The Anthropocene

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Abstract

The start of the period of large-scale human effects on this planet (the Anthropocene) is debated. The industrial view holds that most significant impacts have occurred since the early industrial era (~1850), whereas the early-anthropogenic view recognizes large impacts thousands of years earlier. This review focuses on three indices of global-scale human influence: forest clearance (and related land use), emissions of greenhouse gases (CO_2 and CH_4), and effects on global temperature. Because reliable, systematic land-use surveys are rare prior to 1950, most reconstructions for early-industrial centuries and prior millennia are hind casts that assume humans have used roughly the same amount of land per person for 7,000 years. But this assumption is incorrect. Historical data and new archeological databases reveal much greater per-capita land use in preindustrial than in recent centuries. This early forest clearance caused much greater preindustrial greenhouse-gas emissions and global temperature changes than those proposed within the industrial paradigm.

1. INTRODUCTION: AN INDUSTRIAL OR PREINDUSTRIAL START TO THE ANTHROPOCENE?

Crutzen & Stoermer (2000) proposed that human effects on the environment have reached levels severe enough not just to outweigh natural changes but to give the time we live in its own name—the Anthropocene. They proposed placing its beginning at 1850, when the industrial era first began to gain strength at a global scale. In support of this view, there is ample evidence of the widening impact human effects have had on a variety of environmental variables since 1850 (Steffen et al. 2007). Soils have been deeply eroded, ecosystems fragmented, groundwater depleted, and coastal waters choked with algal blooms (**Table 1**). Lakes, streams, rivers, and even the global ocean have become more acidic. In recent decades, stratospheric ozone has been depleted over Antarctica. Most of these trends either began within the past 150 years or accelerated sharply from previously negligible levels.

Evidence from Earth's atmosphere also appears to support the notion that the industrial era was the start of the Anthropocene. Atmospheric concentrations of two major greenhouse gases—CO_2 and CH_4—began to rise exponentially by 1850 (**Figure 1**). These increases are tied to land-use changes caused by rapid population growth and to the burning of fossil fuels. More than 85% of the global population increase to the current level of 7 billion has occurred since 1850. Together, this wide range of evidence leaves no doubt that the industrial era marks a major inflection point in human influences on the environment.

Nevertheless, this industrial view may not provide the full story. Soon after publication of the paper by Crutzen & Stoermer (2000), Ruddiman (2003) proposed the early-anthropogenic hypothesis. This paper cited evidence that important anthropogenic effects on the environment and on global climate began thousands of years ago and grew to substantial size long before the industrial era.

These longer-term changes started with the domestication of crops and livestock (the Neolithic revolution) thousands of years ago in widely scattered regions (**Figure 2**). In places such as New

Table 1 Major transformations during the industrial era

Innovation	Environmental consequence
Mechanized agriculture	Farming in prairies and steppes
	Deep-soil erosion in some areas
Damming of rivers	Siltation of catchments behind dams
Mechanized earth-moving	Greater than all natural processes
	Ecosystem fragmentation leading to species loss
Industrial (nitrogen-rich) fertilizers	Runoff to coasts, algal blooms
Industrial power plants	Release of sulfates to atmosphere
	Acidification of lakes, streams, rivers
Use of fossil fuels	CO_2 emissions
	30% increase in ocean acidity
Use of CFCs for refrigeration[a]	Creation of ozone hole
Mechanized fishing methods	Depletion/collapse of primary fisheries
Mechanized irrigation	Human use of >50% of river water; pollution of many rivers
Mechanized pumps	Depletion of groundwater

[a]CFC, chlorofluorocarbon.

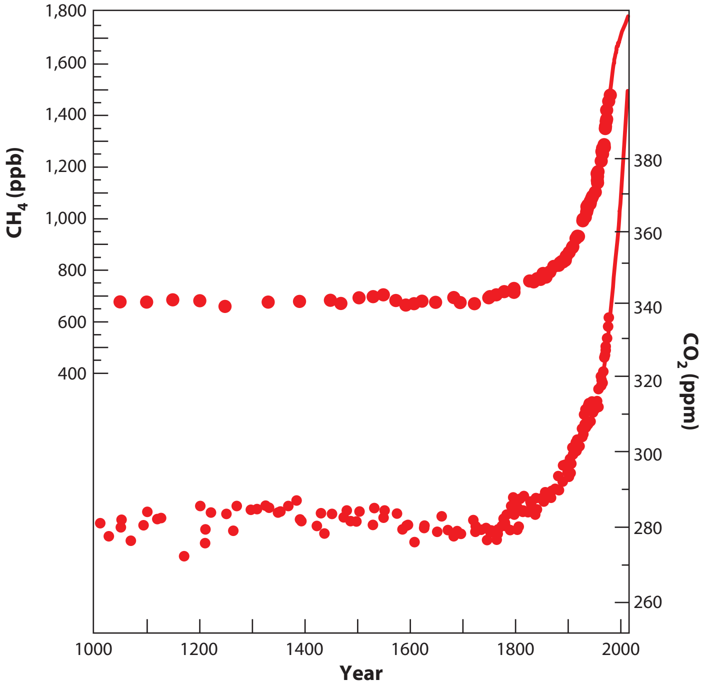

Figure 1

Exponential increases in atmospheric CO_2 and CH_4 concentrations since 1850 (adapted from Raynaud et al. 2002).

Guinea, these innovations remained local in extent, but in other areas, the agricultural innovations spread widely across continents over several millennia.

In the fertile crescent region of the eastern Mediterranean, wheat, barley, peas, and lentils, along with cattle, sheep, goats, and pigs, were domesticated and then spread west across Europe. The time of arrival of this diverse agricultural package was mapped years ago by the first appearance of cultivated plant remains in radiocarbon-dated archeological deposits (Zohary & Hopf 1993). The fertile crescent package had spread across most of Europe by 7,700 years ago and had reached all of its arable regions by 5,500 years ago (**Figure 3**). Even before the Bronze Age began, Europe was an agricultural region.

In China, millet, soybeans, and pigs were domesticated in the early-middle Holocene. Irrigated rice was domesticated by 6,500 years ago in the Yangtze River Valley and adapted across China by 5,000 years ago (Fuller et al. 2011). By 1,000 years ago, livestock tending was widespread, and irrigated rice was grown in every region of southern Asia, where it continues to grow today (**Figure 4**).

These examples from Europe and China, areas with richly detailed paleoecological and archeological information, suggest that the effects of early agriculture became widespread thousands of years before the industrial era. Because Europe and China have long accounted for ∼40% of Earth's human population, this evidence implies that humans could have had large early effects on Earth's surface, contrary to the industrial-era view of mainly post-1850 influences.

The industrial and early-anthropogenic views of the Anthropocene are largely incompatible. Weighing the two choices requires a look at the quantitative evidence supporting each. The next three sections explore evidence for large-scale land use and forest clearance (Section 2),

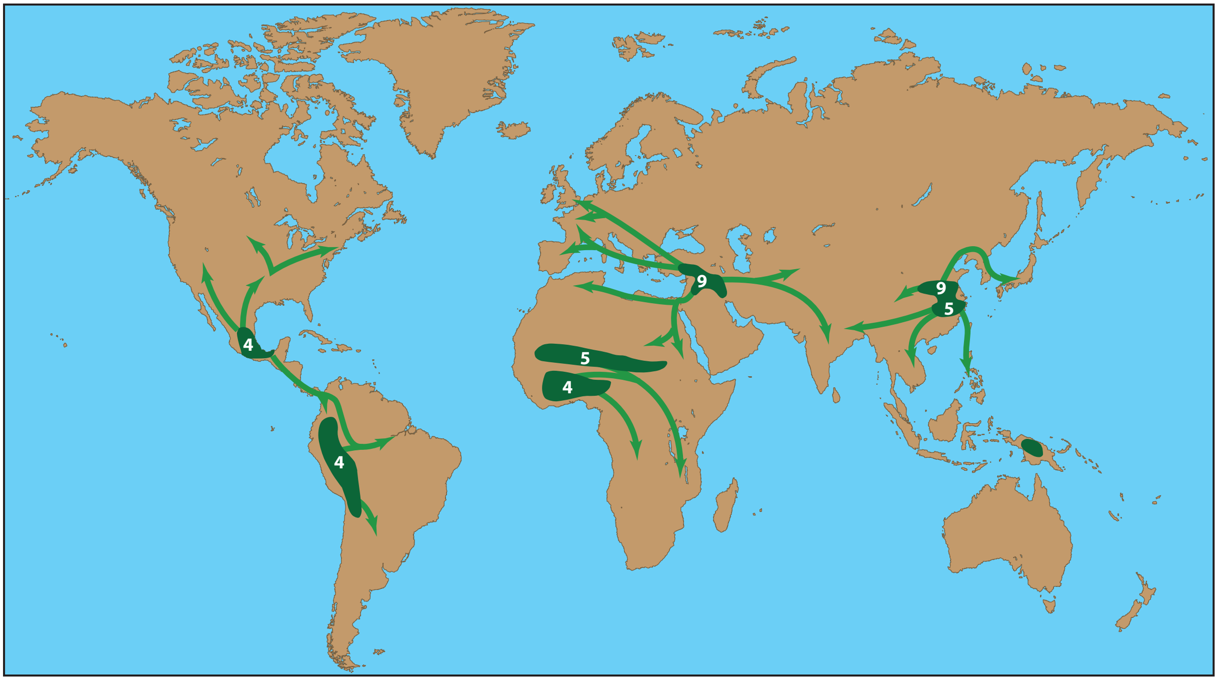

Figure 2

The spread of agriculture from several centers of origin during the past 10,000 years (after Bellwood 2004, Fuller 2010). Numbers (*white font*) mark the time in thousands of years of initial spread from centers of origin.

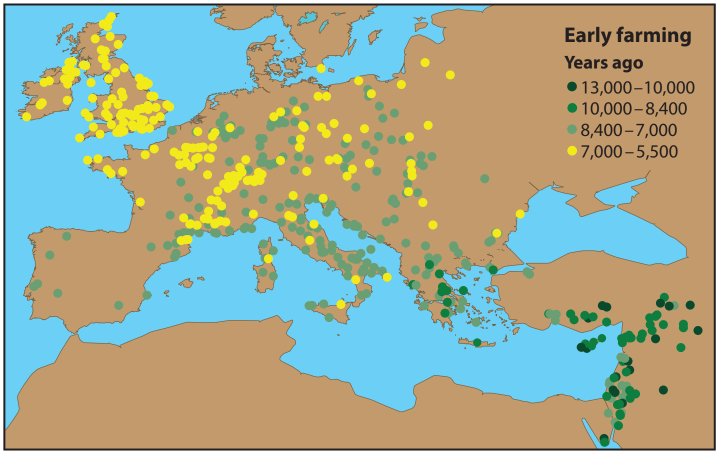

Figure 3

The radiocarbon-dated time of arrival of the fertile crescent crop package in southwest Asia and Europe (after Zohary & Hopf 1993).

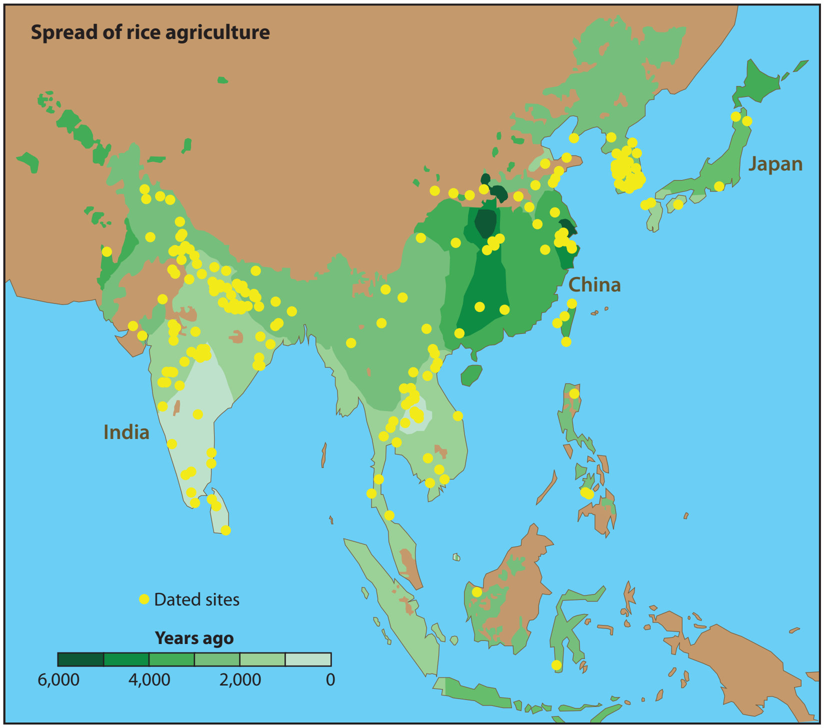

Figure 4

The radiocarbon-dated spread of irrigated rice agriculture across southern Asia (adapted from Fuller et al. 2011).

for greenhouse-gas emissions (Section 3), and for anthropogenic effects on global temperature (Section 4).

2. HISTORICAL AND ARCHEOLOGICAL EVIDENCE OF LAND USE

2.1. Systematic National Surveys

Full assessments of past land use are constrained to times of reliable record keeping, most of which extends back only to the 1950s and 1960s, when the Food and Agriculture Organization (FAO) began collecting systematic surveys (**Figure 5**). These records span less than one-third of the post-1850 industrial era, except for a few regions with longer but less complete records (Europe, North America, and India). DeFries et al. (1999, p. 804) noted that prior to recent decades "spatially explicit global data that historically account for changes in land cover do not exist." As a result, estimates of global land use prior to 1960, and specifically the extent of deforestation and crop cultivation, must be made using hindcasts.

To complicate these efforts further, many regions show reforestation in late preindustrial times, some of which extends through the entire interval of reliable records (**Figure 5**). This limitation is even more severe: How can records that show reforestation be used to estimate earlier deforestation? This problem applies to global land-use estimates extending back from 1960 to 1850, and even more so to simulations of prior centuries and millennia.

In the absence of land-use data, most hindcasts have been based on past population levels, which are reasonably well known for Europe and China during the past 2,000 years, but are not well

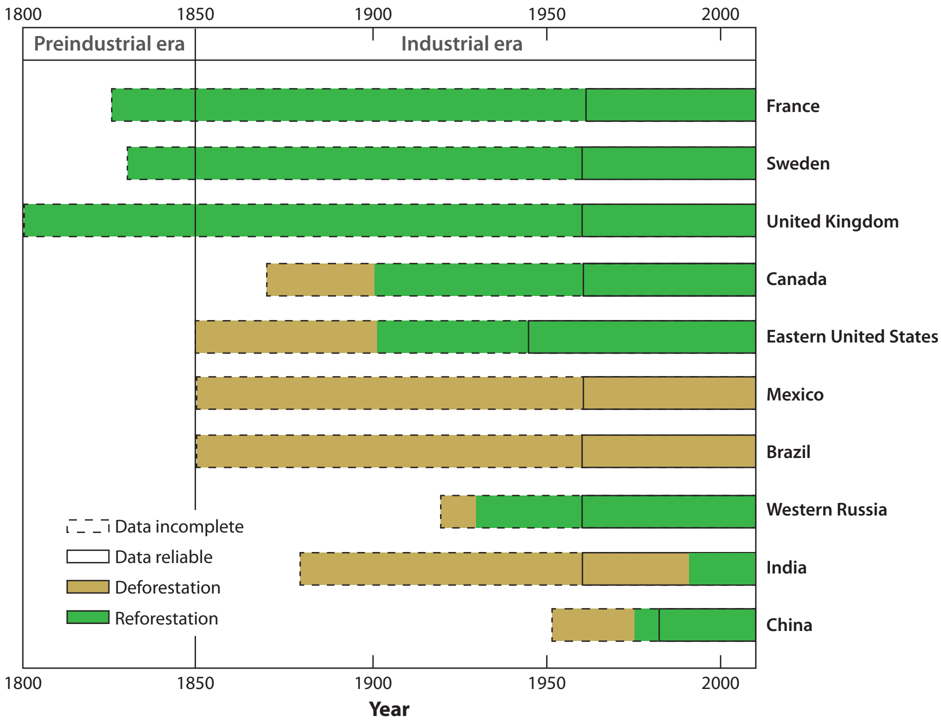

Figure 5

Land-use records (incomplete and fully reliable) of deforestation and reforestation.

constrained anywhere else during most of that interval. Prior to 2,000 years ago, most estimates rely on geometric models of population growth based on assumptions of population doubling times (usually around 1,000 years). As a result, most reconstructions of the Holocene show an exponentially expanding population before 2,000 years ago. In the past 500 years, population growth accelerated rapidly because of improvements in disease control (**Figure 6**).

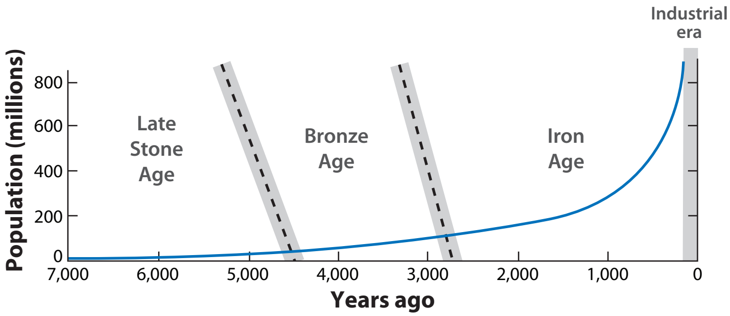

Figure 6

Estimate of global human population and farming technologies during the Holocene (after McEvedy & Jones 1978).

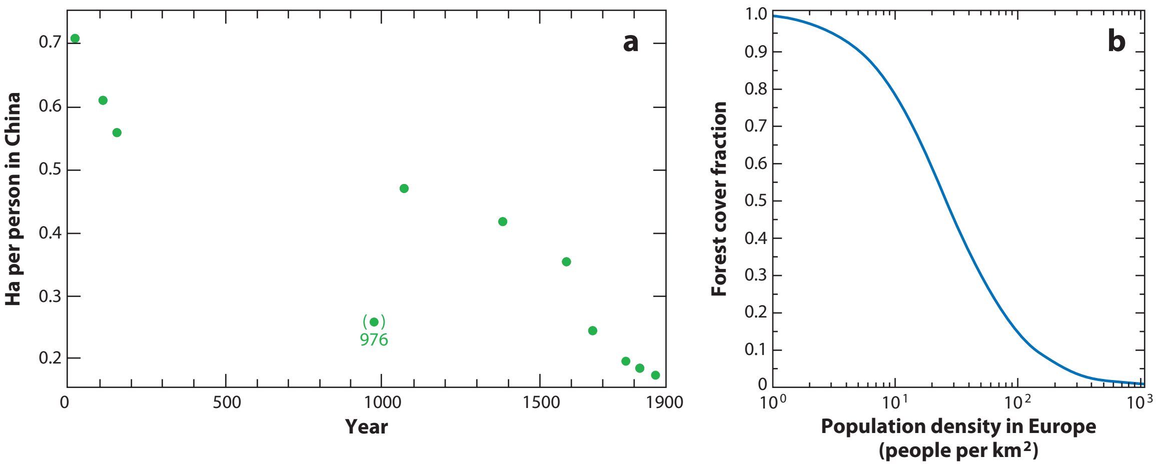

Figure 7

(*a*) Per-capita decrease of cultivated land in China (after Buck 1937, Chao 1986) (the anomalously low cultivation value in the year 976 followed shortly after a war that left much of the land temporarily unused), and (*b*) deforestation extent versus population density in Europe (after Kaplan et al. 2010).

2.2. Historical Evidence of Per-Capita Clearance

During preindustrial times, most agriculture took place in regions where plentiful rainfall had previously sustained forests. Some farming also took place alongside streams and rivers, but, again, often in areas that had been (riparian) forests. As a result, "clearance" before 1850 is nearly equivalent to deforestation. Not until the mechanical agricultural revolution of the mid-1800s were plows able to remove deep-rooted prairie and steppe vegetation and permit farming in most semiarid areas.

To simulate past clearance, most land-use modelers have assumed that farmers always cultivated roughly the same amount of land (a hectare or less per capita) as they did in the centuries just before the advent of mechanized agriculture (Ramankutty & Foley 1999, Klein Goldewijk 2001, Pongratz et al. 2008, Strassmann et al. 2008, Stocker et al. 2011). This assumption inevitably compresses most clearance for cultivation into the past few hundred years of explosively increasing population (**Figure 6**). In addition, these modeling simulations used cultivated land (crops and pastures) as a proxy for clearance, but actual deforestation was probably larger by a factor of two or more. Many deforested areas became pastures left unused for many decades or land so badly degraded that it was abandoned (Houghton & Hackler 2003).

In any case, the assumption of a close link between cultivated land and population is not consistent with available historical evidence. Data from China reveal that per-capita land use (and forest clearance) was much greater two millennia ago but substantially decreased by the centuries just before the industrial era (**Figure 7**). Working in Nanjing prior to World War II, Buck (1937) used central dynastic administrative records to compile land-use trends during the past 2,000 years across the entire agricultural area of east-central China (an effort later updated and refined by Chao 1986). The per-capita area cultivated was 0.6–0.7 hectares per person nearly 2,000 years ago but fell to ~0.15–0.2 hectares by the 1800s.

In Europe, historical data also reveal more extensive early clearance (Mather & Needle 2000, Kaplan et al. 2009). Instead of tracking population changes linearly, forest clearance accelerates quickly at low population densities and is nearly complete by the time population densities reach intermediate levels of 100 people per km^2 (**Figure 7**). Additional population increases have little

Table 2 The Boserup land-use sequence

Long fallow > Short fallow > Annual crops > Double cropping		
Earlier	***Change through time***	***Later***
Low	Population density	High
Low	Labor required per acre	High
Low	Productivity per acre	High
High	Per-capita acreage farmed	Low

or no effect, because by then most of the forest has already been cut. During the past 2,000 years, per-capita deforestation clearance in Europe has fallen by a factor of 3 to 4 (Kaplan et al. 2010), similar to the trend in China. Although the data defining these historical trends are sparse, they show that per-capita forest clearance and land cultivation were much higher in the early historical era 2,000 years ago than in late preindustrial time.

The reason for this long-term trend of decreasing per-capita land use is familiar to field scientists working in archeology, anthropology, and related field-oriented disciplines. Decades ago, Boserup (1965, 1981) proposed that a shift in agricultural methods occurred over many millennia because of innovations and the adoption of new farming skills (**Table 2**). During the earliest phase of long fallow farming, cultivation shifted frequently from plot to plot. After crops were grown for a few years on cleared land, soil fertility dropped and farmers moved to new plots. In some cases, they returned to the original plot that had been left lying fallow for many years and repeated the sequence. This early phase of shifting agriculture used large amounts of land.

Over time (through many millennia), the better nutrition sources provided by farming led to population growth, and claims on the available land increased. As farming families became constrained to smaller holdings, they were forced to produce more food per hectare of land. They did this by learning how to enrich soil quality, initially by mixing in grass and other available vegetable debris, and later by spreading animal and human manure. With these and other innovations, farmers gradually reduced the amount of land used while boosting productivity per hectare. Over time, per-capita land use fell dramatically.

Incorporating this historical evidence for early per-capita land use into model simulations has a dramatic effect on estimates of past clearance (**Figure 8**). Kaplan et al. (2010) found that estimates using historically based land-use information (the KK10 plot) simulated average forest clearance of ∼70% in densely populated areas such as Europe, China, and India by the year 1800. In contrast, estimates based on the simplifying assumption of small and nearly constant land use (the HYDE plot) show very little deforestation by 1800, even in areas where advanced civilizations had existed for millennia.

2.3. Archeological Evidence of Early Land Use

Archeology has also recently begun to provide evidence of early land use in regions devoted to irrigated rice agriculture. Fuller et al. (2011) used the spread of rice across southern Asia mapped in **Figure 4** to estimate the total area planted in rice from 5,000 to 1,000 years ago. They assumed that the density of farming after the first arrival of wet-rice agriculture in each region increased with the square root of population (based on modern spatial patterns) and calculated the growth in the total area of Asia devoted to rice cultivation (**Figure 9**). Fuller and colleagues calculated that 38% of the area currently farmed for irrigated rice was in use as of 1,000 years ago, even though the global population was only ∼6% of modern. This analysis suggests that early rice farmers

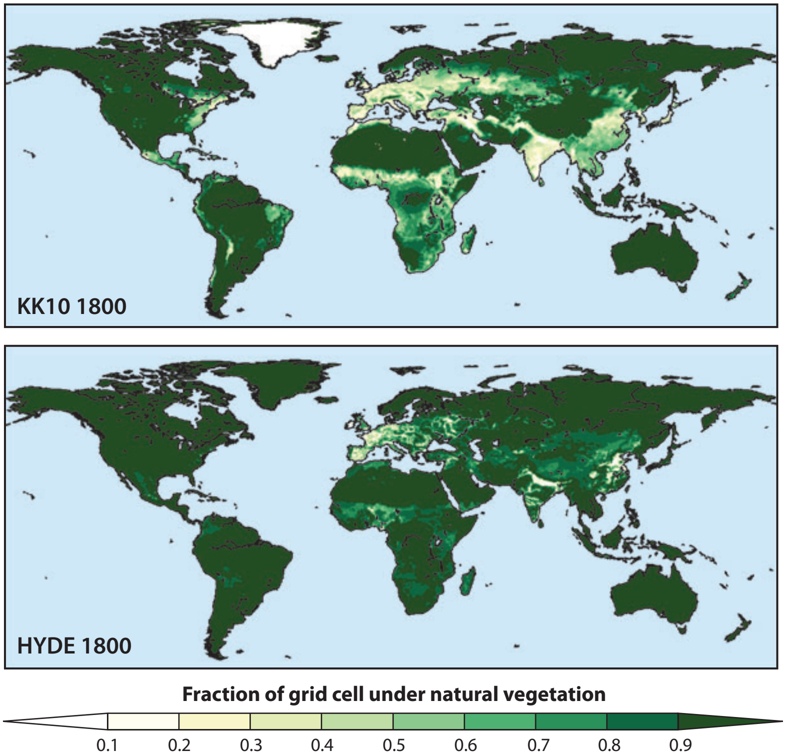

Figure 8

Land-use simulations of clearance of natural vegetation as of 1800 based on (*top*) historical records of large early per-capita clearance (KK10 1800) and (*bottom*) the assumption of small constant per-capita clearance (HYDE 1800) (from Kaplan et al. 2010).

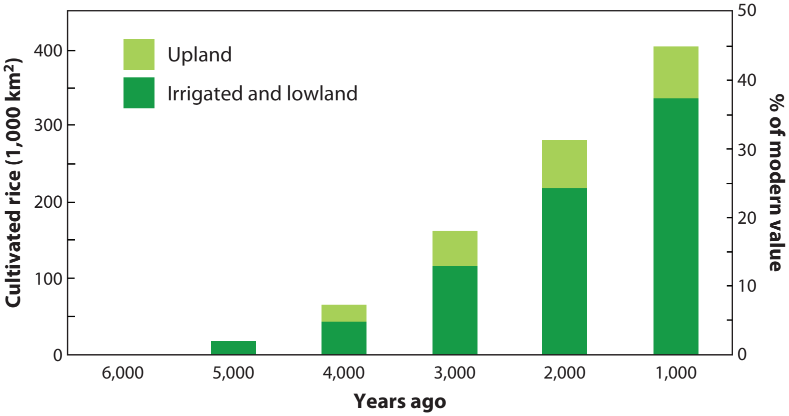

Figure 9

Estimated area of rice farming from 5,000 to 1,000 years ago (after Fuller et al. 2011).

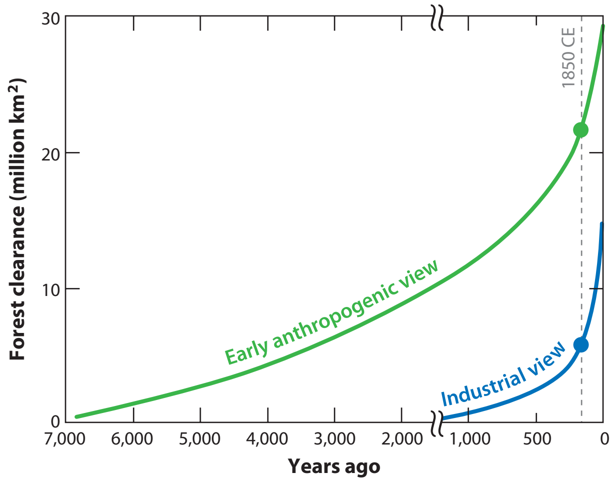

Figure 10

Two schematic plots of the relative amount of forest clearance during industrial and preindustrial times. Note scale changes at 1,000 years ago.

were using more than six times as much land as would be estimated by hindcasting from current population levels and rice area farmed using the assumption of constant per-capita land use.

Ellis & Wang (1997) compiled historical land-use information from an area in the lower Yangtze River Valley that has long been dominated by irrigated rice agriculture. In general agreement with the archeological evidence from Fuller et al. (2011), they found a fourfold decrease in per-capita rice irrigation between 1000 and the 1800s, as populations continued to grow but the amount of arable land remained nearly constant as rice agriculture approached its upper limit.

The two contrasting views of the history of deforestation are compared schematically in **Figure 10**. Studies favoring the industrial-era view suggest that roughly two-thirds of total forest clearance occurred during the industrial era, and only one-third prior to 1850. But studies that incorporate historical (and archeological) evidence indicate that a large majority (perhaps three-fourths) of total forest clearance occurred prior to the start of the industrial era. The available historical and archeological evidence of per-capita land use supports the early-anthropogenic view rather than the industrial one.

3. EVIDENCE OF ANTHROPOGENIC GREENHOUSE-GAS EMISSIONS

Section 1 above (**Figure 1**) discusses how human activities caused a rapid rise in atmospheric CH_4 and CO_2 concentrations after 1850 that far exceeded the range of values during previous centuries. These trends appear to support the industrial view of an 1850 start to the Anthropocene, but analyses of a series of previous interglaciations provide a different perspective on greenhouse-gas trends during the past several thousand years.

3.1. Natural Greenhouse-Gas Trends

Ruddiman (2003) first pointed out that the upward trends in CO_2 and CH_4 during the past several thousand years differ from the downward trends during the most similar intervals of the three previous interglaciations. These "wrong-way" trends in CO_2 and CH_4 during recent millennia

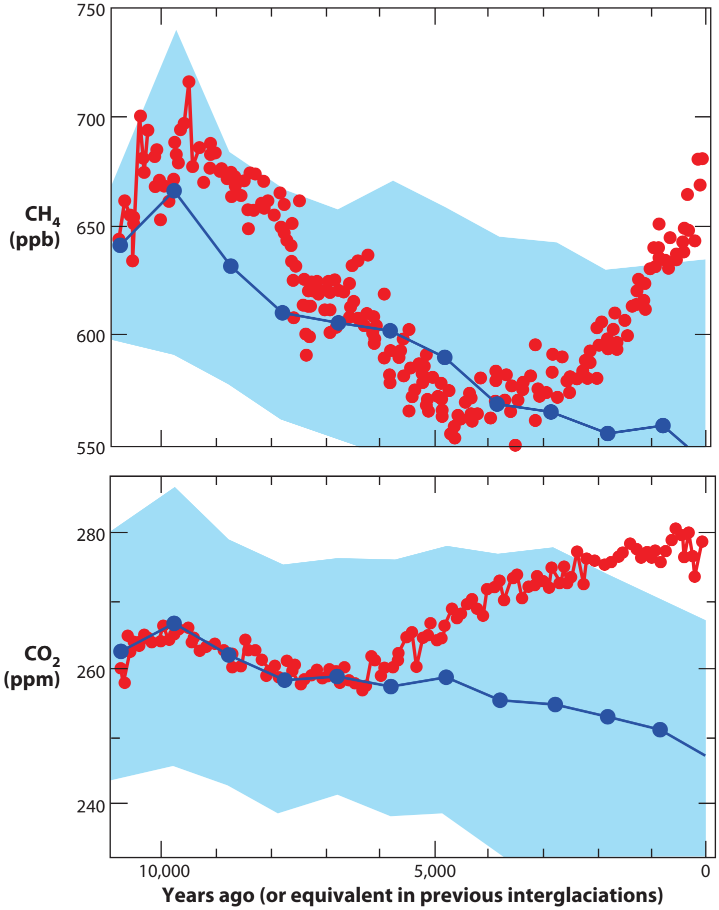

Figure 11

Preindustrial Holocene CH_4 and CO_2 concentrations (*red circles*) compared with average (*dark blue circles*) and standard deviation (*light blue shading*) during previous interglaciations (based on information from EPICA Community Members 2004).

suggest that humans could have had a significant effect on greenhouse-gas concentrations long before the abrupt increases during the past 150 years. New ice drilling and analysis during the past decade have provided gas records from several other previous interglaciations.

Findings from these additional gas trends support the conclusion that the CO_2 and CH_4 increases of the past several thousand years are anomalous compared with past trends. During the most recent deglaciation and the early part of the Holocene, CO_2 and CH_4 trends both fall within the wide range of variability during previous interglaciations (**Figure 11**). About 7,000 years ago, however, the Holocene CO_2 trend turned upward while the average from previous interglaciations continued to fall. After 5,000 years ago, the methane trend shows the same upward divergence from previous trends. By 2,000 years ago, both CO_2 and CH_4 trends had risen above the one standard deviation envelope of variation around the previous interglacial average. These findings strongly suggest that the wrong-way Holocene trends are not natural and thus are most likely anthropogenic. The rest of this section explores historical and archeological evidence used to test this conclusion.

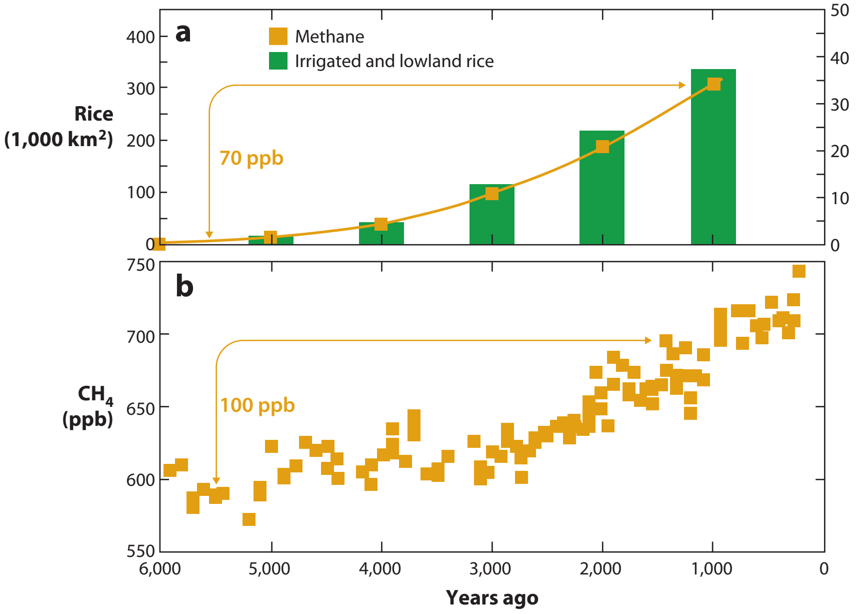

Figure 12

(*a*) Estimated effect of CH_4 emissions from irrigated rice agriculture on atmospheric concentrations compared with (*b*) CH_4 values measured in Dome C ice core prior to the industrial era (EPICA Community Members 2004).

3.2. Early Agricultural Methane Emissions

Fuller et al. (2011) estimated the increase in atmospheric CH_4 concentration caused by the expanding area of rice irrigation in Asia (**Figure 9**). To arrive at this estimate, they used the modern area of rice irrigation and its estimated effect on atmospheric CH_4 and then scaled down this relationship to the smaller areas irrigated in the past. They estimated that the increase in rice irrigation from 5,000 to 1,000 years ago would have produced an atmospheric CH_4 increase of ~70 ppb, a large fraction of the 100-ppb increase measured in ice cores for that interval (**Figure 12**).

Fuller et al. (2011) also drew on archeological data from Asia and Africa to map the spread of another methane-producing farming activity—livestock tending (**Figure 13**). Prior to 5,000 years ago, evidence of pastoralism is confined mostly to arid regions that had low carrying capacities and are unlikely to have had much effect on global methane emissions. After 5,000 years ago, however, livestock remains appear throughout wetter regions such as India and China where large human populations are concentrated today. Although Fuller and colleagues made no attempt to estimate past methane emissions, present-day livestock emissions of methane are larger than those from rice irrigation. Past methane emissions from the spread of livestock are likely to have added substantially to those from rice irrigation.

Singarayer et al. (2011) used a combined climate/vegetation model to estimate natural methane emissions during the past 130,000 years in response to orbital forcing. They concluded that natural methane sources in South America could be responsible for a substantial part of the preindustrial methane increase of the past 5,000 years. But the estimated emissions from rice irrigation (**Figure 12**), the substantial additional contributions likely from livestock (**Figure 13**), as well as other emissions from biomass burning and human waste suggest that natural sources may not be needed to account for the methane budget.

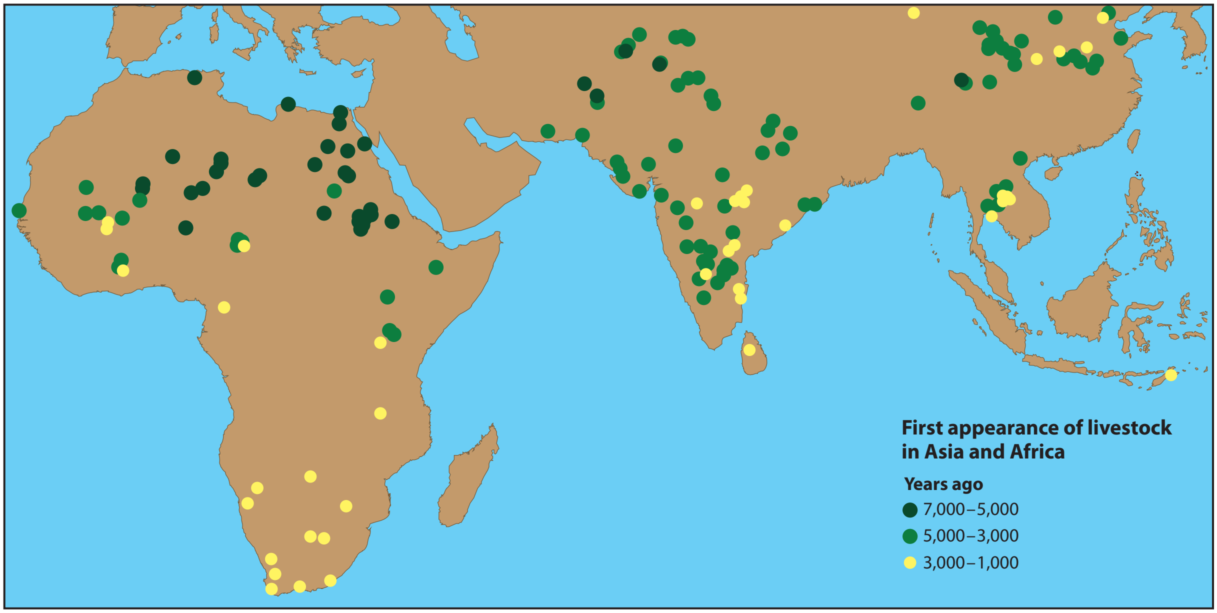

Figure 13

Radiocarbon-dated first appearances of domesticated livestock in Asia and Africa (after Fuller et al. 2011).

3.3. Early Agricultural CO_2 Emissions

The amount of preindustrial CO_2 emitted to the atmosphere is largely a function of the amount of deforestation.

3.3.1. Basis of carbon emissions estimates. Several land-use model simulations that assumed nearly constant per-capita clearance through time yield an average estimate of cumulative preindustrial carbon emissions of approximately 70 billion tons (the HYDE-based estimates in **Table 3**). If converted to the effect on atmospheric CO_2 concentration (by dividing by 14.2 GtC/ppm), these estimates point to a net CO_2 increase of 5 ppm, far below the 40-ppm value proposed in the early-anthropogenic hypothesis. But the assumption of small early per-capita clearance that underpins these estimates disagrees with historical evidence summarized in Section 2 (**Figures 7 and 8**).

In contrast, Kaplan et al. (2010) ran a simulation based on the historical evidence of larger early per-capita clearance. Their simulation yielded an estimated 343 billion tons of cumulative

Table 3 Preindustrial and industrial carbon emissions (billions of tons)

Source	Pre-1850	Post-1850	Total
Houghton (1999)[a]	–	124	
DeFries et al. (1999)	48–57	125–151	182–199
HYDE-based estimates[b]	69	141	210
Ruddiman (2003)[c]	320	–	
Kaplan et al. (2010)	343	108	451

[a]Preindustrial emissions not estimated.
[b]Average of Strassmann et al. (2008), Pongratz et al. (2008), and Stocker et al. (2011).
[c]Industrial-era emissions not estimated.

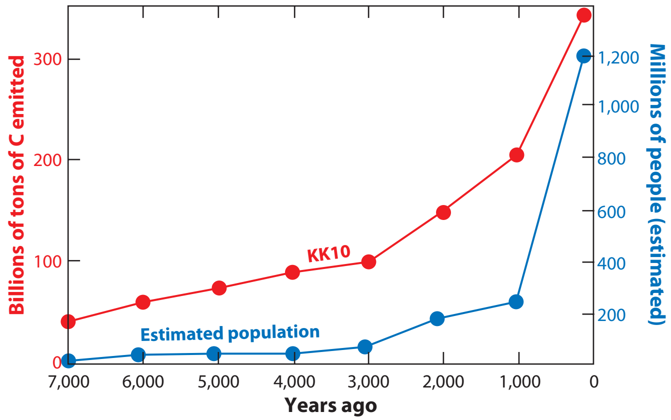

Figure 14

Model simulation of cumulative release of carbon (KK10 carbon emissions curve) caused by preindustrial land clearance from 7,000 years ago until the year 1850 compared with estimated population levels (adapted from Kaplan et al. 2010).

preindustrial carbon emissions (**Figure 14**). If converted to atmospheric CO_2 levels, the carbon-emissions estimate from Kaplan et al. (2010) implies a net increase of 24 ppm.

The two reconstructions also differ in the total amount of carbon emissions (preindustrial plus industrial). The estimate by Kaplan and colleagues of 451 billion tons is more than double the average of 210 billion tons from the HYDE-based simulations. The primary reason for this discrepancy is the fact that the HYDE-based estimates included only land under active cultivation for crops or in continual use as pastures or meadows. Land types omitted from the HYDE-based calculations include regions once farmed but now abandoned (such as areas of shifting cultivation), areas degraded beyond possible use for agriculture, and nonarable land such as rocky or steep terrain. As noted in Section 2, Houghton & Hackler (2003) estimated that including these once-forested categories could double the amount of total deforestation estimated by using the HYDE formulation. In support of this conclusion, Ellis (2011) mapped regions that have been converted from natural biomes to anthropogenically altered "anthromes" and placed large areas into categories that are not presently cultivated but once were forested.

Based on the historical and archeological evidence of large early per-capita clearance, the estimates from Kaplan et al. (2010) are better justified than the HYDE-based estimates. The greater per-capita land use through earlier millennia boosts the preindustrial KK10 carbon emissions curve above the trend of estimated population (**Figure 14**), but the initial rise in the KK10 curve of cumulative carbon emissions still falls well short of the large early increase in atmospheric CO_2 (**Figure 11**). The main rise in the CO_2 curve was largely complete by 3,000–2,000 years ago, but more than half of the preindustrial increase in estimated carbon emissions came after that time.

Two factors not fully included in the Kaplan KK10 carbon emissions estimate may account for this mismatch. First, the late-rising exponential trend of population growth estimated for the past several thousand years (**Figure 15**) may not be valid. For prehistorical time (before 2,000 years ago), this trend is based on the assumption of a constant geometric rate of increase (roughly a doubling every 1,000 years). This method implicitly assumes that the conditions that controlled population growth remained constant through all those millennia. But other demographic models assume that early populations rose most rapidly when farming had not approached regional carrying capacities and then slowed as available resources dwindled and as increased disease in crowded urban areas culled more of the population. These logistic demographic models show large early

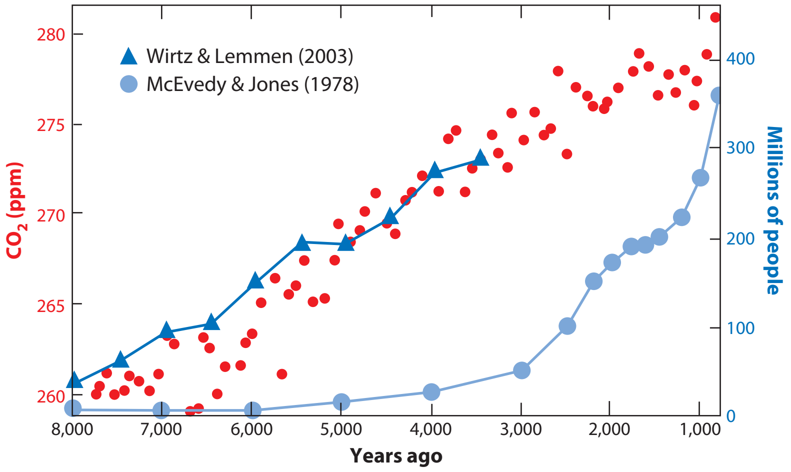

Figure 15

Holocene trend in atmospheric CO_2 concentration compared with two differing estimates of past population levels: CO_2 concentrations from EPICA Community Members (2004) (*red circles*); population values from McEvedy & Jones (1978) (*light blue circles*) and Wirtz & Lemmen (2003) (*dark blue triangles*).

rises in population prior to 3,000–2,000 years ago and a leveling off afterward. The population reconstruction of Wirtz & Lemmen (2003) in **Figure 15** plots almost directly on the CO_2 trend. Recent DNA work by Gignoux et al. (2011) indicates very rapid population increases among early agriculturalists.

Second, well-documented charcoal and pollen sequences from New Zealand document massive use of fire to clear forests by the Maori within two centuries of their arrival in 1280. Per-capita clearance on South Island was close to 100 ha/person (McWethy et al. 2009), or approximately 15 times the clearance rates assumed in the KK10 simulation. Many scientists have also inferred large-scale use of fire when humans first arrived in Australia 50,000 to 45,000 years ago (Flannery 1995, Miller et al. 2005). In addition, extensive use of fire by early farmers (and remaining hunter-gatherers) could have boosted carbon emissions estimates prior to 3,000 years ago.

3.3.2. $\delta^{13}CO_2$ constraint on preindustrial carbon emissions. The carbon-isotopic composition of CO_2 molecules in ice-core air bubbles provides another way to estimate changes in terrestrial carbon during the past 7,000 years. The $\delta^{13}C$ value of CO_2 represents the sum of several kinds of exchanges of terrestrial carbon: emissions by natural processes and by humans as well as burial in peatlands.

On the basis of the small negative (–0.05‰) trend in $\delta^{13}CO_2$ in Dome C ice during the past 7,000 years, Elsig et al. (2009) inferred a preindustrial anthropogenic carbon release of 50 billion tons, equivalent to an atmospheric CO_2 increase of 3.5 ppm. But their mass-balance analysis assumed a net burial of carbon in peatlands of just 40 billion tons (**Figure 16*a***), whereas credible estimates by Gorham (1991) and Yu (2011) indicate carbon burial of 275–300 billion tons during the past 7,000 years.

If these larger burial estimates are correct, they require much larger emissions to balance the $\delta^{13}CO_2$ budget (**Figure 16*b***). Because natural emissions are unlikely to have filled this gap, anthropogenic emissions are the most likely candidate (Ruddiman et al. 2011). Adjusted for the slightly more negative $\delta^{13}C$ composition of peat carbon relative to average terrestrial carbon, the

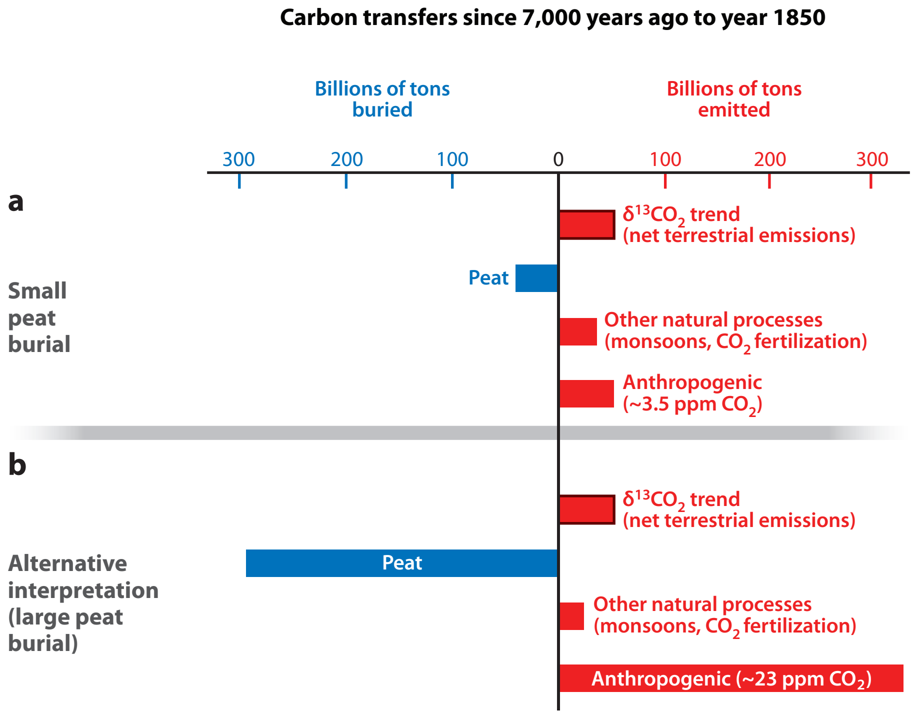

Figure 16

Two estimates of carbon transfers among major reservoirs that account for a net release of ∼50 billion tons of carbon to the atmosphere in the past 7,000 years: (*a*) small peat burial and anthropogenic carbon emission (from Elsig et al. 2009); (*b*) larger peat burial and carbon emission (from Ruddiman et al. 2011).

higher peat burial estimates require anthropogenic emissions of 300–325 billion tons, equivalent to a CO_2 change of ∼21–23 ppm, close to the 24-ppm estimate from Kaplan et al. (2010).

3.3.3. Anthropogenic CO_2 budget. The two estimates of 300–340 billion tons of carbon emissions (21–24 ppm CO_2) from anthropogenic deforestation far exceed the average of 69 billion tons (5 ppm CO_2) from earlier land-use model simulations (**Table 3**) but still fall short of the amount needed to account for the 40-ppm anomaly in the original early-anthropogenic hypothesis. Other anthropogenic emissions probably added only small amounts to this total. Coal has been burned for 2,000 years in China and (along with peat) for several hundred years in northern Europe. Rough back-of-the-envelope calculations of the possible CO_2 effects of these sources amount to 1–2 ppm (Ruddiman 2003, 2007), bringing the anthropogenic total to ∼22–26 ppm.

Ocean feedback processes would have added to the anthropogenic total from direct emissions. Ruddiman (2007) pointed out that an atmosphere warmed by anthropogenic emissions would have warmed the ocean and driven positive feedback processes that sent extra carbon back into the atmosphere (**Figure 17**). The best-constrained feedback comes from the fact that a warmer ocean holds less CO_2 in solution (Martin et al. 2005). If direct anthropogenic emissions account for a 24-ppm CO_2 increase and a 250-ppb CH_4 increase, the resulting radiative warming of the ocean would have released ∼7 ppm of CO_2 to the atmosphere (Kutzbach et al. 2011), bringing the anthropogenic total to ∼29–33 ppm. Other positive-feedback process linked to responses

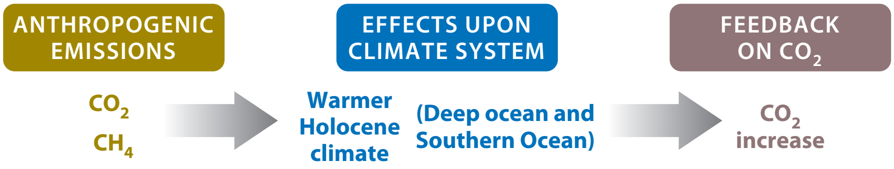

Figure 17

Direct anthropogenic emissions of CO_2 and CH_4 warm the ocean, which sends additional CO_2 to the atmosphere as a feedback.

in the Southern Ocean could have added more CO_2 and pushed the total closer to the 40 ppm proposed in the original early-anthropogenic hypothesis.

In summary, the industrial-era view of the history of anthropogenic greenhouse gases (with the main focus here on CO_2) holds that preindustrial emissions were much smaller than those during the industrial era, whereas the early-anthropogenic view posits large preindustrial emissions, although not as large as those in the industrial era (**Figure 18**). Because the early-anthropogenic view is based on land-clearance histories documented by historical and archeological evidence (**Figures 7–9**), it is likely to be more accurate than the industrial view, but further research is needed to quantify the preindustrial history of carbon emissions.

4. ANTHROPOGENIC CHANGES IN GLOBAL TEMPERATURE

The historical and archeological evidence summarized in Sections 2 and 3 indicates extensive deforestation and large greenhouse-gas emissions in the preindustrial era. This conclusion is further supported by the contrast between downward greenhouse-gas trends in previous interglaciations and upward gas trends during the Holocene (**Figure 11**). These independent lines of evidence suggest that natural CO_2 and CH_4 levels would be much lower than they are now had humans not interfered in the operation of the climate system.

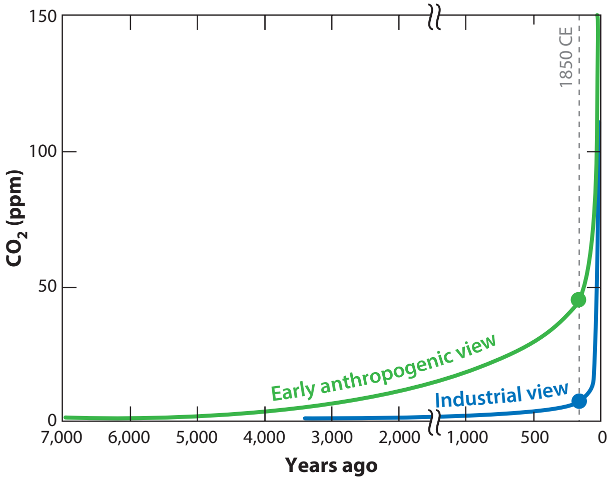

Figure 18

Two schematic plots of increases in atmospheric CO_2 concentrations caused by anthropogenic carbon emissions during industrial and preindustrial times. Note scale changes at 1,000 years ago.

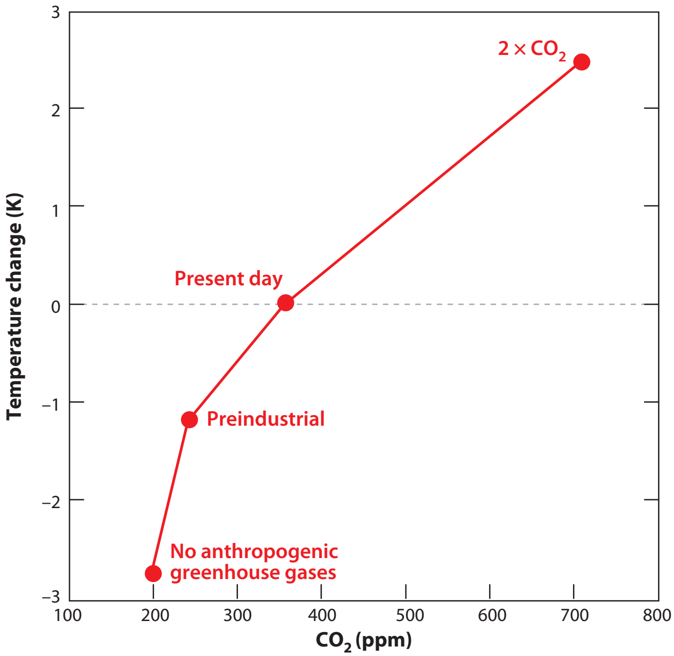

Figure 19

Change in global average temperature for different concentrations of atmospheric CO_2 (courtesy of J.E. Kutzbach, work in progress).

4.1. Enhanced Climate Sensitivity

The relative effect of preindustrial- versus industrial-era changes in anthropogenic gas emissions on global and regional temperatures has been tested in three atmosphere-ocean GCM (general circulation model) experiments (Kutzbach et al. 2011). One experiment used present-day (1990) gas concentrations and aerosols, the second used preindustrial (1850) gas levels, and the third was based on a hypothetical no-anthro world with neither industrial-era gas emissions nor the hypothesized early-agricultural additions. All simulations were run out to equilibrium conditions.

The choice of 1990 for the present-day simulation reflects the fact that the climate system takes decades to respond in a nearly complete way to imposed forcings (Hansen et al. 1985). Even though greenhouse-gas levels have risen steeply since 1990, the modern climate is closer to being in equilibrium with the 1990 gas levels than with the current ones. Modern industrial aerosols were also included as an atmospheric boundary condition for the 1990 simulation. In the case of the preindustrial simulation, the 1850 greenhouse-gas concentrations had not yet begun to rise rapidly, so that the ice-core concentrations measured for that time could be used directly (285 ppm for CO_2, 790 ppb for CH_4). The no-anthro simulation used the gas concentrations proposed in the early-anthropogenic hypothesis: 240 ppm for CO_2 and 450 ppb for CH_4.

The difference between the 1990 and 1850 simulations is a measure of the industrial-era effect on climate, and the difference between the 1850 and no-anthro simulations is a measure of the estimated preindustrial (mostly agricultural) effect. Given the larger industrial-era rise in greenhouse-gas concentrations compared with preindustrial times, a larger industrial-era warming would seem likely, but this is not the case (**Figure 19**). The simulated preindustrial warming is slightly larger than the industrial one.

One likely reason for this unexpected result is the cooling effect of aerosols in the 1990 simulation, which have canceled a portion of the industrial greenhouse-gas warming, although the magnitude of this effect is highly uncertain. Aerosol concentrations are unknown for preindustrial times, but they seem unlikely to have played a large role millennia ago. With factory smokestacks not yet in existence, industrial aerosols were not important, except perhaps for localized emissions from iron forges in late preindustrial time. And with preindustrial farming concentrated in wetter regions, relatively little mineral dust would have been raised by plowing. Small cookstoves and fireplaces in homes would have contributed aerosols, but populations through most of preindustrial time were less than 10% of modern levels.

A more fundamental reason for the large size of the preindustrial- versus industrial-era warming is the increased sensitivity caused by greater sea-ice cover. The extent of sea ice increases from the present-day to the 1850 simulation, but the increase from the 1850 to the no-anthro simulation is larger and produces a correspondingly greater temperature response. Snow cover also contributes to the increased sensitivity. The increased climate sensitivity for a colder climate reported by Kutzbach et al. (2011) agrees with an earlier attempt by Manabe & Bryan (1985) to simulate climate for varying CO_2 levels with a simpler coupled ocean-atmosphere model.

4.2. Renewed Glaciation?

In the simulated no-anthro world, global mean temperatures are ~1.3–1.4°C cooler than in the preindustrial experiment (Kutzbach et al. 2011, Vavrus et al. 2011). At polar and subpolar northern latitudes, the amplifying effects of increased sea ice and snow cover boost the cooling to levels at least twice the global mean value. As a result, snow cover persists year-round in several regions, including the northern Canadian Rockies, the Canadian archipelago, the northern Arctic margin of Eurasia, and eastern Siberia (**Figure 20**). Because of time and cost constraints, GCM experiments are not run long enough to simulate the slow growth or melting of ice sheets, but the presence of year-round snow cover is considered equivalent to glacial inception. When snow cover persists through warmer late-summer months, it leaves a base on which new snow can accumulate and eventually thicken into glacial ice. When this evidence is summed together, the areas with year-round snow cover are larger than the present-day Greenland ice sheet.

The early-anthropogenic hypothesis (Ruddiman 2003) included a prediction that the early stages of a new glaciation would have begun sometime before the present day (perhaps a millennium or two ago) if early agricultural gas emissions had not kept climate warm. The permanent snow cover simulated in the no-anthro model simulations supports the prediction that the early part of the “next” glaciation is currently overdue.

The biogeochemical warming produced by greenhouse-gas emissions is only part of the effect of early agriculture on climate. Forest clearance can also alter climate via biogeophysical effects—changes in the albedo of land surfaces that alter the reflection of incoming solar radiation. In general, forest clearance at higher latitudes tends to cool climate by changing darker radiation-absorbing evergreen canopies to brighter, more reflective pastures, especially during cold-season snow cover (Bala et al. 2007). Climatic effects are more subtle in the tropics, where clearance reduces evapotranspiration as well as the amount of high clouds and their reflection of solar radiation.

Prior to the industrial era, most people lived in the tropics or midlatitudes rather than at high latitudes, where biogeophysical impacts were smaller. Pongratz et al. (2010) simulated a very small net global cooling from the albedo effects of agricultural clearance that might have offset 10% of the hypothesized early anthropogenic greenhouse-gas warming summarized above.

The prevailing industrial-era view of the history of anthropogenic effects on climate is that the warming since 1850 far exceeds that during preindustrial time (**Figure 21**). If, however, the

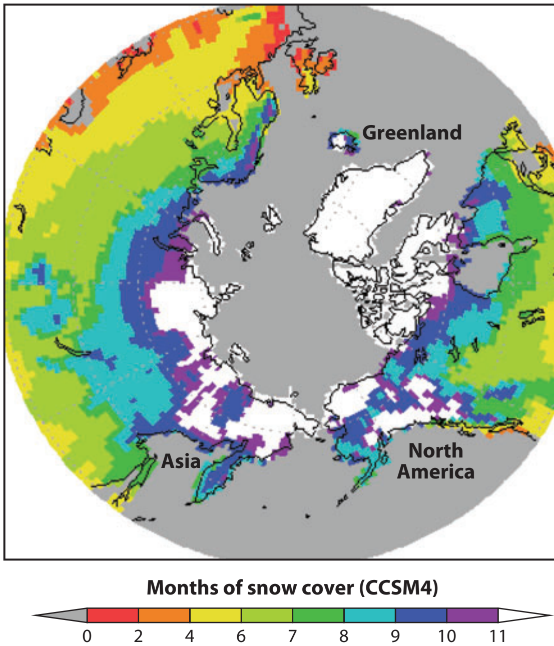

Figure 20

Model simulation of months of permanent snow cover if greenhouse-gas concentrations today were as low as those predicted by the early-anthropogenic hypothesis (adapted from Vavrus et al. 2011). Abbreviation: CCSM4, Community Climate System Model 4.

early anthropogenic evidence of major land clearance (**Figure 10**) and substantial greenhouse-gas emissions (**Figure 18**) is correct, and taking into account the nonlinear climate sensitivity (**Figure 19**), the preindustrial anthropogenic warming was actually larger than the warming to date during the industrial era (**Figure 21**). Such a reassessment would more than double the cumulative effect of humans on global temperature to date.

Preindustrial greenhouse-gas increases did not produce a net warming. Instead, they offset much of a natural cooling that would, by now, have made the planet cool enough to have ice sheets growing in the far north (**Figure 20**). This early-agricultural view does not alter the mainstream scientific consensus about the current global warming trend and our much warmer climatic future. Instead, it lowers the natural baseline from which the industrial-era and future anthropogenic effects have risen.

5. CONCLUSIONS

The past 150 years have seen widespread anthropogenic impacts on Earth's environments (**Table 1** and **Figure 1**). But prior to 1950, we have few reliable and systematic surveys to quantify past land use (**Figure 5**), so most projections for earlier intervals have assumed a close one-for-one link to population. Because populations were dramatically lower prior to the past few centuries (**Figure 6**), these hindcasts inevitably predicted very small early anthropogenic effects on land use and greenhouse-gas emissions.

In contrast, historical and archeological data reveal much larger forest clearance in preindustrial times because early farmers used much more land per capita than those in recent preindustrial centuries (**Figures 7–9**). This early deforestation, along with other effects of early agricultural activities, resulted in large greenhouse-gas emissions (**Figures 12–14**) consistent

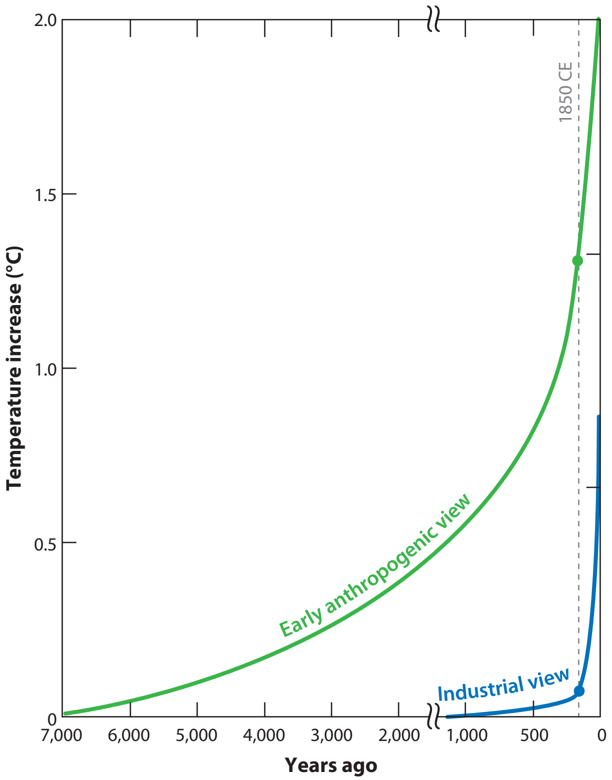

Figure 21

Two schematic plots of the relative size of anthropogenically driven temperature increases during industrial and preindustrial times. Note scale changes at 1,000 years ago.

with the anomalous CO_2 and CH_4 increases seen when compared with decreases during previous interglaciations (**Figure 11**). If these historically based and archeologically supported reconstructions are valid, preindustrial temperature changes caused by humans could be more than double the anthropogenic warming caused by the industrial era (**Figure 21**). The evidence of unexpectedly large preindustrial anthropogenic effects is clear, but much remains to be done to synthesize and analyze archeological data and, perhaps, to uncover new historical sources.

This article opened with the question of when the Anthropocene started. The evidence in Sections 2–4 provides an historical and archeological perspective for addressing this question. Deforestation during preindustrial time was larger than during the industrial era; preindustrial greenhouse-gas emissions were smaller, but substantial; and the net anthropogenic effect on global temperature was probably larger in preindustrial than industrial time. Given the size of these early changes, defining 1850 as the start of the Anthropocene does not make sense, despite the marked acceleration of many anthropogenic effects after that time.

One possible solution would be to define a two-phase Anthropocene:

1. An early phase with anthropogenic effects that began at a very small level thousands of years ago but slowly grew to considerable size by the end of preindustrial time
2. A later explosive phase of wide-ranging anthropogenic impacts during the industrial era

For scientists concerned with formal stratigraphic nomenclature, however, this proposed solution would create a new problem by eliminating much of the Holocene interval (the past

12,000 years). This problem is further aggravated by the fact that many scientists think that humans are responsible for the massive megafaunal extinction in the Americas nearly 12,500 years ago. Using that catastrophe to define the start of the Anthropocene would entirely eliminate the Holocene, which has long been in use.

Another problem is the fact that scientists who want to define the start of the early Anthropocene in a formal way with some kind of globally traceable "golden spike" are requesting the impossible. Agriculture began at different times in different areas and probably at amplitudes too low to be initially detectable. Alternatively, we could choose not to formally impose the simplifying term "Anthropocene" on all the rich complexity of human history: the spread of agriculture, the growth in populations, the creation of civilizations, the onset of the industrial era, and the superinterglacial climate looming ahead. Informal use of the term Anthropocene makes more sense.

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