THE ANTHROPOGENIC GREENHOUSE ERA BEGAN THOUSANDS OF YEARS AGO

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Abstract. The anthropogenic era is generally thought to have begun 150 to 200 years ago, when the industrial revolution began producing CO_2 and CH_4 at rates sufficient to alter their compositions in the atmosphere. A different hypothesis is posed here: anthropogenic emissions of these gases first altered atmospheric concentrations thousands of years ago. This hypothesis is based on three arguments. (1) Cyclic variations in CO_2 and CH_4 driven by Earth-orbital changes during the last 350,000 years predict decreases throughout the Holocene, but the CO_2 trend began an anomalous increase 8000 years ago, and the CH_4 trend did so 5000 years ago. (2) Published explanations for these mid- to late-Holocene gas increases based on natural forcing can be rejected based on paleoclimatic evidence. (3) A wide array of archeological, cultural, historical and geologic evidence points to viable explanations tied to anthropogenic changes resulting from early agriculture in Eurasia, including the start of forest clearance by 8000 years ago and of rice irrigation by 5000 years ago. In recent millennia, the estimated warming caused by these early gas emissions reached a global-mean value of $\sim$0.8 °C and roughly 2 °C at high latitudes, large enough to have stopped a glaciation of northeastern Canada predicted by two kinds of climatic models. CO_2 oscillations of $\sim$10 ppm in the last 1000 years are too large to be explained by external (solar-volcanic) forcing, but they can be explained by outbreaks of bubonic plague that caused historically documented farm abandonment in western Eurasia. Forest regrowth on abandoned farms sequestered enough carbon to account for the observed CO_2 decreases. Plague-driven CO_2 changes were also a significant causal factor in temperature changes during the Little Ice Age (1300–1900 AD).

1. Introduction

Crutzen and Stoermer (2000) called the time during which industrial-era human activities have altered greenhouse gas concentrations in the atmosphere (and thereby affected Earth's climate) the 'Anthropocene'. They placed its start at 1800 A.D., the time of the first slow increases of atmospheric CO_2 and CH_4 concentrations above previous longer-term values. Implicit in this view is a negligible human influence on gas concentrations and Earth's climate before 1800 AD.

The hypothesis advanced here is that the Anthropocene actually began thousands of years ago as a result of the discovery of agriculture and subsequent technological innovations in the practice of farming. This alternate view draws on two lines of evidence. First, the orbitally controlled variations in CO_2 and CH_4 concentrations that had previously prevailed for several hundred thousand years fail to explain the anomalous gas trends that developed in the middle and late Holocene.

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Second, evidence from palynology, archeology, geology, history, and cultural anthropology shows that human alterations of Eurasian landscapes began at a small scale during the late stone age 8000 to 6000 years ago and then grew much larger during the subsequent bronze and iron ages. The initiation and intensification of these human impacts coincide with, and provide a plausible explanation for, the divergence of the ice-core CO_2 and CH_4 concentrations from the natural trends predicted by Earth-orbital changes.

2. Early Anthropogenic Methane Emissions

Several studies have inferred anthropogenic methane emissions in pre-industrial centuries (for example, Etheridge et al., 1996), but Ruddiman and Thomson (2001) proposed that large-scale generation of methane by humans actually began back in the middle Holocene, when natural processes lost control of methane trends. For hundreds of thousands of years, CH_4 concentrations in Vostok ice had followed the 23,000-year orbital insolation cycle (Figure 1a). The highly coherent match between methane and insolation reveals this natural orbital control. Age offsets between the time scale shown (from Ruddiman and Raymo, 2003) and earlier time scales based on ice-flow models (Jouzel et al., 1993; Petit et al., 1999) lie within the estimated errors of the latter.

This coherent relationship supports the view that orbital-scale methane variations primarily reflect changes in the strength of tropical monsoons (Chappelaz et al., 1990; Blunier et al., 1995; Brook et al., 1996). The orbital monsoon theory of Kutzbach (1981) posits that increases in summer insolation heat land masses and cause air to rise, and the rising air lowers surface pressures and draws in moist air from the ocean. As the incoming ocean air rises over high topography and cools, it drops moisture in heavy monsoon rains. The monsoon rains flood wetlands, which release methane. The methane signal follows a 23,000-year tempo because orbital precession dominates summer insolation changes at low latitudes where monsoons occur.

Differences in CH_4 concentrations in Greenland versus Antarctic ice indicate that ~2/3 of the CH_4 flux on orbital time scales comes from tropical monsoon sources, and the remaining third from high northern latitudes (Chappellaz et al., 1997; Brook et al., 2000). Both of these sources follow the same 23,000-year tempo, because the insolation peaks that heat low-latitude landmasses and create monsoons also warm higher latitude wetlands that release additional CH_4.

Annually layered GRIP ice in Greenland provides a more stringent test of these proposed controls (Figure 1b). The most recent CH_4 maximum is centered between 11,000 and 10,500 years ago (Blunier et al., 1995), coincident with the last maximum in July (mid-summer) insolation. This timing agrees both with the orbital monsoon theory and with simultaneous precession control of boreal (mainly Siberian) CH_4 sources. Although brief CH_4 minima interrupted this trend during

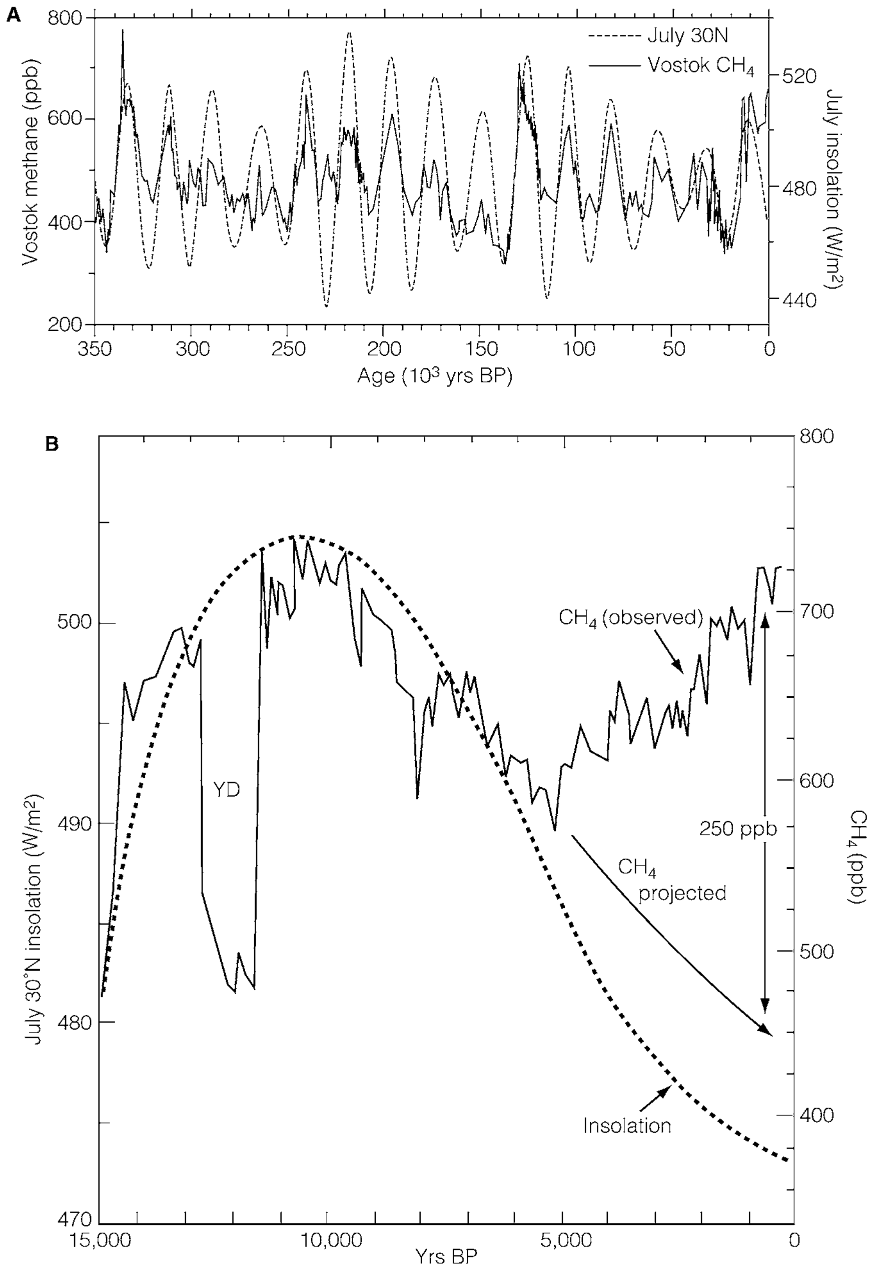

Figure 1. Comparison of July insolation values from Berger and Loutre (1996) with ice-core concentrations of atmospheric CH_4. (a) Long-term Vostok CH_4 record of Petit et al. (1999), using time scale of Ruddiman and Raymo (2003). (b) GRIP CH_4 record from Blunier et al. (1995), dated by counting annual layers. Early Holocene CH_4 trend projected in late Holocene to values reached during previous early-interglacial CH_4 minima.

the Younger Dryas and near 8100 yrs BP, CH_4 values then returned to the broader trend predicted by the Earth-orbital forcing.

This expected pattern continued until 5000 years ago, with the decline in CH_4 values matching the decrease of insolation. Near 5000 yrs BP, however, the CH_4 signal began a slow increase that departed from the continuing decrease expected from the orbital-monsoon theory (Figure 1b). This increase, which continued through the late Holocene, culminated in a completely anomalous situation by the start of the industrial era. With insolation forcing at a minimum, CH_4 values should also have reached a minimum, yet they had instead returned to the 700-ppb level typical of a full monsoon (Figure 1b). The late-Holocene CH_4 trend cannot be explained by the natural orbital CH_4 control that had persisted for the previous 350,000 years (Figure 1a).

Decreases in the CH_4 concentration gradient between Greenland and Antarctica indicate that the late Holocene CH_4 increase came from north-tropical sources rather than from boreal sources near the latitude of Greenland (Chappellaz et al., 1997; Brook et al., 2000). Chappellaz et al. (1997) concluded that the increased tropical CH_4 emissions since 5000 BP could have come from natural or human sources, or some combination of the two.

Ruddiman and Thomson (2001) pointed out that the broad-scale moisture patterns assembled by COHMAP (1988) from large arrays of pollen and lake-level data overwhelmingly confirm an ongoing drying trend after 9000 yrs BP across tropical Africa, Arabia, India, and Asia. As a result, natural (monsoonal) sources could not possibly have been responsible for the CH_4 increase and should instead have caused a further decrease. They concluded that the CH_4 increase could only have been anthropogenic in origin. They further noted that humans had adapted wild rice to cultivation by 7500 yrs BP (Chang, 1976; Glover and Higham, 1996) and had begun to irrigate rice near 5000 yrs BP (Roberts, 1998). By 2000 years ago, advanced civilizations in China and India had organized large-scale water-management projects for irrigation and other uses.

Ruddiman and Thomson (2001) proposed that the actual size of the anthropogenic CH_4 anomaly just prior to the industrial era must have been larger than the observed increase (Figure 1b). They reasoned that the full anomaly must include not just the 100-ppb CH_4 rise observed since 5000 years BP, but also the natural decrease that would have occurred had the CH_4 trend continued falling along with summer insolation. One basis for estimating the full anomaly is evident from the long Vostok CH_4 record in Figure 1a. Most CH_4 minima are 'clipped' (truncated) near a value of 450 ppb, except for lower values near large glacial maxima. The full CH_4 anomaly caused by humans is therefore $\sim$250 ppb, the difference between the 'natural' 450-ppb value and the 700-ppb level actually reached just prior to the industrial era.

The measured CH_4 increase of 100 ppb can be explained by a simple linear scaling of 1990 population and anthropogenic CH_4 emissions to 1750 population levels, but the full 250-ppb anomaly requires an early anthropogenic CH_4 source that was disproportionately large compared to human populations in 1750 AD. Ruddiman and Thomson (2001) suggested that the most likely such source is the inefficiency of early rice irrigation: extensively flooded wetlands harboring numerous weeds would have emitted large amounts of methane while feeding relatively few people.

In summary, the ‘anomalous’ late Holocene CH_4 increase cannot be explained by natural forcing, but it coincides closely with innovations in agriculture that produce methane in abundance. The anthropogenic greenhouse era began at least 5000 years ago.

3. The Holocene CO_2 Trend Is Also Anomalous

Carbon dioxide is a much more abundant gas than methane, and its variations have had a larger climatic impact over all time scales. The issue addressed in this section is whether or not the late-Holocene CO_2 trend exhibited the ‘natural’ behavior typical of longer orbital time scales or became ‘anomalous’. Natural orbital-scale CO_2 trends are more complicated than those of methane. CO_2 variations occur at all three orbital periods, with the 100,000-year cycle dominant (Lorius et al., 1985; Petit et al., 1999). The origins of these CO_2 cycles are not yet clear. This uncertainty complicates efforts to project natural CO_2 trends into the Holocene and detect any ‘anomalous’ trend (similar to that of methane)

One way to detect any anomalous pattern is to compare Holocene CO_2 trends to previous interglaciations, the times that provide the closest climatic analogs in the natural record (Figure 2a). Each of the last four deglaciations has been marked by a rapid CO_2 rise to a maximum timed just ahead of an ice volume ($\delta^{18}O$) minimum. For the three previous interglaciations, CO_2 values then dropped steadily for more than 10,000 years (Figure 2b). At times, the CO_2 decreases leveled off briefly, but in no case did they reverse direction and return to the late-deglacial CO_2 maximum.

The Holocene trend is different. Indermuhle et al. (1999) published a high-resolution, high-precision CO_2 record of the last 11,000 years at Taylor Dome, Antarctica (Figure 2c). This record confirmed a trend in the lower-resolution Vostok record of Figures 2a, b. CO_2 values reached a peak of 268 ppm between 11,000 and 10,000 years ago. This late-deglacial peak has the same relative placement as the CO_2 peaks reached during the three previous deglaciations. CO_2 values then decreased to 261 ppm by 8000 years ago, initially following a downward trend similar to the three earlier interglaciations.

Near 8000 years ago, however, the CO_2 trend began an anomalous increase that has no counterpart in any of the three preceding interglaciations, with values rising in recent millennia to 280–285 ppm, some 15 ppm above the late-deglacial peak. This 20–25 ppm CO_2 increase during the last 8000 years is anomalous in a manner similar to the CH_4 increase of the last 5000 years.

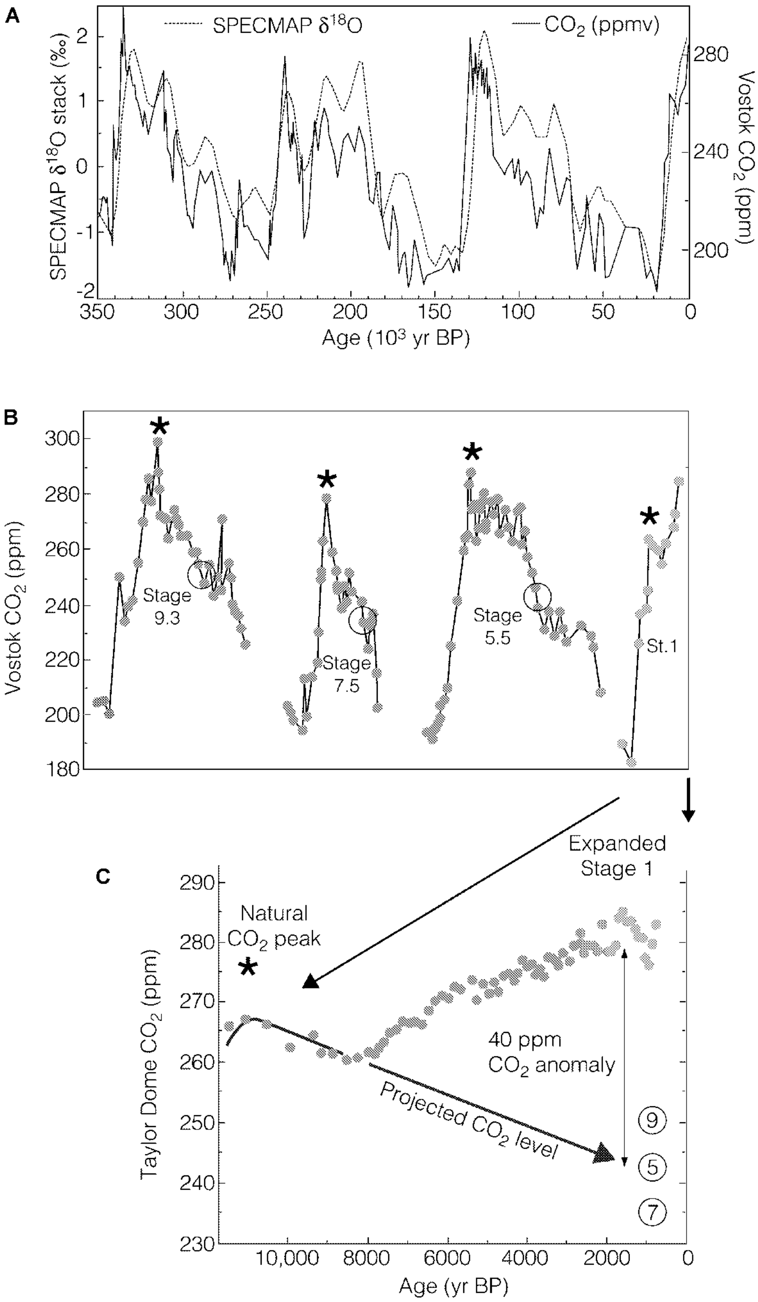

Figure 2. Concentrations of atmospheric CO_2 in Antarctic ice cores. (a) CO_2 trends from Vostok ice record of Petit et al. (1999) using time scale of Ruddiman and Raymo (2003). Marine $\delta^{18}O$ signal from SPECMAP (Imbrie et al., 1984). (b) CO_2 trends during 4 deglacial-interglacial intervals. Asterisks mark late-deglacial CO_2 maxima; circles show positions of early-interglacial CH_4 minima that follow 11,000 years later during insolation minima similar to today. (c) High-resolution CO_2 record from Taylor Dome of Indermuhle et al. (1999). Early-Holocene CO_2 trend projected during late Holocene toward circled values reached during previous interglaciations.

As was also the case for CH_4, the full Holocene CO_2 anomaly must actually be larger than the observed increase, because it should also include the amount by which the CO_2 concentration would have fallen had it continued the downward trend typical of previous interglaciations. The natural 23,000-year 'metronome' embedded in the CH_4 record at Vostok (Figure 1a) provides a way to estimate the size of this expected CO_2 decrease.

Today, summer insolation is at a minimum at low latitudes (Figure 1b). If anthropogenic CH_4 emissions had not over-ridden the natural monsoon control for the last 5000 years, present CH_4 values would also be at an orbital-scale minimum trailing one half-cycle (11,000 years) behind the late-deglacial CH_4 maximum. This insolation/CH_4 link allows us to pinpoint the analogous levels in the ice-core record of the three earlier interglaciations. These levels occur at the first CH_4 minimum after the prominent late-deglacial CH_4 maxima.

The positions of these previous early-interglacial CH_4 minima are marked by open circles in Figure 2b. The CO_2 concentrations at these levels range from 235 to 251 ppm and imply that CO_2 concentrations should naturally have fallen to 240–245 ppm by pre-industrial times. Instead, CO_2 values slowly rose to the observed range of 280–285 ppm. The full Holocene CO_2 anomaly is then $\sim$40 ppm, rather than the 25-ppm increase observed.

A potentially more insightful way to evaluate the possibility of anomalous CO_2 behavior in the Holocene is to examine the CO_2 trends at each of the three major orbital cycles, define their natural phasing with respect to changes in the corresponding orbital parameters, and then project this average long-term phasing forward into the Holocene. The CH_4-tuned time scale of Ruddiman and Raymo (2003) shown in Figure 1a provides an objective way to do this, because it was created without using CO_2 in the tuning process. The average phases between CO_2 and the orbital parameters in this time scale also match those determined by Shackleton (2000) based on orbital tuning of the ice-core record of atmospheric $\delta^{18}O_{atm}$ (a gas) to the marine $\delta^{18}O$ signal.

The phase of the 23,000-year CO_2 signal lags northern hemisphere summer insolation by less than 1000 years. This phasing predicts a CO_2 maximum near 10,000 years ago, followed by a continuous CO_2 decrease until the present. The observed CO_2 record matches this prediction until 8000 years ago, but the CO_2 rise since that time is anomalous. The phase of the 41,000-year CO_2 signal lags summer insolation by an average of 6,500 years and predicts a CO_2 decrease beginning 3500 years ago. The observed rise in CO_2 disagrees with this prediction during the last 3500 years. At the dominant 100,000-year cycle, CO_2 is nearly in phase with eccentricity, although large variations in relative phasing occur between cycles (Raymo, 1997). Because the last eccentricity maximum occurred $\sim$13,500 years ago, a CO_2 maximum should have occurred at or near that time, followed by a long-term decrease. The observed CO_2 increase since 8000 yrs BP disagrees with this prediction. In summary, separate analysis of CO_2 signals at all three orbital cycles confirms the conclusion derived from a direct comparison of the last four interglaciations: the observed 20–25 ppm CO_2 increase since 8000 years ago is anomalous.

This conclusion might be challenged based on the argument that insolation changes at the precession cycle have been smaller in the last 10,000 years than in previous interglaciations because of weaker amplification by the 413,000-year eccentricity cycle. Such a conclusion can be refuted by two arguments. First, the amplitude of insolation changes at the precession cycle varied by comparable amounts among the three previous interglaciations for the same reason, yet all show decreasing CO_2 trends. It is difficult to see why an additional decrease in insolation at the precession cycle should cause a complete reversal in the CO_2 trend. In addition, changes of insolation at the obliquity cycle have been nearly identical in both direction and amplitude during all four intervals. The late Holocene CO_2 trend is anomalous.

4. Previous Explanations for the CO_2 Increase

Two explanations based on natural processes have been proposed for the CO_2 rise since 8000 BP. This section evaluates (and rejects) those explanations.

4.1. NATURAL LOSS OF TERRESTRIAL BIOMASS

Indermuhle et al. (1999) proposed that the 20–25 ppm CO_2 increase during the last 8000 years resulted from a slow natural loss of terrestrial biomass. They chose terrestrial carbon as the likely explanation because of a negative trend in $\delta^{13}C$ values of atmospheric CO_2 during that interval. Terrestrial carbon has an average $\delta^{13}C$ value near –25‰, whereas the large ocean carbon reservoirs average close to 0‰. As a result, an atmospheric trend towards negative $\delta^{13}C$ values indicates a growing influx of terrestrial carbon. Indermuhle and colleagues used the Bern carbon-cycle model to assess possible combinations of carbon release from the land and uptake by the ocean because of surface-water cooling. The best model fit to these constraints indicated a terrestrial biomass loss of slightly less than 200 GtC between 7000 and 1000 years ago.

Indermuhle et al. (1999) noted that results from one biome model pointed to the north tropics as a potential source of terrestrial carbon. The model indicated a 30 GtC loss in the Sahel region of north-tropical Africa where monsoon moisture was decreasing. However, 85% of the inferred biomass loss remained unexplained by this result. More importantly, other vegetation modeling spanning a global scale argues against major biomass losses from natural causes during the Holocene. Foley (1994) published an estimate of biomass changes between 6000 years ago and today, using a process-based ecosystem model called DEMETER. First, changes in surface climate were simulated by driving the Genesis global climate model using changes in orbital parameters between 6000 years ago and the present. Then, major vegetation groups were simulated using the global biome model of Prentice et al. (1992). Finally, the DEMETER model was used to convert the simulated biome changes to estimates of carbon-budget changes.

In the tropics, the estimated net change in carbon storage between 6000 yrs BP and today was negligible (Table Ia). As in Indermuhle et al. (1999), carbon losses occurred where deserts advanced into grasslands as the northward limit of the summer monsoon retreated. But these losses were canceled by larger carbon gains along the northern margins of the tropical forests where rainfall increased because of the more persistent year-round presence of monsoon rains.

Holocene biomass losses might also be anticipated in boreal regions because declining summer insolation caused expansion of tundra into areas of former boreal forest and taiga (Nichols, 1975). But again, the net change in carbon simulated by DEMETER was minimal: increased carbon storage in soils beneath advancing tundra offset above-ground carbon losses from retreating taiga and boreal forest (Table Ia). Overall, the DEMETER model simulated a natural global carbon decrease of 36 Gt from 6000 yrs BP until today, equivalent to just ∼1.5% of the total terrestrial carbon biomass estimated for both 6000 yrs BP and today (Table Ib). The 36 GtC loss accounts for only ∼18% of the ∼200-GtC change calculated by Indermuhle et al. (1999) as necessary to explain the observed 20–25 ppm CO_2 increase. And if the full CO_2 anomaly is actually ∼40 ppm, proportional scaling puts the full carbon requirement at ∼320 GtC. In that case, natural changes in carbon since 6000 years ago can explain only ∼11% of the required terrestrial loss.

The PMIP project examined results of experiments comparing natural changes between 6000 yrs BP and today using ten general circulation models (Harrison et al., 1998). The climatic output from each model was used as input to the biome model of Prentice et al. (1992) to predict global-scale changes in biome groups. Although these comparisons did not attempt to estimate carbon biomass, they provide an indication of whether or not the biome-model results used in the Demeter model are reasonable. All ten models gave the same direction of biome changes in the tropical and boreal regions discussed above, and the estimates from the Genesis model used by Foley fall close to the middle of the model range. These results indicate that the biome estimates used by Foley (1994) are representative of the current state of such models. The model-to-model variations also suggest that the small change in the global carbon budget from 6000 yrs BP to today simulated by the DEMETER model is not likely to be significantly different from zero. In summary, natural changes in vegetation cannot be the major cause of the late-Holocene CO_2 increase.

Changes in Ocean Carbonate Chemistry

Broecker et al. (1999) proposed that the ocean could have caused the late-Holocene CO_2 increase (Figure 3). They noted that prior to 8000 years ago forests had been expanding across vast areas where ice sheets had just melted. They proposed that

Table I
Estimates of carbon storage (in GtC) from DEMETER model (Foley, 1994)

	Vegetation	Litter	Soils
a. Net C biomass changes from 6000 BP to today			
Tropics			
Tropical rain forest	+5	0	+3
Tropical seasonal forest	+19	+1	+13
Tropical dry forest	+1	–1	0
Warm grass and shrub (C4?)	–5	–5	–22
Total	+20	–5	–6
Net tropical change: +9 GtC			
Boreal regions			
Tundra	+3	+I	+48
Boreal forest/taiga	–23	–4	–29
Cool conifer	0	0	0
Total	–20	–3	+19
Net boreal change: –4 GtC			
Global total	–33	–16	+13
Net global change: –36 GtC			
b. Carbon available in forest biomes at 6000 BP			
Boreal forest/taiga	124	23	229
Cool conifer	65	7	55
Cold mixed	9	1	13
Cool mixed	67	13	91
Broad-leaf evergreen/mixed	77	12	104
Cold deciduous	28	4	63
Temp. deciduous	72	13	84
Tropical dry forest	73	18	128
Tropical seasonal forest	92	4	71
Tropical rain forest	129	3	65
Total	736	98	903
Total Global Forest carbon: 1737 Gt			

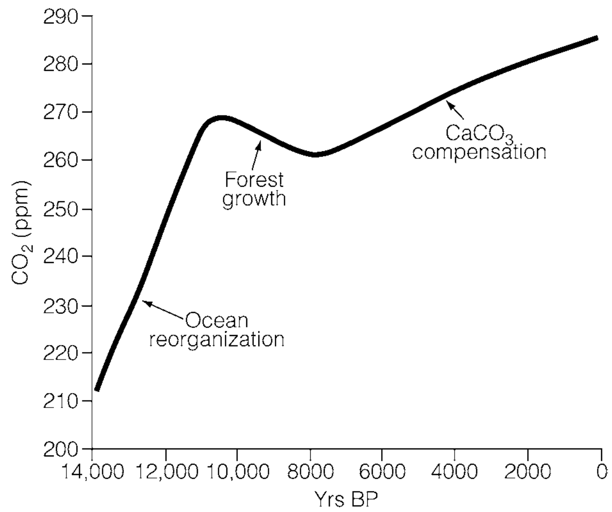

Figure 3. Proposed explanation of late-Holocene CO_2 rise based on ocean carbonate compensation (Broecker et al., 1999).

these growing forests extracted CO_2 from the ocean-atmosphere system, made the ocean less acidic, and caused deposition of extra $CaCO_3$ in the deep ocean. Then, when forest expansion ceased near 8000 yrs BP, the net extraction of CO_2 carbon from the atmosphere and ocean ended. This change had the same net effect as adding CO_2 to the ocean: it acidified ocean water (reduced its CO_3 ion content) and caused dissolution of the 'excess' sedimentary $CaCO_3$ previously deposited. Because of the large time constant of $CaCO_3$ dissolution, the process of restoring the CO_3 ion balance of the ocean has continued for thousands of years, and atmospheric CO_2 values have gradually risen. In effect, the CO_2 rise proposed in this hypothesis results from a delayed deep-ocean recovery from conditions imposed by late-deglacial forest growth (Figure 3).

One problem with this hypothesis is that the CO_2 'rebound' from 8000 yrs BP to the present has been $\sim$4 times the size of the early Holocene CO_2 decrease invoked as the cause. A greater problem is that fact that the hypothesis predicts similar CO_2 rises after the earlier deglaciations, when rapid melting of large ice sheets had also occurred in 10,000 years or less, and forests had also grown in the regions where the ice had melted. Yet no CO_2 increase occurred in any of the last three interglaciations; instead, CO_2 concentrations dropped continuously throughout their early and middle portions (Figure 2b). The absence of the expected CO_2 increases is a fatal flaw in the ocean-chemistry hypothesis.

In summary, neither of the two published explanations of the late-Holocene CO_2 increase is tenable. Both face a problem common to any explanation based on natural processes: the lack of substantial differences in orbital-scale forcing during the Holocene compared to the three previous interglaciations. In all four cases, coincident insolation maxima (and positive feedbacks) had driven deglaciations that ended with similarly reduced ice sheets and very similar global vegetation. Then, during an interval when ice sheets had not yet begun growing, when forests remained in their interglacial locations, and when insolation trends were moving in the same direction, CO_2 trends declined during the three previous interglaciations, yet rose during the Holocene. The Holocene CO_2 response is thus anomalous not just with respect to orbital insolation forcing, but also with respect to all major sources of forcing internal to the climate system. No known natural trend can explain the Holocene CO_2 rise.

5. Pre-Industrial Land Clearance Can Explain the Holocene CO_2 Rise

By process of elimination, the failure of orbital explanations to account for the anomalous CO_2 increase of the last 8000 years points to an anthropogenic origin. At first, however, such a conclusion may seem unlikely. The $\sim$200 GtC loss of terrestrial carbon estimated by Indermuhle et al. (1999) exceeds the total carbon input from industrial-era land-use changes from 1850 to 1990 (Houghton, 1999, 2000). And, if the actual pre-industrial carbon loss was actually closer to $\sim$320 GtC, the pre-industrial total would have to have been twice that of the industrial era. How could pre-industrial carbon emissions have been so large with populations so much smaller and technology so much more primitive than today?

In apparent confirmation of this view, a plot of rates of estimated carbon emissions from land-use changes during the industrial era (Figure 4a) shows that while recent rates have exceeded 1.5 GtC/yr, the rates were only 0.3–0.4 GtC/yr in the middle 1800s when CO_2 levels began to rise noticeably, and smaller still in the late 1700s (based on rough extrapolations). The trend shown in Figure 4a seems to leave little room for significant pre-industrial carbon emissions.

The first problem with this 'industrial era' view is that it neglects the impact of time. Per-annum rates of carbon release in pre-industrial times may have been smaller by an average factor of 10 or even considerably more, but the cumulative emissions could still have been enormous because of the much longer interval of time over which they operated (Figure 4b). The pre-industrial 'tortoise' (starting very early, even though at a slow rate) can cumulatively outdo the industrial 'hare' (faster rates, but starting much later) by a factor of two:

7800 years $\times$ 0.04 GtC/yr average $=$ 320 GtC cumulative total

200 years $\times$ 0.8 GtC/yr average $=$ 160 GtC cumulative total.

The second, and far more telling, problem with the 'industrial-era' view (Figure 4a) is that it is profoundly at odds with an enormous range of evidence of major human influences on the Eurasian landscape many millennia before the industrial era. Houghton (1999), a key figure in estimates of industrial-era landscape clearance, noted 'considerable uncertainty in estimates of deforestation prior to 1850,

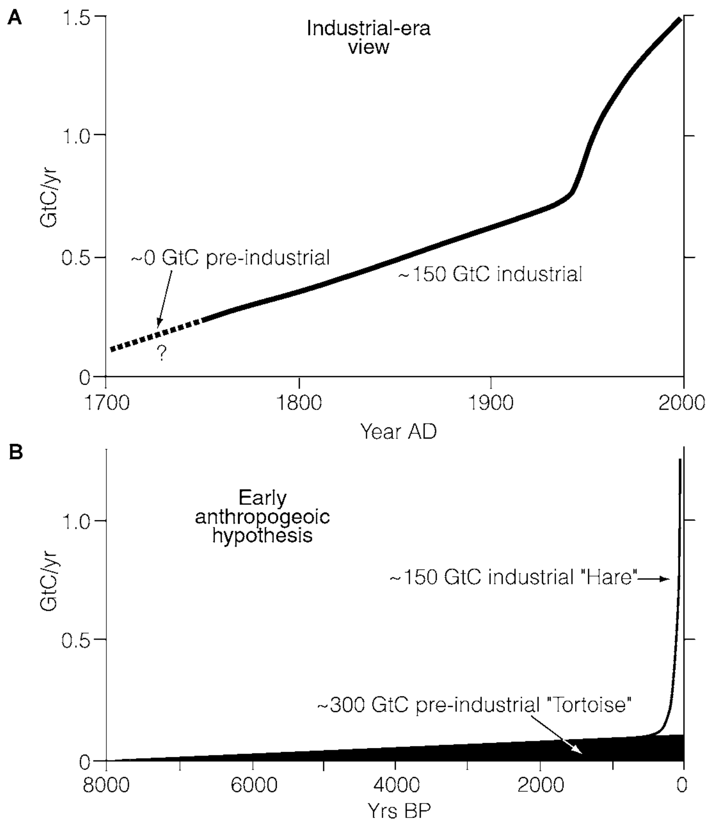

Figure 4. (a) Industrial-era perspective suggests that most land clearance occurred in the last 200 years. (b) Early-anthropogenic perspective suggests that much slower but longer-operating pre-industrial land clearance cumulatively exceeded clearance during the industrial era.

particularly for the three regions where human habitation has had a long history: Europe, Asia, and Africa'. The rest of this section investigates that issue.

The hypothesis put forward here is that pre-industrial forest clearance in Eurasia explains the CO_2 rise between 8000 yrs BP and 1800 AD. To be validated, this hypothesis has to meet three tests based on features evident in the Holocene CO_2 trend (Figure 2c): (1) clearance must begin near 8000 yrs BP (when the CO_2 rise began) on a small, yet 'non-negligible' scale; (2) clearance must grow large enough by ~2000 yrs BP to explain ~80% of the pre-industrial CO_2 anomaly; and (3) the negative CO_2 oscillations of 4 to 10 ppm after 2000 yrs BP also need an explanation.

Test 1: Did the Onset of Significant Land Clearance Occur near 8000 yrs BP?

Several lines of evidence confirm that initial deforestation by humans occurred near 8000 yrs BP. Based on the first appearance in well-dated sediments of a distinctive 'package' of grains initially domesticated in the fertile crescent of the

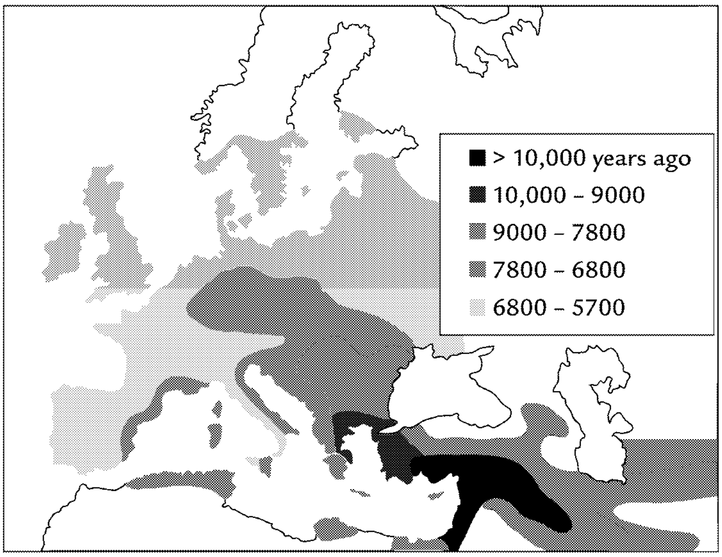

Figure 5. Spread of agriculture out of the eastern Mediterranean fertile crescent across Europe, based on the first appearance of a distinctive package of domesticated grains (after Zohary and Hopf, 1993).

eastern Mediterranean, Zohary and Hopf (1993) mapped the spread of agriculture (Figure 5). The advance across the Hungarian Plain and into the forested regions of south-central Europe occurred between 8000 and 7000 yrs BP, essentially coincident with the first upturn of the CO_2 trend (Figure 2c). At this time, much of agriculture in Europe consisted of slash-and-burn clearance of small patches of forest, planting of crops in the clearings, and movement from site to site. Most sites show early increases of disturbance-related herb and grass pollen, and many show increases in charcoal (Roberts, 1998). These alterations of the environment became far more noticeable after the arrival of bronze-age plows near 6000 to 5000 yrs BP (for example, Taylor, 1983; Zolitschka et al., 2003).

Other naturally forested regions that have not yet been as intensively studied also show signs of disturbance beginning around this time. Agriculture appeared in forested regions of China by 9400 yrs BP (Weming, 1991), and Ren and Beug (2002) concluded that a pervasive decrease in forest pollen in China by 6000 yrs BP was caused in part by increasing disturbance of natural vegetation by humans. The fertile crescent package of grains also first appeared in western India by 8500 yrs BP (Zohary and Hopf, 1993). All of this evidence is consistent with the start of small but non-negligible forest clearance near 8000 yrs BP.

Test 2: Did Extensive Deforestation Occur by 2000 yrs BP?

The anomalous CO_2 rise reached $\sim$80% of its maximum value by 2000 yrs BP, long before the start of the industrial era (Figure 2c). So early a CO_2 increase offers a

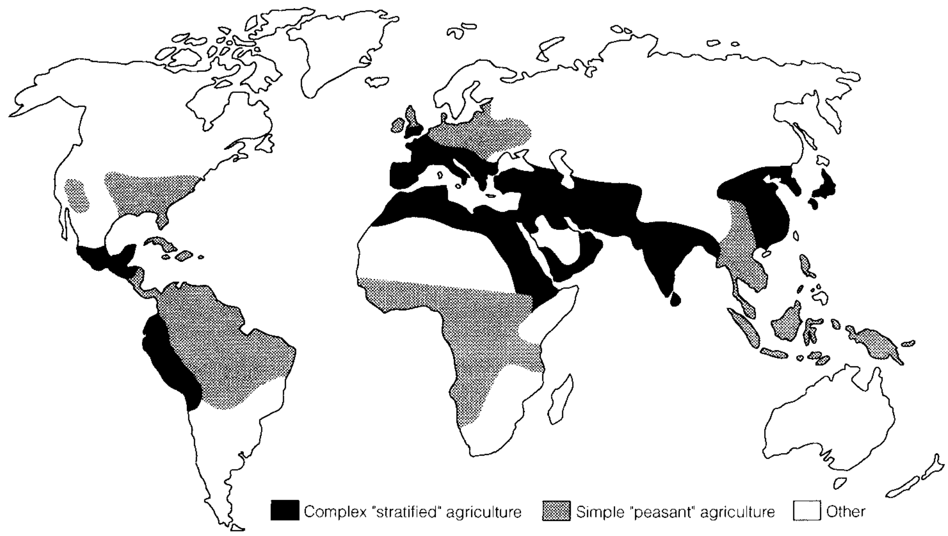

Figure 6. Areas of complex 'stratified' agriculture and simple 'peasant' agriculture at 2000 yrs BP (after Roberts, 1998; largely based on Lewthwaite and Sherratt, 1980). Areas of stratified agriculture include advanced civilizations of eastern China, India, and the Roman Empire, all of which had been naturally forested areas.

very strong challenge to the anthropogenic hypothesis: Could forest clearance by 2000 yrs BP have been sufficiently extensive to explain such a large increase?

By 2000 yrs BP, life for most humans in Eurasia had changed dramatically from 8000 yrs BP (Sherrat, 1980). The ox-drawn plow was introduced by 6000 yrs BP, and innovations in metallurgy had led to the start of the Bronze Age by 6000–5500 yrs BP and the Iron Age by 3300–2500 yrs BP. Horses were domesticated by 6000 yrs BP and water buffalo by 5000 yrs BP. Irrigation became widespread in Eurasia between 6000 and 4000 yrs BP. Almost every major food crop grown today was cultivated by 2000 yrs BP.

These major advances had produced food surpluses and rapid population growth in the Roman Mediterranean, the Indus and Ganges River valleys of India, and the Yellow and Yangtze River valleys of eastern China. These regions had all seen the emergence of organized societies, large cities and sophisticated agricultural practices characterized by diverse crops and multiple annual plantings. Drawing on primary sources and summaries by Lewthwaite and Sherratt (1980), Taylor (1983), and Simmons (1996), Roberts (1998) mapped the estimated extent of this 'stratified' agriculture as of 2000 yrs BP (Figure 6).

A broad array of evidence indicates early and pervasive deforestation of these naturally forested regions (Hughes, 1975; Fairservis, 1971; Thirgood, 1981; Simmons, 1996). Writers and historians (Plato and Strabo in ancient Greece, Leucretius in Rome) noted the rapid retreat of forests up the sides of mountains within their lifetimes. The already-sizeable populations of the time required large amounts of wood (charcoal) for home heating and cooking, not just around major cities but also in rural areas. Records of mercantile exchanges show that these civilizations were constrained by shortages of wood, and that declining wood resources were a major reason for invasions of other countries. Archeological digs and aerial photography provide constraints on the size of rural villages and the extent of ancient field cultivation during the Roman era in intensively studied regions like Britain (Taylor, 1983) and Germany (Zolitschka et al., 2003). Even higher mountainous regions were vulnerable to deforestation. In Mediterranean climates, shepherds set fire to higher-altitude forests to open the land for summer pasturing. Once the forests had been burned, browsing by goats and sheep prevented regeneration of trees. As yet, southern and eastern Asia have not yet been studied as intensively as Europe.

The inference of major forest clearance and landscape disturbance in these regions by 2000 yrs BP is supported by paleoenvironmental evidence. Changes in human impacts on the environment can be approximated as the product of population increases, technological improvements, and increases in affluence (Holdren and Erlich, 1974). Between 8000 and 2000 yrs BP, populations had increased enormously, new technologies had completely altered the practice of agriculture, and some people had attained true ‘wealth’ for the first time in human history.

As a result, the impacts on the environment were large. Pollen sequences in central Europe younger than 6000 to 5000 yrs BP are sufficiently altered that pollen analysts regard them as unrepresentative of the natural vegetation (Huntley and Birks, 1983). Rapid increases in rates of sediment accumulation in central European lakes between 5000 and 3000 yrs BP also indicate extensive clearance of forested watersheds (Taylor, 1983; Simmons, 1996; Roberts, 1998). Nearer the Mediterranean, the composition of pollen sequences shows human influences by 4000 yrs BP, and valley and coastal sediments record large alluvial influxes by 3000–1700 yrs BP from watersheds that had been deforested and left vulnerable to erosion (Hughes, 1975; van Andel et al., 1990). During this interval, many Mediterranean coastal ports became choked with alluvium and were relocated seaward. Evidence from China and India is less complete, but evidence for early forest clearance at a large scale has already been noted.

Based on this array of information, Simmons (1996) compiled the degree of global deforestation at 7000, 2000, and 1000 yrs BP (Table II). The level of deforestation by 2000 yrs BP was listed as ‘great’ (meaning ‘mostly deforested’) in all of the regions mapped as ‘stratified’ agriculture in Figure 6: southeast Asia (China), southern Asia (India), and Mediterranean Europe. Simmons also inferred that heavy deforestation had occurred in southeast Asia between India and China, along with considerable deforestation in north-central Europe.

To test the hypothesis that humans are responsible for the CO_2 rise of the last 8000 years, this qualitative information on forest clearance needs to be converted into at least semi-quantitative form. The first step is to establish as a ‘target’ the cumulative carbon emissions between 8000 and 2000 yrs BP needed to satisfy the anthropogenic hypothesis. Based on the above estimate that the pre-industrial

Table II
Degree of deforestation during the Holocene (from Simmons, 1989)

Region	7000 BP	2000 BP	1000 BP
Europe	Sporadic	Persistent	Great
Mediterranean	Sporadic	Great	–
SW Asia	Widespread	Great	–
S Asia	Limited	Continuous recession of forests	
E & SE Asia	Small-scale	Great	–
N America		Limited	Limited
C & S America		Limited	Limited

carbon emission totaled ∼320 Gt, and the observation that ∼80% of the measured CO_2 rise had occurred by 2000 yrs BP, this target value is ∼250 GtC (0.8×320 GtC).

The second step is to determine whether plausible estimates of regional carbon emissions from cumulative forest clearance by 2000 yrs BP sum to this target value. Based on Figure 6, the GtC emitted from each region can be calculated as the product of three numbers: the area of natural forest (from Smith and Smith, 1998) that is easily accessible to cutting (<1000 m in elevation); the fraction of natural forest estimated to have been cut by 2000 yrs BP (based on Table II from Simmons, 1996); and the amount of carbon emitted by converting 1 m^2 of various kinds of forest to cropland or pasture (from Table I in Houghton, 1999).

Estimates of regional carbon emissions by 2000 yrs BP are listed in Table III. This compilation reveals that the carbon released from areas mapped as 'stratified' agriculture in Figure 6 would have totaled ∼150 GtC (Table III), or ∼60% of the 'target' total, if the most densely populated and advanced civilizations of Eurasia had already cut most (90%) of their low-elevation natural forests.

Several regions mapped as 'peasant agriculture' in Figure 6 would have added substantially to this total, including Southeast Asia, northern Europe, central and southern Africa, Central and South America, and eastern North America. Heavy deforestation (estimated here at 50–75%) had occurred in Southeast Asia and 'persistent' deforestation (estimated at 25%) in north-central Europe (Tables II and III). Estimated contributions from these regions bring the carbon-emissions total to ∼205–230 Gt. Limited clearance (estimated at 5%) of tree savanna in the Sahel and southern Africa, tropical rain forest in Africa and in the Amazon of South America, and deciduous forest in east-central North America brings the estimated total to ∼220–245 GtC. This total is ∼85–95% of the target needed to validate the hypothesis that humans caused the rise in CO_2 after 8000 yrs BP.

Although these estimates of land clearance and carbon emissions are obviously just rough first-approximations, direct evidence from one region confirms that early

Table III
Estimated terrestrial carbon release due to deforestation by 2000 yrs BP

Region	Natural forest	Accessible area (10^{12} m^2)	Fraction converted	Net loss C 10^2g/m^2	Total C loss 10^{15} g
Heavy deforestation ('stratified' agriculture)					
NE China	Deciduous	1.2	0.9	180	20
SE China	Tropical wet	1.0	0.9	281	25
Northern India	Tropical dry	2.3	0.9	169	36
Southern India	Tropical wet	0.7	0.9	281	19
Central Europe	Deciduous	1.8	0.9	163	27
Med. Europe	Evergreen	0.7	0.9	188	12
Med. Africa	Evergreen	0.4	0.9	188	7
Korea & Japan	Deciduous	0.5	0.9	175	4
Central America	Tropical wet	0.2	0.9	219	4
South America	Montaine	0.2	0.9	163	2
			Estimated total Gtc:		**156**
Moderate/limited deforestation ('peasant' agriculture)					
Malay/Indonesia	Tropical wet	3.6	0.50–0.75	281	50–75
Western Russia	Deciduous	0.5	0.25	163	2
NE Europe	Deciduous	0.9	0.25	163	3
Tropical Africa	Tropical wet	2.5	0.05	281	4
Subtropical Africa	Tropical dry	6.3	0.05	25	1
Trop. South America	Tropical wet	4.3	0.05	219	5
North America	Deciduous	3.2	0.05	163	3
			Estimated total GtC:		**68–93**
		Estimated total GtC from forested areas cleared at 2000 yrs BP:			**224–249**
		2000 yrs BP 'GtC target' of early anthropogenic hypothesis:			**255**

clearance occurred on a very large scale. In 1086 AD, William the Conqueror ordered the Domesday survey of England's resources. The survey found less than 5% of the natural forest cover remaining over lowland regions, and less than 15% across the entire country (Rackam, 1980). Pollen and cultural records and river-mouth siltation histories indicate that the major part of this forest clearance had occurred much earlier, primarily between 4000 and 2000 yrs BP (Taylor, 1996; Roberts, 1998).

The 1086 Domesday survey, along with the evidence for prior deforestation, is a critical reference point with which to assess other regions. If Britain, still a remote outpost of the Roman Empire by 2000 yrs BP, was already largely deforested, how could the more heavily populated regions of Eurasia mapped as 'stratified agriculture' in Figure 6 have avoided such a fate? In all those areas (western and southern Europe, the Mediterranean, India, and eastern China), agriculture had appeared and advanced civilizations had developed thousands of years ahead of England.

A survey of China in 1 AD during the Han dynasty counted 57 million people (Loewe, 1980), indicating a population density some 4 times larger than the 1.5 million people counted in the 1086 Domesday survey of England. By analogy, China should have been heavily deforested by 1 AD. It also stands to reason that at-least comparable levels of forest clearance must have occurred in the other heavily populated regions of southern Eurasia. In summary, forest clearance at a level of 100s of GtC is not just plausible but unavoidable, based on a wide array of evidence.

Other anthropogenic sources of carbon could have contributed to total emissions during the last 8000 years, but probably at much smaller levels. Burning peat for heating and cooking, especially in cold northern regions with depleted woodlands and nearby sources of peat, emits CO_2 and adds to the atmospheric carbon load. The size of this contribution is difficult to estimate, but 5 million homes ($\sim$25 million people) burning 10 half-kg peat bricks (composed of 33% carbon) each day of the year for 2000 years would cumulatively have emitted on the order of 10 GtC, a relatively small amount compared to the hundreds of GtC calculated from deforestation.

CO_2 is also emitted from burning limestone ($CaCO_3$) to produce lime (CaO) for mortar and plaster. Such techniques have been in use for at least 4500 years, as shown by plaster coatings of Egyptian pyramids and Roman cements of a quality not surpassed until less than 200 years ago. But tens to hundreds of millions of CaO-mortared and plastered homes and other structures would be needed to account for even 1 GtC of emissions. In summary, forest clearance appears to have been by far the major early-anthropogenic source of carbon.

Test 3: Why did Several CO_2 Minima Interrupt the Rise after 2000 yrs BP?

Several CO_2 minima interrupted the steady long-term rise after 2000 yrs BP, with values returning to (or close to) the previous long-term upward trend between and after each minimum. The most detailed CO_2 record prior to 1000 AD is from Taylor Dome (Figures 2c and 7). This record is dated by correlating its CH_4 signal to methane in annually layered GISP ice in Greenland (Blunier et al., 1995). Indermuhle et al. (1999) estimate the dating uncertainty prior to 1000 yrs BP at +/– 500 years. The earliest CO_2 anomaly in this record, with an amplitude of –4 to –5 ppm, has an estimate age of 200 to 600 AD (Figure 7).

For the last 1000 years, the Taylor Dome CO_2 record has an estimated age uncertainty of +/– 100 years, and it overlaps the high-resolution CO_2 record at Law Dome (Etheridge et al., 1996). The upper parts of two Law Dome records are dated using a model of air diffusion and enclosure confirmed by bomb-produced

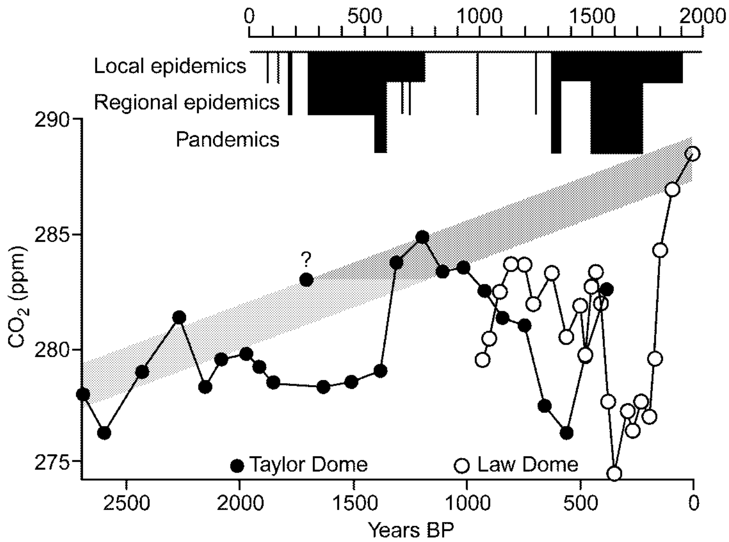

Figure 7. Correlation between intervals of plague outbreaks (compiled from Cartwright, 1991; Bray, 1996) and CO_2 minima in ice-cores from Taylor Dome (Indermuhle et al., 1999) and Law Dome (Etheridge et al., 1996). Shaded bar is a projection of the average rate of CO_2 increase from 8000 BP to 1800 AD.

$^{14}CO_2$. For pre-industrial levels, ages were estimated by correlation to the GISP CH_4 record and confirmed by correlation of acidic ice layers to volcanic eruptions. Both records show –10 ppm CO_2 anomalies, although they fall at different ages: 1300–1400 AD at Taylor Dome and 1600–1800 AD at Law Dome.

Because these anomalies are superimposed on a long-term CO_2 rise attributed in this paper to anthropogenic carbon release, the challenge is to provide a mechanism that could reverse the slow rise in CO_2 emissions within time spans as short as a century or less (Figure 7). The mechanism must involve some kind of major impact on human population levels that appears and then disappears in a relatively short time span.

Famines induced by drought or cold are one source of human mortality, but no famine has ever lasted for as long as a few hundred years or affected most of the vast Eurasian continent. Mortality can also be high during war, but usually within relatively restricted regions. In addition, wars have occurred nearly continuously throughout the last two millennia, rather than being restricted to discrete intervals like the CO_2 minima in Figure 7.

Only one factor has killed humans on a truly broad regional scale and within concentrated time intervals: bubonic plague. Bubonic plague (and many other diseases) first appeared during the last two millennia as an indirect result of agriculture. Human populations fed by agricultural food surpluses had increased rapidly and coalesced into villages and then cities. Sanitation was poor in most regions, and the fixed habitation required by agriculture left Eurasian civilizations vulnerable to

Table IV
Major epidemics and pandemics of the last 2000 years

Year (AD)	Region	Disease	Intensity (% mortality)
79, 125	Rome	Malaria?	Local epidemic
164–189	Roman empire	Smallpox?	Regional epidemic
265–313	China	Smallpox	Regional epidemic
250–539	Roman empire	Bubonic plague	Regional epidemics (decadal repetition)
540–542	Med./Europe	Bubonic plague	*Pandemic* (25%)
540–590	Med./Europe/N. Africa	Bubonic plague	Continuing pandemic (decadal repetition)
581	India	Smallpox	Regional epidemic
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
1258–1259	Europe	Unknown	Regional epidemic
1332–1361	Western Eurasia	Bubonic plague	*Pandemic* (25–33%)
1499–1720	Europe, Russia	Bubonic plague	Regional epidemics (decadal repetition)
1492–1680s	The Americas	Smallpox	Regional epidemics (50–90%)
1817–1902	India/China/Europe	Cholera	Pandemic (small %)

disease (Diamond, 1997). Outbreaks of diseases with high mortality rates can be categorized as local epidemics (occurring at the scale of cities or single countries), regional epidemics (sub-continental to continental in scale), and pandemics (multi-continental). The time history shown in Figure 7 and listed in Table IV is compiled primarily from Cartwright (1991) and Bray (1996).

A regional smallpox epidemic (Galen's plague) struck the Roman Empire in 164–189 AD and was followed by decadal-scale outbreaks of bubonic plague from 250 until 590 AD. The sequence culminated with a major pandemic, the plague of Justinian in 540–542 AD, in which 25% or more of the population in Europe and North Africa died, and still more succumbed in the following decades. Taylor (1983) estimated that more than half of the population of England died during this interval. An interval of repeated smallpox outbreaks also occurred in China during 265–313 AD. This interval of disease matches the 200–600 AD age range estimated for the first CO_2 minimum (Figure 7). After a last regional outbreak in 749 AD, no plague epidemics were recorded for almost 600 years. This gap in plagues is roughly aligned with the rebound of the Taylor Dome CO_2 curve to its long-term rising trend from ~600 AD until ~1000 AD or later (Figure 7).

A second plague pandemic, the largest in history, swept through the Middle East and Europe between 1347 and 1352, with succeeding outbreaks until 1377 AD. Cumulative mortality appears to have reached 40 to 50% in many regions (Taylor, 1983; Bray, 1996). Historians disagree about whether plague occurred in (or originated from) China and central Asia or was restricted to regions west of Iran (Bray, 1996). The timing of this 'Black Death' outbreak matches the –10 ppm CO_2 minimum at Taylor Dome (Figure 7), although the Law Dome anomaly is considerably smaller.

No major plagues are recorded in Europe and the Mediterranean from 1377 AD until 1499 AD, and this small gap in plagues may correlate with a prominent rebound in Taylor Dome CO_2 values and a lesser rise at Law Dome (Figure 7). After 1499 AD, repeated decadal-scale waves of plague occurred in Europe and the Mediterranean until 1720 AD, with small-scale outbreaks as late as the early 1900s in Manchuria. The extended sequence of plagues between 1499 and 1720 AD matches (within the dating uncertainties) the –10 ppm CO_2 minimum in the Law Dome record (Figure 7). During this same interval, Native American populations were being decimated at a level of 80% to 90% by smallpox and other diseases from initial contacts with Europeans (Hudson, 1976). In the 1800s, cholera epidemics originated in India and at times spread elsewhere, but the mortality rates did not match those during the bubonic plague pandemics.

A correlation between the plague pandemics and the CO_2 decreases is apparent, but what mechanism actually links the two? The deaths of tens of millions of people because of plague would slow the long-term rate of rise of carbon emissions, but the CO_2 curve would then simply rise more slowly or level off. To cause CO_2 values to decrease by 4 to 10 ppm, CO_2 must be taken out of the atmosphere and then put back within intervals as short as a century or so.

Historical records provide a plausible mechanism. The mortality rates of 25 to 40% during the major plague pandemics caused widespread abandonment of farms and rural villages. Huge amounts of carbon could then be rapidly extracted from the atmosphere and sequestered in new forests growing on the abandoned farmland. Land-use modelers note that abandoned cropland and pasture reverts to full-forest carbon levels in 50 years or less (Houghton, 1999). Later, as people returned to the farms and cut back the newly grown forests, the temporarily sequestered carbon would have been restored to the atmosphere. Historical records indicate that re-occupation of farms occurred in less than a century if the plagues quickly abated, but could be delayed by a century or two if repeated outbreaks kept population levels low (Bray, 1996).

But is the plague/reforestation explanation sufficient quantitatively? To estimate the amount of carbon sequestration needed to cause CO_2 anomalies in the range of 4 to 10 ppm, the model results from Indermuhle et al. (1999) can be used in a simple scaling exercise. As noted earlier, that study arrived at an estimated 200 Gt increase in terrestrial carbon to explain a 20–25 ppm rise in atmospheric CO_2 during the middle and late Holocene. Scaled down to the observed CO_2 minima, carbon sequestration in the range of ∼35 to ∼90 GtC would be needed to explain CO_2 decreases of 4 to 10 ppm.

But this estimate fails to allow for the much smaller role the deep ocean plays in short-term than in long-term CO_2 changes. The carbon-cycle model used by Indermuhle et al. (1999) indicated that 70% of the terrestrial carbon released during the long-term Holocene CO_2 rise was used to dissolve $CaCO_3$ on the sea floor, with the rest taken up by the surface ocean and the atmosphere. In contrast, during reforestation pulses lasting just decades to a few centuries, the surface ocean and atmosphere would have provided almost all of the carbon, because the deep ocean could not have participated significantly in such brief events. As a result, the observed CO_2 anomalies in the atmosphere can be produced with a factor of ∼3.3 less carbon sequestration on land (30% divided by 100%) than in the initial scaling calculation. This correction reduces the terrestrial carbon storage needed to explain CO_2 anomalies ranging from 4 to 10 ppm to the range of 11 to 27 Gt.

These estimates provide a ‘target’ value against which to compare carbon sequestration caused by plague-induced abandonment of farms. Across the regions struck by major plague pandemics, the total amount of carbon lost to earlier deforestation (using the 2000 yrs BP estimates from Table III) can be compiled. The percentage of this regional total that must be sequestered by reforestation in order to match the above ‘target’ values can then be calculated. This percentage, which must be roughly equivalent to the mean rate of farm abandonment in the plague-stricken region, can be compared with historically recorded mortality rates in the same area.

The sequence of disease outbreaks (including plague) from 164 to 592 AD mainly struck Europe and North Africa. Based on the above calculations, the CO_2 anomaly of –4 ppm (Figure 7) requires ∼11 Gt of carbon sequestration. With ∼50 GtC of previous deforestation in those regions (Table III), the ∼11 GtC requirement can be met by reforesting ∼22% of the area. This estimate is well within historical estimates of mortality rates during the plague of Justinian (Cartwright, 1991; Bray, 1996). Outbreaks of smallpox in China could also have contributed to the total, thereby reducing the amount of carbon sequestration required from Europe and North Africa.

The Black Death pandemic of 1347–1352 AD appears correlative with a CO_2 anomaly of –5 to –10 ppm in the ice-core records (Figure 7). In the millennium since the Roman era, substantial additional deforestation had occurred in northern Europe and west-central Russia (Djevsky, 1980), and more agricultural land had become available that could then revert to forest. With a total of about 60 GtC of previous deforestation in the plague-stricken region, the 14 to 27 Gt of carbon sequestration required to account for the observed range of CO_2 anomalies amounts to reforestation at a level of 25% to 45%. This range of estimates matches historical estimates of mortality during the Black Death and subsequent decades.

The CO_2 minimum of –10 ppm between 1550–1800 AD correlates with an extended interval of plagues that again struck Europe and North Africa. But during this same interval, most of the native population in the Americas was also succumbing to European diseases (Hudson, 1976). Based on DeSoto's journal observations of large villages and extensive cultivation in all the major tributaries of the Mississippi River Valley (Shaffer, 1992), as well as widespread burning of eastern forests for game control, a plausible guess is that 5 to 10% of the North American forest had been cut before disease decimated Native Americans. Reforestation in North America, as well as in parts of Central and South America that saw similar population losses, could have contributed ∼5–10 Gt of carbon sequestration during the early part of the interval from 1550 to 1800 AD.

This estimate would leave about 20 GtC to be accounted for by deforestation in Europe and North Africa and require a reforestation rate of about 33%. This requirement may be harder for the plague explanation to meet. Despite the centuries-long recurrence of plagues from the 1500s into the 1700s, some historians seem reluctant to use the term 'pandemic'. It may be that observers were suffering from 'reporting fatigue' in which successive outbreaks made less of an impression than had the first shocking outbreak during the Black Death. And again, disease and farm abandonment in India and China (McNeil, 1976) could have added to the total sequestration of carbon and thereby reduced the contributions required from Europe and North Africa. In any case, disease-driven reforestation must have contributed significantly to this most recent CO_2 drop.

Evidence summarized in the next section shows that natural (solar-volcanic) forcing may not be a viable explanation of the 10-ppm CO_2 minima during the last 2000 years. If so, reforestation of abandoned farms stands as the only viable explanation of the observed CO_2 anomalies.

The above interpretation of the most recent CO_2 minimum – initial deforestation, disease-induced reforestation during the 1500s to early 1700s, and then a second deforestation in the late 1700s – has important implications for carbon emissions during the early industrial era. Based on the scaling exercise noted above, the amount of deforestation and carbon sequestration needed to explain the –10 ppm CO_2 anomaly between 1500–1800 AD is ∼27 GtC. If the subsequent (and second) deforestation occurred from ∼1750 to ∼1850 AD, the mean rate would have been ∼0.25 GtC/yr (25 GtC in100 yrs). This rate falls within the 0.2–0.4 GtC/yr range of emissions estimated by Houghton (1999, 2000) for the same interval. The apparent conclusion is that reconstructed rates of carbon emission from land clearance during the early industrial era result only in part from first-time clearance of 'virgin' forest. These rates may also include a substantial contribution from re-cutting of forests that had originally been cleared before the middle ages but then had later grown back during the last of the plague intervals.

6. Effect of Early Anthropogenic Greenhouse Gases on Climate

Sections 2 and 5 presented the case for major anthropogenic increases in atmospheric CH_4 and CO_2 prior to the more dramatic industrial-era changes (summarized in Figures 8a,b). To evaluate the climatic impacts of these pre-industrial greenhouse-gas increases, the following analysis uses the IPCC (2001) estimate of a 2.5 °C equilibrium sensitivity of global climate to a CO_2 doubling.

The Holocene increases of CH_4 and CO_2 were so gradual that the climate system had ample time to come to thermal equilibrium with the radiative forcing. The estimated early- anthropogenic CH_4 increase of 250 ppb would have warmed global climate by 0.25 °C, and the estimated 40-ppm CO_2 increase would have added another 0.55 °C, for a total warming of ∼0.8 °C by 1800 AD (Figure 8c). In comparison, the industrial-era warming since 1850 has reached ∼0.6 °C, of which ∼0.45 °C is attributed to several anthropogenic impacts and the rest to solar and volcanic variability (Wigley et al., 1998). At first, these two results seem incompatible: the smaller pre-industrial increase in greenhouse gases has had a larger impact on global-mean temperature.

One factor that resolves part of this apparent inconsistency is the long thermal response time of the ocean, estimated at 3 or more decades (Hansen et al., 1984). Because half of the industrial-era increases in CO_2 and CH_4 has occurred within the last 30 years, the ocean has not yet had time to register a large portion of the equilibrium warming, and this future warming is still ‘in the pipeline’ (Figure 8c). A second factor is cancellation of some of the greenhouse-gas warming by industrial-era aerosol emissions (Charlson et al., 1992), although the size of this effect is highly uncertain. The assumption here is that aerosol cooling did not counter the early-anthropogenic increases in greenhouse gases, because much lower smokestack heights and furnace temperatures restricted early emissions to lower levels in the troposphere.

At high latitudes, snow cover and sea ice provide positive albedo feedbacks that amplify global-mean temperature changes by a factor of 2 to 3. Allowing for this positive feedback, the 0.8 °C pre-industrial global warming caused by humans should have been ∼2 °C at higher latitudes. If this estimate is accurate, how could such a large anthropogenic warming have escaped notice?

One reason is that the warming was spread over 8000 years and thus imperceptibly gradual. The main reason is that the anthropogenic warming has been masked by a larger cooling trend caused by decreasing summer insolation. For high northern latitudes, general circulation model experiments predict a cooling of 2 to 3 °C since 6000 yrs BP in response to declining summer insolation at the obliquity and precession periods (Kutzbach et al., 1996). Proxy climatic indicators sensitive

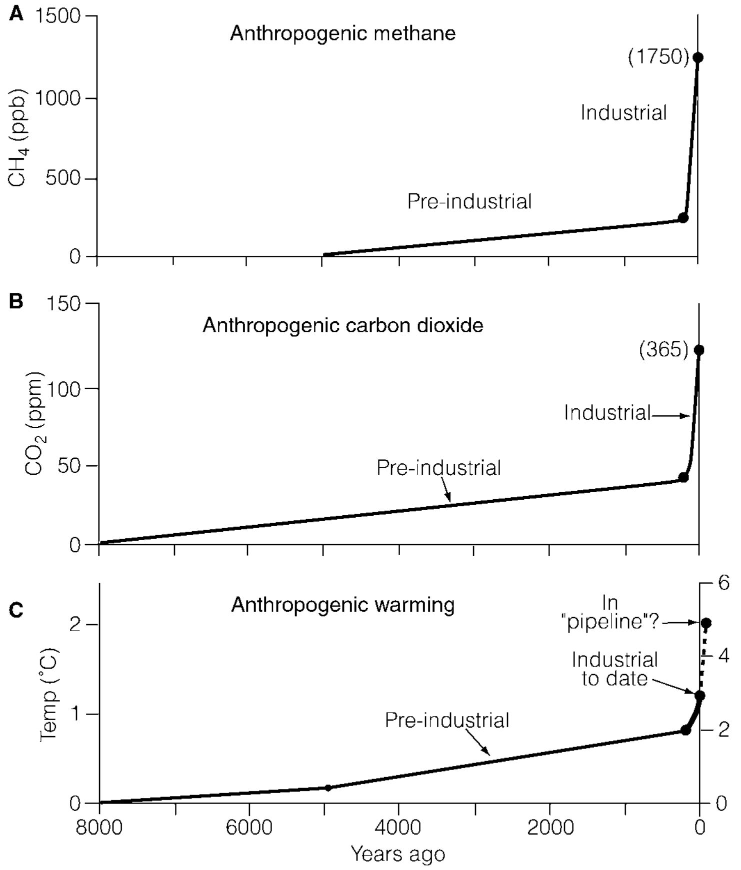

Figure 8. Early anthropogenic hypothesis: (a,b) Pre-industrial and industrial-era CH_4 and CO_2 increases from anthropogenic sources. (c) Warming caused by anthropogenic greenhouse gases, with global mean temperature on scale at left and high-latitude temperature on scale at right.

to summer-season temperature indicate a net cooling since 6000 yrs BP (for example, Koerner and Fischer, 1990; Koc et al., 1992). The anthropogenic greenhouse warming in the summer season has thus been offset by declining insolation. High southern latitudes also show a Holocene cooling (Hays et al., 1976), suggesting that stronger natural cooling trends in the southern hemisphere have also masked the early anthropogenic warming (Ruddiman, 2003).

Two independent lines of evidence point to the intriguing possibility that glaciation may have been averted at high northern latitudes in recent millennia by the 2 °C pre-industrial greenhouse-gas warming. A schematic summary of this interpretation is shown in Figure 9.

First, a large area of the eastern Canadian Arctic from Baffin Island at 65° N to Ellesmere Island at 83° N is very close to a glaciated condition today. Small ice caps lie on higher terrain near the Labrador Sea, and much of this region barely

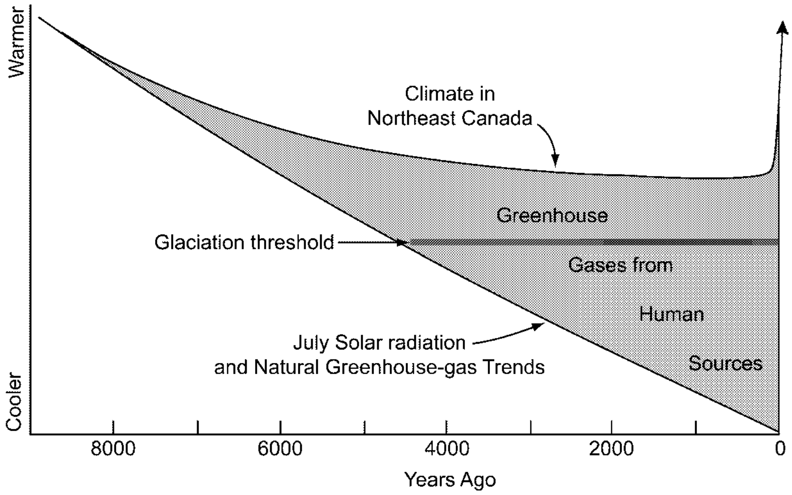

Figure 9. The natural summer cooling driven by Holocene insolation and greenhouse-gas trends should have produced a new glaciation by ~5000–4000 years ago. Early anthropogenic emissions of CO_2 and methane kept climate warm enough in northeastern Canada to prevent glaciation.

loses its snow and sea-ice cover in summer. This region is also considered a likely nucleation center for North American ice during glacial cycles (Andrews et al., 1976).

Dead lichen arrayed in broad halos around the ice caps on Baffin Island are thought to have been killed by permanent snowfields that formed in the recent past but failed to become glaciers (Andrews et al., 1976). Energy balance modeling shows that snowfields would have been able to exist in these regions during the cooler pre-industrial conditions prior to 1900 AD (Williams, 1978). Then a subsequent industrial-era warming of ~1.5 °C occurred in this area, melted the snowfields, and allowed new lichen to grow. In the absence of the industrial-era warming, large areas of high terrain on Baffin Island would lie right at the glaciation threshold today.

The same energy-balance model study indicated that the altitude of the glaciation limit during the Little Ice Age dropped to lower elevations in regions west of the Baffin Island plateau, so that broad areas of moderately high terrain in interior northeastern Canada lay just 100–200 meters below it. Williams (1978) concluded that an additional cooling of 1–2 °C beyond average pre-industrial conditions would have caused the glaciation limit to descend onto much of this region.

In the absence of the early anthropogenic greenhouse warming summarized above, Canadian Arctic temperatures would have been ~2 °C cooler during much of the last millennium prior to the industrial era. Based on the modeling results of Williams (1978), the glaciation limit would then have reached not just the high plateaus on Baffin Island and the rest of the Labrador coast, but also a broad region of interior northeast Canada. A significant part of northeast Canada should then have been glaciated during the last millennium (and presumably considerably earlier).

A second line of evidence supports this conclusion that a glaciation is overdue in northeast Canada. Numerical models tuned to reproduce δ^{18}O ($\sim$'ice volume') cycles over the last several hundred thousand years 'predict' that ice sheets should have begun to grow in the last 3000 to 6000 years (Imbrie and Imbrie, 1980). This conclusion is also implicit in the long-term ice-volume phasing used in the SPECMAP time scale (Imbrie et al., 1984). The 5000-year lag of δ^{18}O ($\sim$ice volume) behind precession forcing predicts that a new glaciation should have begun 6000 years ago, while the 8000-year lag of ice volume behind obliquity forcing predicts that ice should have begun forming by 2500 years ago. Ruddiman (2003) assessed the likely effects of temperature on the mean phase of orbital-scale δ^{18}O signals in the 5 cores used to create the SPECMAP time scale and inferred that ice should have begun forming by 5000 yrs BP at the precession cycle and by 4000–3000 yrs BP at the obliquity cycle. All of these results are consistent with Milankovitch (1941) who estimated a 5000-year lag of ice volume behind summer radiation forcing. The lag inferred by Milankovitch predicts new ice sheets by $\sim$6000 years ago for precession and $\sim$5,000 years ago for obliquity.

Berger and colleagues use zonal energy balance models to simulate changes in ice volume. Early versions of the model showed an ice-growth phase beginning near 6000 to 5000 yrs BP, although from an incompletely melted northern hemisphere ice sheet (Berger et al., 1990). Later versions of the model (Berger and Loutre, 1996) did not show late-Holocene ice growth, although they also had difficulty matching the smaller ice volumes during interglacial isotopic substages.

A more basic argument supporting the idea of an overdue late-Holocene glaciation comes from comparing the current level of summer insolation to the values when ice first appeared at the end of the last interglaciation (during the δ^{18}O substage 5e/5d transition). The SPECMAP time scale puts the start of this transition at 121,000–120,000 yrs BP and the midpoint at 115,000 yrs BP. Allowing for newer Th/U dates on coral reefs and other factors, Ruddiman and Raymo (2003) suggested that the ages of the SPECMAP time scale should be shifted 1500 years earlier, similar to a 2000-year shift proposed by Shackleton (2000). These shifts place the start of ice growth near 122,000 yrs BP and the midpoint near 117,000 yrs BP. The present-day value of July insolation at 60° N (435 W/m^2) is the same as the value at 119,000 yrs BP, some 3000 years into the last ice-growth interval. This comparison thus suggests that a glaciation should have begun several thousand years ago in northeast Canada. Early anthropogenic emissions of CO_2 and CH_4 are the most likely reason that it did not.

A final climate-related issue is the role of plague-induced CO_2 decreases in the cooling of the Little Ice Age ($\sim$1300–1900 AD). Figure 10 compares the Mann et al. (1999) reconstruction of northern hemisphere temperature during the last millennium with potentially important sources of climatic forcing. Solar and volcanic changes are widely recognized as important in decadal- and century-scale temper-

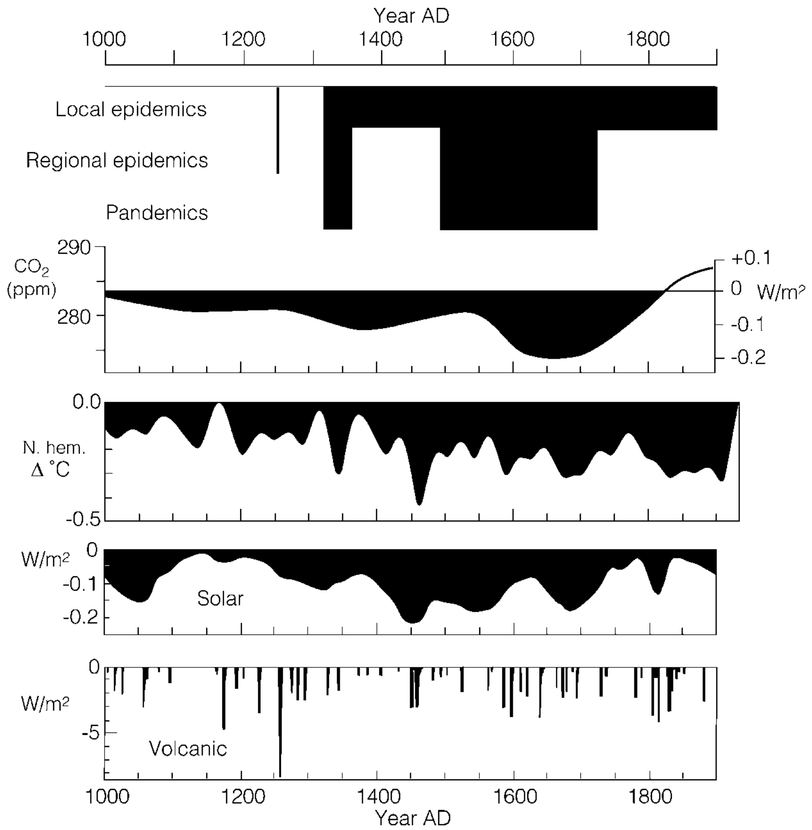

Figure 10. Estimated mean northern hemisphere temperature changes from 1000–1900 AD (Mann et al., 1999) compared to: plague epidemics and pandemics; ice-core CO_2 (average of changes at Taylor Dome and Law Dome shown in Figure 7); and solar and volcanic radiative forcing (from Bard et al., 2000; Crowley, 2000).

ature changes (Lean, 1994; Crowley, 2000), and Gerber et al. (2003) used a version of the Bern carbon-climate model to assess the effects of solar-volcanic radiative forcing on the climate of the last millennium. They found that plausible changes in solar-volcanic radiative forcing could match both the northern-hemisphere temperature reconstruction of Mann et al. (1999) and an averaged 'stack' of CO_2 records from several ice cores spanning all or part of the last 1000 years.

On the other hand, this conclusion does not hold if the CO_2 records from Law and Taylor Domes (Figures 7 and 10) are used as the target signal. In that case, the Bern model cannot simultaneously explain the northern-hemisphere temperature curve of Mann et al. (1999) and the larger oscillations in these two CO_2 records. In order to reproduce the observed CO_2 drops of 10 ppm, the model requires that northern hemisphere temperatures decrease by more than 0.8 °C, an amount far more than permitted by the reconstruction of Mann et al. (1999). And if the radiative forcing is reduced to the point that it matches the small amplitude of the temperature curve, it then accounts for less than 3 ppm of the 10-ppm decrease in CO_2.

In contrast, a self-consistent story emerges if carbon sequestration on farms is assumed to be the first step in the causal chain. If the 10-ppm CO_2 decreases are caused by plague-induced reforestation events, they would cool northern hemisphere temperatures by $\sim$0.17 °C, assuming a 2 $\times$ CO_2 sensitivity of 2.5 °C. A cooling of this amplitude fits well within the constraints of the temperature record reconstructed by Mann et al. (1999). In short, if the CO_2 records from Taylor and Law Domes are a more accurate measure of past CO_2 changes than other ice-core records from Antarctica, then plague-induced reforestation events are strongly implicated in the amplitude and timing of the 10-ppm drops in CO_2.

Moreover, if plague caused most of the 10-ppm CO_2 drops shown in Figures 7 and 10, it must also have been a major factor in the climatic cooling that led from the relative warmth of 1000 years ago to the cooler temperatures of the Little Ice Age. A tentative assessment based on the relative radiative forcings shown in Figure 10 is that CO_2 changes were on average comparable in importance to solar and volcanic forcing in this cooling. Solar and volcanic forcing appear to have been dominant at times such as the cooler decades near 1450 and 1825 AD. Plague-driven CO_2 decreases were probably most important just after 1350 AD and between 1500 and 1750 AD. A more complete assessment of the role of plague-driven CO_2 changes in climate change during the last millennium would require a narrowing of uncertainties in both the spatial and temporal occurrence of plague and in the amount of farm abandonment (and reforestation), as well as a resolution of the inconsistencies among the CO_2 trends from different Antarctic ice cores.

Finally, Lamb (1977) has argued that cooler Little Ice Age climates caused famine and depopulation, as well as increased incidence of disease. This study comes to nearly the opposite conclusion: plague outbreaks caused major population reductions and at the same time contributed significantly to cooler climates.

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