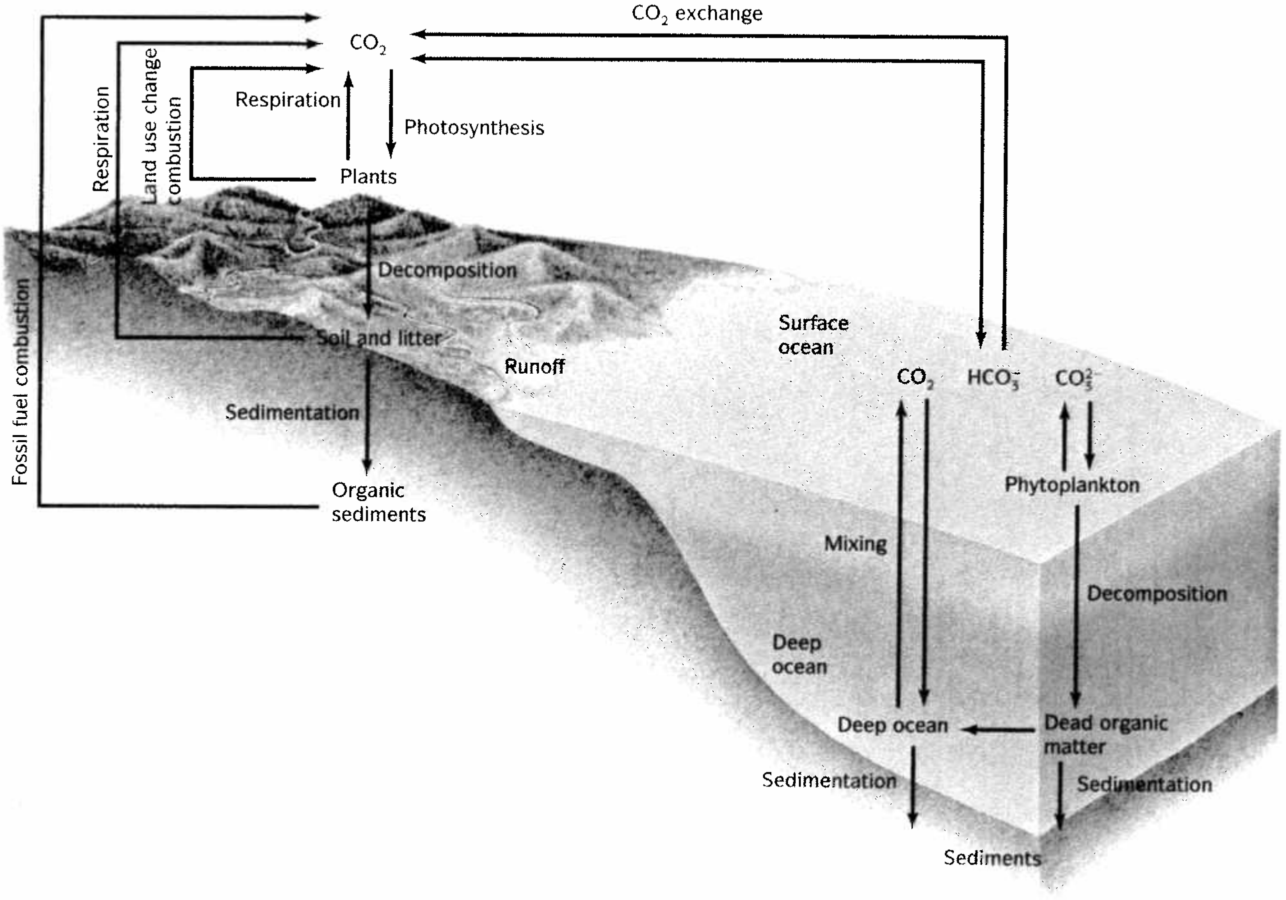
CHAPTER 4

Changing the Carbon Cycle

For millennia, humans have been intervening in carbon's biospheric cycle. Until recently most of these interventions took the form of a gradually expanding transformation of natural ecosystems. We have converted forests and grasslands to cropland and cut trees and shrubs to supply the rising demand for fuelwood, charcoal, and timber. These transformations have created new, man-made landscapes, first throughout the Middle East, then in most of Europe and in large areas of monsoonal Asia, and later in eastern North America and in parts of South America and Australia.

Yet until the middle of nineteenth century the pace of these changes was slow, and their consequences for the global carbon budget marginal when compared to the usual fluctuations seen in natural carbon flows. In contrast, recent interventions in the carbon cycle have a far greater potential to change and disrupt natural flows and stores. Although our transformations of the landscape intensified in the decades since 1850, they are not the main cause of concern: our worries have arisen mainly because of a profound change in civilization's energy base.

Solar radiation supplied the energy needs of all preindustrial societies—either by its virtually instantaneous conversion to heat or to water and wind flows, or by its just slightly delayed transformation to chemical energy through photosynthesis. The latter transformation is responsible for producing new phytomass and, indirectly through food and feed, it has made possible all human and animal labor. In contrast, although the fossil fuels that we rely on today are also sequestered sunlight, the biomass transformed during their formation was synthesized at least thousands of years ago, in the case of peats, and as much as hundreds of million years ago, in the case of hard coals.



Today's biospheric carbon cycle. The red arrows mark the two most important direct human interferences in the cycle—combustion of fossil fuels and land use changes, above all deforestation in the tropics.

While traditional societies tapped only a tiny fraction of the practically inexhaustible supply of solar energy, modern civilization has been depleting enormous, but finite, reserves of fossil energies. Just before the end of the nineteenth century, the combustion of fossil fuels had become the most important energy conversion of the industrializing world, and today it is by far the largest single human-controlled factor perturbing the carbon cycle.

The first, prolonged, phase of this new high-energy era ended with the industrialization of North America, most of Europe, and Japan. The second phase, beginning around 1950, has been characterized by a further substantial rise in Western standards of living, by huge increases in the poor world's population, and by the rapid modernization of many Asian, Middle Eastern, and Latin American economies. Through our conversion of fossil fuels we have achieved unprecedented rates of economic growth and impressive advances in life expectancy and standards of living, even with a relatively fast-growing population. But as this transformation proceeded, it began to increase carbon's atmospheric presence at rates that were much faster than any known natural process had achieved since the emergence of the first complex civilizations less than 10,000 years ago.

Our interference in the carbon cycle is both ubiquitous and intense. We already consume or destroy—directly and indirectly, as food crops, animal feed, fish catches, wood harvests, and in phytomass fires set to clear plant cover—at least a fifth of the new plant mass produced annually. Every year we add about 8 Gt of carbon from fossil fuel and phytomass to the atmosphere; roughly two-fifths, or more than 3 Gt of this carbon, remains aloft, a rate of enrichment unprecedented during the current interglacial period.

One consequence of this enrichment is by far the most worrisome: the possibility of pronounced, and relatively rapid, global warming. If realized, this change would have a variety of effects on the environment, economy, and society, some virtually assured, others less certain. Although we have identified a large number of such consequences, enormous uncertainties are the rule in almost every particular case. The only sure conclusion is that—given our dependence on fossil fuels and given the persistence of CO_2 in the atmosphere—these concerns will remain with us for many generations to come.

The Earliest Carbon Losses

Even the small, roaming groups of foragers of prehistory could leave long-lasting marks on their environment, especially if they repeatedly set fires or persisted in the hunting of large herbivores. Their actions sometimes drastically altered the local species composition, but they did little to change carbon's stores or flows beyond the local, or sometimes regional, level. More extensive, and usually more lasting, changes came when human communities gradually adopted shifting agriculture and settled cropping.

A group of Russian biologists has reconstructed what the preagricultural vegetation cover might have been; they estimate that continental phytomass stored almost 1100 Gt C some 5000 years ago. This is about twice as large as the median value given by estimates available for the late twentieth-century phytomass, which range between 420 and 840 Gt C. These figures imply that on average some 100 Mt of phytomass carbon has been lost per year since the time of the first high Middle Eastern cultures.

Societies that practised shifting cultivation reaped a few harvests from a plot, then moved on, leaving the original plot to revegetate for a period of many years, often for several decades. These cultivators had to periodically destroy the existing natural plant cover, either partially or totally, and burning was the easiest way to accomplish this. The net effect was a rapid release of carbon in fires (mostly as CO_2, but also as CO, CH_4, particulate organic carbon, and the elemental carbon in soot). This initial loss was followed by further gradual carbon losses from the decomposition of the partially burned phytomass and from faster decay of organic matter in soil.

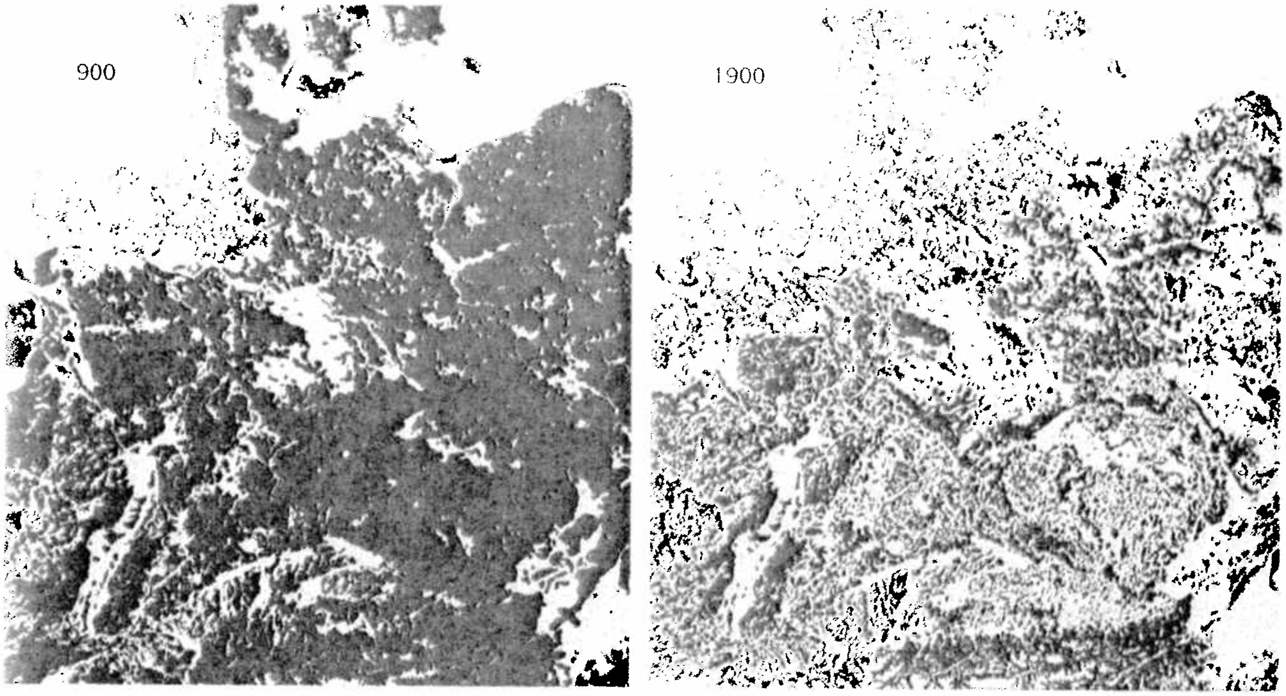
Similarly, when settled farming replaced forests or grasslands with permanent fields, prompt CO_2 losses from the burning of phytomass were followed by long spells of elevated CO_2 emissions from faster decay of organic matter in soils. Replacing the original trees or grasses with crops did little to restore the initial carbon stores. The carbon tied up temporarily in food, feed, and fiber crops added up to only a small fraction of the element present in the natural phytomass. While a mature temperate forest in western Europe would store between 100 and 200 t C per hectare, the staple grain crops that medieval peasants planted in its place would contain mostly between 2 and 4 t C per hectare at the time of harvest, after four to six months of growth. And because of their extensive roots, even the unimpressive-looking short grasses of the steppe or prairie would contain much more carbon than a wheat crop that supplanted them.


Shifting (slash-and-burn) agriculture destroying forests on the slopelands of Mindanao, in the Philippines.

By converting forests to new cropland, in order to feed growing populations, our ancestors deforested extensive areas throughout the ancient Middle East and parts of Europe and Asia, transferring billions of tonnes of carbon from plants and soils to the atmosphere and, eventually, to the ocean. For millennia, farming societies carried out this existentially imperative assault without many qualms: they thought of forests as hostile and dangerous places, and, in any case, the extent of treed lands was seemingly inexhaustible.

We have enough archaeological and historical evidence to establish the periods when deforestation was at its most destructive. The great surge of clearing for farmland that swept Europe in the Middle Ages was over by the beginning of fourteenth century, and a new wave, begun after 1500, was heightened by the rising demand for wood to be used in shipbuilding and, as charcoal, to provide the heat needed for metal smelting. But we do not have enough evidence to make satisfactory estimates of aggregate phytomass losses. Even estimates for the eighteenth and a part of the nineteenth century must be arrived at indirectly, by multiplying the best available population totals by typical rates of land conversion per capita.

The reconstructions carried out by Richard Houghton at the Woods Hole Research Center in Massachussetts and by John Richards at Duke University have global cropland more than doubling in

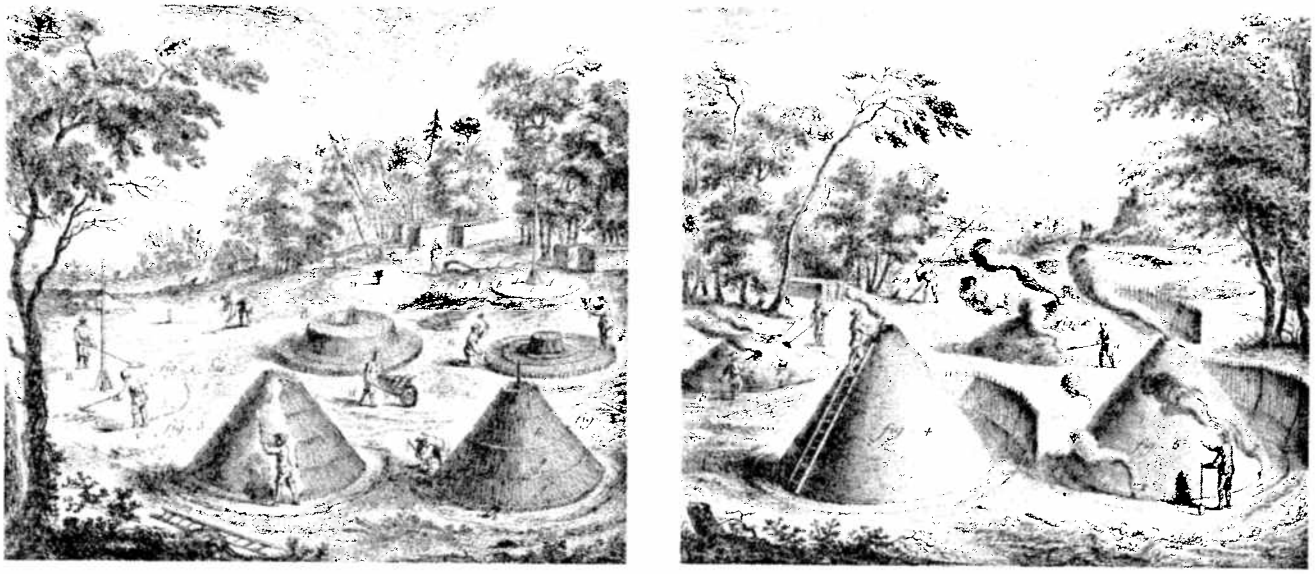


The extent of Central European forests in 900 and 1900. Most of the lowland forests were converted to farmlands, while many mountainous areas lost their tree cover to the growing demand for charcoal.

150 years, from about 260 million hectares (Mha) in 1700 to almost 540 Mha by 1850, with nearly all of this gain coming from the conversion of forests and woodlands. By far the largest absolute gains of that period took place in Russia (about 60 Mha), China (nearly 50 Mha), and the United States (also close to 50 Mha). A highly conservative estimate would suggest that CO_2 emissions from such conversions totaled at least 35 Gt C during the 150 years before 1850, an annual mean of close to 250 Mt C.

Over centuries the portion of CO_2 emissions originating in the preparation of charcoal gradually became larger. Traditional societies had always burned wood and crop residues (mainly straws) for heat, but because of its high energy density and clean burning, charcoal became the preferred fuel. But to produce a kilogram of charcoal required at least 4 kg, and up to 7 kg, of air-dry wood. A large medieval city of 100,000 people located in a temperate climate (Paris or Beijing of the twelfth century would be a good example) needed more than 150,000 t of wood a year if half of its fuel supply came as charcoal. Depending on the productivity of the surrounding forests, a city that wanted a sustainable supply of fuel would have to rely on an area of forest up to 200 times the city's size. Not surprisingly, extensive deforested zones developed around most larger cities in the preindustrial world.

Because of its low efficiency, the traditional smelting of metals placed an enormous burden on local wood supplies. Copper's high melting point (1083 °C) made its smelting, especially from common sulfide ores such as chalcopyrite ($CuFeS_2$), very energy-intensive. The late Romans needed



French charcoaling practices of the mid-eighteenth century, as depicted in an etching from *L'Encyclopedie*, Diderot and D'Alembert's pathbreaking summary of everyday activities, sciences, and arts. The construction of a symmetrical wood pile and its plastering by clay (left) were followed by firing and the raking out of the charcoal (right).

about 90 kg of wood to smelt one kilogram of copper, and this rate remained largely unchanged during the Middle Ages. In contrast, the techniques of iron smelting advanced substantially during that time, as the Europeans introduced ever more efficient furnaces. Fires enclosed in shallow, clay- or stone-lined pits were replaced by clay-enclosed hearths and gradually by taller stone-lined furnaces, and the first simple blast furnaces producing pig iron appeared just before 1400.

Nevertheless, charcoal remained the sole fuel consumed in these furnaces throughout the nearly three millennia of their evolution. Ancient iron smelting usually consumed an amount of charcoal more than 25 times the mass of the metal produced. Although this ratio dropped to between 10 and 20 for medieval hearths, to about 8 for furnaces around the year 1700, and to just over one for the best Swedish furnaces in 1900, the increase in the amount of metal being smelted more than made up for these savings. The large efficiency gains could not prevent extensive deforestation in early modern Europe. The wood needed to fuel a single early eighteenth-century English furnace for one year had to be cut from anywhere between 1500 and 5000 ha of trees, a forest area as large as a circle with a 4-km radius.

Based on the best available totals of global population and worldwide consumption, I have estimated that the annual consumption of wood for fuel and charcoal was less than 1 Gt before the year 1600, and that it roughly doubled by the year 1800. The burning of wood and charcoal would have released annually less than 500 Mt C as CO_2 during the late Middle Ages and more than 700 Mt C during the nineteenth century.

What was the total amount of CO_2 emitted from vegetation destroyed to make room for crops or burned for fuel during the preindustrial era? Coming up with an estimate inevitably involves some double-counting—for we can only guess what shares of fuelwood and charcoal came from trees cut during the conversion of forests to fields. Whatever the actual gross CO_2 releases from deforestation and wood consumption may had been before the modern era—and they were almost certainly less than 500 Mt C a year before 1500, and no more than 1.5 Gt C by 1850—they were completely submerged within the natural fluctuations of the carbon cycle, clearly too small to leave any discernible imprint on background concentrations of the gas reconstructed from tiny bubbles caught in polar ice.

Vanishing Ecosystems and Carbon Losses: The Modern Era

The destruction of phytomass continued to be a large source of atmospheric CO_2 during the second half of the nineteenth century. The overall demand for fuelwood remained high in spite of the enormous growth of fossil fuel combustion, and a new surge in the conversion of forests and grasslands to arable land took place. Wood consumption in North America peaked only during the 1870s, and not until the late nineteenth century did the expansion of the ironmaking industry consume such huge amounts of fuel that even the wood-rich United States had to switch from charcoal to coke.

European colonization of the Americas and Australia—more than 60 million people migrated to these lands—was the main impulse for the massive forest and grassland conversion of the nineteenth century's later decades. In the United States the colonizers and their descendants cleared about 460,000 km^2 of forest during the two centuries before 1850 (an area slightly larger than Sweden), but almost 800,000 km^2 (an area equivalent in size to Turkey) between 1850 and 1910, when the country's population nearly doubled from 66 million to over 121 million. The process peaked during the 1870s, when about 200,000 km^2 of forest was cleared, and a slow reversal began after 1900. Inexpensive steel tools (axes, saws, plows) and powerful horses provided the means for such rapid transformation of the landscape.

Elsewhere, the search for new cropland led to the loss of about 30 percent of all woodland in India between 1880 and 1950, and about one-fifth of all woodland in Burma. All but about one-tenth of Brazil's species-rich subtropical Atlantic forest was turned into farmland, charcoal, and fuelwood. At the same time, settlers accelerated the conversion of grasslands to cropland in a number of far-flung locations: on America's Great Plains and the Canadian Prairies, on Argentinean chacos and pampas, in Australia, on the plains and marshes of China's Jilin and Heilongjiang provinces, and on the steppes of southern Siberia and Kazakhstan. Conversions in the last two regions peaked only after 1950, but elsewhere the expansion was largely over by the 1930s.

Wetlands, too, were destroyed on a large scale to create new farmland. These ecosystems are not only among the biosphere's most productive plant communities (many of them producing annually more phytomass than some tropical forests), they are also among the richest harbors of biodiversity, and among the most effective means of protection against floods and coastal erosion. And they also provide an important carbon sink, for they sequester large amounts of the element in peats.

We do not know the real extent of wetland losses because we do not even know reliably the area of existing wetlands. In the United States, the country with one of the most extensive surveys and assessments, recent estimates of total wetland area have varied nearly twofold. The best American assessment suggests that by 1980 the country's wetlands had shrunk to 47 percent of their 1780 area. Florida's Everglades and California's Sacramento–San Joaquin delta are the two best-known regions that have suffered substantial losses. In the

Pioneer farmers used steam tractors to break up huge tracts of prairie grassland in South Dakota during the 1890s. The settling of North America's interior entailed a massive release of plant and soil carbon, as well as a huge loss of soil nitrogen.

Everglades, peats are exposed to the air as tracts of swamp are drained for fields and housing development and as irrigation and urban water demand cause water levels to fall. The oxidation of exposed peats releases every year CO_2 amounting to almost 40 t C from every hectare of drained land.

CO_2 emissions from fires and land conversions are still quite substantial, but there has been a clear shift in their regions of origin. Forests have made appreciable, in some cases spectacular, comebacks in most industrialized countries, mainly because farmers have abandoned marginal farmland. Some European nations (including France, Italy, Austria, and the Czech Republic) have gained between 25 and 40 percent more forest since 1950. For the continent as a whole, the area of forests and woodlands grew by about 15 Mha (amounting roughly to a ten percent increase) between 1960 and the mid-1990s, and the quantity of wood gained annually through new growth has been surpassing by nearly a third the quantity lost through felling.

By far the largest absolute increase has come in eastern North America, as crop production has become more concentrated on the richer soils of the Midwest. Here, more than 200,000 km^2 of farmland reverted to forest, mostly after 1950. The trend has been most obvious throughout New England (where forests now cover four-fifths of Vermont, compared to just one-third in 1850), in parts of Appalachia, and throughout the coastal southeastern plain.

In spite of these gains, the total forested area of the United States has declined as cutting has increased in the West. And the world's forests and woodlands have diminished in area faster during the second half of the twentieth century than during the first half. One statistic in particular gives a revealing indication of the recent magnitude of this change: the area cut and burned between 1950 and 1990 (well over 300 Mha) was larger than the total area deforested between 1700 and 1850.

Most of these losses have come in the tropics, and most of the vanished forest has been cut by subsistence peasants and plantation owners. Expansion of grazing land, mostly for beef exports, has been also important in a number of Latin American countries. Other less prominent causes of deforestation include commercial logging and construction of roads, dams, and new mines. Whereas the mature forest may store more than 150 Mt C/ha, grasslands growing in its place will typically store less than one-tenth, and croplands usually less than one-twentieth, as much carbon.

No remaining region of large contiguous tropical forest has entirely escaped this onslaught, but the destruction of the Brazilian Amazon has attracted most of the international concern, and much of the scientific scrutiny. The attention it has received is not surprising, for the Amazon basin is the single largest and richest tropical biome on the Earth, totaling about 5.5 million km^2.

The Brazilian RADAM project of the early 1970s, using airborne side-looking radar, found the amount of clearing to be insignificant. Soon afterward, however, the newly available LANDSAT images began to reveal that the rate of deforestation was accelerating: about 0.75 percent of all Amazonian forests had been cleared before 1975, but that figure had risen to nearly 4 percent by 1978, and to 7.5 percent of the original area 10 years later. Most of the clearing destroyed forests in the three states of Mato Grosso, Pará, and Amazonas, and was encouraged above all by tax incentives for cattle ranching and subsidies for creating new farmland. In the early 1990s medium- and large-scale ranchers were responsible for about 70 percent of Amazonian deforestation, and farmers clearing less than 100 ha per family for less than a third.

Nor is the cutting of forest for charcoal, to be used in iron ore smelting, a matter of history. Brazil's enormous iron ore deposits in Carajás, the world's largest store of high-grade ore, will be reduced to the metal with charcoal. Since it would be too costly to establish and maintain the fast-growing tree plantations that would be required to supply

Subsistence peasants put in the first crop after the destruction of yet another patch of the Amazon's rain forest.

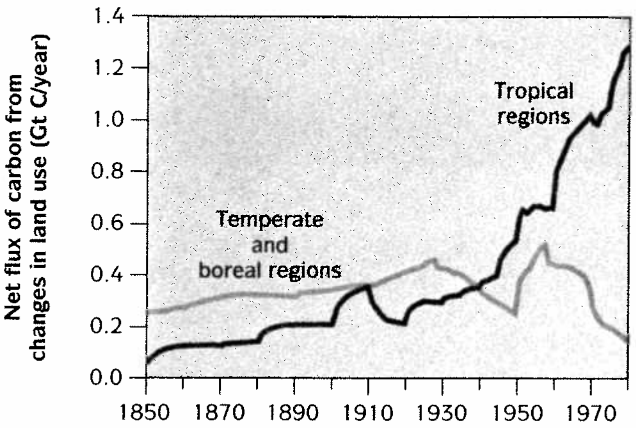
the 20 planned pig iron plants, most of the wood, up to about 10 Mt a year, will come from the surrounding tropical forests. Satellite monitoring of Amazonian deforestation has shown a succession of hopeful and alarming shifts. First, the annual rate fell from a mean of about 2.2 Mha between 1978 and 1988 to 1.1 Mha by 1991, than it rebounded to more than 2.9 Mha by 1995, declined to 1.8 Mha by 1996, and went up sharply once again in 1998.

In a comprehensive evaluation prepared in 1982, the FAO put the annual mean rate of global deforestation at 11.3 Mha, an area slightly larger than Iceland. A decade later a new FAO report indicated that the global deforestation rate had risen by nearly 40 percent during the 1980s, to 15.4 Mha/year, with slightly more than half of these losses in Latin America. On the other hand, the report stressed that 76 percent of the tropical rain forest zone was still covered with forest. The widespread use of remote sensing during the 1980s led to some downward revisions of previously exaggerated deforestation estimates, but also to some worrisome reevaluations. Most notably, at 1.5 Mha/year the rate of deforestation in India was found to be an order of magnitude higher than earlier estimates.

But tropical deforestation is not the greatest cause of CO_2 release from vegetation—grassland fires are. Only a small portion of these fires are intended to clear the land for cultivation: most of them are set regularly, often every year, by pastoralists to reduce weeds and accumulated grass litter, and to eliminate shrubs and tree seedlings whose unchecked growth would make pastures unsuitable for grazing. Wei Min Hao, who works at the Intermountain Fire Sciences Laboratory in Missoula, estimates that pastoralists and peasants burn annually almost 4 Gt of phytomass, releasing about 1.7 Gt C, nearly half of it from the savannas of sub-Saharan Africa.

How much CO_2 is released by grassland fires is uncertain because substantial amounts of carbon are liberated in relatively stable, elemental form as charcoal and soot. Combustion efficiency during the flaming phase of a grassland fire may surpass 95 percent, but smoldering fires can oxidize no more than 50 percent of the phytomass carbon, leaving behind ash with a high carbon content. Of course, the prompt regrowth of the burned grass takes up most of the released carbon again, and savanna fires may have almost no net CO_2 emissions if calculated on an annual, or better yet, biannual basis. Indeed, because these fires cause the formation of black carbon, which is resistant to oxidation, there may actually be a net sink of atmospheric CO_2.

Complexities like these make it difficult to estimate the net CO_2 release from the burning of phytomass worldwide, including the release of carbon from forest fires (clearly a more permanent loss) and the burning of fuelwood and crop residues (again, some of that carbon is assimilated by the next crop's straws and stalks). All phytomass burning now releases annually almost 3 Gt C, and CO_2 emissions from decomposing slash and wood



John Houghton's reconstruction of the cumulative carbon emissions that have resulted from worldwide land use changes for the period 1850 to 1980. Emissions from tropical deforestation have more than made up a sharp post-1960 decline of emissions from temperate and boreal forests.

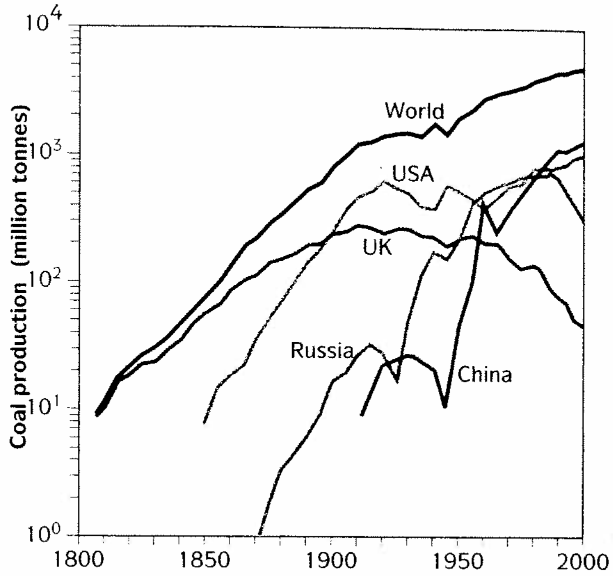
products, and the enhanced flux of CO_2 from soils, add up to at least that amount. Consequently, gross carbon releases from phytomass are over 6 Gt C a year, about four times as much as during the 1850s.

Richard Houghton has put the net total amount of carbon released through changes in land use (including logging) at almost 150 Gt C between 1850 and 1990, with about 125 Gt C going into the atmosphere and the rest into long-lived litter and soils. For comparison, fossil fuel combustion enriched the atmosphere by roughly 240 Gt of carbon between 1850 and 1995. Perhaps the best illustration of the importance of the former flux is that its annual rate was larger than the emissions from fossil fuel combustion until about the late 1940s.

The Arrival of Fossil Fuels

For millennia, successive civilizations on all continents relied on wood and other biomass fuels as their primary sources of heat, yet this dependence came to an end fairly quickly once fossil fuels began to be produced in large amounts. At the beginning of the nineteenth century, only the national economies of England and the soon-to-be-independent Belgium and Netherlands were powered largely by the combustion of coal, and coal was also the dominant fuel in a number of small regions in France, Germany, and the Austrian Empire. In terms of total gross energy content, the global output of coal and crude oil surpassed the annual combustion of biomass fuels only at the very end of the nineteenth century—but by 1950 less than a quarter of the world's useful energy came from wood and crop residues.

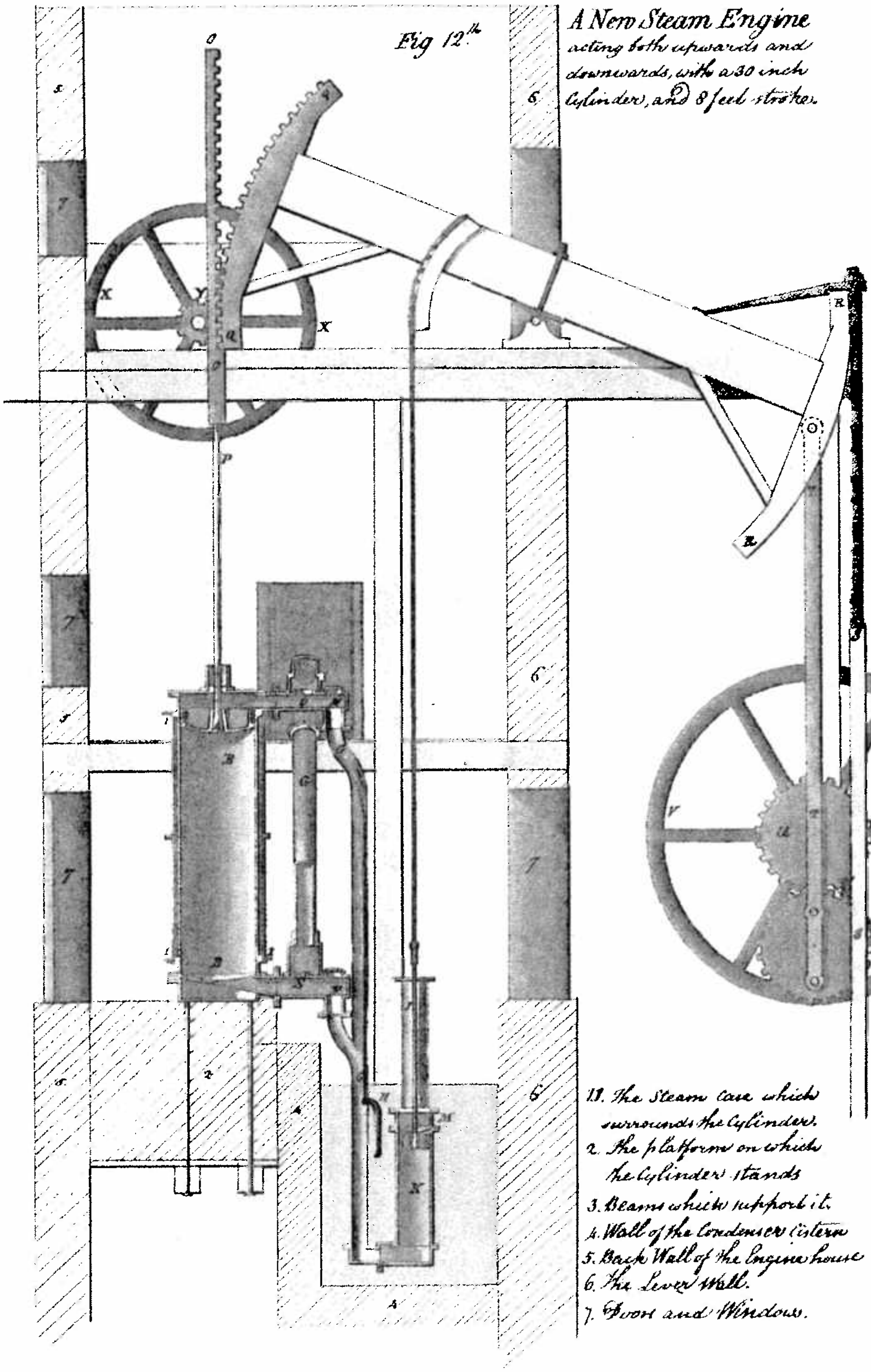
The seventeenth-century Dutch shift from wood and straw to peat had provided the energy foundation for the republic's Golden Age, but with this single exception the transition to fossil fuels began with the expansion of coal mining. Coal was known for centuries in both Europe and Asia, although it was used only for some smelting and forging of metals, and only where it was readily accessible in outcrops. Europeans began extracting coal from underground seams in Belgium during the twelfth century, and England was the first country to accomplish the transition from wood to coal, achieved before the end of the seventeenth century.



A history of coal extraction. Since the 1890s, primacy in total production has shifted from the United Kingdom to the United States, then briefly to the USSR, and now to China, a country that will almost certainly remain the largest producer during the coming generation.

English output surpassed 2 Mt by 1650, when households commonly burned coal for heat and cooking, and manufacturers used coal for purposes ranging from metal forging to starch making. Coke was first used in drying malted barley. This nearly pure form of carbon is prepared by driving off virtually all volatile matter from suitable bituminous coals by heating them in the absence of air. The English ironmaker Abraham Darby succeeded in smelting pig iron with coke in 1709, and the new fuel dominated English ironmaking after 1750.

In the United States and Russia, two large iron producers with abundant wood supplies, coke



This engineer's drawing accompanied James Watt's 1782 patent application for a new steam engine. Steam injected into the grey cylinder on the left drives a piston inside the cylinder. Unlike in earlier engines, the steam is not condensed in the cylinder but in a separate vessel shown inside a blue rectangle at the bottom. This separate condenser saved the heat previously wasted by alternative heating and cooling of the cylinder.

prevailed only during the latter half of the nineteenth century. In 1810, American iron smelters annually used up wood from a forest area equivalent to a square with sides 50 km in length. By 1910 the approximately 25 Mt of pig iron produced yearly would have consumed, even with higher furnace efficiencies, a forest area equivalent to a square with sides longer than 400 km, enough to connect Philadelphia and Boston. Only the use of coke could meet that huge energy demand.

Another growing market for the fuel was in the production of coal gas; this fuel, consisting mostly of methane and hydrogen, was made by heating coal in the absence of air. The gas was piped to factories and households in English cities starting after 1810, and its use soon spread to all industrializing countries. But by far the most important market for coal emerged with the radical improvement of the steam engine, the first inanimate prime mover powered by combustion. The steam engine became truly practical during the 1770s, when James Watt added a separate condenser to the inefficient Newcomen engine that had been in use for about half a century. This, and Watt's other innovations, opened the way for the installation of more powerful steam engines in every type of manufacturing enterprise, and after 1800 high-pressure machines began to be used first in water transport, and then in land locomotion.

Small river steamboats became fairly common after 1810, oceangoing vessels (first propelled by paddlewheels, then by screw propellers) after 1830. After more than two decades of experiments with short private railways, the construction of public railroads commenced in England during the 1830s, and on the continent and in the United States shortly thereafter. But the British lead in coal mining declined only slowly; the country still produced over 50 percent of the world supply in 1870, but after 1900 its coal output was rapidly surpassed by that of the United States.

In the preindustrial world, crude oils were an even more marginal fuel than coal. Modern oil production began on August 27, 1859, at Oil Creek, Pennsylvania, when Colonel Edwin Drake drilled a shallow well using a steam engine–driven percussion bit. At first, the industry expanded mainly to fulfil the demand for kerosene as a cheaper replacement for expensive whale oil, but refined oil products turned out to have several inherent advantages.

Most significantly, these liquids have an energy density about 50 percent higher than the energy density of standard coal—that is, for the same weight of fuel, they provide 50 percent more energy (42 MJ/kg for oil vs 29 MJ/kg for coal). They are also easier to handle than solid fuels, and hence cheaper to transport and to store. The combination of high energy density and easy portability makes them the ideal fuel for all forms of transportation. Demand for these fuels took off after the German inventor Gottlieb Daimler introduced the first practical, light, high-speed, gasoline-powered internal combustion engine in 1885. Seven years later Rudolf Diesel patented a high-compression engine running on a heavier, and hence cheaper, kind of liquid fuel, and in 1903 an improved gasoline engine powered the Wright brothers first flights of a heavier-than-air plane.

Thomas Edison's pioneering designs made possible the commercialization of large-scale electricity generation beginning in 1882. Its pace was greatly accelerated by the invention of the steam turbine by Charles Parsons, a British engineer, in 1884, the electrical transformer by William Stanley in 1885, and the alternating-current induction motor by Nikola Tesla in 1888. These innovations opened up huge new markets for electricity, and hence for coal and fuel oil burned to power large electricity-generating plants. Only natural gas production had to wait until after 1950 for its takeoff.

The statistics capturing coal and crude oil extraction are far from perfect, but they are sufficiently reliable that we can reconstruct global output since the beginning of the nineteenth century. In 1800 the quantity of fossil fuel produced in a

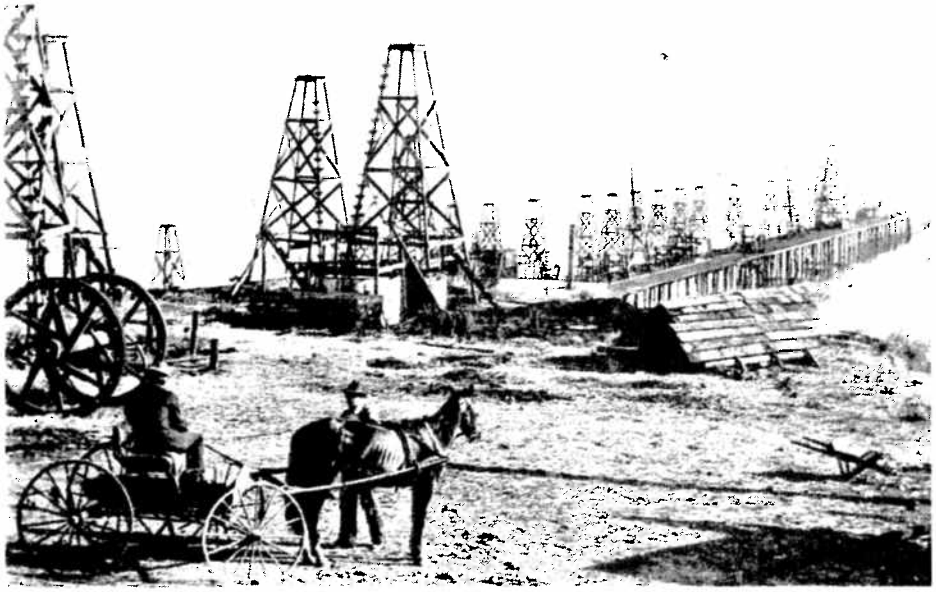
Carbon and Energy Equivalents of Fossil Fuels

All combustion is a rapid oxidation of the fuel that releases heat (thermal energy). The complete combustion of one kilogram of carbon releases 33 million joules (MJ) of thermal energy; it requires 2.66 kg O_2 (that is, 11.53 kg of air) and it generates 3.66 kg of CO_2. The combustion of hydrogen yields much more energy, releasing 121 MJ per kg; it requires 7.94 kg O_2 (34.34 kg of air) and generates 8.94 kg H_2O. A few examples illustrate what can be accomplished with such quantities of energy. A complete production sequence of one kilogram of paper starting from standing timber, or one kilogram of steel starting from iron ore, will consume 30 MJ, and an efficient subcompact car can run on that amount of energy (contained in roughly one liter of gasoline) for at least 15 km.

Coals are sedimentary rocks formed by subjecting dead phytomass accumulated in wetlands to prolonged pressure and heat; they are widely variable in the amount of carbon they contain. The element dominates in anthracites, constituting over 95 percent of the best varieties; but where ash and water content are high, its level may be depressed to as little as 15 percent, as in the poorest European brown coals (lignites). The carbon share for bituminous coals (Europe's black coals), the most common solid fuel used in electricity generation and coking, is around 70 percent. Because the oxidation of carbon accounts for virtually all the heat released from coal, the energy densities of commercial coals range from just around 8 MJ/kg for the poorest lignites to more than 30 MJ/kg for the best anthracites.

Crude oils embrace a range of lighter-than-water fluids distinguished readily by their color, density, and viscosity, but their elemental composition is fairly uniform. All oils consist of mixtures of hydrocarbons, compounds made up of long carbon chains to which hydrogen atoms are attached. Carbon accounts for between 84 and 87 percent of the mass, and hydrogen for between 11 and 14 percent, producing a narrow span of energy densities, just between 42 and 44 MJ/kg.

The natural gases are even more uniform. They are mostly mixtures of the three lightest alkanes: methane (CH_4), ethane (C_2H_6) and propane (C_3H_8). Methane dominates, taking up between 75 and 95 percent of the total, and a few heavier hydrocarbons (mostly butane and pentane) may be also present, increasing the energy density. Pure methane is 75 percent carbon, and common mixtures are rarely more than 76 percent carbon. The lowest energy density of raw natural gases is around 30 MJ/m^3, the highest above 40 MJ/m^3, and CH_4 rates as 35.5 MJ/m^3.



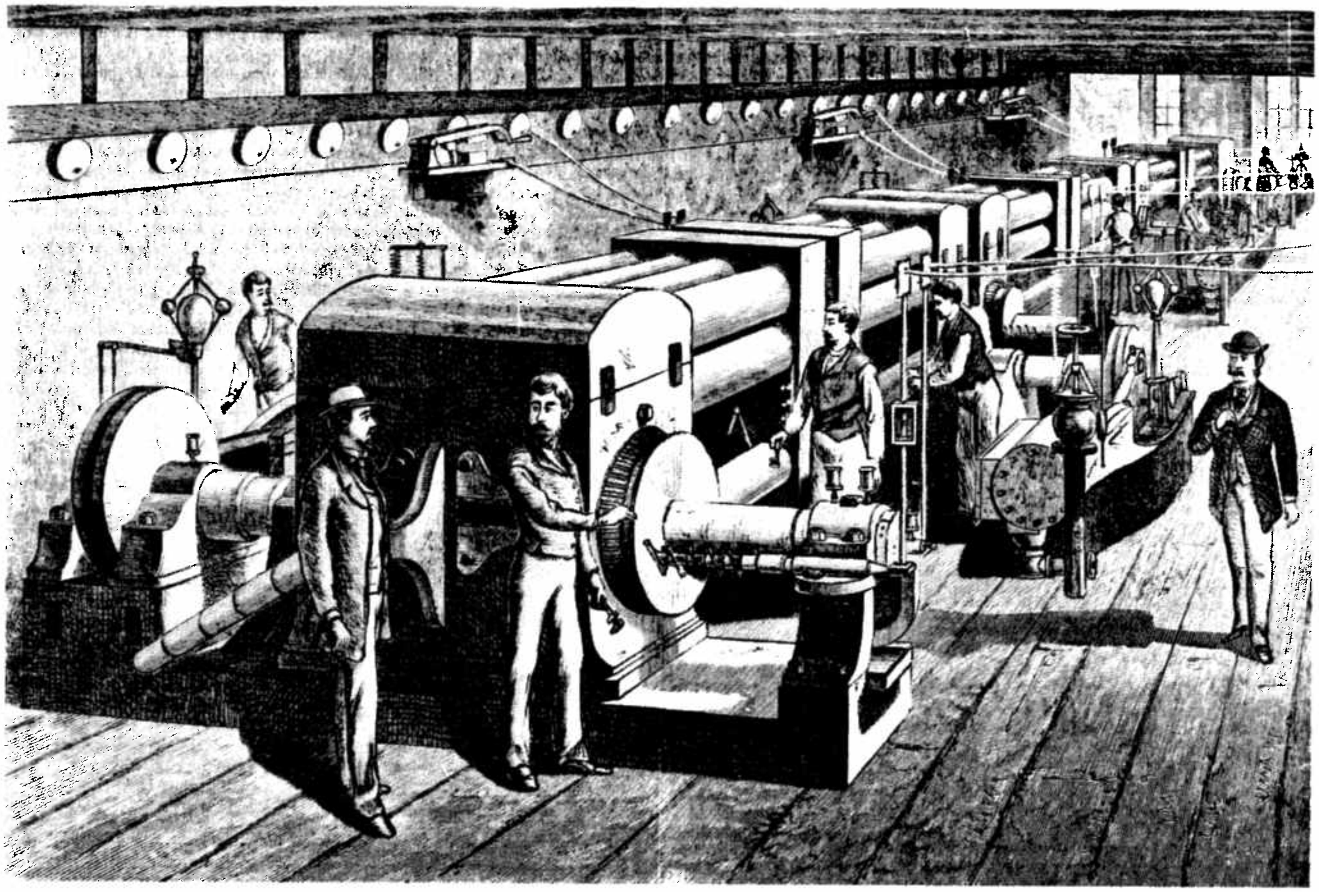
Oil derricks, on land and on a pier, in the Summerland Field, Ventura County, California, in 1902.

year, all of it as coal and peat, stood at about 30 Mt of coal equivalent. A century later annual production stood at about 1 Gt, and at the beginning of World War II it reached almost exactly 2 Gt of coal equivalent (with about a quarter of the total coming from oil and gas). The uncertainties of this record, relatively minor to start with, grow only a bit larger when these quantities are converted to carbon equivalents.

The annual CO_2 emissions from fossil fuel combustion rose from just a few Mt C in 1700 to a still very low total of some 30 Mt C in 1800, then to about 70 Mt C in 1850, followed by a huge increase to more than 500 Mt C by 1900. By 1950 the emissions had more than tripled to about 1.6 Gt C. But the total amount of CO_2 emitted annually from fossil fuels during the early 1950s was still below the quantity released from the conversion of forests and grasslands and from the burning of biomass. And as the 1940s showed a clear global cooling trend, there was hardly any concern about the climatic consequences of rising fossil fuel combustion. This situation changed rapidly in the course of the next generation.

The Dominance of Fossil Fuels

During the second half of the twentieth century, human activities have come to interfere in the carbon cycle to an extent well beyond anything seen before, and this leap can be traced to two fundamental causes. Rich, industrialized countries have reached unprecedented levels of affluence thanks to huge increases in fossil fuel combustion. Until the late 1970s most of the new energy demand came from this relatively small group of nations, which includes the United States, Canada, Japan, Australia, New Zealand, most of Europe, and the former Soviet Union. In 1950 these countries had only about one-third of the world's population, but they consumed more than nine-tenths of all commercial energy. Four decades later their share of global



The dynamo room of Thomas Edison's first electricity-generating plant in New York in 1882. A month after its opening, the direct current generated by the plant energized some 1300 light bulbs in the city's financial district.

population had fallen to one-fifth, but they still claimed more than four-fifths of the world's energy supply, by then greatly expanded.

The second great impulse has come from an equally unprecedented expansion of the poor world's population. Although its relative growth rates peaked in the early 1960s at nearly 2.5 percent a year, the absolute annual additions in Asia, Africa, and Latin America have risen from about 40 million people a year during the 1950s to 60 million during the 1970s and 80 million during the 1990s. Inevitably, these regions have come to require much higher provisions of energy, food, and materials, first just to meet the necessities of this new wave of humanity, and then to begin the difficult quest of raising its average standard of living.

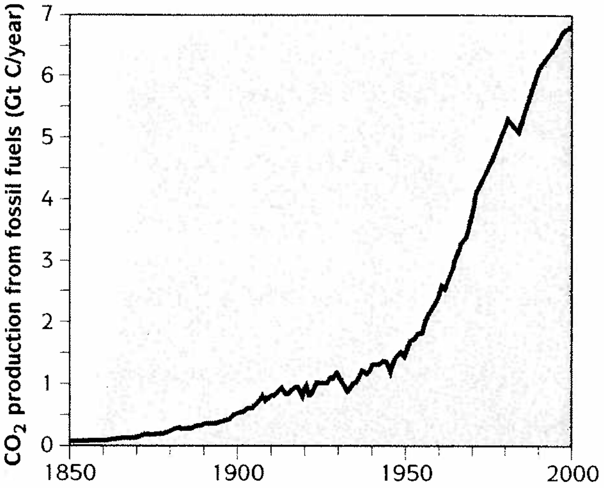
Although some countries have achieved little, or even no, progress (notably sub-Saharan Africa), most of the nations of East Asia and a number in Latin America have made impressive advances toward modernization. These nations, with their large populations, have begun changing the global pattern of consumption. Since the early 1980s most new energy demand has come from the rapidly industrializing countries of East Asia, above all China, and Latin America.

The world's energy suppliers could not have met this huge global demand without the introduction of many technical innovations. Two universal trends have greatly boosted coal production: the mechanization of underground mining and the growing share of surface mining done by very large machines. Crude oil exploration has benefited from advances in geophysical prospecting; crude oil production from the ability to drill deeper wells and to operate ever farther offshore; and crude oil transportation from the building of larger-diameter pipelines and the launching of giant tankers. Natural gas is now transported long distances, forced through high-pressure seamless steel pipes by gas turbine–powered compressors, and overseas deliveries became a reality with the introduction of tankers equipped to carry the gas in liquefied form.

The share of fossil fuels used indirectly as a source of energy, to generate electricity, has risen steadily: in 1945 less than one-tenth of all coals and hydrocarbons were burned in the boilers of electricity-generating plants; by the year 2000 the share reached about one-third. Modern power plants have become huge point sources of CO_2: a plant with an installed generating power of one gigawatt releases from its tall stacks as much CO_2 annually (almost 9 Mt) as the wood-burning stoves that warmed one million mid-nineteenth-century Americans.

Nowhere is the rise in demand for fossil fuels clearer than in the increased per capita combustion of liquid fuels by passenger cars and in commercial aviation. Global car registrations grew by an order of magnitude between 1950 and 2000, to nearly 600 million vehicles, and the introduction of commercial jet planes led to a nearly 20-fold jump in the

A typical large coal-fired power plant—in this image La Cygne in Kansas—has tall stacks, efficient electrostatic precipitators to remove more than 99 percent of fly ash, and each of its units has an annual capacity measured in hundreds of megawatts.



Global CO_2 emissions from fossil fuel combustion have been increasing exponentially since the mid-nineteenth century, and half the cumulative total for the period 1850 to 1995 has been produced since 1975.

number of passenger-kilometers logged between 1960 and 2000.

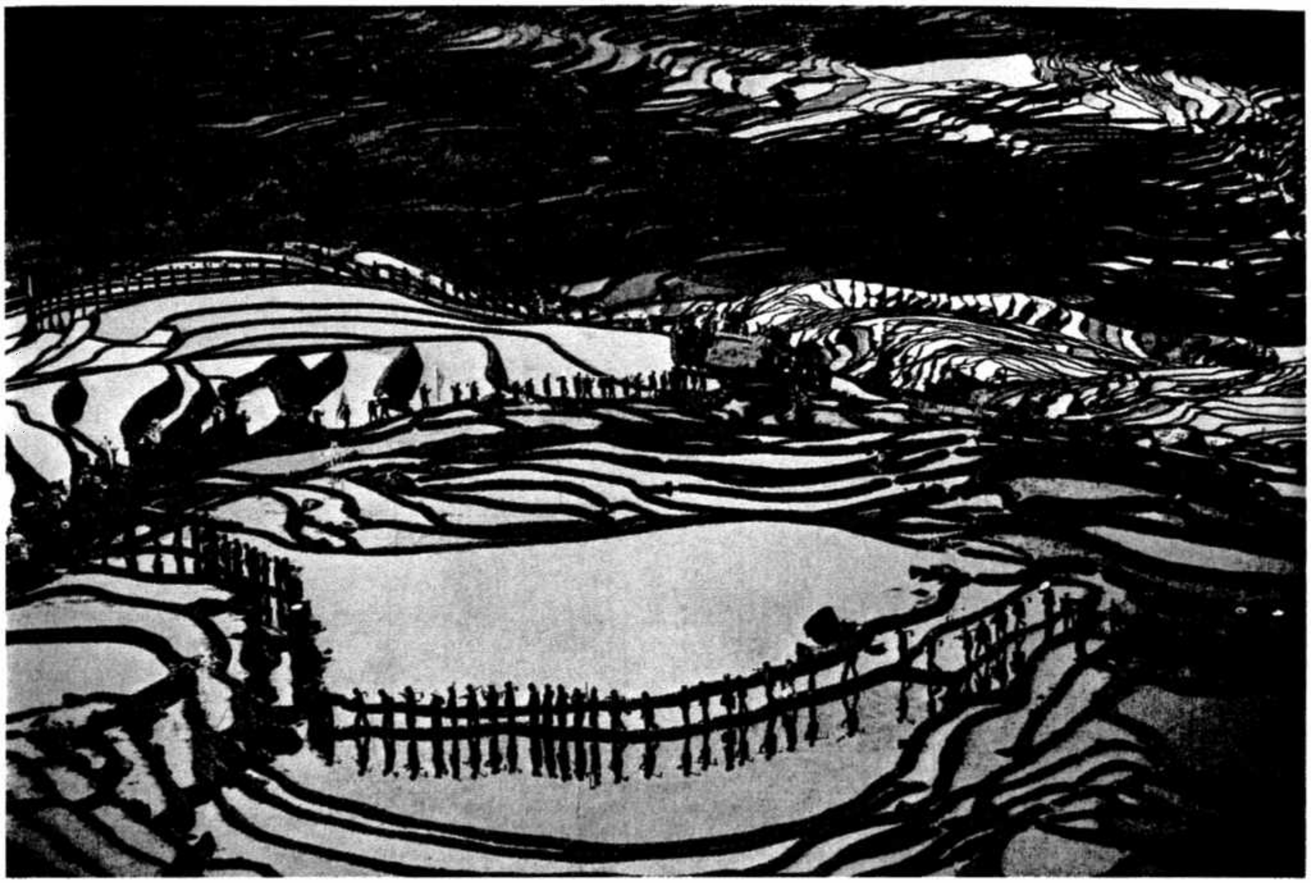
By 1995 total CO_2 emissions from the combustion of fossil fuels surpassed 6 Gt C. This prorates to about 1.1 t C per capita, although extremes range from less than 0.1 t per capita in many African countries to more than 5 t per capita in the United States and Canada. The emissions are obviously distributed unevenly: the United States accounts for just over one-fifth of the global total, and China and Russia each for roughly a tenth. The seven richest major economies (G7 countries), with little over 10 percent of the world's population, produce almost 40 percent of all fossil fuel CO_2. And nothing could be a better reminder of the recent exponential growth in these emissions than the fact that half the grand total of gas emitted from 1850 through 2000 was released between 1976 and 2000.

To the CO_2 emitted from the combustion of fossil fuels must be added the CO_2 released during the making of cement, concrete's bonding agent. Cement is made by grinding clays or shales with limestone, chalk, or marl, burning the mixture in rotary kilns at up to 1500 °C, then mixing it with gypsum and grinding it again to a requisite fineness. This process releases about 140 kg CO_2 per tonne of the final product. Industry was producing about 150 Mt of cement a year by 1950, and its CO_2 emissions equaled about one percent of those from fossil fuels.

These emissions have expanded considerably with the ubiquitous construction of concrete buildings and highways. With more than 6 Gt of the material emplaced every year, concrete is now the world's leading material in terms of the total mass used. Its low cost and versatility ensure that it continues to displace wood in buildings, steel in bridges, plastics in pipes, and asphalt in pavings. CO_2 emissions from this source have risen nearly an order of magnitude since the early 1950s, but they still equal only about 3 percent of the emissions from fossil fuels.

Although methane is a much less important greenhouse gas than CO_2, its emissions have been increasing even faster. Some of this CH_4 is lost during the extraction and transportation of natural gases, especially in Russia, and some emanates from coal seams. But the bulk of new CH_4 emissions is a consequence of human population growth and our desire to eat more animal foods.

Asia's rice output rose about 3.5-fold during the second half of the 20th century, and even though most of this gain came from higher yields, the area occupied by paddy fields has expanded by more than 40 percent. The anoxic soils in these fields provide a perfect environment for methanogenic bacteria, which produce methane gas by the reduction of CO or CO_2. As we consume more beef and dairy products, the global cattle count has risen by about 40 percent between 1950 and 2000. Because modern animals are heavier, this gain has resulted in a more than commensurate rise in CH_4 from enteric fermentation. Recent estimates put these emissions at close to 100 Mt a year, a rate comparable to the flux from paddy fields.

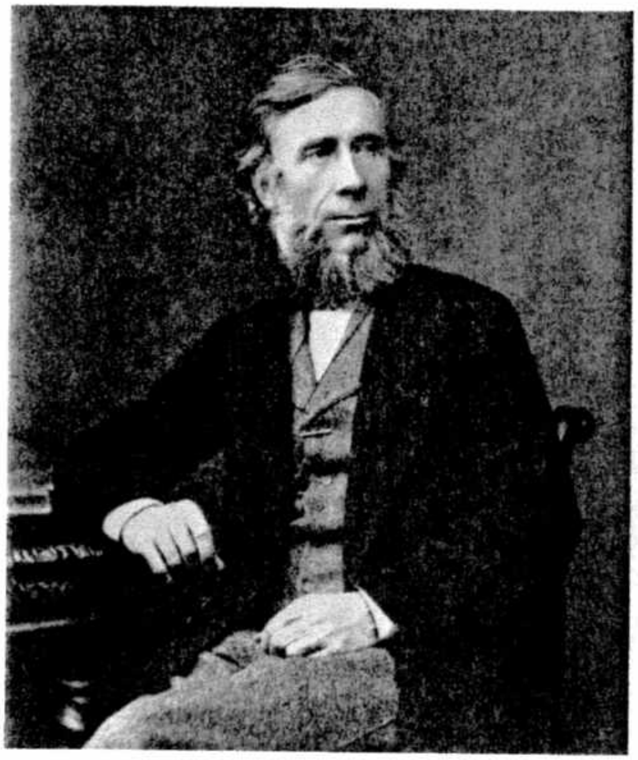


Asian rice fields—here shown in Yunnan province in China—are a major source of the methane produced by bacteria in anoxic soils.

Climatic Change and the Biosphere

Of all the changes with which modern civilization threatens biospheric cycles, one is of by far the greatest concern, and it has become the most prominent environmental preoccupation of the waning twentieth century. This is the possibility that rising CO_2 emissions could set off rapid global warming. Our awareness that CO_2 can induce climatic change is not new: indeed, one scientist correctly grasped the underlying process by which it does so at the very beginning of studies to address the atmosphere's absorption of radiation.

The English physicist John Tyndall, the first scientist to study this process in detail, is now best remembered for solving the puzzle of why clouds are white and tobacco smoke blue. Cloud droplets are roughly equal in size to or larger than the wavelengths of visible light, and hence they scatter light at all its wavelengths, producing white color. In contrast, the tiny particles that make up tobacco smoke scatter mostly the blue light, to whose wavelengths



John Tyndall (1820–1893), an English physicist, was the first researcher to examine systematically the absorption of heat by different gases, including CO_2.

they are a near match in size. Measuring the absorption and radiation of heat by gases, a study to which Tyndall also turned, was a kindred challenge.

Tyndall wished to measure the absorption of heat by different gases, but he had first to find a practical way of enclosing them in a vessel transparent to longwave radiation. Glass, he knew from observing the greenhouses that sheltered palms and bananas through English winters, "would be scarcely more suitable" than if the ends of his experimental tube "were stopped by plates of metal." Rock salt (NaCl), a common substance transparent to such radiation, offered a perfect solution, but it was not easy to locate plates of suitable size and transparency. Eventually his assistant built a four-foot-long tin tube capped by plates of rock salt set in vulcanized rubber. Tyndall then measured the absorption of heat by different gases enclosed in his tin tube: by air, by air's key constituent molecules, by water vapor, and by about a dozen different compounds. He did so by using a sensitive galvanometer to record the changes of the electric current passing through the gases irradiated by heat.

In 1861 Tyndall summarized his measurements by noting that water vapor accounts for most of the atmosphere's absorption of heat and hence "every variation of this constituent must produce a change in climate. Similar remarks would apply to the carbonic acid diffused through the air . . ." And he concluded with both confidence and caution: "the facts above cited remain: they constitute true causes, the *extent* alone of the operation remaining doubtful." This remains, verbatim, a perfect summary of our expectations of greenhouse gas–induced climatic change.

There the matter was left until just before the end of the century, when one of the most respected scientists of the day revisited the subject. In 1896 Svanté Arrhenius—a creator of ionic theory and one of the first to receive the Nobel Prize in chemistry—offered the first calculations predicting the rise in global surface temperature that should result from an eventual doubling of atmospheric CO_2 compared to its preindustrial levels. His conclusions agreed with modern understanding in predicting that a geometric increase of CO_2 would produce a nearly arithmetic rise in surface temperatures, and that surface temperatures would rise most in polar regions. The results of his calculations also roughly resembled those of today's global climate models: he predicted average annual increases of 4.95 °C in the tropics and just over 6 °C in the Arctic.

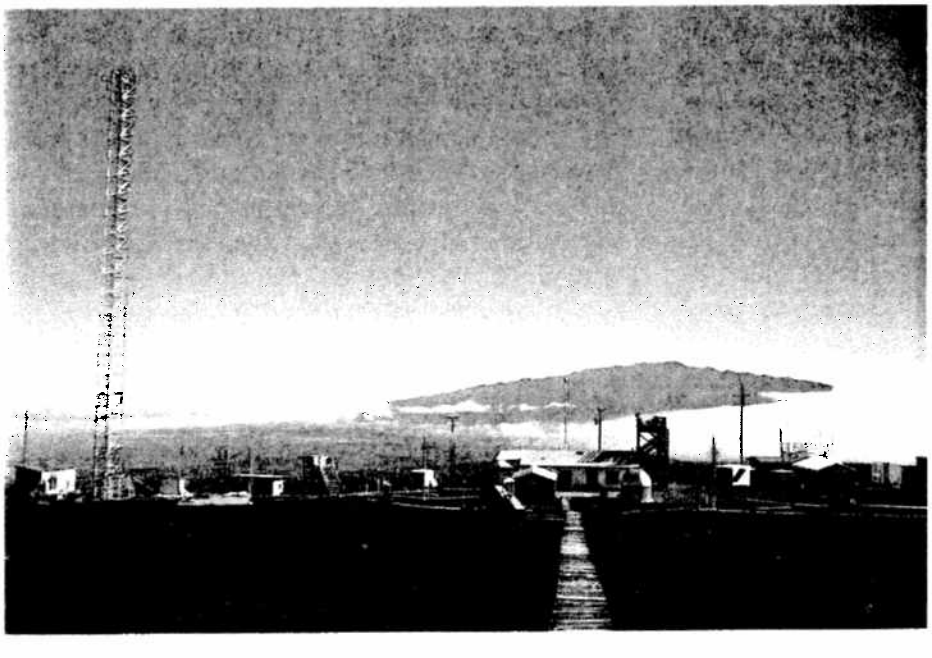
Arrhenius's work, much like Tyndall's, did not spark any sustained interest among scientists studying the atmosphere. The idea that a link existed between CO_2 and climatic change was resurrected only in 1938 by George Callendar, a steam technologist with a British research association. Although his information base was skimpy, Callendar did have better values for CO_2 absorption of infrared radiation, and with these he was able to calculate a more realistic temperature rise. He was also able to document a slight pre-1940 warming trend. In his later writings Callendar recognized the importance of carbon emissions from deforestation and other changes of land use. His conclusions—that a 1.5 °C rise in temperature would follow from CO_2 doubling, and that global temperature had risen 0.25 °C during the preceding half century—are virtually identical to the best scientific consensus of the 1990s.

The next hiatus ended with the publication of a handful of papers in *Tellus,* a Swedish journal of atmospheric science. Gilbert Plass at Johns Hopkins University carried out the first computerized calculation of the radiation flux in the main infrared region of CO_2 absorption. His results—predicting an average surface temperature rise of 3.6 °C following the doubling of atmospheric CO_2—were published in the same 1956 issue of the journal in which two Swedish researchers presented the most complex model of the global carbon cycle constructed up to that time.

But neither of these papers received as much attention as a 10-page paper that Roger Revelle and Hans Suess, at that time at the Scripps Institution of Oceanography in La Jolla, published in the first issue of *Tellus* for 1957. They summarized the problem created by the continuing combustion of fossil fuels in such a way that the key sentences have become a citation classic:

> Thus human beings are now carrying out a large scale geophysical experiment of a kind that could not have happened in the past nor be reproduced in the future. Within a few centuries we are returning to the atmosphere and oceans the concentrated organic carbon stored in sedimentary rocks over hundreds of millions of years.

One response to the article was almost instant: scientists set up the first station for the measurement of background CO_2 concentrations. The

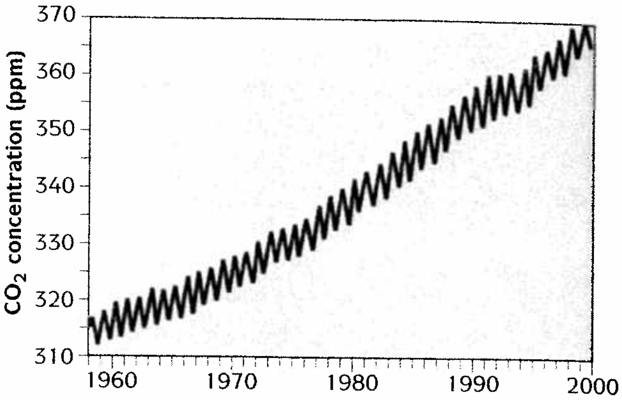


Mauna Loa Observatory on the northern slope of the world's most massive mountain. Air for analyses is sampled from the tall tower on the left as well as from the tops of lower towers. In this image, Mauna Kea volcano rises above the saddle between two mountains, draped by rain clouds that persistent trade winds bring from the northeast.

station sits on the northern slope of Mauna Loa on the island of Hawai'i, 19.5° north of the equator, 3400 m above sea level, and some 800 m below the Mokua'weoweo crater surmounting the planet's most massive mountain. This location offers a nearly perfect site for monitoring background concentrations of atmospheric gases since there are no major nearby sources of CO_2. The island is more than 3000 km from the nearest continent; the closest plants grow about 17 km from the observatory, which is surrounded by enormous dark lava fields; temperature inversions keep the air from forests and cane fields well below the site; and prevailing east-northeast trade winds bring air free from boundary-layer contamination.

The observatory was set up in 1953 by Harry Wexler of the U.S. Weather Bureau; David Keeling, a chemist from the Scripps Institution of Oceanography, began daily CO_2 measurements at the site in March 1958. Except for a few spring months in 1964, monitoring has continued at the site without interruption. Air samples are taken from the tops of four towers four times every hour. A gas analyzer passes a beam of infrared light through the sample, and the degree of its absorption by CO_2, directly proportional to the concentration of the gas, is recorded with an accuracy of about 0.1 ppm. In 1958 the mean CO_2 concentration at Mauna Loa was 315.5 ppm, in 2000 it just surpassed 370 ppm. CO_2 measurements at the South Pole began shortly after those at Mauna Loa, and two more baseline sites were later added at Barrow on Alaska's North Slope and on Tutuila Island in American Samoa. Finally, a network of more than 30 periodically sampled sites was established as well.

With improving computer capabilities, it became possible to construct the first three-dimensional models of global atmospheric circulation during the late 1960s. These general circulation models (or GCMs) were originally designed for weather forecasting. Syukuro Manabe and Richard Wetherald of the Geophysical Fluid Dynamics Laboratory in Princeton first made use of them to create simulations of future, CO_2-influenced climate in 1967. After nearly three decades of gradual improvements in these models, the best among them can replicate fairly well a number of important global climate features, and they offer a valuable tool for exploring climate change.



The observatory at Mauna Loa has recorded a steady rise in atmospheric CO_2 concentrations since their monitoring began in 1958. The undulating pattern is the biospheric breath: this annual variation in CO_2 level, having an amplitude of 6 to 7 ppm, reflects the difference between the northern hemisphere's maximum rate of photosynthesis in September (carbon "inhalation" and CO_2 minima) and the peak rate of respiration in May (carbon "exhalation" and CO_2 maxima).

But the overall predictive power of GCMs is still too weak for them to be relied on for any clear-cut decision making: forecasts of the global temperature rise that should result from a CO_2 doubling still span a rather wide range. This shortcoming is not unexpected considering that the models represent the complex processes controlling climate only incompletely and that insufficient computing power limits their spatial resolution.

To start off, modelers specify atmospheric conditions such as temperature, pressure, and humidity at points on a horizontal grid and at several altitudes within the air column. The model plugs these values into equations describing key physical processes that take place in the atmosphere. The computer then calculates solutions to the equations that give future conditions at each point on the grid. The spatial resolution of the grids is fairly rough. The horizontal distance between grid points has ranged between 300 and 1000 km; even the lowest value is equivalent to the distance from Manhattan to Boston, clearly too large to capture small regional details. Not surprisingly, the regional predictions of GCMs are particularly questionable.

Grids should become finer in the future as computing capacity expands, but finer grids will not automatically result in highly reliable simulations because modelers use simplifying assumptions to represent even some key variables. Current models are also incapable of reproducing the intricacies of several critical feedbacks, especially those involving clouds and ocean-atmosphere interactions. Not surprisingly, while different models may agree on a number of outcomes, all occurring on very large spatial scales, and on the direction of a simulated change, they disagree substantially even about such key predictions as the future amount of precipitation or soil moisture.

Most climate simulations have been looking at the possible effects arising from the doubling of preindustrial CO_2, to levels around 600 ppm. This approach was adopted before scientists had recognized the substantial contribution of other greenhouse gases (in 2000 gases other than CO_2 accounted for about 45 percent of the total warming effect), and it remains a favorite choice in climate change forecasts. A more accurate restatement of the problem would be: What will happen when all greenhouse gases cause tropospheric warming equivalent to that brought on by the doubling of preindustrial CO_2?

Climate modeling has been responsible for only a portion of recent advances achieved by research aimed at elucidating the changing carbon cycle. Studies of the cycle have proliferated enormously since the late 1970s, a trend driven by concerns about long-term energy strategies (especially acute in the aftermath of OPEC-induced oil price rises) and by a much heightened worldwide awareness of the environmental risks. Perhaps the most distinguishing quality of these new inquiries has been their increasingly interdisciplinary nature. A number of biologists, meteorologists, oceanographers, geologists, and geochemists have moved beyond narrow disciplinary boundaries to advance our understanding of the biospheric carbon cycle. The contributions of Bert Bolin, Wallace Broecker, Richard Houghton, Jorge Sarmiento, William Schlesinger, Ulrich Siegenthaler, Taro Takahashi, Pieter Tans, and George Woodwell have been particularly notable.

Despite the difficulties, scientists have reached a broad consensus on the effects of CO_2 doubling, whose key points have been summarized by the Intergovernmental Panel on Climatic Change in its latest exhaustive review published in 1996. The doubling of CO_2 should slightly cool the upper stratosphere, because at higher concentrations the gas will reradiate more energy back to space. In the troposphere, surface temperatures will rise by an average of about 2 °C, but the actual increases may be as low as 1 °C, and as high as 3.5 °C. Because of the ocean's high heat capacity, the temperature rise should be more pronounced on land. The result would be to amplify the temperature gradients between land and sea. This temperature difference would increase in the poleward direction, and be more pronounced in winter than in summer.

This high-latitude winter maximum is explained by a feedback mechanism. As higher temperatures melt snow and ice cover, more land and ocean are exposed to sunlight. The darker surfaces absorb, and reradiate, more energy and so amplify the initial warming. In addition, more of the ocean's heat can escape from high-latitude seas that are no longer covered by sea ice. As a result, winter surface temperatures in the polar regions could rise by three, even four times the global mean. In warmer and wetter regions at high latitudes, the greater formation of clouds may substantially moderate the degree of warming, since the presence of clouds tends to lower the surface temperatures.

Warming would increase the volume of water evaporated and bring more frequent, and heavier, rains and snowfalls. Again, this effect would be more pronounced in higher latitudes, especially during the wintertime when the air becomes saturated with water vapor at lower temperatures. In contrast, some dry regions may actually become more arid. Nearly all additional energy absorbed by arid surfaces will go into heating the overlying air; the warmer air will reduce the formation of low-level clouds, and surface temperatures will become even higher and the overlying air still warmer. This positive feedback could cause already existing hyperarid areas to expand and new ones to emerge.

A warmer world with increased evaporation could be also visited more frequently by extreme weather events, above all by cyclones ranging from large thunderstorms to hurricanes. The development of these low-pressure systems depends on the availability of heat and moisture, and a warmer, wetter climate would tend to generate larger convective cells with higher cloud tops. The number of these events could multiply even with a relatively small rise in mean temperature.

Increased surface temperature and evaporation would also bring more precipitation in the Asian monsoon, whose rains affect nearly half the world's population. The faster warming of land areas would increase average rainfall; it would also enhance the land-sea temperature gradient and intensify the moisture convergence over land. At the same time, the monsoon could become slightly more variable from year to year.

As the temperature rises, seawater should slowly expand, and mountain glaciers gradually melt (up to half could disappear). The result could be an appreciable rise in sea level. Already the mean ocean level has risen by 10 to 25 cm during the past century, and much of this rise may be related to higher tropospheric temperatures. Adjusted radar altimeter data from the TOPEX/POSEIDON satellite, available since August 1992, indicate that the sea level continues to rise at an annual rate of 1 to 3 mm.

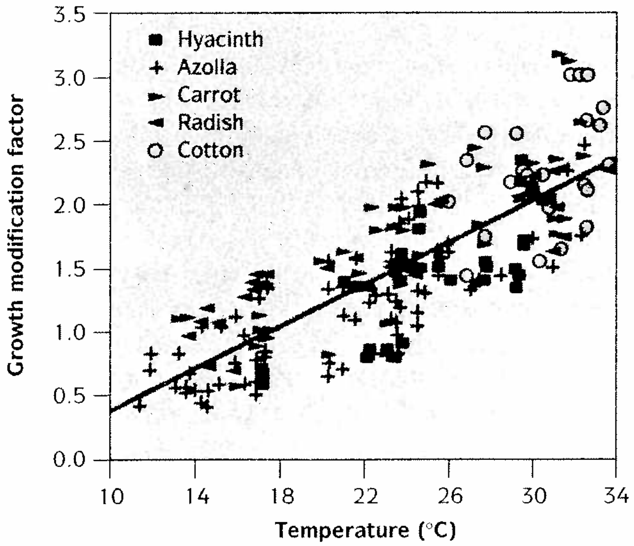
How much the sea level would change under global warming is uncertain; the mean rise that would follow CO_2 doubling could be as low as 10 cm and as high as one meter. Little melting of polar ice caps is expected during the twenty-first century, but their long-term stability under continued warming is highly uncertain. The northernmost ice shelves of the Antarctic peninsula have been in a rapid retreat during the past 50 years, although the reasons for their breakup are unclear. The ice shelves stabilizing the huge West Antarctic ice sheet have remained unchanged, but glaciologists have advanced contradictory arguments regarding their future behavior; some contend that the ice sheet has a great stability, and others that it shows a worrisome lability. If it did melt, its waters could add 4 to 5 m to the mean sea level.

Even temperature changes near the lower bound of the estimates would profoundly affect the biosphere. As was true for forecasts of climate change, some predictions describing the impacts on life are fairly confident and others highly speculative. But there is no doubt that major changes affecting Earth's plant life would be unavoidable, their impacts on our civilization immense.

Life in a Greenhouse

Higher CO_2 levels in themselves should be a boon to the biosphere. During most of their evolution, plants lived in atmospheres much richer in CO_2 than ours is today. CO_2 is both an activator of Rubisco, the enzyme that catalyzes the first step in photosynthetic reduction of the gas, and the molecule on which Rubisco acts; with CO_2 at 350 ppm, the enzyme works at no more than three-quarters of its capacity. Higher levels of the gas would improve the performance of Rubisco in still another way, by lowering the enzyme's affinity for O_2. Because the two gases bind to the same site in Rubisco's molecule, both compete to react with the enzyme; but higher levels of CO_2 would make O_2 less competitive. And because Rubisco uses O_2 to prime photorespiration, higher CO_2 levels would also help to lower these losses. Taken in combination, these changes would increase the productivity of all C_3 plants—that is, some 95 percent of all terrestrial vegetation: plants would grow larger leaves, trees would have denser canopies.

The benefits for cyanobacteria and algae, as well as for C_4 species, would not be as impressive. The former are already able to raise the levels of CO_2 around Rubisco by up to three orders of magnitude, and C_4 species, too, concentrate CO_2 much above the ambient level in their bundle sheaths. But all these photosynthesizers would share with C_3 plants the ability to enjoy another direct benefit of higher CO_2 concentrations: reduced loss of water from their leaves. Leaf stomata close partially in higher CO_2 levels, and this adjustment lowers the rate at which water vapor is transferred from within the leaf to the surrounding air. A doubling of CO_2 would lower this transpiration loss by as much as 30 to 60 percent in some plants, and it would work for both land and aquatic species. Plants, then, will need less water to survive, an especially desirable trait in times of drought.



The productivity of plants grown with the same elevated CO_2 concentration (an additional 300 ppm) increases with higher average air temperature. As these experimental results show, this trend is very similar for a variety of species.

Moreover, on a planet experiencing global warming, the rising temperature would amplify the positive effects of elevated CO_2 on photosynthesis. A doubling of CO_2 would raise optimum temperatures for C_3 photosynthesis by about 5 to 10 °C from the current 25 to 30 °C—and CO_2-induced temperature increases would help make such higher temperatures more common. In some species the increase in productivity stimulated by higher temperatures could equal the increase stimulated by enhanced CO_2 uptake without any temperature change.

The magnitude, and even direction, of many other changes is less certain. A substantial proportion of carbon may continue to accumulate in woody phytomass as it has done in some ecosystems in the recent past, but experiments indicate that in many species a disproportionate share may be channeled into roots rather than into leaves and stems. As noted already, respiration per unit of phytomass should decline with higher CO_2 levels, and plant productivity should rise as a consequence, but this benefit could be negated by the increase of total phytomass and by higher temperatures.

Other experimentally confirmed benefits include higher nitrogen fixation in legumes; a greater abundance of nutrient-scavenging mycorrhizal fungi (as plants will have more carbohydrates to share with symbionts); better growth in low-intensity light; better ability to withstand lower temperatures and air pollutants (largely because the partly closed stomata take up less gas from the air); and a better tolerance of soil and water salinity.

FACE (Free Air Carbon Dioxide Enrichment) experiments—here shown in a cotton field in Arizona—use microcomputer-controlled delivery of CO_2 to maintain preset concentrations of the gas over open field plots inside circles up to 30 m in diameter.

For many decades the operators of commercial greenhouses have achieved superior yields by enriching CO_2 levels to between 600 and 2000 ppm. Field crops, if well watered and fertilized, should behave similarly, and their responses to heightened CO_2 have been the most thoroughly investigated of CO_2-plant interactions. These investigations have ranged from monitoring individual leaves in laboratory growth chambers to conducting the most realistic Free-Air Carbon Dioxide Enrichment (FACE) experiments in the fields. Pioneered by George Hendrey of the Brookhaven National Laboratory, FACE studies use microcomputers to maintain, within a narrow range, preset CO_2 concentrations over open field plots up to 30 m in diameter.

Regardless of the technique used, these experiments agree in their results. A doubling of CO_2 should increase average yields of virtually all crops, although diminishing returns will become pronounced as CO_2 levels approach 1000 ppm. The gains in C_3 species, averaging about 30 percent, would be substantially higher than in C_4 plants. As 12 out of the world's 15 leading crops are C_3 plants (including all staple cereals except corn and sorghum), their greater productivity would perhaps be the most beneficial consequence of CO_2 doubling. Some agronomists argue that CO_2 enrichment has already helped to raise yields by at least 10 percent above the gains brought by new cultivars, fertilizers, and pesticides.

Not surprisingly, experiments also confirm that species will differ in their response. Cotton has shown by far the most impressive gains—its annual yields rose between 50 and 70 percent during several years of FACE trials at a CO_2 level of 650 ppm. Under the same conditions, wheat yields increased by only about 10 percent. Soybean growth continues to increase in step with the CO_2 level even at concentrations as high as 900 ppm, while rice responds vigorously only below 500 ppm.

Crops grown experimentally in doubled CO_2 have averaged about a 30 percent gain in water use efficiency in the case of C_3 plants, and up to a 10 percent gain in the case of C_4 species. As a result, crops grown with adequate nutrients and moisture should yield more while using less water. Crops grown in arid regions could still match, or surpass, their current yields even with slightly lower precipitation. As a most welcome benefit, there would be additional water available to streams and aquifers.

At the same time that higher CO_2 levels could be helping to raise yields, warmer climates might be reducing them in some regions. Longer, and more pronounced, hot spells could lower the yields of some varieties of staple cereals grown today in the principal agricultural regions of the northern hemisphere. Several computer simulations have predicted minor to substantial (over 15 percent) yield declines for both corn and wheat grown in the major cereal regions of the United States. Additional hot spells during a sensitive period of growth could make the decline in yields still larger, higher precipitation could offset it.

Most agronomists think that we should be able to breed new cultivars, better adapted to the warmer conditions, fast enough to avoid yield losses. Even if the new varieties were to increase their yields just one percent a year for the next two generations—a performance equal to just half, or at best two-thirds of, the record during the past 40 years—the addition to the harvests would easily surpass the anticipated losses.

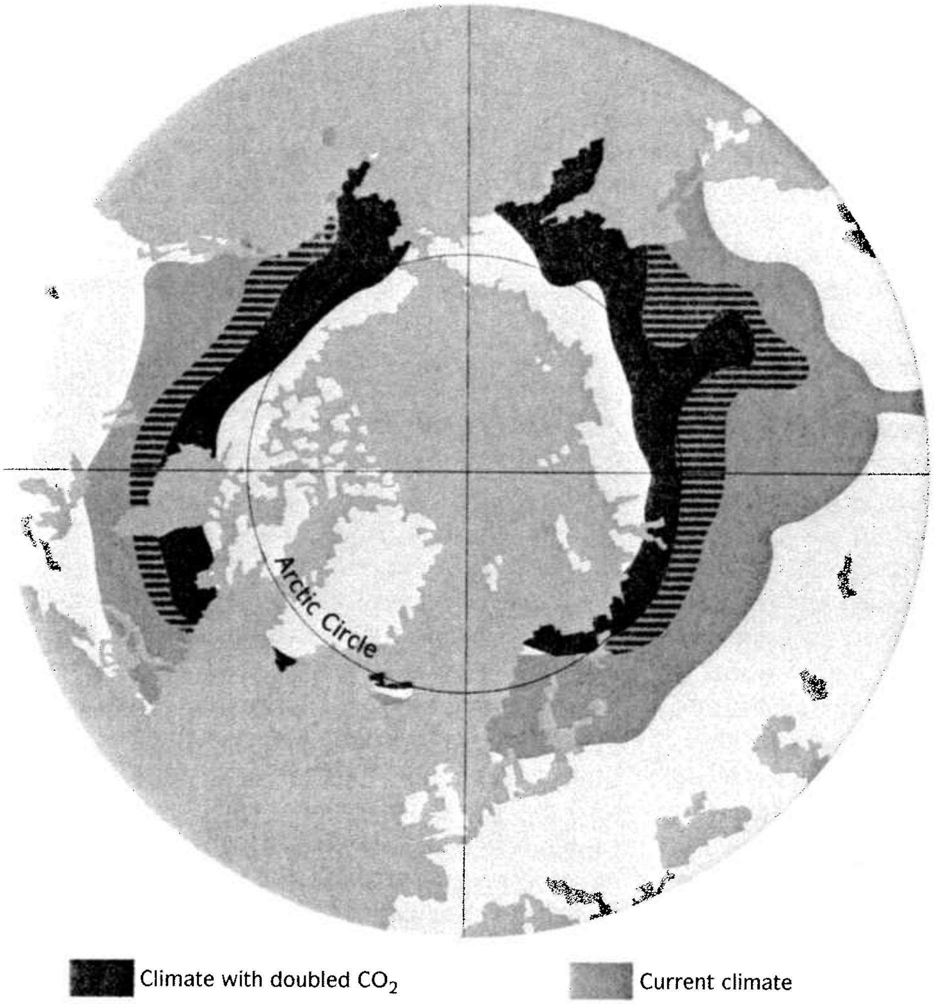
Scientists are relatively confident of their ability to predict the response of agricultural ecosystems to CO_2 enrichment. They have found it incomparably more difficult to assess the effects on natural terrestrial ecosystems. I will review some of their recent findings in the penultimate chapter. While we may not be able to say how much more productive a forest will become after a century of doubled CO_2, we are on firmer ground in pointing out where the forests of the future might be situated given a particular increase in average surface temperatures. Forests are sensitive even to relatively small temperature changes, and a rapid warming would force a northward relocation of their boundaries, and hence a likely temporary decline of their phytomass. About a third of the area forested at present may have to shift, either poleward or to higher altitudes.

With warming greater in higher latitudes, boreal forests would have to migrate north the fastest. The massive translocation that would be required is not unprecedented in Earth's history: most recently, a northward forest migration followed the retreat of the continental glaciers that began some 15,000 years ago. These forests left behind a well-studied record of vegetation changes in the pollen that were preserved in sediments at the bottoms of lakes. About 10,000 years ago the southern border of America's great boreal forest coincided with southern shores of the Great Lakes, but 5000 years later the border had moved to just north of Lake Superior. Tree species advanced northward at an average annual rate that varied between 100 m, for chestnuts, and 400 m, for jack pines. In postglacial Europe, chestnuts, firs, and linden trees were slow migrants, while alders advanced by more than one kilometer a year.

But even the fastest-migrating trees from the postglacial era would be too slow to keep up with the changing climate that should result if temperatures rose an average 3.5 °C in a century. Such a rapid warming rate could push isotherms northward by as much as 550 km. Boreal forests could eventually shift so far poleward that their new southern boundary would almost coincide with their present-day northernmost growth. In contrast, a mean temperature rise of just 1 °C would lead to a poleward shift of only about 150 km.

Siberian forests currently account for one-fifth of the world's forested area and nearly half its conifers. Warming would certainly change the extent of these forests, and it could also affect the region's extensive bogs sitting on permafrost. Much of Siberia is underlaid by permafrost, a zone of perennially frozen ground topped by a layer of soil undergoing seasonal thawing and freezing. Were the annual thawing to penetrate deeper and last longer, the overall volume of Siberia's extensive bogs could increase. The expanded bogs might sequester more carbon, although that effect, in turn, may be largely, or completely, negated by the faster decomposition that would take place in warmer bogs.

We should not imagine that a forest would move northward as a unit, with all species migrating together an equal distance. Rather, as already noted, individual species would differ greatly in the eventual extent of their northward displacement. North America's birches would remain largely within their current territory, but beeches would not. Beech trees now cover virtually all of eastern North America, but in a warmer world they would thrive only north of the Great Lakes and in New England. A doubling of CO_2 levels would make hardly any direct difference to microorganisms and other creatures dwelling in the soil, since they already live amid concentrations 5 to 100 times those in the ambient air.



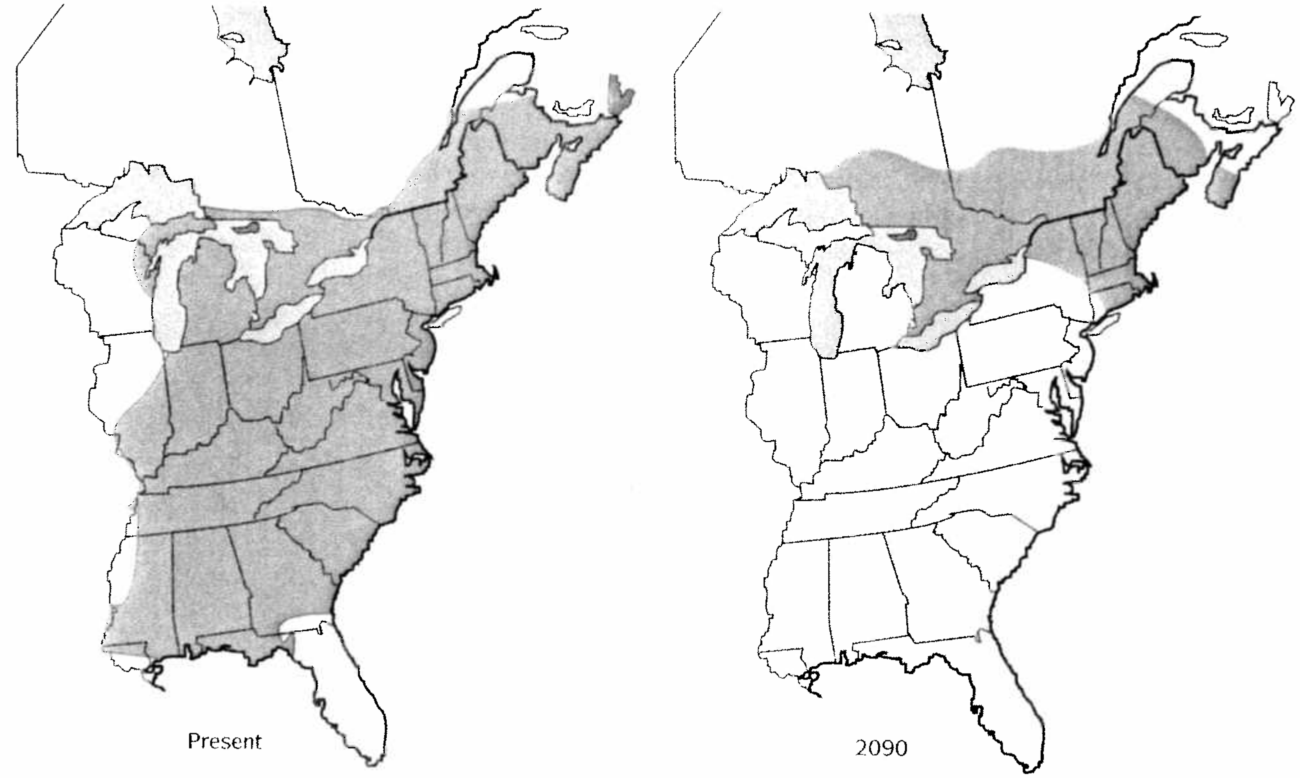
Should there be a doubling of CO_2, the southern boundary of boreal forests would shift hundreds of kilometers northward.

A rise in CO_2 would, in the long run, affect aquatic life more by raising water temperatures and sea level than by increasing the amount of carbon. The higher atmospheric CO_2 levels will, fairly promptly, increase the availability of carbon within the euphotic layer, but photosynthesizers will not be able to take advantage of the additional carbon, for the key growth-limiting nutrients (phosphorus and iron) these organisms need to grow would remain as scarce in the open ocean as they are today.

Higher water temperatures should reduce the latitudinal and seasonal extent of sea ice, a change that may result in new migration and feeding patterns. Accelerated weathering—a result of higher atmospheric CO_2 levels and increased precipitation and temperature—should bring a higher influx of nutrients into coastal waters. The additional nutrients would enhance near-shore photosynthesis, stimulate the growth of plankton, and improve the survival of fish. Warmer oceans would bring a general poleward translocation of many habitats, and migration patterns would change in response. Another possible effect of warmer seas may be the bleaching of corals. In the process corals expel algae living within their cells and become snowy white; if the stress persists, they die. Bleached corals have been recently observed at a number of locations, but whether the damage is linked to overall ocean warming remains controversial.

Any rise in sea level would inevitably affect today's coastal ecosystems—and overwhelmingly to their detriment. Beaches would be inundated, shoreline erosion accelerated, wetlands obliterated. The damage from storms and flooding would increase, and salt water would intrude into marshes, rivers, and aquifers. Their low elevation and limited area makes coral atolls particularly vulnerable. Even a minor rise in the sea level would claim large stretches of existing shores and threaten freshwater pools within the atolls. A rise of one meter would flood densely populated low-lying lands, above all along the Bay of Bengal and in the deltas of many major rivers (including the Nile and the Yangzi).

An overall rise in average temperature of 1 to 3 °C should not in itself present any serious threat to human health. Although elevated mean summer temperatures are predicted for the densely populated mid-latitudes, they should not pose any



The growing range of the North American beech (green area) is predicted to shift considerably northward in an atmosphere with a doubled CO_2 concentration.

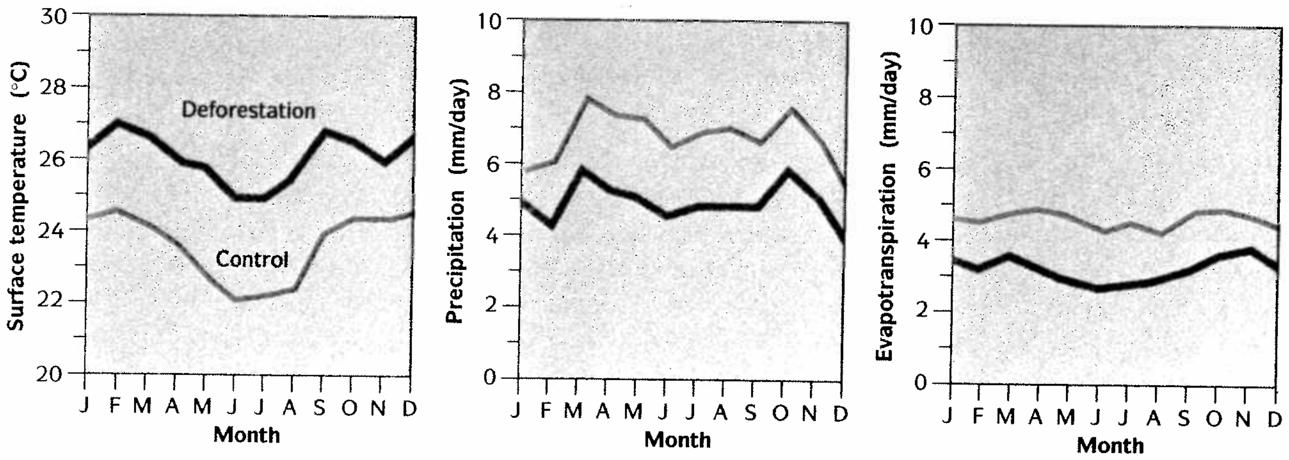
serious risk to healthy people, even in the absence of air conditioning. No other mammal can match the human body's thermoregulatory capacity, and healthy individuals adapt to higher temperatures in a matter of days. But even a slight elevation in the annual temperature mean would be of concern if it were accompanied by more frequent and longer-lasting summer heat waves. Those continuing more than three days (the recent American median has been close to two weeks) are life threatening, above all to infants and elderly people with cardiovascular and respiratory diseases. Breathing may also become more difficult for asthmatics as warming increases seasonal burdens of pollen.

Coping with heat waves and allergens would be easier than dealing with a second, though indirect, threat to human health. Many of the insects and parasites that transmit and cause tropical diseases live in habitats that could extend northward in a warmer world, bringing malaria, trypanosomiasis, leishmaniasis, amoebiasis, and filariasis to higher latitudes. A warmer climate could make the mid-latitudes more hospitable to mosquitoes and ticks, as well as plasmodia and viruses, increasing the risks of acquiring Lyme disease, Rocky Mountain spotted fever, dengue fever, and arbovirus encephalitis.

The possible spread of malaria into new regions poses the greatest risk. In spite of vigorous efforts to control the disease, it is currently prevalent in regions housing some 2 billion people, and more than 250 million new cases are recorded each year. Warming would make little difference to areas already infested year-round with *Anopheles* mosquitoes and *Plasmodium* parasites—but it could expand (by up to 50 percent) the area plagued by seasonal malaria, bringing it into temperate regions of the northern hemisphere and Australia. The populations in these regions, lacking immunity to the disease, would be more likely to experience recurring epidemics and higher mortality.

Some Other Changes

Finally, a few paragraphs about those changes in the carbon cycle that would have undesirable consequences even if there were no CO_2 buildup. As deforestation replaces moist, dark-colored tropical forests with fairly dry, lighter-colored grasslands, a



Modeled environmental changes following the deforestation of Amazonia: surface temperatures would be about 10 percent higher throughout the year, while precipitation and evapotranspiration would be, respectively, about 25 and 30 percent lower.

greater share of the incoming solar radiation is reflected and hence less of it is available to evaporate water. Evapotranspiration is commonly reduced by 20, even by 30 percent, and precipitation is lowered by a similar margin. The shift from tall, mature tree canopies to grasses decreases surface roughness, leading to higher surface wind speeds. Both changes greatly affect surface temperatures, the formation of clouds, and air circulation.

Simulations indicate that were Amazonia to be turned into a giant pasture, temperatures would be about 2.5 °C higher. In some regions, a reduction in the cloud cover, a consequence of lowered evapotranspiration, could boost this increase to 4 or 5 °C. The dry season may also become longer. The falloff in precipitation may be discernible even in one to two day means, extending downwind from deforested areas. Drier areas will be more prone to fires, and their soil to erosion following infrequent downpours. A nearly complete Asian deforestation could radically alter the distribution of monsoon rains because evapotranspiration would bring less moisture into the air from previously vegetated areas.

Naturally, deforestation also reduces litter fall, and this loss, together with the faster decomposition of organic matter caused by higher soil temperatures, would lower the amount of carbon stored in soils. Most soils lose at least a fifth, and some up to a half, of their organic carbon within a short period after land is converted to cropland. A comparison of 1100 paired samples showed that on average farmed soils had 25 percent less carbon than their undisturbed counterparts. Because abundant organic matter acts as a sponge, its loss impoverishes the soil by lowering its water-holding capacity, increasing the soil's tendency to compact, and reducing the amount of substrate available for microbial and invertebrate metabolism.

In aggregate, cultivated soils now contain almost 200 Gt C. About 60 Gt of carbon have already been released into the atmosphere as a result of agricultural expansion—but farm soils could reabsorb a large fraction of that total through proper agronomic practices. By taking appropriate measures, farmers can produce surprisingly large increases in soil carbon in just a decade or two. These measures include regular application of farmyard manure (rather than exclusive reliance on synthetic fertilizers), suitable crop rotations (rather than monocropping), and the practice of conservation tillage (rather than traditional plowing). If persevered in, these practices prevent any loss of organic matter even after many generations of cultivation.

Such measures would also help to maintain a balanced nitrogen cycle. As we shall see in the next chapter, flows of that element, too, have been changed and disrupted—not, as in the case of carbon flows, in the quest for more energy, but rather mainly in the quest for more food.