and ice. These models attempt to simulate all of these interconnected responses, rather than analyzing them one-by-one in isolation. When scientists specify changes in the amount of solar radiation entering the climate system as a result of volcanic eruptions and/or changes in Sun strength, the models simulate the integrated response of the many parts of the climate system, including the changes in temperature and atmospheric CO_2 levels.

Examining one of these modeling studies, I noticed a result that seemed to indicate a major flaw in the natural explanation. To match the largest (10 parts per million) decreases in CO_2, the model had to cool climate by almost 1°C, yet the reconstructed temperature trend in figure 12.3 permitted a decrease of only 0.1–0.2°C between the warmer interval from 1000 to 1200 and the cooler one from 1500 to1750. Conversely, to stay within the bounds of the small temperature changes in this reconstruction, the models would allow CO_2 changes of only 2–3 parts per million, compared to the 10 parts per million changes observed (fig. 12.1). Whichever way I looked at it, the CO_2 changes were simply too large relative to the temperature changes. Something seemed to be seriously wrong with the conventional explanation.

The natural explanation also struck me as suspect for another reason. The rates of change during these CO_2 drops looked very abrupt, in fact much faster than the natural changes that had occurred at the end of the last deglaciation, and during the previous three deglaciations as well. As shown in figure 9.1, CO_2 concentrations during each of these deglaciations rose by almost 100 parts per million within a span of not much more than 5,000 years, for an average rate of about 2 parts per million per century. In contrast, the CO_2 concentrations in figure 12.1 fell and then rebounded by 10 parts per million within only a century or so, a rate approximately five times as fast as the deglacial changes. Why would CO_2 values change at a faster rate during a time of almost stable global climate than they had during the highly dynamic climatic changes that occurred at the end of the major glacial cycles? This didn't make any sense.

So once again, an explanation based on natural climatic changes had come up short. And again it seemed to me that the only solution to this apparent dead end must be an explanation lying outside the realm of "natural" causes, an explanation somehow linked to humans. The explanation had to lie in some kind of process that could reverse the slow deforestation and accompanying CO_2 releases that had been occurring for thousands of years and could cause abrupt CO_2 decreases that lasted for decades to a century or two.

Chapter Thirteen

THE HORSEMEN OF THE APOCALYPSE: WHICH ONE?

Historians have long sensed that the last centuries of the Roman era, and those that followed, were something of a reversal in the "onward and upward" march of human progress typical of previous centuries, at least in Europe. The Romans had for a while achieved a level of engineering technology and general prosperity that would not be repeated again in most of the West for over a millennium. Aqueducts brought to their cities fresh water of a quality not equaled until less than 200 years ago in London or Paris. The aqueducts, as well as baths and public structures not intentionally destroyed by human hands, have stayed intact for almost two millennia because they were bound by cement of a quality that Europeans still could not match in the early 1800s. The durability of Roman roads was also unsurpassed. In most respects, life in Rome during the height of the Roman Empire had much more in common with life during the early 1800s than it did with conditions 8,000, 6,000, or 4,000 years ago. Similar advances had also occurred by 2,000 years ago in the advanced civilizations of China and India.

But soon after the height of the Roman era, Western civilization entered the "Dark Ages," a time marked in most areas by a regression in technological knowledge and a general loss of respect for, or interest in, scientific inquiry. In much of the West, this stagnant condition was to last until the Renaissance almost a millennium later. The Dark Age was also a difficult time in a more fundamental sense: world population growth slowed and even stopped during some intervals, apparently because of rising mortality rates. A woodcut in 1528 by Albrecht Dürer left an enduring image of several kinds of devastation that added to normal mortality during this era: the four horseman of the apocalypse. This image came originally from Revelations, the last book of the New Testament. The identities of the horsemen have been variously interpreted through history, but the typical version names three of them war, famine, and pestilence, with death the fourth.

The horsemen of the apocalypse seemed like a useful starting point to search for the cause of the unexplained CO_2 drops during the Dark Ages. Whichever horseman had killed the most humans might explain the CO_2 reductions: fewer humans, and less CO_2 release. Although not a historian, I began to explore the last 2,000 years of recorded human history, optimistically searching for any link to those dips in the CO_2 concentrations (see fig. 12.1), with the horsemen of the apocalypse as my gloomy guides.

An ancient, and somewhat fatalistic, wisdom acknowledges that human progress is not always a one-way process, and a popular song lyric from recent decades captures this attitude well: "one step forward, and two steps back." The initial discovery of agriculture, and all of the innovations that followed, had for several millennia been of unprecedented benefit to humanity. With more food available, human populations grew as never before. With dependable sources of food in a single region, people could stay in one place, rather than constantly having to pack up and move on. With their livestock nearby, people had easy access to protein-rich meat, milk, butter, and cheese to supplement crops rich in carbohydrates. With orchards of fruit and nut trees, diets became more nutritious still. With crop excesses stored away for lean years, extreme swings in weather could often be ridden out. Compared to the more vulnerable existence of those who had lived by hunting, fishing, and gathering, agriculture had transformed existence on Earth.

But agricultural progress came at a cost. Embedded in this new way of life were changes that would lead to problems on a scale previously unknown in human history. Each of the first three horsemen of the apocalypse is, indirectly or directly, linked to the unprecedented success of agriculture. And gradually, after 2,000 years ago, the "forward" steps of agricultural success would begin to produce "backward" feedback effects that would grievously afflict humanity.

Consider war, obviously a major killer of humans. By 2,000 years ago, war was occurring on previously unprecedented scales. Stone Age clans moving from site to site in forest clearings no doubt fought often over resources, but they did so locally, with deaths on a smaller and more random scale. But after agriculture produced far larger societies with much greater wealth, these cultures began to pay a class of full-time warriors to defend that wealth and to invade other regions to obtain even more. In addition, as different religions came into being from region to region, differences in beliefs became a common motivation for war.

If war had been the major cause of human mortality, I would have expected to see the largest wars clustered within intervals of low CO_2 concentrations at roughly AD 200–600, 1300–1400, and 1500–1750, with little warfare from 600 to 1300. Yet a cursory look at the history of warfare showed little or no obvious correlation of this kind. We (humans) have rarely allowed much time to pass without a major war, and no era of any length has been entirely free from it on one scale or another. An animated world map of the history of warfare would show endless overlapping battles of considerable intensity throughout every interval of history. To my eye, no convincing link to the three intervals of low CO_2 was apparent.

Some might still be tempted to infer that a significant concentration of wars occurred during the decline of the Roman Empire from 200 to 600, the first low-CO_2 interval. The Huns, the Visigoths, and then the Vandals invaded southward from Germany beginning in 370 and through the middle 500s, followed by the Avars in the 500s to 600s and the Slavs in the 500s to 700s. Large disturbances also occurred in China and India during this time. But war did not subsequently cease for the next 600 years when CO_2 levels rose. Later warring groups included the Franks in the 700s, the Vikings in the late 700s to the 900s, the Magyars in the 800s and 900s, and the Muslims from the 600s and until the Saracen resurgence of the 1200s. With no obvious gap in the frequency of warfare, little correlation to CO_2 emissions was apparent.

One important exception may exist: the Mongol invasions throughout Eurasia that began in the early 1200s and reached a peak during the middle 1200s left effects that lasted for centuries afterward. Genghis Khan and his successors invaded every region from China in the East, to India in the South, to Europe in the West, and in several regions they ripped up the very fabric of the societies they conquered. Tens of millions may have died in China at Mongol hands in the 1200s. In the arid Near East, where agriculture had originated, the Mongols destroyed most of the existing irrigation-based agriculture, and populations fell precipitously. War and systematic destruction at this large a scale is unusual, and CO_2 concentrations were falling during this interval, so a causal link is possible in this case.

But in all other respects, war seemed an unlikely explanation of the CO_2 drops during preindustrial times, at least to my nonhistorian's eye. Even the 8 million Germans and Belgians who died during the Thirty Years War between 1618 and 1648 were "only" 1–2% of the global population of that time. War is deadly, but seemingly not deadly enough to qualify as the horseman I sought.

Famine is another potential killer, and to some extent also an outgrowth of the success of agriculture. With gradual improvements in agricultural techniques, farmers gradually began taking the risk of growing crops closer to the limits nature sets: in far-northern regions and on mountain flanks where cold temperatures set natural limits, and in warmer semi-arid regions where drought is the limit. Crops grown in these environments naturally became more vulnerable to year-to-year freezes or droughts, and even more so to longer-term climatic changes. The most severe famine in preindustrial European history in terms of mortality occurred in 1315–1322, and another in the 1430s.

But was famine really a major factor on a global scale? Like today, very small fractions of the total human population on Earth lived along the northern or high-altitude limits of agricultural regions. When crops failed in these cooler regions, the deaths they caused tended to be relatively small on a global scale. Even the famine of 1315–1322 mainly affected far-northern and high-elevation regions of Europe. By 1322 good crops were again coming in, and population levels seem to have quickly recovered.

What about the tropics and subtropics, where most humans actually live and where the most serious climatic concern is drought? Could drought-induced famine be a major killer across large areas of the tropics and subtropics? This possibility seem unlikely for several reasons. For one thing, irrigation provided much of southern Eurasia with a buffer against the worst impacts of drought. Many of Eurasia's agricultural regions had dependable supplies of water from rivers that flowed from well-fed mountain sources that received considerable rainfall even during droughts.

In addition, the likelihood of drought striking vast areas of Eurasia simultaneously is unlikely on a meteorological basis. On a global scale, very nearly the same amount of rain falls each year. Solar radiation evaporates very nearly the same amount of water vapor from the oceans and land each year, but the atmosphere can store only so much water vapor before it sends it back to Earth. As a result, global rainfall does not vary much from year to year.

Of course precipitation does vary widely on a local basis. One town can be as green as a golf course late in June, with another town nearby parched and brown; yet a month later the two regions may have switched colors, as the scattered thunderstorms that first favored one area then fell on the other. This same uneven distribution of rainfall occurs at larger regional scales, with one country suffering a multiyear drought while a neighbor has heavy rains and flooding. But on a larger, more nearly global scale, the droughts and floods (and normal rainfall elsewhere) tend to balance out. It is nearly impossible for a region as large as the entire southern tier of Eurasia to be gripped in drought at a single time. To my knowledge, no climate historian has ever claimed that drought has simultaneously afflicted this largest and most populated of continents during the last 2,000 years. Because neither freezes nor droughts are likely to produce simultaneous crop losses across large portions of Eurasia, famine does not seem to be the horseman I sought.

What about the horseman called pestilence, or disease? One afternoon when I had just begun wondering about those CO_2 dips, I was eating lunch and reading a book review when the word "plague" caught my eye. I put down my sandwich and walked over and pulled out the encyclopedia. There, I quickly relearned that bubonic plague had caused the Black Death pandemic of the mid-1300s, as well as later outbreaks during the 1500s and 1600s, but I also learned for the first time that a major pandemic had occurred during the Roman era in AD 540–542. The rates of mortality in both pandemics had been incredibly high (killing over 25% of the population), and at first glance the pandemics correlated fairly well with the dips in CO_2. Here was a more promising explanation of the CO_2 drops: pestilence, the rider of the pale horse.

As Jared Diamond summarized in *Guns, Germs, and Steel*, the very successes of agriculture had also been favorable to the spread of disease. In earlier times, people living the hunting-fishing-gathering life were dispersed in small clans or tribes. If disease struck a clan or local group, some (or even most) of its members might die, but the likelihood of them transmitting it to other clans was limited. Hearing about strange deaths in one group, people nearby could flee to areas beyond reach of the disease. People died from disease, but primarily at the limited scale of clans or tribes.

By 2,000 years ago, the rapid growth of populations had eliminated some of this natural protection. Ample production of food in the populated regions of eastern Asia, India, and Europe had led to the growth of towns and then cities. Because dense concentrations of people are natural breeding grounds through which contagious diseases can be transmitted quickly, both the victims and the carriers of virulent diseases were now conveniently clustered close together.

In addition, the fact that farmers lived settled, sedentary lives helped to breed disease. In preagricultural times, when food sources were depleted, hunting-gathering clans had been forced to move to new sources, leaving their refuse behind. Now, with large food surpluses from agriculture, people could live in one place and in ever-greater numbers, and their dwellings were surrounded by growing amounts of rubbish and waste. Permanent houses attracted mice and rats, carriers of diseases, and in many towns and cities the sanitation was primitive and the streets strewn with refuse, excellent breeding grounds for disease. Human feces were spread on fields for manure, and even irrigation ditches became potential sources of contagion.

Even worse, the livestock that humans had begun tending thousands of years earlier were carriers of diseases that afflicted people. Cattle carry smallpox, measles, and tuberculosis. Pigs carry influenza. Another factor indirectly related to agriculture was the increase in travel because of improved ships and greater use of overland routes for trading goods. Agricultural success generated increased wealth and increased trade, and trade put regions in closer contact. Now, when disease hit one area, it could more easily be carried to others. For all of these reasons, agricultural successes gave disease wider access to human victims.

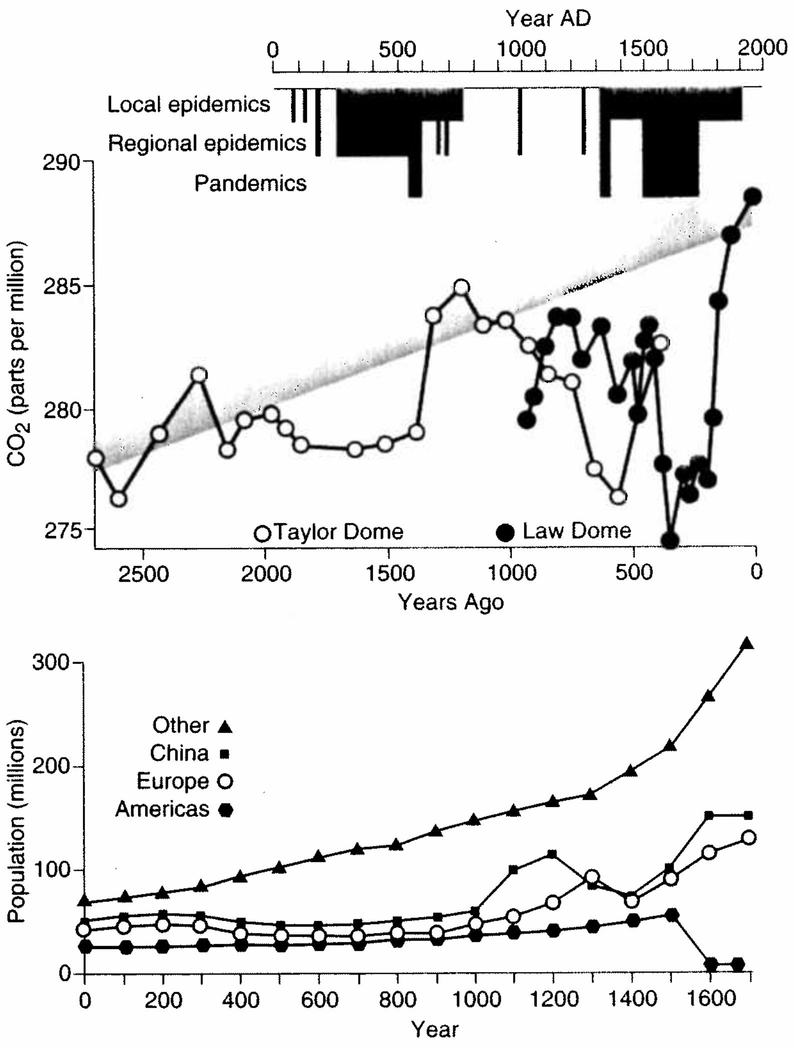
Until the historical era, little is known about disease. The Old Testament mentions pestilence several times (for example, in First Samuel). As the historical era began, written records of disease in some regions give us a limited picture of this history. I had initially hoped to find a graphic plot of disease mortality through the historical era, but I have not yet succeeded, although such a plot may well exist somewhere. Instead I compiled my own plot based mainly on *Plagues and Peoples* by W. McNeil, *Disease and History* by F. E. Cartwright, and *Armies of Pestilence* by R. S. Bray.

An accurate, reliable plot of the entire history of disease mortality seemed impossible. Instead, I chose to portray a general sense of the scope of mortality

TABLE 13.1
Epidemics and Pandemics of the Last 2000 Years

Year (AD)	*Region*	*Disease*	*Intensity (% Mortality)*
79, 125	Rome	Malaria?	Local epidemic
160–189	Roman Empire	Smallpox?	Regional epidemic
265–313	China	Smallpox	Regional epidemic
251–539	Roman Empire	Smallpox? or bubonic plague?	Regional epidemics (decadal repetition)
540–590	Europe, Arabia, and North Africa	Bubonic plague	*Major pandemic* (25%) Decadal repetition (40%)
581	India	Smallpox?	Regional epidemic
627–717	Middle East	Bubonic plague	Local epidemics
664	Europe	Bubonic plague	Regional epidemic
680	Med. Europe	Bubonic plague	Regional epidemic
746–748	Eastern Med.	Bubonic plague	Local epidemic
980	India	Smallpox	Regional epidemic
1257–1259	Europe	Unknown	Regional epidemic
1345–1400 1400–1720	Europe Europe/North Africa	Bubonic plague Decadal repetition	*Major pandemic* (40%) Regional epidemic
1500–1800 1500–1800	Europe Americas	Smallpox	Regional epidemic *Major pandemic* (80–90%)
1489–1850	Europe	Typhus	Regional epidemic
1503–1817 1817–1902	India India/China/Europe	Cholera	Local epidemic Pandemic (< 5%)
1323–1889 1918–1919	Europe Global	Influenza	Regional epidemic Pandemic (2–3%)
1894–1920	Southeast Asia	Bubonic plague	Regional epidemic (small %)

through time by plotting historically recorded outbreaks on three spatial scales: local epidemics, which affected towns or parts of countries; regional epidemics, which affected several countries or small parts of more than one continent; and pandemics, which affected large parts of several continents. The major disease outbreaks are listed in table 13.1 and plotted alongside changes in ice-core CO_2 and the populations of disease-afflicted continents in figure 13.1. The population



13.1. Intervals of low CO_2 concentrations in Antarctic ice cores correlate (within dating uncertainties) with major pandemics that decimated populations in Eurasia and the Americas.

numbers for Eurasia come from McEvedy and Jones's *Atlas of World Population History*. In my opinion, the correlation between pandemics, population losses, and dips in CO_2 minima looked suggestive enough to be worth pursuing.

The historical record of disease began when a pestilence of unknown origin struck Athens in 430 BC, decimating the Athenian army during the Peloponnesian

War with Sparta. Outbreaks of what may have been malaria occurred in Italy in AD 79 and 125 (the latter called the plague of Orosius). Malaria is not usually fatal today, but these outbreaks killed large numbers of people, perhaps because natural resistance to it had not yet developed. The disease hit especially hard in the countryside, and many farms went out of cultivation as farmers moved into the cities. Still, these outbreaks seem to have been relatively local in scale. A somewhat more extended outbreak, apparently of smallpox, the Antonine Plague, struck the Roman Empire between 160 and 189, killing the Roman emperor Marcus Aurelius. At its peak, some 2,000 people died each day. The symptoms (fever, skin eruptions, and inflammation of the mouth and throat) match those of smallpox. Mortality rates were high enough that farmers were drafted to fill the depleted ranks of the Roman army.

The year 251 saw a renewed pestilence called the plague of Cyprian after one of its early victims. The type of disease is again uncertain, but smallpox and bubonic plague are among the more likely choices. Whatever its origin, it was lethal and lasted for 16 years, becoming nearly pandemic from Egypt to Scotland. Anecdotal information from some regions indicates more deaths than survivors in the wake of this pestilence, with large areas of farmland in Italy reverting to the wild. Once again, people fled from the countryside to the cities, where they may have been more vulnerable. Recurrent outbreaks of bubonic plague continued in the Roman Empire for three centuries, and some (but by no means all) historians infer that the Roman Empire began to be seriously weakened by this ongoing loss of population.

Some historians also claim that the extended sequence of pestilence between the first and fourth centuries AD contributed to the growth of Christianity. As many people grew ill and died, the terrified survivors would have found little consolation in the jealous infighting of the older Roman gods. By contrast, Christianity offered the hope of miracles in this life (healing of the sick and casting out of spirits) and the promise of life after death. As conversions to Christianity accelerated during the plagues, it moved from an outlawed religion of martyrs to the official religion of the empire by the end of the fourth century.

But the pestilence continued during Christian times, culminating in 540–542 with a plague of unprecedented intensity named after Justinian, emperor at that time and destined to be the last of the line. This pandemic, almost certainly bubonic plague, was first recorded in Egypt, swept north into Palestine, Greece, and then the Black Sea and Constantinople, by that time the center of authority for the remnants of the empire. It then moved through the cities of North Africa along the Mediterranean coast and into southern and western Europe. It generally arrived first at coastal seaports and then spread into the interior cities and countryside. Because its lethal effects were felt on several continents, this plague was the first great pandemic.

Most of the plague during this era was probably carried by fleas hitching rides on rats. The fleas bit humans and transmitted the disease, which began with a fever, followed by large swellings (buboes) in the groin or armpits, and then a coma. Any physical movement on the part of those afflicted caused excruciating pain. Shortly after death, black spots appeared on the body. In one sense, at least, bubonic plague had a merciful side: death came quickly, usually within a week. At the height of the plague of Justinian, 5,000 to 10,000 people died each day in Constantinople, too many to be buried by the survivors. Their rotting bodies, filling the cities with the stench of death, were dumped into the empty towers of forts or loaded onto ships that were set adrift on the ocean. This time, not just villages and towns but even some cities ceased to exist, as the social order largely collapsed, and agriculture almost entirely ceased in many regions. Some 25% of the population may have died in this one outbreak.

Lesser but still extremely severe outbreaks of bubonic plague continued in Europe at intervals of 10 to 20 years until AD 590. The reason for the roughly decade-long spacing of outbreaks may be that most survivors had a natural resistance to the disease, and so the plague briefly abated for lack of available victims. After 15 or 20 years passed, many members of the newest generation lacked immunity, and plague would flare up anew. Some 40 percent of the population of Mediterranean Europe may have died in the cumulative outbreaks by 590 (fig. 13.1). For some countries, these losses were not replaced for four or five centuries.

For unknown reasons, the disease began to abate in Europe after 590, with regional epidemics recorded for the next 150 years, even though nearly continuous outbreaks of plague continued to afflict the Muslim-dominated Middle East between 627 and 717. After an outbreak in 746–748, bubonic plague disappeared for some 600 years.

The long Roman-era interval of epidemics that culminated in a major pandemic matches fairly closely the first extended CO_2 minimum in the ice-core record (fig. 13.1). The subsequent plague-free interval from 749 to the middle 1300s also correlates reasonably well with the rebound of the CO_2 trend (given the dating uncertainties in the latter), and of European and Chinese populations, to higher values. At least at a glance, it seems plausible that pandemics, populations, and CO_2 levels may have been linked during this interval.

Another devastating plague pandemic struck in the late 1340s. Originating perhaps in Central Asia, it reached the Near East by 1347 and swept across Europe from the Black Sea to the British Isles and into North Africa by the early 1350s. This plague was transmitted not just by fleas and rats, but also by pneumonic bacilli spread by coughing, sneezing, kissing, and even just breathing. Of an estimated 75 million people living in Europe just before the plague hit, at least 25 million, or one out of three, died within a few years.

Once again, farms, small villages, and even entire towns were abandoned, their inhabitants having died or fled to the cities. Crops again lay unharvested in the fields, and vineyards untended. As before, the cities provided no refuge, with mortality rates as high as 70 percent in the hardest-hit areas, although some regions were spared. Bodies of people from lower-class families were dragged out into the streets and left to rot, and few dared come to funerals held for the wealthy. The Pope was forced to consecrate the Rhone River near the city of Avignon so that bodies dumped there could be said to have received a Christian burial. Ships that had lost their entire crews to plague drifted aimlessly across the Mediterranean and North seas.

Some historians believe that the Black Death changed the feudal structure of medieval England, and perhaps elsewhere. Prior to the plague, poor serfs worked the land of their lords without much hope of improvement in their position. But after plague killed so many people, the resulting shortage of farm workers gave the survivors some bargaining power. For the first time, laborers moved around the countryside looking for higher wages and better situations. A form of tenant farming took hold—not complete freedom, but better than serfdom.

This first plague pandemic was followed by several more virulent outbreaks through the 1390s. By then, an estimated 40–45 percent of the population may have been killed in many parts of Europe. Entire villages simply disappeared, some forever. The impact of these plagues lingers today in phrases we use without giving their origin any thought: "avoiding someone like the plague"; a problem that "plagues us"; or "wishing a plague upon someone."

I find it difficult to imagine the horror of a disease that suddenly arrives from unknown sources by unknown means, kills an average of one out of three of your family members and your neighbors in a year or two, and then abates, at the point when you had begun to give up hope of surviving. Even more cruelly, by the time you have finally begun to feel safe and perhaps guardedly hopeful, the disease returns 15 or 20 years later and claims still another generation of victims. The Black Death pandemic and subsequent plague outbreaks through 1400 line up well with a dramatic CO_2 decrease in the Taylor Dome ice-core record, although the better-dated ice-core record from Law Dome shows a much less obvious drop (fig. 13.1).

Plague outbreaks continued in Europe for the next 300 years. Some historians refer to the worst of these outbreaks as pandemics, and thousands of people died in London each week at the height of an outbreak in 1665, just one of many during this interval. And by this point in human history, other diseases had also joined the "army of pestilence" in taking a toll on human populations. Influenza (from pigs) became a major problem by the early 1300s. Smallpox (from cattle) became epidemic in Europe in the 1500s and remained a major killer until the 1800s. Regional epidemics of cholera struck India after 1500, with an unusually lethal outbreak in 1543.

Yet this disease-ridden interval in Europe does not seem to rank as a true pandemic. After the Black Death horror of the mid-1300s, European populations rebounded to preplague levels within a remarkable 150 years and continued to grow from the 1400s through the 1800s (fig. 13.1). Mortality rates must have been considerably smaller than during the Roman or medieval eras.

But a third (and worst) preindustrial pandemic was still to come—the one resulting from European entry into the Americas. Europeans carried many diseases to which they had gained a large measure of immunity, but which decimated Native American populations from Canada to Argentina. Some of the diseases were carried on the persons of the Europeans, at that time mostly a flea-infested, lice-ridden people who abhorred bathing as unhealthy. Diseases also arrived on their pigs, cattle, and other livestock. This wave of invading pestilence, unprecedented in history, included smallpox, influenza, viral hepatitis, diphtheria, measles, mumps, typhus, and whooping cough, and somewhat later, scarlet fever, cholera, and bubonic plague. Even diseases such as mumps and measles that sound trivial today were often fatal for people with no natural immunity.

In recent decades, estimates of the size of the pre-Columbian populations in the Americas have soared. Where once historians thought that 10 to 20 million people lived in the Americas, conservative estimates from reputable sources like W. Denevan (*The Native Population of the Americas in 1492*) are now in the range of 50 to 60 million people, with more extreme proposals exceeding 100 million. The largest populations were the Aztecs in Mexico, the Inca in Peru and Bolivia, and the surprisingly large populations living in the tropical rain forests of Central America and the Amazon Basin. The much larger population estimates for the Amazon in recent years come from new archeological methods such as low-level airplane overflights that trace out road and village patterns or terraced hillside gardens, followed by detailed studies on the ground.

After the Europeans made contact, up to 90 percent of the native populations died. Entire villages that once lined the valleys of the lower Mississippi River system were abandoned, along with endless cornfields in between. After the forests again took over, the only obvious evidence left of the former existence of these agricultural people was massive earthen mounds used for ceremonial purposes. Most of these mounds were plowed by settlers and flattened to create towns and cities. In the Amazon Basin and other rain forest regions, lush tropical vegetation swallowed up most evidence of former habitation. Many decades later, so little evidence remained of the former occupation of North America that scientists and historians in the 1800s and early 1900s assumed that populations had been relatively small. For the few regions (like Cahokia, Illinois) where massive structures indicative of more advanced civilizations survived, scientists and historians discounted the obvious explanation (that they were of Native American origin) and assumed that European people must have created these structures in an earlier era.

Today, the best estimate is that some 50 million people died just from having come into contact with Europeans. This was the greatest pandemic in all of preindustrial history, and, in proportion to the size of the global population, the worst pandemic of all time. Out of roughly 500 million humans then alive on Earth, 50 million (10%) died in the Americas.

The indigenous populations of the Americas never recovered from this great pandemic. Not until large-scale European settlement after 1750 did the total population in the Americas reach the pre-Columbian level. The overall duration of this third great "American Pandemic"—1500–1750—closely matches the third and largest CO_2 drop in the Law Dome ice core (fig. 13.1). In this case, the age of the CO_2 minimum in the ice core is firm, and its correlation in time with the pandemic is certain.

Since the 1800s, mortality from diseases has been lower than before, with some exceptions. The last recorded epidemic of bubonic plague occurred in southern France and northern Africa in 1720. The near-disappearance of plague during the 1700s is often credited to improved sanitation, but this explanation is disputed by some medical historians who infer that the species of rat that carried plague-bearing fleas was for some reason displaced by a species that did not. Vaccines for bubonic plague became available only in 1884, but a serious outbreak still occurred in 1910 in Manchuria, and isolated cases occur even now. Gradually, improvements in sanitation and new medicines have suppressed the worst forms of many diseases, although AIDS has killed millions of people despite the best modern medical efforts. In any case, the rebound from low CO_2 levels after 1750–1800 seems to correlate reasonably well with the reduced incidence of high-mortality disease.

Historians must weigh and balance many contending explanations for the complex array of developments that determine the course of history. Still, the evidence in hand leads me to a clear conclusion: the major CO_2 dips in the ice-core records correlate more persuasively with population drops caused by major pandemics than they do with times of war or famine.

It was tempting to conclude that pandemics must be the primary *cause* of the CO_2 drops. But an old adage in science holds that "correlation does not prove causality." Two trends may be wonderfully correlated in time and yet not related in a cause-and-effect sense. It was still possible that the CO_2 values and the disease/population trends were each responding to some other common factor but were not actually linked in a causal sense at all. I still needed to find a specific, plausible causal mechanism that linked CO_2 and pandemics.

Chapter Fourteen

PANDEMICS, CO_2, AND CLIMATE

THE CORRELATION BETWEEN pandemics and drops in atmospheric CO_2 concentrations was suggestive, but what was the connection? How could plague and other diseases cause the drops in CO_2? Part of the answer to these questions comes from historical records summarized in chapter 13. These records document abandonment of farms and farm villages on a massive scale during and after all three major pandemics. In the wake of the European plagues, abandoned farms are described as having gone to waste or ruin. Those words bring to mind doors flapping in the breeze, roofs sagging and collapsing in upon houses and barns, and wild vines creeping up and strangling rotting fences. But nature was doing much more than that. Nature was busy turning pastures and croplands back into forest, and remarkably quickly.

A little over a decade ago, we bought the property where we now live. The former owner had begun a small Christmas tree farm in the lower part of the meadow where our house stands. He kept most of the meadow in good trim by "bush hogging," a method far cruder than cutting hay. The drive from a tractor spins a blunt blade that whacks down the grass by brute force, along with anything else that sprouts (saplings, shrubs, etc). Two summers had passed between the time when we bought the land and the point when house construction started, and in that short a time the meadow had begun to be invaded by forest. Young cedar trees sprouted along the meadow edges where berries fell from mature trees in nearby woods. Locust saplings sprouted well out into the meadow by a combination of root propagation and seed dispersal by pods. Several kinds of shrubs and cedars that had been whacked down but not killed by bush hogging also started to grow here and there. This meadow had no fences, or otherwise the birds would have started rows of trees on the ground just below by depositing seeds in ready-made fertilizer capsules. To me, a product of the suburbs, this instant eruption of trees was astonishing. It made me realize how much work it takes to keep a meadow a meadow. You can always put livestock out to browse down the invading vegetation, but only goats eat everything in sight. Extra cutting is needed to fight off tree and shrub invasions in fields with only cattle or horses.

Here in Virginia, cedars and locusts are the meadow invaders. To the north, in New York, maples are the aggressors. In northern New England, it's the birches. Looking at the remains of the abandoned farms throughout New England, Robert Frost might just as well have written "Something there is that doesn't love a meadow." In all naturally forested regions, forests can reoccupy abandoned pasture or cultivated land with amazing speed.

History shows that many farms in Europe were not reoccupied for many decades or even a century or two after major plagues. The amount of time until reoccupation depended in part on whether or not the plague outbreaks repeated, thereby keeping populations low and people off the available land. In the absence of humans, vegetation began to reclaim the farms, and as it grew it pulled CO_2 out of the atmosphere. Based on field evidence and models, ecologists have found that abandoned pasture and cropland regain the carbon (biomass) levels typical of full forests within 50 years. At first, the invaders are shrubs and tree saplings competing for sunlight and soil. In time, some trees begin to out-compete others, and the thickets thin out a bit. After 50 years, sizeable trees exist, not old-stand forests with mature trees, but full forests nevertheless in terms of the amount of carbon stored in roots, trunks, and branches. From the perspective of the CO_2 being removed from the atmosphere, it is as if the land has completely reverted to forest in just 50 years.

Here, then, is a possible mechanism to pull CO_2 out of the atmosphere in a few decades: widespread reforestation as a result of pandemic mortality. Imagine the following scenario. During the years before the plague hits, gradual deforestation has been slowly removing carbon from the land at rates typical of the interval between 8,000 years ago and the industrial era. As a result, atmospheric CO_2 levels have been slowly rising. Then a pandemic strikes, causing mass human mortality, widespread farm abandonment, forest regrowth, and CO_2 removal from the atmosphere over the next 50 years. The rates of CO_2 removal in reforestation are much higher than the very gradual rates of CO_2 addition from deforestation, and 50 years or so after the onset of the plague, CO_2 concentrations have fallen to a minimum value.

At this point, several scenarios are possible. If the pandemics end, people will soon begin to reoccupy the farmland, cut back the newly grown forest, and restore the farmland to agricultural use. As they do so, carbon will be returned to the atmosphere, and CO_2 levels will rise rapidly back to the preplague trend. But if repeated outbreaks of plague occur at decadal intervals following the initial outbreak, over a century could pass before the farms begin to be reoccupied.

History shows that the patterns of the major pandemics were all different. The plague of Justinian in AD 540–542 was the culmination of several centuries of prior epidemics of increasing intensity, and it was followed by more than a century of less-severe outbreaks. Populations in most of Europe didn't fully recover until the start of the medieval era around AD 1000, many centuries later. In contrast, the Black Death struck without warning in 1347–1352 and was followed by several outbreaks, yet populations in most of Europe had somehow rebounded to previous levels by 1500. The American Pandemic after 1500 had no real end: indigenous populations had not even begun to recover when major European settlement started in the middle and late 1700s.

One aspect of the Roman-era and Black Death pandemics that struck me as curious remains unexplained. During the same centuries that plague was decimating Europe, populations in China were falling and then recovering in almost identical patterns (see fig. 13.1). Because China and much of Europe had numerous census counts throughout these intervals, this striking similarity in population changes is hard to reject as some kind of artifact of historical inaccuracies. Yet most of the primary sources on the history of disease do not mention bubonic plague in China during these intervals, or anywhere else east of Iran.

In any case, I omitted China from my assessment of the effects of reforestation on atmospheric CO_2 during both the Roman and medieval eras. Largely anecdotal historical evidence indicated that all of the arable land in China had been deforested some 3,000 years ago, at least in the populous north-central regions. By that time, China had passed the population density of 11 people/km^2 that caused near-total deforestation of England in 1089 (the Domesday Survey). I reasoned that the large excess of people available in China would have occupied any farmland abandoned during the population drops of the Roman and medieval eras, so that reforestation would have been minimal despite the enormous mortality at those times.

This left Europe and other circum-Mediterranean lands as the regions of likely reforestation during the first two pandemics, and the Americas during the third. To estimate the amount of farmland abandoned, I again turned to the concept of a per capita footprint of each human on the forest (chapter 9) but this time used it in the opposite sense—to quantify farm abandonment. Since each Stone Age or Iron Age person occupied an estimated 0.03–0.09 km^2 of land, I assumed that each person killed by plague would also leave that much land abandoned. Regrowth of forests on those farms would, after 50 years, pull as much carbon out of the atmosphere as the earlier forest clearance had once put into it. The total carbon pulled from the atmosphere is calculated as:

$$\begin{pmatrix}\text{\# people killed}\\ \text{by disease}\end{pmatrix} \times \begin{pmatrix}\text{farmland abandoned}\\ \text{per person}\end{pmatrix} \times \begin{pmatrix}\text{C per km}^2\\ \text{reforested}\end{pmatrix}$$

The carbon sequestered in the growing trees does not come entirely from the atmosphere. The atmosphere constantly exchanges carbon with the surface layer of the ocean and with all of the world's plant matter (both terrestrial and marine) within a few years, so these other reservoirs would also have contributed their share to the carbon used for reforestation. These contributions reduce the amount of CO_2 required from the atmosphere. Allowing for all these factors, I found that reforestation after each pandemic would have been large enough to account for the observed CO_2 decreases of 4–10 parts per million.

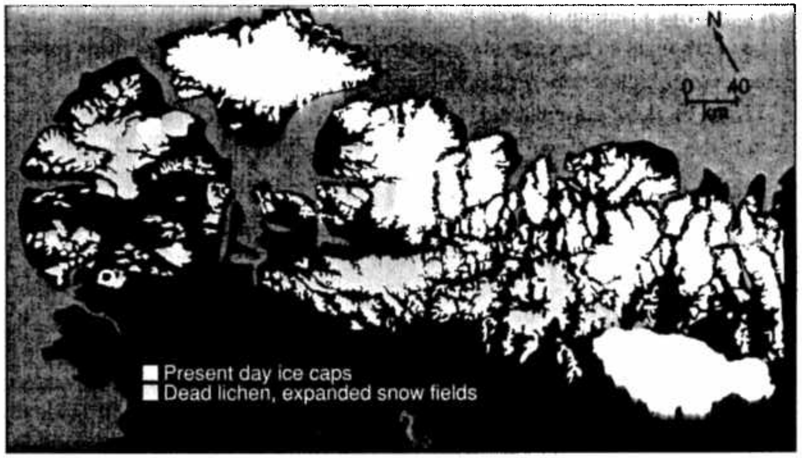
It also occurred to me that pandemics could have caused a drop in the concentration of CO_2 in the atmosphere by slowing the global-average rate of deforestation. Although CO_2 was constantly being added to the atmosphere by deforestation over many millennia, it was also constantly being removed by uptake in the ocean. The processes that transfer CO_2 into the deep ocean work far more slowly than the changes in the rate of deforestation caused by a major pandemic. If a pandemic abruptly reduced the rate of CO_2 input, but the rate of removal to the ocean slowed only a little, the total amount of CO_2 in the atmosphere would have to drop.

Major pandemics are likely to have brought deforestation to a complete halt in the afflicted areas, based on historical evidence that reforestation actually occurred in such regions instead. These abrupt halts to deforestation across the stricken regions would then overwhelm the slow, steady deforestation still occurring in parts of the world spared by the pandemic. As a result, the global-mean rate of deforestation would drop, and atmospheric CO_2 concentrations would follow.

Humans could also have contributed to the CO_2 drops in a third way. In north-central China, where deforestation had occurred more than 2,000 years ago, most people are thought to have burned coal for heat and cooking. The massive levels of mortality during the Roman and medieval eras would have reduced CO_2 emissions from coal burning by amounts roughly proportional to the population losses in those regions. All of these factors—reforestation, reduced deforestation, and decreased coal burning—would have reduced atmospheric CO_2 concentrations. If natural (solar-volcanic) changes cannot provide an explanation, humans must have been an important factor.

One implication of these results is that CO_2 changes driven by pandemics could have played a significant role in climatic variations over the last 2,000 years. For a climate-system sensitivity of 2.5°C to CO_2 doubling, pandemic-driven reductions of CO_2 levels by 4 to 10 parts per million would have cooled global climate by 0.04 to 0.1°C. Such coolings would represent a significant fraction of the temperature changes observed (see fig. 12.3) between the cooler Roman era (200–600), the warmer medieval era (900–1200), and the cooler Little Ice Age interval (1300–1900). None of this rules out a role for solar-volcanic factors in these temperature changes, but the pandemic idea does manage to explain the size of the CO_2 reductions without violating the reconstructed temperature decreases, whereas natural solar-volcanic processes did not pass that test.

Part 3 of this book ended with the conclusion that a small glaciation should have begun several thousand years ago but was averted by a warming caused by slow increases in CO_2 and methane emissions by humans. For CO_2, the total anomaly caused by humans had grown to as much as 40 parts per million by medieval times. Then, during the Middle Ages, pandemics (perhaps aided by solar-volcanic changes) caused the CO_2 level to drop by as much as 10 parts per million. In effect, the pandemics eliminated a substantial fraction of the human-produced greenhouse "defense" that had been holding off a renewed glaciation. This abrupt CO_2 drop brought the climate system closer to the point of that long-overdue glaciation.



14.1. Surrounding small ice caps on Baffin Island that are rapidly melting today are halos of dead lichen that were smothered by the thick year-round snow cover prior to the 1900s.

Indications of how close northeastern Canada may have come to being glaciated a few hundred years ago can be found on Baffin Island. There, as noted in chapter 9, several small ice caps today lie perched on the high plateau terrain. Surrounding these ice caps are large halos of dead lichen (fig. 14.1). These lichen halos are ghostly remnants of an ice age that nearly got under way during the Middle Ages.

Lichen are thin, green-gray blobs that grow on the surfaces of trees and rocks. Like other vegetation, lichen need sunlight, CO_2, and nutrients to power photosynthesis and permit growth. The Sun provides the needed light, and CO_2 is readily available from the air. But in contrast to most other forms of vegetation, lichen obtain nutrients from an unusual source: the seemingly inhospitable surfaces on which they grow. The lichen attack the rock and break it down into its component minerals and elements, which they then use as nutrients. Arctic lichen are also well adapted to extreme cold, since winter nights are often many tens of degrees below zero. As a result, extreme cold cannot kill the high-Arctic species.

Yet something did kill those areas of lichen and produce those ghostly halos. The only plausible explanation seems to be that the lichen were denied sunlight, and the best way to cut off sunlight is to bury them under thick piles of snow that are replenished in winter and never entirely melt in summer. So the dead-lichen halos are thought to be remnants from a time when permanent snowfields covered large areas of high terrain on Baffin Island.

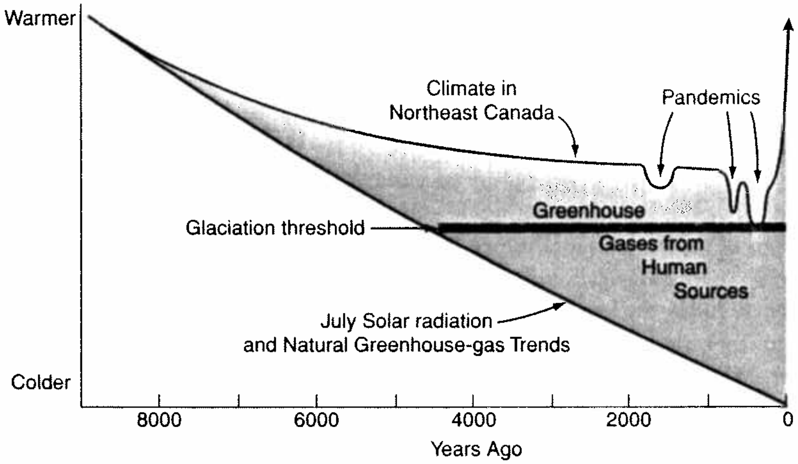
Living on these same plateau crests today are younger lichen that have grown within the last 100 years. The interval during which these newer lichens have been growing corresponds to the recent warming since the end of the Little Ice Age. Taken together, the evidence tells this story: lichen once grew in the regions where now only the halos exist, then they were killed by the accumulation of permanent snowfields, and still later, about 100 years ago, the snowfields began to melt and new lichen began to grow. Decades ago, this evidence led scientists to conclude that the expansion of permanent snowfields that killed the earlier generation of lichen occurred during the Little Ice Age.

When snow persists from year to year in permanent snowfields, it gradually turns to granular snow (firn) and then to ice because of the pressure of the overlying snow and other processes. At first, the snow and firn and ice simply pile up in place but do not move. Only when the thickness of ice reaches several tens of meters does it begin to flow, at which point it can be called a glacier. As far as is known, the snowfields (or ice fields) atop Baffin Island during the Little Ice Age never thickened enough to flow, so technically they were not glaciers and this was not the start of a glaciation. But they were obviously a significant step in that direction.

In the same sense, the Little Ice Age was not really an ice age, just a time of slightly cooler climate. Still, in that one region of northeastern Canada, a first small step in the direction of a real ice age did occur, for a few centuries. I concluded that this small step toward glaciation had resulted in part from the drops in atmospheric CO_2 values caused by the American pandemic after 1500, combined with natural solar-volcanic changes (fig. 14.2). If such a small CO_2 drop (10 parts per million) had helped bring this region so close to a state of glaciation, then it seems likely that a significantly larger portion of northeastern Canada would have been glaciated if the remaining CO_2 anomaly as well as the methane anomaly caused by humans were removed from the atmosphere.

The pandemic/CO_2/climate connection has other implications. As noted in chapter 13, some climate scientists and historians have hypothesized that intervals of cold climate produce famines that cause population decreases, at least in highly vulnerable regions of the far North. During times of cold, wet weather, crops freeze or rot in soggy fields, and people starve. Cold has also been suggested as a cause of disease and death in populations weakened by hunger.

Recently, the link between human populations and climate during the last 2,000 years has been interpreted in a more provocative way. Based on the observation that global populations have tended to expand during warmer climates and contract during colder ones, the conclusion has been drawn that warm climates must in general be good for humanity, and that cold climates must be bad. This conclusion has been injected into the global warming debate: any future greenhouse warming must be a good thing for humanity.



14.2. CO_2 drops caused by major pandemics probably brought parts of northeastern Canada to the threshold required for renewed glaciation.

But does such a link between climate and population really make sense on a global scale? Historians have generally been resistant to this form of "environmental determinism"—the idea that climate is a major control on human population. One of their criticisms is that even the extreme decades of the Little Ice Age are thought to have been no more than 1–2°C cooler in winter, and only a few tenths of a degree cooler during the summer growing season. A second problem is that temperature drops of this size occurred only in far-northern and high-altitude regions, while subtropical and tropical latitudes and lower-elevation regions cooled even less.

Very few people actually live at the high altitudes and latitudes where the larger coolings occur, because agriculture in such places is marginal during the best of times. As a result, crop failures and famines in those regions have little or no impact on a continental or global scale. Most of humanity lives in the tropics and moist regions of the subtropics and has done so for millennia. To those at warmer latitudes, a small temperature decrease might well be welcome, if a cooling of a few tenths of a degree centigrade were even noticed. The major part of the world's population would seemingly not be impacted by a Little Ice Age cooling in any significant way.

Still, the data (see fig. 13.1) do suggest some correlation between global population and climate. Even though "correlation is not causality," this apparent correlation invites an explanation. My findings provide a possible answer: both the cooler intervals and the simultaneous population losses are independent responses to pandemics. Pandemics cause massive population losses for obvious reasons, but they also cause CO_2 reductions that contribute to cooler climates. In short, population losses do indeed correlate with cold intervals, but they are not caused by them. The common causal factor here is disease.

The connection between pandemics and CO_2 is also relevant to studies of estimated carbon emissions during the early part of the industrial era. Reconstructions of carbon emissions caused by land-use changes extend back to AD 1840, with cruder extrapolations back to about 1800. The current interpretation of the trends during the late 1700s and early 1800s is that land clearance had begun to increase early in the industrial era but had not yet accelerated as abruptly as it would after 1840.

The pandemic/CO_2 hypothesis adds a new factor to consider in these reconstructions. The American pandemic was still in full effect when the industrial era began because indigenous populations had never recovered from the decimation caused by European diseases. As European settlement began, huge expanses of forest were cut, usually beginning with the prime bottom land in and near fertile river floodplains. Almost all of these areas were the same regions that had once been cleared, densely occupied, and heavily farmed by native Americans but had reverted to forest after being abandoned. By implication, the rather high rate of deforestation and carbon emission in the Americas during the 1700s and 1800s was not entirely the result of a first cutting of virgin forest; it resulted in part from a *recutting* of forests that had initially been removed much earlier by indigenous peoples but had later grown back as millions of people died. If so, some of the clearance that has been included as part of the early industrial-era total actually represents a recovery from the impact of the American pandemic.

Finally, the results summarized in parts 3 and 4 of this book greatly complicate studies of climatic changes over the last several millennia. Until now, one of the primary reasons for studying these earlier intervals has been to define the natural behavior of the climate system prior to the onset of significant human impacts that were assumed to have begun 200 years ago. The goal has been to quantify the natural behavior of the climate system accurately so that we can isolate and clarify the effects of humans on the planet. But now it seems that no part of the last several thousand years of climate change is actually free from potentially significant human impacts. Good reasons still exist for studies of recent millennia and centuries, but the more important (and more difficult) task may now be to separate human impacts on climate from natural variations.

PART FIVE

Humans in Control