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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, could indeed alter global climate—humanity. As scientists looked more deeply into how carbon moved in and out of the atmosphere, they discovered many ways that other organisms could also exert powerful influences. Forests in particular were deeply 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 were major players in the climate changes that would determine their own future.

This essay includes separate sections on the Controversy over the Carbon Budget, Methane and the Gaia Hypothesis.

"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 Azore 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.

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

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

[2] Colón (1960), p. 147.

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 follows the plough, or flees 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, 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]

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 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,

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[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.

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 than the air holds in CO_2). 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—plants 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 chemicals that it seems natural and inevitable, but in fact it became familiar only in the late 1950s.)[2]

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.

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[1] Hutchinson (1954), 389-90; see also Hutchinson (1948).

[2] 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).

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 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.[1] 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.[2] 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.[3]

The first primitive models suggested that the systems should behave in the manner long assumed. Sea water 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.[4] 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).[5] 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.[6]

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.[7] 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

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[1] Craig (1957a).

[2] Eriksson and Welander (1956).

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

[4] Eriksson and Welander (1956).

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

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

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

conclusions about stability relied not just on objective calculations but also on what seemed plausible.

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 sea water. 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.[1] 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.[2]

Yet as the panel realized, the planetary environment was certainly affected by at least one species—our own. During the 1960s, evidence mounted 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

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[1] "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).

[2] National Academy of Sciences (1966), p. 11.

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 figure how many tons of carbon cycled through the plants each season.[1] The consumption was not keeping up with the quantities of the gas that humans were putting into the atmosphere: year by year the level ominously mounted.

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 ominous 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."[2]

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 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.[3]

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 rain forest 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 suggested that along with overgrazing, human emissions, not only of greenhouse gases but also of industrial haze, had caused changes in 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

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

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

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

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. It could itself be a source of the kind of "positive" feedbacks that brought instability.[1]

Where Does the Carbon Go? (1971-1988)

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 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 given the first big 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.

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[1] 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.

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, to push 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, including the carbon processed by living creatures. They calculated that something like 40% of new CO_2 dissolved into the surface layer of sea water, 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 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 sinking into the biosphere. Perhaps trees and other plants were growing more lushly thanks to CO_2 fertilization?[3]

If so, that was hard to check. 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 and warmth increased. Some ocean carbon calculations entirely left out not only plants but all the terrestrial biota, that is, all organisms on land. Plant biologists—a type of specialist that had scarcely interacted with climate scientists—had published few solid studies of fertilization. Scientists could well suspect that pumping CO_2 into a greenhouse and seeing the plants grow better said little about the complex interactions in an open field, but studies that would confirm the suspicion did not get well underway until the 1990s.

What was clear, as Keeling pointed out in 1973, 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. 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.[4] As a sign of the uncertainty, some rough calculations suggested that land plants might

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[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.

[3] 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.

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

not be a sink 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.[1]

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 through deforestation of the tropics, plus the decay of plant matter in soils damaged by agriculture, we were 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 than anyone had thought. Bolin admitted that "This result is difficult to reconcile with present models of the role of the oceans."[2]

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 nature but also to avoid disrupting the climate.[3]

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, "stimulating much discussion."[4] 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.[5]

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 to the plants of the Amazon and Siberia. When he invoked field

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

[2] 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).

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

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

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

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.

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 more recently the situation had changed, with nearly all the new carbon coming from fossil fuels. The 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 becoming a popular idea in the growing environmental movement—a movement in which Woodwell had long been a leader.[2] Other scientists, however, gradually concluded that his claims were exaggerated. 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, and 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 much precision until they could say how the planet's living systems affected the level of CO_2.

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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.

Taking his own advice, Broecker began to look at sea water as a container not only of chemicals but of life. In 1982, he drew attention to what was later called a biological carbon "pump."[1] The plankton that grow abundantly in surface waters use carbon to build their bodies and shells. After they die, fragments eventually snow down to the ocean floor, where the carbon is buried in sediments. One might suppose that this would immediately reduce the amount of CO_2 in the atmosphere. Further investigation, however, showed that the short-term effect is not straightforward. When creatures make calcium carbonate for their shells, they alter the complex chemistry of sea water, which actually ends up releasing more of the gas into the air. Scientists had much to study in the many biochemical changes that occur as plankton flourish and dissolve.

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. Moreover, boreholes drilled in ice sheets showed that the atmosphere's CO_2 content and temperature went up and down together. Were they on the track of the "holy grail" of geochemical research, the mechanism that dominated ice age cycles?[2]

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 nutrients, 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 biological activity and climate. Only ocean biology, however, seemed likely to explain the evidence that global temperatures and CO_2 shifted in tandem, and over mere centuries.

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 sea water would more easily dissolve the compounds that made up shells. Whether that would endanger sea creatures, and what would eventually result from all this, nobody could guess.[3]

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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).

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

[3] 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);

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. Indeed it seemed 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.[1]

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 the literature, it is extremely difficult to calculate” what was happening between the biosphere and the atmosphere.[2] Woodwell insisted that if not now, then in the future, global warming would cause vegetation to release overwhelming amounts of CO_2. Through the 1980s, debate continued 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.”[3]

The story of the missing carbon is continued below in the “After 1988” section.

Methane (1979-1988)

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 of CO_2 and also other greenhouse gases. Methane gas (CH_4) in particular had a significant part to play in the global carbon budget.[4] And scientists had recently realized that methane, molecule for molecule, was many times more effective than CO_2 as a greenhouse gas.

The gas came mainly from living creatures: bacteria lurking everywhere from soil to sea water to the guts of elephants. 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, are the

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Sarmiento and Toggweiler (1984); Knox and McElroy (1984); for a later example, Boyle (1988a); a review: Sigman and Boyle (2000).

[1] Houghton et al. (1983).

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

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

[4] “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).

largest source of the methane in the atmosphere.[1] These natural emissions were much greater than the amount of methane that escaped as humans extracted and burned natural gas. Moreover, people were beginning to recognize that the world's wetlands were rapidly changing under human impact. And that was not all.

An especially thought-provoking calculation showed that a huge reservoir of carbon was frozen in the deep permafrost layers of peat that underlay northern tundras—perhaps half as much carbon as in all the world's tropical forests and jungles.[2] As global warming reached these peat beds, they might release a huge amount of $CO_{2.}$ The soggy tundras, covering millions of square kilometers and highly sensitive to temperature change, might also emit massive quantities of methane.[3] 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 positive feedback—more greenhouse warming, thus more emission, and so on up.

Besides living vegetation like trees and plankton, and dead vegetation like humus and peat bogs, 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 domestic animals, and the rapid increase in meat and milk production added significantly to the rising level of the gas in the atmosphere. Rice paddies too had been spreading swiftly, with methane bubbling up from the mud.[4] Even termites, found everywhere on the planet that 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.)[5] 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 be affected by climate change itself. All these interlocked effects would somehow have to be taken into account.

Meanwhile studies of ancient ice pulled up from deep in the Greenland and Antarctic ice caps showed that during past ice ages, the levels of both CO_2 and methane in the atmosphere had gone through big swings up and down, roughly in step with the rise and fall of global temperatures. Nobody could think of any physical or chemical effect strong enough to cause this. That left the biosphere. Some examples were the way shifts of temperature must have changed the abundance

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[1] Ehhalt (1974).

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

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

[4] For references, see Mooney et al. (1987).

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

of marine life (and thus its emission and absorption of CO_2 and methane), or the way climate could have affected how forests and bogs took up or released the gases.[1] Reversing the sequence, if the greenhouse gas abundances had changed first because of something happening in the biosphere, climate change would have followed.

Gaia (1972-1988)

Geoscientists had 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 player in the global carbon budget. Indeed it dominated the game on the human timescale of centuries. For other chemical elements, for example the cycle 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.[2]

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.[3]

Back in the 1960s, Lovelock had proposed measuring gases in the Martian atmosphere as a way to look for traces of life. Living creatures, he realized, emitted gases that would 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.[4]

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

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

[2] Lovelock et al. (1972).

[3] “products:” Lovelock and Margulis (1974), p. 9.

[4] Hitchcock and Lovelock (1967), “disequilibrium” p. 150, “blindness” p. 158.

aware of this fundamental difference of viewpoint." Lovelock's difficulties illustrated how hard it was to grasp that living creatures could play a huge role in the geochemistry of their planet.[1].

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 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 and indeed 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.[2]

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."[3] However, one could also imagine scenarios where global warming killed off plankton, bringing no beneficial feedback but 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 misleading, 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 it 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

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

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

[3] Charlson et al. (1987), p. 661. The central idea was first proposed by Shaw (1983).

corner of atmospheric chemistry—which in turn affected everything from clouds to the weathering of rocks. "The science of Gaia is now part of conventional wisdom," boasted Lovelock in 1991 with only partial exaggeration, "and is called Earth system science; only the name Gaia is controversial."[1] For both scientists and the public the debate promoted an understanding that life interacts with climate in ways unforeseeable and disturbingly powerful.

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 here it was at the center. 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.[2]

From the 1980s forward, a variety of experts did extensive work on how human agricultural and economic systems as well as natural ecosystems might interact with global warming and a rise of CO_2 levels. Those studies mostly fall outside the scope of these geophysical essays and are not discussed here.

After 1988

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 rain forests that had been cut down

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[1] Lovelock (1991), p. 1

[2] Fisher (1988); earlier diagram: Kellogg and Schneider (1974).

showed a measurable decrease in rainfall, since moisture was no longer evaporated back into the air from the leaves of trees—in Brazil, rain fled from the plough. 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 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. Deforestation and other deliberate changes in land use seemed less likely to to make a great difference outside the region that people were altering.

That left open the question of inadvertent changes, as vegetation everywhere reacted to greenhouse gases. 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 and heat the air, adding to global warming.[1]

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 such details as the way increased levels of CO_2 would affect the evaporation of moisture from leaves. And since nothing influenced vegetation so much as humans, the models must also somehow include social and economic forces.[2]

Some scientists stuck by the old view that natural systems were self-stabilizing, and 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.[3] 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 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 use more carbon. The increase in plant growth would level off. Some experts predicted that warming would eventually foster decay, with a net *emission* of greenhouse gases, bringing yet more warming.

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[1] The pioneering demonstration that the Amazon Basin generated much of its own rainfall was Salati and Vose (1984); Couzin (1999). More rain (in dry season only): Negri, 2004.

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

[3] Especially Idso (1989).

By now, most specialists in paleobiology, geochemistry 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 runaway positive feedbacks. Studies of fossil pollen confirmed a growing suspicion that as climate changed, entire assemblages of species might be driven into configurations that had never been seen before.[1] Some began to foresee extinctions of species and the impoverishment, perhaps the utter failure, of vital ecosystems.

A few people suggested solving the greenhouse problem by using biology deliberately. Perhaps we could manipulate the "biological pump" of dead plankton that snowed down upon the ocean floor, taking carbon with them? The plankton did not flourish without trace minerals, which are scarce in mid-ocean. For decades there had been talk about improving the biological productivity of barren ocean regions by adding nutrients, something like the traditional nitrate and phosphate fertilizers used by farmers. Studies in the late 1980s and 1990s suggested that iron was the keystone fertilizer. By dumping iron compounds where the element was lacking, we might be able to stimulate plankton to bloom. Could the 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!"[2]

Scientists began planning experiments to see just how much carbon they could send to the sea 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 rain forest. 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.[3]

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[1] Webb (1986).

[2] 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, according to John Weier, obituary at http://earthobservatory.nasa.gov/Library/Giants/Martin/. Examples of papers confirming that fertilization of the oceans by iron could have played a role in ice ages: Moore et al. (2000); Kohfeld et al. (2005); Abelmann et al. (2006).

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

Moreover, as increasing amounts of CO_2 dissolved into the oceans, the surface waters were growing more acidic. Many creatures would find it increasingly difficult to make their shells. Unless humanity restricted its emissions, in future centuries the oceans would inevitably become more acidic than they had been for hundreds of millions of years. That would reduce some the planet's grandest and oldest 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 fisheries but might reduce the capacity of the biological "pump" to sequester CO_2 in the ocean depths. Exploring how sea water 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 manyf decades.[1]

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. Meanwhile some continued to present arguments that excess CO_2 was mostly sinking into the oceans, opposed by others who came up with equally persuasive argument that the gas was mostly going into plants. Only more data could resolve these questions. Particularly helpful were regular measurements of CO_2 levels at many locations, made by the U.S. government (to be precise, NOAA, with analysis chiefly under Keeling at Scripps). Flasks of air were gathered at a string of stations running from the South Pole 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, Charles David's son.[2] 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 by new studies, which 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 various things, such as the weather fluctuations brought on by El Niño events.[3]

(2000).

[1] "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 (2006).

[2] 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.

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

By the early 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. The emissions were continuing to increase, indeed accelerate, 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 taken up by 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.[1]

A study published in 2004 took a long-term look at the processes. The oceans had absorbed about half the total carbon produced by humanity since 1800, with the rest remaining in the air. Thus over the past two centuries, emissions due to deforestation and other changes had roughly matched absorption by the terrestrial biosphere. Looking over a much longer term, maverick geoscientist William Ruddiman argued that humanity had been altering climate for thousands of years as the spread of agriculture produced ever more CO_2 and methane. The emissions from rice paddies and so forth might explain why the world had not been cooling as it normally did at this stage of the glacial cycle. That was controversial, but nobody now disputed that human activity, and its interactions with the rest of the biosphere, was 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 emissions mounted and biological systems responded.[2]

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 effects of fertilization—including global fertilization not only by CO_2 but also by our rising emissions of nitrate gases. Experts also began to debate how agricultural practices and other land use by humans affected the storage of carbon in soil, and indeed could 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).[3] All these uncertainties raised severe problems for international negotiators, when they tried to assign responsibility to particular nations for how much they added to the greenhouse effect or subtracted from 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

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[1] Among the many publications see, e.g., Prentice and Lloyd (1998); Schindler (1999); Stephens et al. (2007). “Long-sought”: .Stone (2008).

[2] Ocean study: Sabine et al. (2004). Ruddiman (2005); Ruddiman (2006).

[3] Pielke (2005).

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 warming would make it harder for the planet to take up carbon, and might even trigger increased emissions. In particular, their simulated tropical forests dried up and began to emit massive amounts of CO_2. The team's 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.[1]

In a 2001 report, an intergovernmental panel of experts on climate change (the IPCC) concluded that the net effect of feedbacks from global warming "is always to increase projected atmospheric CO_2 concentrations." As research proceeded, the results continued to be discouraging. An increasing number of groups worked up models that coupled climate changes with changes in soils, vegetation and the oceans. A large international collaboration that compared a variety of these models found many differences and uncertainties, of course, but every team predicted positive feedbacks. It was a matter of simple physics that as the oceans grew warmer, the sea water would absorb gases less readily. Tropical forests would show a similar effect for biological reasons. The worst worry was the Amazon forest, sustained by rains that were largely water evaporated from the jungle itself. Modelers found that warming combined with the rampant deforestation might flip the entire system to parched grassland.

Scientists did not have enough data to say with any confidence what would happen in the Amazon basin, nor in the many other regions with special characteristics. Reports by official panels conservatively played down the extreme scenarios. On the other hand some noted that the models had not yet incorporated factors such as forest fires and insect infestations, which were already noticeably increasing and reducing the ability of plants and soils to take up carbon. On land or in the sea, there were many other biological feedbacks not yet taken into account, which could be either favorable or unfavorable. But overall, everyone agreed that an ever higher fraction of the CO_2 that humanity emitted would stay in the air, adding substantially to global warming.[2]

Field studies were also ominous. For example, a 2005 report indicated that rising temperatures would cause soils in general to decompose organic matter faster, releasing extra CO_2 and accelerating warming. Already in 2003, a measurement of an Arctic bog had showed a sharp rise in methane emissions since 1970, and later studies in Siberia confirmed this was happening all around the Arctic. Meanwhile, there was new evidence that climate had important effects on ocean plankton, while plankton acted on climate in return. In this case, as with some of the complex interactions in soils and so forth, it was not yet clear whether the feedback would help

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

[2] IPCC (2001), p. 186; comparison of 11 models: Friedlingstein et al. (2006); for the 2007 IPCC conclusions see Meehl et al. (2007), pp. 789-93. Amazon: Oyama and Nobre (2003); a review: Malhi et al. (2008). "Fires, storms, insects, and disease... have been largely ignored," Houghton (2007), p. 338 (a review); another review: Heimann and Reichstein (2008).

or hurt. At least the physics of uptake of carbon by sea water was understood. As predicted, the oceans were found to be absorbing less CO_2 —although the situation was worsening more rapidly than expected.[1]

Most of the other new effects that researchers turned up were also bad news. For example, the world's increasing efforts to control air pollution from sulfates and nitrates, however necessary for health and other reasons, worked in the wrong direction when it came to climate. It semed that as we restored cleaner air, forests would take up significantly less carbon. Other research continued to demonstrate that we had a lot to learn about the way increasing temperatures might affect the emissions of greenhouse gases from biological systems. "Ecosystem dynamics are complex and nonlinear," as one expert remarked, "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 were well adapted to the present climate.[2]

Meanwhile cores drilled from ancient ice revealed that such changes had happened in the past. The levels of CO_2 and methane in the atmosphere had lurched far up and down as ice ages came and went. It seemed that the gas levels had changed shortly *after* the temperature shifts. Once something caused a bit of warming or cooling, the planet had responded with a strong rise or fall of the levels of CO_2 and methane. It was a strong confirmation that these gases played a potent role in climate change through feedbacks—whose main engine, it was now clear, was located in the biosphere.

This essay does not discuss the extensive scientific work that has been done on expected "impacts" of global warming on living creatures (including us). See the separate essay on Impacts.

Related:
The Carbon Dioxide Greenhouse Effect
Simple Models of Climate

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[1] Soils: Knorr et al. (2005); 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. Plankton: e.g., Meskhidze and Nenes (2006) on plankton emissions affecting cloudiness, Behrenfeld et al. (2006) on climate affecting plankton blooms. Oceans (where the difference is attributed to changes in the exchange between the surface and lower layers): Schuster and Watson (2007); Le Quéré et al. (2007).

[2] For a summary report on surprises, mostly unpleasant, in the short period 2005-2009 see Richardson et al (2009). Examples: 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). And a multi-year study of grass found carbon uptake sharply decreased in hotter summers: Arnone et al. (2008). "Unexpected phenomena:" Doney (2006), p. 695.