheer good luck. Lovelock himself admitted that the hypothesis might never be proved definitively. In any case, he later added, human interference might be large enough to force the global system beyond the point where nature could maintain a balance. What the Gaia hypothesis did accomplish was to encourage scientists to investigate how biology could show up in every corner of atmospheric chemistry, which in turn affected everything from s to the weathering of rocks. "The science of Gaia is now part of conventional wisdom," Lovelock boasted in 1991 with only partial exaggeration, "and is called Earth system science; only the name Gaia is controversial."[3] For both scientists and the public the debate promoted an understanding that life interacts with climate in ways unforeseeable and disturbingly powerful.

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[1] Lovelock and Margulis (1974), p. 5. The more usual spelling was Gaea.

[2] Charlson et al. (1987), p. 661, known as the "CLAW hypothesis" after the initials of the authors. The central idea was first proposed by Shaw (1983). Later work is reviewed by Ayers and Cainey (2007).

[3] Lovelock (1991), p. 1

Everything is connected to everything else: from a high-minded but nebulous philosophy, this viewpoint had evolved into a scientific requirement for analyzing the planet. The final answer to the question of climate change would be a set of predictions for the levels of gases, temperatures and precipitation, and their impacts on ecosystems and human society. That could come only through calculations with a model that incorporated *all* the significant factors and their interactions. A start at mapping such a model was made at a workshop held in Jackson Hole, Wyoming in 1985. The panelists projected sketches on a wall and scribbled over it until they got a consensus on what the most important subsystems of the model would be. The result, which became known in the modeling community as the "wiring diagram," had more than three dozen arrows connecting an even larger number of boxes. Similar diagrams sketched a decade earlier had ignored biology, but now it was at the center of the diagram. The boxes were highly simplified ("cloudiness," "nutrient recycling," "human land use," "marine biological production," and the like), and the community was a long way from knowing how to calculate what happened in most of them. Even if scientists had known all that, computers that could handle the calculations were decades in the future.[1]

From the 1980s forward there was extensive research on how methane and other emissions from human agriculture and animal husbandry in particular might add to global warming. Some results are described in the essay on Other Greenhouse Gases.

Global Warming Feedbacks

Like clouds drifting in from the horizon heralding the possibility of a storm, the prospect of global warming increasingly caught the attention of scientists far afield from traditional meteorology. They began work to organize big, long-term field studies in dozens of specialized topics of agriculture, forestry, and so forth, to see how climate might interact with the planet's many ecosystems. There was far too little money to support all those studies, but some important questions were at least partly answered.

The oldest question was whether a change in vegetation, especially a change caused by humans, could alter regional climates? The answer was now certain: Yes. At several locations, overgrazed grasslands with dried-out soils had become demonstrably hotter than less-used pastures. And the heating would make it all the harder for grass to return. Some rainforests that had been cut back showed a measurable decrease in rainfall, since moisture was no longer evaporated back into the air from the leaves of trees. On the other hand, work published in 2004 gave a more complex picture: under some circumstances, deforestation could bring more rain storms when air rose

[1] Fisher (1988); for the 1974 diagram: Kellogg and Schneider (1974). The diagram is also known as the "Bretherton Diagram" after Francis Bretherton, who chaired the committee that developed it. See Berrien Moore III Interview by Rebecca Wright, Earth System Science at 20 Oral History Project, NASA, 2011, online at https://historycollection.jsc.nasa.gov/JSCHistoryPortal/history/oral_histories/NASA_HQ/ESS/MooreB/mooreb.htm.

from the hotter ground. Such regional studies were too few to paint a clear picture of how the many types of vegetation in total could affect global climate. The studies did show that wherever vegetation was altered there could be serious feedbacks with a potential for a lasting, self-sustained regional change. However, deforestation and other deliberate changes in land use seemed unlikely to make a great difference outside the region that people were altering.[1]

That left open the question of changes in vegetation that might happen by themselves, regardless of human intentions. In particular, the potential increase in vegetation from CO_2 fertilization and warmer weather could have many effects aside from taking up carbon. For example, some scientists pointed out that if climate change encouraged forests to grow farther north, the dark pines would absorb more sunlight than snowy tundra, heating the air and adding to global warming.[2]

A 1989 review of computer climate studies concluded that the next generation of models would have to include detailed representations of vegetation. By the mid 1990s, biologists and modelers were discussing all sorts of details—for example, the way increased levels of CO_2 would affect the evaporation of moisture from leaves. Small holes (stomata) in every leaf admit the CO_2 that photosynthesis uses as feedstock. As the level of the gas in the atmosphere rose the stomata would close up a bit, and therefore less water would escape. That could have a surprisingly large impact on the amount of moisture in the air, affecting rainfall thousands of miles away. But nothing influenced the world's vegetation as much as human enterprises, so the models would also have to include social and economic forces.[3]

Some scientists, sticking by the traditional belief that natural systems are self-stabilizing, found biological feedbacks reassuring rather than alarming. They held that fertilization from the increased CO_2 in the atmosphere would benefit agriculture and forestry so much that it would make up for any possible damage from climate change.[4] The fertilization effect was confirmed by field measurements of the exchange of carbon in various forests, and by studies of the consequences of blowing extra CO_2 across crops, grasslands, and so forth. For the planet as a whole, biomass did seem to be absorbing more CO_2 than in earlier decades. However, the same studies turned up some unsettling results. The numbers were often very different from what the handful of earlier, more primitive studies had suggested. And the consequences of fertilization were not straightforward. For example, under some circumstances the extra CO_2 (and warmth) might benefit weeds and insect pests more than desirable crops.

In any case, as the level of the gas continued to rise, plants would reach a point (nobody could predict how soon) where they would be unable to benefit from more carbon fertilizer; the

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[1] The pioneering demonstration that the Amazon Basin generated much of its own rainfall was Salati and Vose (1984); more rain (in dry season only): Negri, 2004.

[2] Bonan et al. (1992); Couzin (1999).

[3] Rowntree (1989), p. 174; IPCC (2001a), pp. 440-43.

[4] Especially Idso (1989).

increase in plant growth would level off. In the late 1980s some experts predicted that warming would eventually foster decay, bringing a net *emission* of greenhouse gases and yet more warming. Could such a positive feedback run away exponentially? Teams attacked the question, narrowing the estimates. They quelled fears of a horrid runaway, but they did find that biological activity in tundra and other warming soils would add to the greenhouse gases in the atmosphere. For example, a 1995 survey of laboratory data confirmed that soil decomposition in general might "provide a positive feedback in the global carbon cycle."[1]

By now, most specialists in geochemistry, paleobiology, and the like were coming around to the view that natural systems were not always self-stabilizing—biological and physical systems alike were susceptible to positive feedbacks. Among other evidence, studies of fossil pollen confirmed a growing suspicion that as climate changed, entire assemblages of species could be driven into configurations that had never been seen before. Some biologists began to foresee widespread extinctions of species and the impoverishment, perhaps the utter failure, of vital ecosystems. In one authoritative study, an international group of 19 experts estimated that by 2050, somewhere between 15 and 37% of all the species in a large sample of regions would be "committed to extinction."[2]

A few people suggested solving the global warming problem by using biology deliberately. Perhaps we could accelerate the biological carbon pump of dead carbon-bearing materials that snowed down toward the ocean floor? Plankton did not flourish without trace minerals, which are scarce in mid-ocean. For decades there had been talk about expanding fisheries in barren ocean regions by adding nutrients to boost the biological productivity, like the traditional nitrate and phosphate fertilizers used in farms. Studies in the late 1980s and 1990s suggested that iron was the keystone fertilizer in the open ocean. By dumping iron compounds where the element was lacking, we might be able to stimulate plankton to bloom. Could a supercharged biological pump bury carbon as quickly as our industries emitted it? The pioneer of the theory, John Martin, joked in a Strangelove accent, "Give me a half tanker of iron and I will give you an ice age!"[3]

Scientists began planning experiments to see just how much carbon they could send to the sea

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[1] Early fertilization estimates: Houghton & Woodwell (1989), Jenkinson et al. (1991), Raich & Schlesinger (1992), Tundra emissions: Oechel et al. (1993); quote: Kirschbaum (1995), p. 753.

[2] Pollen: Webb (1986); committed to extinction: Thomas et al. (2004).

[3] The importance of iron was demonstrated by Martin and Fitzwater (1988); Martin (1990); Martin made his famous "half tanker" remark at a Woods Hole 1988 conference, see US Joint Global Ocean Flux Study *Newsletter* 1(2) (US JGOFS Planning Office, Woods Hole Oceanographic Institution, 1990). For the history see Stoll (2020). Examples of papers confirming that fertilization of the oceans by iron could have played a role in ice ages, in particular when a lower sea level and frigid climate led to more dust blown off dry lands: Moore et al. (2000); Kohfeld et al. (2005); Abelmann et al. (2006); Martínez-Garcia et al. (2011), Martínez-García et al. (2014).

floor with a shot of fertilizer. Quite a lot, under the right circumstances, according to studies completed after 2001. But the details of these circumstances were as obscure and complex as everything else in the oceans. Many people warned that in view of how little we knew about ocean ecosystems, this sort of meddling might just make things worse. For example, what if fertilizing plankton made them emit extra methane or other potent greenhouse gases?

Meanwhile Broecker and a few other dedicated specialists tried to unravel the tangled biological and chemical history of the oceans through glacial periods, by following tracer minerals such as cadmium. Broecker's initial ideas were in error, as he realized "almost before the ink had dried on the publication." That was the story of much that followed. As he admitted in 2000, "The prize has yet to be grasped." Oceanographers were just starting to realize that the drifting plankton formed communities as complex as a rainforest. Only a tiny fraction of the marine species had even been identified. Climate change would profoundly affect these communities, but nobody could say just how.[1]

Adding to the uncertainties, as ever more CO_2 dissolved into the oceans, the surface waters were becoming noticeably more acidic. Many creatures would find it increasingly difficult to make their shells. Unless humanity restricted its emissions, in future centuries the oceans would be more acidic than they had been for hundreds of millions of years. Combined with warming, that could reduce some of the planet's grandest and most productive ecosystems to ugly ruin. Already within the next few decades the increasing acidity seemed likely to severely deplete key species—which would not only damage coral reefs and fisheries but might reduce the capacity of the biological pump to sequester carbon in the abyss. In particular, acidity would affect how much carbon plankton could put into their shells and how the shells might dissolve as they sank. Exploring how seawater chemistry and temperature affected each important species, and the interactions among the myriad creatures, and the consequences for the movement of carbon, was a project that would take many decades.[2]

Attempts to balance the current carbon budget continued to hold center stage through the 1990s. Debate persisted over such issues as whether tropical forests were a net source or sink for carbon. Some researchers continued to present arguments that excess CO_2 was mostly taken up by the oceans, opposed by others who came up with equally persuasive arguments that the gas was mostly going into plants. Only more data could resolve these questions. Particularly helpful were regular measurements of CO_2 levels in the air at many locations, made by a U.S. government agency (NOAA). Flasks of air were gathered at a string of stations running from the South Pole

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[1] The Cd pioneer was Edward Boyle, e.g., Boyle (1988b); Coate et al. (1996) was a successful fertilization experiment; for an important 2004 experiment see Smetacek et al. (2012); "ink had dried... prize:" Broecker (2000). For more on this topic see news reports in the journals *Nature* and *Science*, e.g., Chisholm (2000).

[2] "Within a few centuries the ocean pH may reach a level not seen for hundreds of millions of years, and within the present century many organisms are likely to be affected" is the authoritative conclusion of Denman et al. (2007). A popularized summary is Kolbert (2006a).

up to an ice floe in the Arctic Ocean. The variations from season to season said much about the movements of the gas.

Another powerful way to interpret these numbers came from new and precise data on oxygen in the atmosphere. The oxygen level is fractionally altered wherever burning fuel emits CO_2 and wherever plants emit or take up the gas, but the oxygen level is unaffected when CO_2 is taken up in the oceans. The ingenious and painstaking measurements were the work of Ralph Keeling, C.D. Keeling's son.[1] Over the course of the 1990s, the various numbers tended to converge, suggesting that none of the debaters was entirely right or entirely wrong.

The reasons for the long-standing confusion were explained in part when new studies showed that the uptake of carbon by forests and soils was varying erratically and massively. A region that had absorbed carbon overall during one decade might be a major source of carbon in the next. In particular, it seemed that much of the "missing carbon" had been absorbed by Northern Hemisphere forests in some decades, but not in others. The uptake might depend on a variety of things, such as the global weather fluctuations brought on by El Niño events in the equatorial Pacific Ocean.[2]

By the start of the 21st century it was established that overall, humanity was emitting seven billion metric tonnes of carbon each year by burning fossil fuels and another one or two by clearing tropical forests (which turned out to be a net source of CO_2 in spite of fertilization). The emissions were increasing, indeed accelerating, by roughly an additional one percent a year. About half of the new carbon stayed in the atmosphere, and the oceans absorbed a quarter, which left roughly two billion tonnes per year that terrestrial ecosystems must somehow absorb. Some studies pointed to rapidly growing Northern Hemisphere forests, others located the main uptake in tropical forests. One study might turn up evidence of carbon absorbed in peat bogs, another might point to the world's desert soils as "the long-sought missing carbon sink"... or it might be something else entirely. In 2011 an international team largely settled the issue with a major study reporting that forests (mainly in the temperate zones) could account for the missing carbon.[3]

Looking back over a much longer term, maverick paleoclimatoligist William Ruddiman boldly argued that humanity had been altering climate for thousands of years as the spread of agriculture produced ever more CO_2 and methane. Measurements in ice cores showed that these gases had held steady over the last several millennia, whereas they had declined at a comparable point previous interglacial periods. A variety of studies pointed to the emissions from rice paddies ,

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[1] Keeling et al. (1989) (this is C.D.); Tans et al. (1990); oxygen work by Ralph K.: Keeling and Shertz (1992); Keeling et al. (1993); and see Broecker and Kunzig (2008), pp. 85-87.

[2] Among the many publications: Battle et al. (2000), Bousquet et al. (2000), Schimel et al. (2001).

[3] Among the many publications: Prentice and Lloyd (1998), Schindler (1999), Stephens et al. (2007), Baccini et al. (2017). "Long-sought:" Stone (2008). Pan et al. (2011).

deforestation, and so forth as the reason why the world had not been cooling as it normally did at this stage of the glacial cycle. After a decade of controversy, scientific opinion converged on accepting Ruddiman's theory. In any case nobody now disputed that human activity, and its interactions with the rest of the biosphere, was currently responsible for massive changes in the global carbon cycle. Nor did any scientist doubt that the future was likely to see even greater changes as biological systems responded to the mounting emissions.[1]

Looking to the future, experts still had not resolved such basic questions as whether tropical forests, by absorbing or releasing carbon dioxide, were more likely to retard global warming or hasten it. In every ecosystem, the carbon balance would depend heavily on what humans did. Alongside deforestation and reforestation it was important to account for the global effects of fertilizers in the atmosphere—not only CO_2 but also our rising emissions of nitrate gases. Experts meanwhile began to discuss how agricultural practices and other land use by humans affected the storage of carbon in soil, and could even directly change things like rainfall, as observed since the days of Columbus. These changes, one scientist remarked, "may be at least as important in altering the weather as changes in climate patterns associated with greenhouse gases" (if not globally than regionally, which is what most people worry about).[2] All these uncertainties raised severe problems for international negotiations when people tried to assign responsibility to particular nations for how much they were adding to global warming or retarding it.

In the late 1990s, models based largely on speculation and hand-waving began to give way to quantitative models based on solid data. A key result appeared in 2000, published by a team of researchers who had managed to couple computer models for the atmosphere, oceans, vegetation and soils all together. Their preliminary results were ominous. It appeared that on balance, warming would make it harder for the planet to take up carbon, and might even trigger increased emissions. In particular, the team's simulated tropical forests dried up and began to emit massive amounts of CO_2. Their best guess was that around mid-century the planet's biosphere as a whole would turn from a net absorber to a major emitter of carbon, speeding up climate change. The importance of the fertilization mechanism was driven home by a study that showed that if there had been no fertilization in the past, there would now be much more CO_2 in the atmosphere and a corresponding increase in warming.[3]

As research proceeded, the results continued to be disturbing. A 2004 model run estimated that during the 21st century there would be roughly half a degree more warming than would happen if there were no soil feedback. But there were many unknowns in how warming might change the

[1] Ruddiman and Thomson (2001), see Kerr (2004a); Ruddiman (2005, 2010); Ruddiman (2006); evidence against the hypothesis was advanced, e.g., by Elsig et al. (2009); on acceptance see Stanley (2016); Ruddiman et al. (2016a), Ruddiman (2016b), Koch et al. (2019).

[2] Pielke (2005).

[3] Coupled models (emphasizing soil emission): Cox et al. (2000), confirmed by a study with multiple models, Friedlingstein et al. (2001). Historical fertilization: Shevliakova et al. (2013).

global carbon cycle; if we were unlucky, it might lift future warming from, say, three degrees to four or even more.[1] An increasing number of groups worked up models that coupled climate changes with changes in soils, vegetation and the oceans.

Up to this point, modelers had mostly treated plant life as an element of physics, a sort of solid material with a surface roughness and reflectivity, through which water and gases flowed depending on temperature and so forth. But now the modelers understood that carbon cycling was a key issue, and they began to incorporate the physiology of plants and much other detail. Typical was a French model that traced water through 11 levels of soil (of several different soil types) including transfer to plants, evaporation or runoff, taking into account the growth and death of leaves and roots including carbon uptake or release, and even competition between different species as the climate changed. An example of the modelers' complex struggles was a 2010 experiment in which the world's arid regions happened to be assigned too little vegetation to hold the soil in place. The model atmosphere filled with dust, which fertilized the oceans and brought gargantuan blooms of plankton—a disaster presumably unlike our actual planet's future.[2]

The most prominent worry was the Amazon rainforest, sustained by rains that were largely water evaporated from the forest itself. Modelers found that warming combined with the rampant deforestation might flip the entire system to a parched, scrubby mix of forest and grasslands ravaged by fires. Worries redoubled when prodigious droughts struck the Amazon basin in 2005 and 2010, releasing large amounts of carbon into the atmosphere. However, scientists did not have enough data to say with any confidence what would happen there in future decades, nor in the many other regions with special characteristics. Some scientists warned that the models had not yet incorporated important factors, for example insect infestations, which were already noticeably on the rise and reducing the ability of plants to take up carbon.

Another problem scientists were beginning to worry about was wildfires, which not only degraded forests but emitted CO_2 directly on a global scale. Experts had long assumed that warming would provoke an increase in fires; by 2020 this was confirmed as horrendous conflagrations devoured territories from Australia to Siberia. The annual total emissions of greenhouse gases by wildfires was becoming comparable to the fossil fuel emissions from an entire country like Japan.[3]

Reports by official panels conservatively played down the extreme scenarios. On land or in the sea, there were many other biological feedbacks not yet taken into account, which could be either

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[1] Models: Cox et al. (2000), Zeng et al. (2004). Unlucky: e.g., Matthews and Keith (2007).

[2] Dahan (2010); 2010 (Hadley) model: Heffernan (2010).

[3] For wildfire increase see note {17f} in the essay on Impacts of Climate Change. Xiaoying You, "Surge in Extreme Forest Fires Fuels Global Emissions," Nature News (Dec. 20, 2023) [doi.org/10.1038/d41586-023-04033-y], online at https://www.nature.com/articles/d41586-023-04033-y

favorable or unfavorable. But overall, everyone agreed that an ever higher fraction of the CO_2 emissions would stay in the air, adding substantially to global warming. A large international collaboration that compared a variety of models found many differences, but every team calculated that on balance, the feedbacks would add to global warming.

Field studies were also disheartening. By now the research effort, which once could barely muster a few professors and graduate students to survey a single spot in an entire region, had expanded to an enterprise on an almost industrial scale. For example, in 2015 a massive study of the Amazon, with three decades of observations in 321 plots, reported that the forests had been taking up carbon markedly more slowly than in the past. The Brazilian part of the basin, degraded by rampant deforestation and fires, was already emitting more carbon than it absorbed, and there were indications the whole region might be approaching a tipping point where it would transform irreversibly into dry grasslands. A 2022 study reported that in the worst case, the Amazon collapse could begin when global temperature rose as little as 1°C above the present and could be completed within another half-century. Looking more widely, a global survey finally nailed down, as a general rule, what had increasingly turned up in regional studies, a conclusion neatly summarized in the paper's title: "Tropical deforestation causes large reductions in observed precipitation." Brazil was not the only place where replacing trees with crops or cattle was drying the land.[1]

The good news was that while tropical forests were taking up less carbon, the immense boreal forests of Canada and Siberia were expanding northward and taking up more. The net effect on carbon uptake was currently positive, holding back the rise of CO_2. Nobody could say how long that would continue (among other things, warming was inflicting more fires and pest infestations on boreal forests).

Tundra was even more perplexing. Already in 2003, a measurement of an Arctic bog found a sharp rise in methane emissions since 1970, and later studies in Siberia confirmed this was happening all around the Arctic. There were signs that as warming continued, by mid-century the thawing tundra would be making a substantial addition to the atmosphere's burden of greenhouse gases.

The scientists offered their conclusions tentatively, for they had only a scattering of observations of the tortuously complex wetlands systems. For example, studies published in 2020 concluded that methane emissions would be *lower* than expected because methane-eating microbes would oxidize the gas before it could escape. Meanwhile, studies of actual permafrost reported that as soil thawed, it slumped and formed ponds, so that the movement of water and the exposure of long-buried carbon made for much *greater* emissions than expected. It was small wonder, then, that permafrost carbon, as a group of experts warned, was "inadequately represented, or not

[1] Amazon studies: Brienen et al. (2015), Qin et al. (2021), Gatti et al. (2021), Covey et al. (2021), Boulton et al. (2022); Flores et al. (2024) find that "by 2050, 10% to 47% of Amazonian forests" could be triggered to "unexpected ecosystem transitions"; tipping points: Armstrong McKay et al. (2022); precipitation survey: Smith et al. (2023).

represented at all," in the big computer "Earth System" models.

While tenacious biologists trudged or waded through the planet's remotest spots to find out what was happening to plants and soils, an equally complex and massive research enterprise worked with captive organisms. The many facilities ranged from laboratories that incubated microorganisms in samples of jungle soils to full-scale "mesocosms" like a greenhouse or an artificial pond that enclosed an array of interacting flora and fauna. Manipulating environments, scientists observed the effects on respiration, that is, emissions of CO_2 and other gases. Despite these efforts, a review worried that "The interaction between [soil respiration] and environmental change... remains one of the greatest sources of uncertainty in climate and earth system projections."[1]

Ocean ecosystems also proved hard to untangle. During the 2010s ambitious computer modelers tried to pin down the crucial biological carbon pump in actual numbers. They failed. Carbon was indeed leaking downward from the surface waters, fast enough to help slow global warming. But how? Measures of the "marine snow" sinking under the pull of gravity found it drifting downward far too slowly to carry all the carbon. Something was out of balance.

The solution was discovered in an astounding biological process. In the 1940s, Navy sonar operators had observed a reflective layer a hundred or so meters deep in the oceans, sometimes thick enough to hide a submarine. The layer turned out to be countless minuscule creatures. During the day they hid from predators in the lightless depths; every evening they swam to the surface to feed. At dawn, stuffed with the carbon in their food, the creatures descended to their deep home, where they emitted the carbon in respiration and feces. Since the 1960s, a few scientists had speculated that this transport of carbon might be significant. But with measurements difficult and varying greatly from place to place, most did not think the mechanism important. It was not until 2019 that a team showed that the migrating creatures "probably sequester as much carbon as the gravitational pump, helping to close the carbon budget." Meanwhile a new look at a population of seemingly insignificant fish, each a few centimeters long or less, found that they comprised an astounding nine-tenths of all the oceans' fish by weight—and they too swam up and down every day. The diurnal shuttling of tiny invertebrates and fish is Earth's grandest migration, and a surprising key to how the oceans sequester CO_2.

Answering that question, researchers turned to another: how would global warming and ocean acidification affect the biological carbon pump? (And the pump seemed all the more important

[1] Boreal net effect positive: Tagesson et al. (2020). Methane: Christensen et al. (2004), surprising results of Keppler et al. (2006), Walter et al. (2006), etc.; for examples and discussion see Flannery (2006), pp. 196-98. Substantial addition from tundra: Schuur et al. (2009); Dorrepaal et al. (2009); Schaefer et al. (2011). Microbes: Oh et al. (2020), Dyonisius et al. (2020); slumping: Rodenhizer et al. (2020), similarly for thermokarst lakes, Zandt et al. (2020). "Inadequately:" Schädel et al. (2024). Lab studies, mesocosms, respiration: Bond-Lamberty et al. (2024).

because the heating of surface waters was increasing the "stratification" that impeded the physical overturning of seawater.) Biologists argued over huge differences in their estimates of the many factors involved; computer models could not even agree on whether the sum of all the influences and feedbacks in the changing climate would make the biological pump stronger or weaker. And there might be other effects as ocean ecosystems changed; for example, plankton directly affect cloudiness through the aerosol particles they emit (DMS, as noted above). As with terrestrial soils, wetlands, and so forth, there were so many different organisms, interactions, and unknowns that researchers were not likely to predict changes confidently before the changes became actually observable. Adding yet another uncertainty, in the early 2020s scientists began to worry about proposals to convert the migrating layer to fishmeal on an industrial scale. Human enterprise might be able to weaken the carbon pump, as in earlier times sailing ships had nearly exterminated the great whales.[1]

For terrestrial ecosystems, one major effect was now clear. In the 2010s, advocates for burning ever more fossil fuels could point to studies that found that vegetation was "greening" around the world. Whatever might happen later in the century, at present plants were growing more abundantly due to increased CO_2 fertilization (along with warmer weather in some regions). The effect was pinned down in 2017 by ingenious measurements in Antarctic ice cores, showing that terrestrial uptake of carbon had risen a remarkable 30% during the 20th century. The extra plant growth not only improved crop yields but was sequestering extra carbon in living plants and their decay products, helping significantly to slow the rise of atmospheric CO_2.

However, the fertilization was not an unalloyed benefit. It might be helping weeds as much as the desired crops, and the fast-growing crops themselves were becoming measurably less nutritious. Also, when fertilization enhanced the growth of dark vegetation around the Arctic, that made for more absorption of sunlight and accelerated the Arctic warming feedback loop.

Meanwhile long-term studies of plants confirmed the suspicion that fertilization by CO_2 was limited by the availability of other nutrients. Advances in soil science had overturned the traditional belief that soils would always provide reliable long-term carbon storage. It seemed that the standard Earth System models for climate change overestimated the value of forests for absorbing carbon as the world got warmer. By 2020, global surveys from satellites and many kinds of studies on the ground in dozens of countries had confirmed that since the 1980s the fertilization benefit had been fading away. The "greening" was progressively slowing, and "browning" emerged in some regions as soils got hotter and drier. With continued warming, tropical forests in particular would stop taking up carbon altogether and become net emitters even if governments halted deforestation. This "saturation," two experts declared, was "a terrible

[1] Stratification: Li et al. (2020). Plankton, some examples of studies: climate affecting plankton blooms, Behrenfeld et al. (2006); trends toward less ocean carbon sequestration detected, Schuster and Watson (2007), Le Quéré et al. (2007); affecting cloudiness, Meskhidze and Nenes (2006). An example of a review emphasizing the need for much more work on phytoplankton response: Hutchins and Tagliabue (2024).

omen for the future pace of climate change."[1]

There seemed no end to the unexpected but significant effects that biologists turned up as they worked through the staggering complexities of ecosystems. The biggest concern was enhanced biological greenhouse gas emissions. In particular, experimental studies found that the emission of carbon by microbes in Arctic soils would increase as global temperatures rose, and likewise for tropical forests in night-time respiration. As one team put it, "rising temperatures will stimulate the net loss of soil carbon to the atmosphere, driving a positive land carbon-climate feedback that could accelerate climate change." The concern was reinforced by a 2018 analysis of observations around the globe which suggested that a sustained trend of soil carbon loss was underway. On the other hand, studies of isolated lakes and uplands in tundra regions indicated that methane emissions from these particular sources were not a grave threat. It was an open question whether plants, from bacteria to trees, were still growing and storing carbon faster than they were emitting it.

Arguably the most difficult problem was the future behavior of the various kinds of soils around the world, which together stored perhaps three times as much carbon as the atmosphere. A round of supercomputer studies that concluded in 2014 (CMIP5) could not even agree on whether soils would store more carbon as the world heated up, or would end up releasing carbon. The next round, concluded in 2022 (CMIP6), agreed that there would be a net uptake of carbon—good news, although the estimates of the amount varied by a third up or down. A closer look showed the agreement was partly coincidental, for the models diverged widely when it came to individual soil types and regions. The "consensus obscures substantial model disagreement on the mechanisms underlying soil C[arbon] response," a group of reviewers warned, "calling into question the reliability of model predictions."[2]

Observations of the actual carbon cycle were increasingly alarming. In 2023 global temperatures rose more swiftly than anyone expected, fueling record-breaking heat waves. The level of the

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[1] Greening: Zhu et al. (2016), quantified by Jeong et al. (2014); increased uptake ("primary production"): Campbell et al. (2017); helps sequester carbon, Keenan et al. (2023). Less nutritious: Myers et al. (2014), Broberg et al. (2018). Darker vegetation: Jeong et al. (2014). Fertilization limitation: Reich and Hobbie (2012). Soil carbon storage: Terrer et al. (2021), Soong et al. (2021), Gabriel Popkin, "A Soil-Science Revolution Upends Plans to Fight Climate Change," Quanta (July 27, 2021), online at https://www.quantamagazine.org/a-soil-science-revolution-upends-plans-to-fight-climate-change-20210727. Surveys: Wang et al. (2020), many studies: including Sullivan et al. (2020), Hubau et al. (2020), Duffy et al. (2021); Nottingham et al. (2020), Koch et al. (2021); "browning:" Winkler et al. (2021); "omen:" Rammig and Lapola (2021).

[2] Arctic soils: Karhu et al. (2014); Maes et al. (2024), see also Smith et al. (2019). Tropical forests: Anderegg et al. (2015); accelerate: Crowther et al. (2016), see also He et al. (2016). Sustained trend: Bond-Lamberty et al. (2018) Tundra lakes: Bogard et al. (2019), dry uplands: Voigt et al. (2023). Computer intercomparison: Shi et al. (2024).

CO_2 in the atmosphere also shot up at the fastest rate ever—yet human fossil fuel emissions had almost leveled off as solar and wind energy expanded. The most likely source of the extra CO_2 was the droughts that ravaged large areas that year, killing vegetation and aggravating forest fires. Emissions from fires in particular had increased some 60% since 2020. Models had not taken such emissions into account, nor how fires were weakening the ability of forests to take up and store carbon. "We are already reaching the point of significant change in ecosystems," a research team warned. "The obvious question," another researcher said bluntly, was "are we on the cusp of a tipping point in natural ecosystems?"

While forests were becoming less effective as a sink taking up carbon, Arctic permafrost seemed to be shifting already from a sink to a source. A comprehensive analysis of more than a thousand measurements in tundra, lakes, and bogs found the Northern Hemisphere permafrost region was now a net source of methane and nitrous oxide. Living vegetation continued to take up CO_2 so the balance of that gas was roughly neutral. Overall, it was increasingly apparent that warming would increase emissions from natural ecosystems, although on a timescale closer to centuries than decades. The first computer study to look at carbon cycle feedbacks as they could develop in future centuries reported that it might be possible that enough emissions would accumulate to raise global temperature by more than 6°C. That would match the "hothouse" climate that prevailed 40 milllion years ago—climate conditions for which human civilization and even human physiology were utterly unprepared. [1]

Scientists still had a lot to learn about how the rising CO_2 levels and temperatures would affect biological systems. And understanding the mechanisms one at a time, it turned out, was not enough. "The last decade has seen revolutionary advances in understanding," a marine biologist remarked in 2021. The traditional relatively stable picture, in which different effects of climate change added up separately, was giving way to ideas about effects interacting and multiplying one another. That raised "the possibility of sudden and unexpected shifts" as entire systems passed tipping points.

A new research specialty emerged as ecologists tried to identify signals that would warn when a particular system was approaching a fatal tipping point. The problem was so difficult, however, that a breakdown might not be discovered until it was unstoppable. "Ecosystem dynamics are complex and nonlinear," another expert explained, "and unexpected phenomena may arise as we push the planet into this unknown climate state." Any surprises would probably be unpleasant ones, given that natural ecosystems and human agriculture are well adapted to the traditional

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[1] Ke et al. (2024). Increased wildfire emissions: Jones et al. (2024); "change in ecosystems:" Burton et al. (2024b); "obvious question," Rob Jackson, quoted in Sarah Kaplan, "What a Record Spike in Planet-warming Gases Says about the Health of the Earth," *Washington Post* (April 16, 2025), online at https://www.washingtonpost.com/climate-environment/2025/04/16/what-record-spike-planet-warming-gases-says-about-health-earth/. Permafrost region: Ramage et al. (2024). More than 6°C (if sensitivity is well above the "most likely" value): Kaufhold et al. (2025).

climate.[1]

Underlying these concerns were the detailed studies of ice cores, beginning in the 1990s, that showed how the levels of CO_2 and methane in the atmosphere had swung up and down almost exactly in tandem with temperature as ice ages came and went. Once something caused a bit of warming or cooling, the planet had responded with a strong rise or fall of the levels of greenhouse gases, which led to further warming or cooling, and so forth. It was a strong

[1] For a summary report on surprises, mostly unpleasant, in the short period 2005-2009 see Richardson et al (2009). Other examples: a multi-year study of grass found carbon uptake sharply decreased in hotter summers, Arnone et al. (2008); since leaves function more efficiently in diffuse light than in dappled bright-or-dark direct light, clearer skies will reduce carbon uptake, Mercado et al. (2009); a controversial study reported detecting severe loss in abundance of ocean phytoplankton, Boyce et al. (2010); warming kills plankton, resulting in less emission of DMS and thus less cooling clouds, Six et al. (2013); changes in Arctic rivers and coastlines could bring more carbon loss than models anticipated, Abbott et al. (2016); a 7-year laboratory study found warmed wet tundra produces more methane than expected in relation to CO_2, Knoblauch et al. (2018); carbon emissions from peatlands drained and converted to croplands had been overlooked, Qiu et al. (2021); on the other hand, warming and adaptation of ocean systems may bring more carbon uptake than models expect, Lomas et al. (2022), and models could show less warming if they included the daily vertical migration of ocean plankton, Dunne (2022).
"Revolutionary advances:" Gary Griffith, "Coming to Recognize Marine Ecosystems as Complex Adaptive Systems," in *Nature Climate Change* (2021); "Ecosystem dynamics:" Doney (2006), p. 695.

confirmation that the gases played a potent role in climate change because of feedbacks—some of whose main engines, it was now clear, were located in the biosphere.

This essay only touches on the extensive scientific work on expected impacts of global warming on living creatures (including us). See the separate essay on Impacts.

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