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Viewpoint

The case for human causes of increased atmospheric CH_4 over the last 5000 years

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Abstract

We propose that humans significantly altered atmospheric CH_4 levels after 5000 years BP and that anthropogenic inputs just prior to the industrial revolution accounted for up to 25% of the CH_4 level of 725 ppb (parts per billion). We base this hypothesis on three arguments: (1) the 100 ppb increase in atmospheric CH_4 that occurred after 5000 years BP follows a pattern unprecedented in any prior orbitally driven change in the ice-core record; (2) non-anthropogenic explanations for this increase (expansion of boreal peat lands or tropical wetlands) are inconsistent with existing evidence; and (3) inefficient early rice farming is a quantitatively plausible means of producing anomalously large CH_4 inputs to the atmosphere prior to the industrial revolution. If the areas flooded for farming harbored abundant CH_4-producing weeds, disproportionately large amounts of CH_4 would have been produced in feeding relatively small pre-industrial populations.

1. Holocene methane trends in ice cores

A high-resolution Holocene record of methane changes from Greenland ice (Fig. 1a, Blunier et al., 1995) shows a broad CH_4 peak of 725 ppb between 12,000 and 8500 cal BP. Following a brief oscillation near 8100 cal BP, CH_4 values gradually declined to a 625 ppb minimum near 5000 cal BP and then slowly returned to a level of 725 ppb by AD 1700. Since AD 1700, CH_4 values have rapidly increased to more than 1700 ppb.

Humans have unquestionably been the primary driver of the abrupt methane increase during the last 300 years (Khalil and Rasmussen, 1983). Human-related methane sources include livestock tending, rice irrigation, biomass burning, fossil-fuel extraction, and municipal landfill construction (Table 1). Today, these anthropogenic inputs of methane exceed natural sources.

In contrast, the early Holocene methane peak between 12,000 and 8500 cal BP is widely ascribed to natural climatic variations caused by an orbital-scale summer insolation maximum centered near 11,000 cal BP (Blunier et al., 1995; Brook et al., 1996). Insolation values 9% higher than today drove a strong wet summer monsoon in the northern tropics and also caused ice-free boreal regions to warm. The moist tropical monsoon maximum in the early Holocene is readily apparent in the synthesis of North African lake levels in Fig. 1b (Kutzbach and Street-Perrott, 1985) and in lake levels and other moisture proxies across much of India and southeast Asia (COHMAP, 1988). This wet summer monsoon filled lakes, flooded natural wetlands, and created huge natural sources of methane to the atmosphere.

But what of the intervening interval between 5000 and 300 years ago? Why did the post-monsoon CH_4 decline end, and why did CH_4 values subsequently increase all the way back to monsoon-like levels prior to the start of the industrial (and agricultural) revolution?

2. The late Holocene trend is anomalous compared to earlier CH_4 trends

One key observation is that the CH_4 trend of the last 5000 years is anomalous compared to the ice-core trends over the previous 400,000 years (Chappellaz et al., 1990, 1997; Petit et al., 1999). The most obvious difference is that none of the preceding CH_4 maxima show the double peaks that occurred in the early and late Holocene. All previous maxima were single-peaked, whether they occurred during full interglacial climates or during times of more glacial conditions. Some earlier peaks show brief millennial-scale interruptions like the

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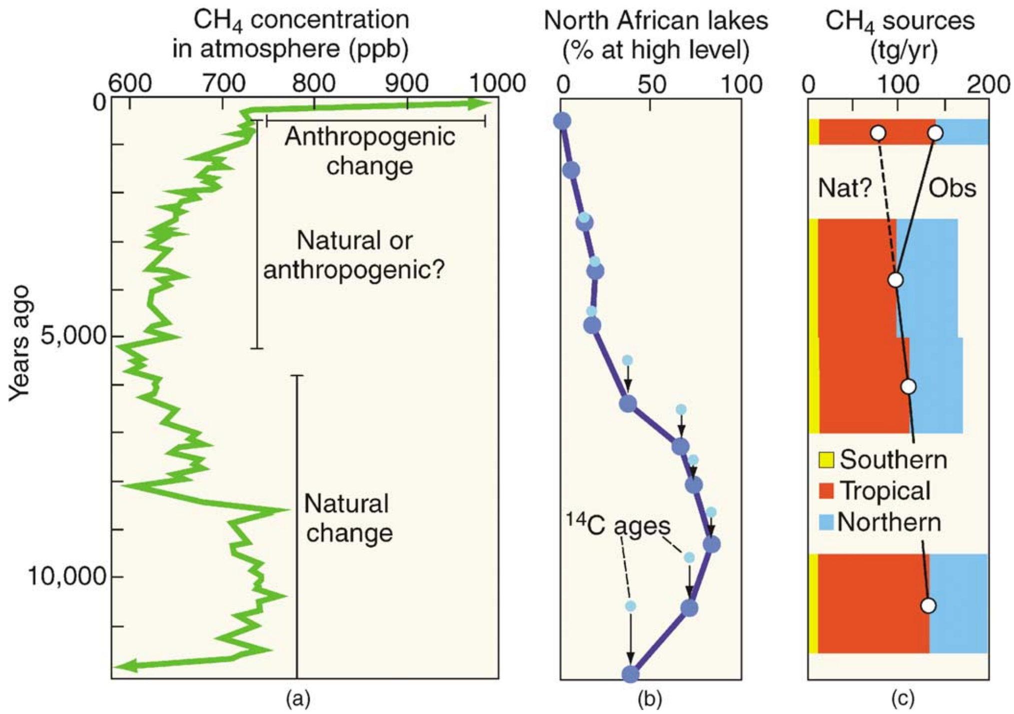

Fig. 1. Atmospheric methane variations from 12,000 to 5000 years ago (a) from Blunier et al., (1995) were primarily caused by monsoonal rains that filled tropical lakes and other wetlands (b) from Kutzbach and Street-Perrott, 1985. In contrast, the abrupt CH_4 rise after AD 1700 resulted from human activities. The intervening 100 ppb CH_4 increase from 5000 cal BP to AD 1700 occurred during a time of early anthropogenic influences, including irrigation of land for rice farming. Bar graphs (c) show estemated CH_4 inputs in tg/yr from boreal, tropical and southern hemisphere sources based on changing interhemispheric CH_4 gradients in ice cores (Chappellaz et al., 1997). Dashed-line projection shows hypothesized projection of the natural trend through recent centuries.

Table 1
Estimated 1990 methane budget (in tg/year; IPCC, 1994)

Total CH_4 sources	530
Natural CH_4 sources	160
Wetlands	115
Termites	20
Oceans	10
Recent anthropogenic sources	140
Fossil fuels	100
Municipal landfills	40
Early anthropogenic sources[a]	230
Rice paddies	80
Livestock	60
Biomass burning	40
Animal waste	25
Domestic sewerage	25

[a] Sources that could have been significant prior to the industrial revolution.

pulse at 8100 years ago in Fig. 1a, but none are longer-lived double peaks separated by 10,000 years like those in the Holocene.

All pre-Holocene CH_4 peaks within the relatively well-dated ice-core record of the last 140,000 years are spaced at intervals near 22,000 years. This observation supports the interpretation that successive maxima in summer insolation at the precession cycle controlled past methane concentrations by creating maxima in monsoon intensity, as well as boreal warmth (Prell and Kutzbach, 1987; Blunier et al., 1995; Brook et al., 1996).

The weighted mean values of the last six CH_4 peaks are aligned to a common zero age in Fig. 2 for intercomparison. Within the uncertainties of ice-core dating and CH_4 analyses, each pre-Holocene CH_4 peak rises to a maximum and returns to a lower baseline within one half (11,000 years) of a 22,000-year insolation cycle. The ice-core time scale for the last full interglaciation (oxygen isotope or OIS substage 5e) is less certain, but the record again shows a rise to a single well-marked peak and then a gradual decline to a lower value within one half of a precession cycle. The absolute concentrations reached in each CH_4 maximum and minimum vary, presumably because the intensity of the monsoon is modulated by the amount of ice present at high northern latitudes and the resulting (variable) cooling of temperatures and precipitation at lower latitudes.

The pattern following the most recent CH_4 peak is fundamentally different. Until 5000 years ago, the post-monsoon CH_4 values followed a similar path toward lower levels, but then reversed and began a slow rise that

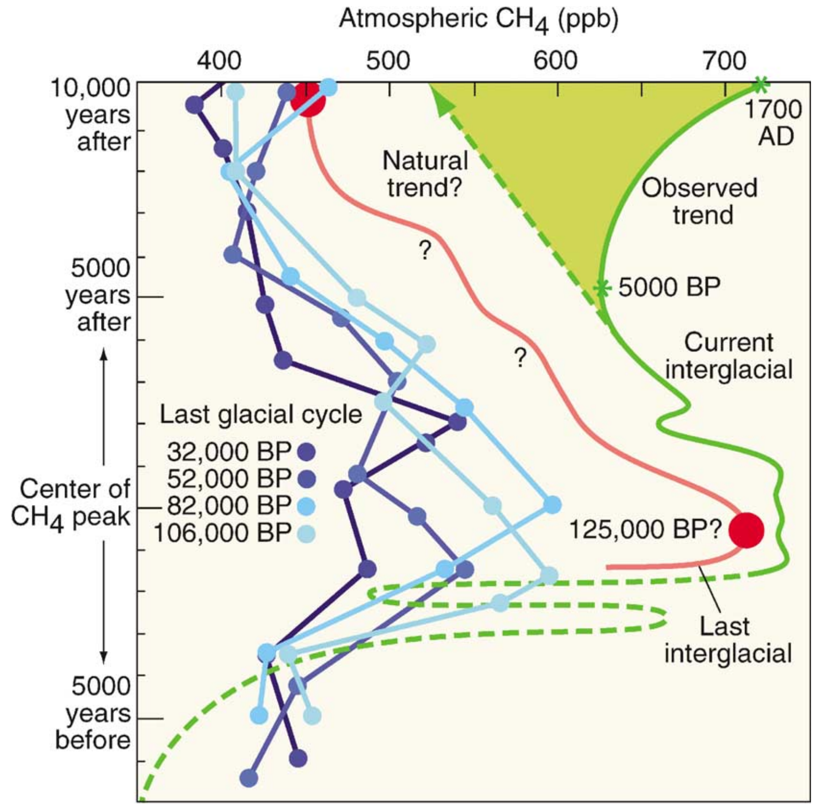

Fig. 2. Following the most recent natural (monsoon-driven) peak in atmospheric methane (far right), the level of atmospheric CH_4 initially followed a downward trend similar to previous peaks that had been driven by the same kind of orbital forcing (left), but methane concentrations after 5000 cal BP began a slow rise unprecedented in the earlier record. Dashed green line shows the hypothesized projection of the natural trend through recent centuries.

eventually totalled 100 ppb. We propose that this anomalous reversal marks the onset of detectable human influences well before the industrial era.

3. Rejection of the peat lands hypothesis

Initially, the gradual 100-ppb increase in CH_4 from 5000 to 300 BP was attributed to growth of carbon-rich peat basins north of 45°N (Blunier et al., 1995). Peat lands expanded rapidly after 6000 BP east of the Ural Mountains (Neustadt, 1984; Gorham, 1991; Smith et al., 2000).

Recent work exploring differences in CH_4 content between Greenland and Antarctic ice cores has undercut the peat lands hypothesis. Present-day ice-core CH_4 values in Greenland exceed those in Antarctica by more than 100 ppb, and the difference over the several thousand years prior to the industrial revolution varied between 30 and 60 ppb (Chappellaz et al., 1997).

This interhemispheric difference is the result of several factors. First, most methane sources are in the northern hemisphere, closer to Greenland than Antarctica. Second, the average CH_4 molecule resides in the atmosphere for only 7–10 years before oxidizing. As a result, more CH_4 from predominantly northern sources is consumed before reaching the distant Antarctic ice sheet than the nearby Greenland ice sheet. The result is an interhemispheric CH_4 gradient.

Chappellaz et al. (1997) modeled changes in this interhemispheric methane gradient during the pre-industrial Holocene in order to detect shifts in methane source areas. Increases in the CH_4 gradient should indicate greater methane input from boreal sources close to Greenland, thus producing relatively higher values there than in Antarctica. Decreases in the interhemispheric gradient point to greater methane input from tropical sources lying more equidistant between the two ice sheets.

Chappellaz and colleagues modeled the average change in CH_4 inputs across several broad time intervals. In comparing an interval lasting from 5000 to 2500 years ago against another lasting from 1000 to 250 years ago, they found that CH_4 inputs from boreal ("northern") sources decreased toward the present (Fig. 1c). This decrease in boreal input coincided with the main part of the pre-industrial increase in CH_4 (Fig. 1a). If this result is correct, it refutes boreal peat lands as the explanation of the CH_4 increase since 5000 cal BP.

The decrease in north–south CH_4 gradients further indicates a 55% increase in CH_4 from tropical sources during the same interval. But was this tropical methane source natural or anthropogenic?

4. Rejection of the natural tropical wetlands hypothesis

Chappellaz et al. (1997) noted that one plausible explanation for the 55% increase in tropical CH_4 input prior to industrialization is an expansion of natural wetlands. In support of this explanation, they cited trends from one lake record in the Amazon Basin and one from India.

We argue here that this explanation must be rejected. The overwhelming message from moisture indicators in the tropics over the last 5000 years is that climate has become drier, not wetter. Lake and river levels continued to fall during that interval not only in Africa (Fig. 1b), but in a broad arc stretching across Arabia, India and southeast Asia (COHMAP 1988; Winkler and Wang, 1993). The wet summer monsoon has been in retreat from southeast Asia for the last 9000 years (An et al., 2000). Individual records at specific locations often show brief (millennial-scale or shorter) reversals back toward moist conditions, but the underlying trend over the last several thousand years has been toward drier conditions.

Trends in tropical South America during the last 5000 years are more complex and regional in scale, with no pervasive trend toward greater or lesser aridity evident in pollen records from this region (Markgraf, 1993; Colinvaux et al., 2000). One region—the high Bolivian altiplano and its eastern margins—does show a coherent trend toward wetter climates during the last 5000 years (Seltzer et al., 2000). This reduction in rainfall also affected the outflow of the Amazon River (Maslin and Burns, 2000). Both Seltzer et al. (2000) and Maslin and Burns (2000) convincingly interpreted this trend as the result of an intensifying monsoon driven by summer insolation following the phasing characteristic of southern hemisphere precession changes.

We offer two arguments here why this regional South American response is not a plausible explanation for the atmospheric CH_4 increase of the last 5000 years. First, all earlier orbital-scale CH_4 maxima in the best-dated parts of the ice-core record follow the northern hemisphere monsoon trend, which has a timing exactly out of phase with that in the southern hemisphere (precessional insolation reverses season between hemispheres). It is not reasonable to argue that this region in South America would suddenly "take charge" of global CH_4 emissions in the last 5000 years, when it had not done so for the preceding 400,000 years. Our second argument is simply that it is not credible that a regional moisture increase in part of South America could have overwhelmed the effects of an ongoing drying trend covering a vast region of Asia, India, and Africa.

In addition, ice cores show a slow CO_2 increase of 20 parts per million (ppm) over the last 7000 years (but prior to industrialization), and this trend has been attributed to the gradual loss of about 10% of Earth's terrestrial carbon biomass (Indermuhle et al., 1999). This trend is consistent with a large-scale tropical drying, but opposite in sense to a net increase in tropical moisture levels.

In summary, increases in natural tropical wetlands are not a viable explanation for the pre-industrial increase in CH_4. Indeed, the evidence for a pervasive natural drying trend in the tropics, combined with the results from modeling of interhemispheric CH_4 gradients, puts an even greater burden on the search for an explanation of the methane rise that began 5000 years ago. Now we must find a growing source of tropical methane large enough to not only explain the subsequent 100 ppb rise in CH_4, but to also offset ongoing methane losses from natural sources.

The only other naturally based explanation for an increase in tropical methane input is one tied to variations in global sea level that would cause flooding of low-lying tropical wetlands. But most tropical coastlines far from northern regions of ice–bedrock interactions have had stable sea levels for 6000 years, and so this explanation is not promising.

In any case, *any* explanation that calls on a natural mechanism must still face the critical issue raised earlier: why does no previous interglaciation or glaciation show a reversal in CH_4 trend? What natural process would *only* be at work during the most recent interglaciation ?

5. Early anthropogenic input of methane

The only plausible source for enhanced methane input from the tropics since 5000 cal BP is humans. This option was also cited by Chappellaz et al. (1997), but not preferred over changes in CH_4 input from natural wetlands. Etheridge et al. (1998) also noted the possibility of a significant (but unspecified) anthropogenic input to explain pre-industrial CH_4 levels in the atmosphere. Here we outline arguments that both support and strengthen this "early anthropogenic CH_4 hypothesis".

The earliest evidence for livestock tending in the Near East dates to 10,000 years ago for sheep, goats and pigs, and 8000 years ago for cattle (Roberts, 1998). Domestication of wild rice in southeast Asia began by 7500 cal BP (Chang, 1976; Glover and Higham, 1996), with human control of irrigation beginning between 6000 and 4000 cal BP (IRRI, 1991). This range of evidence shows that early anthropogenic methane sources existed by 5000 cal BP, however small in size.

Table 2
Estimates of early anthropogenic CH_4 inputs

	AD 1990	AD 1700
Atmospheric CH_4 level (ppb)	1700	725
Early anthropogenic CH_4 input required (in tg/year)	230	32 (minimum case)[a] 60 (maximum case)[b]
World population (in millions)	5200	640
CH_4 Inputs scaled linearly to population		
1. Domestic sewerage	25	3.1
2. Livestock	60	7.4
3. Animal waste	25	3.1
4. Biomass burning	40	4.9
5. Rice farming	80	9.8
Total	230	28.3
CH_4 Inputs required for the "maximum-case" of the hypothesis		
Factors 1–4 from above list, all scaled linearly to population	18	
Rice farming input needed (60–18 tg/yr)	42	
Total contribution of anthropogenic inputs to atmospheric CH_4 level in AD 1700 (ppb)	100 (minimum case)[a] 192 (maximum case)[b]	

[a] The "minimum case" of the early anthropogenic CH_4 hypothesis is based on the CH_4 input needed to support an atmospheric methane level of 100 ppb at AD 1700.
[b] The "maximum case" value was derived by linearly projecting the trend of tropical CH_4 input estimates (Fig. 1c) toward lower levels at AD 1700 and then calculating the difference between this projected value and the total tropical input derived from the model of Chappellaz et al. (1997).

By AD 1990 these combined sources were emitting an estimated 230 tg/year of CH_4 to the atmosphere (Table 1), more than 40% of the modern CH_4 input (IRCC, 1994).

One way to evaluate the early anthropogenic CH_4 hypothesis is to estimate the level to which these methane inputs had grown by AD 1700, just before the industrial revolution. At a minimum, inputs sufficient to explain the observed 100 ppb rise in atmospheric CH_4 levels between 5000 and 300 years ago are needed. Because the residence time of CH_4 in the atmosphere is 7–10 years, atmospheric CH_4 concentrations at any time must be nearly proportional to annual methane inputs (see, for example, Quay et al., 1988). Scaling down from 1990 values, we calculate that the 100 ppb rise in CH_4 values that occurred between 5000 years ago and AD 1700 would have required an added CH_4 input of 32 tg/year (Table 2). We will refer to this estimate as the "*minimum-case*" requirement of the early anthropogenic hypothesis.

But the evidence already presented argues for a larger early anthropogenic effect. The fact that the late Holocene CH_4 trend (Fig. 2) fails to follow the path of its predecessors to lower values implies that an additional input of CH_4 must have occurred to counter this "natural" trend. A crude way to estimate the size of this additional input is to project the post 5000 BP CH_4 curve to lower values along a trend parallel to those of the earlier intervals. Methane values would then have followed the green dashed line in the upper part of Fig. 2 and fallen to the range of 500–550 ppb. This requires a net anthropogenic CH_4 input by AD 1700 of between 175 ppb (the observed 725 ppb minus 550 ppb) to 225 ppb (725–500 ppb). The annual input of CH_4 required to support a level of 175–225 ppb in the atmosphere is 55–70 tg/yr.

We can make a similar (but independent) projection using the CH_4 input trends calculated from the interhemispheric gradients of Chappellaz et al. (1997). They estimated a 45 tg/yr increase in tropical methane between the 5000–2500 and the 1000–250 cal BP intervals, but this value fails to take into account the additional CH_4 increase needed to compensate for the continued drying in the tropics. If we calculate the rate of decrease of natural methane input modeled by Chappellaz et al. (1997) for the two Holocene intervals prior to cal 5000 BP and linearly project this trend forward to AD 1700 (Fig. 1c), we find that an additional 15 tg/year of CH_4 input could have been lost from natural sources after 5000 cal BP but prior to the industrial revolution. Adding this value to the modeled change of 45 tg/year, we arrive at a total early anthropogenic CH_4 input of 60 tg/year, a value lying near the middle of the 55–70 tg/yr range derived by the projection of atmospheric CH_4 levels. We will use 60 tg/yr as our estimate of the "*maximum-case*" requirement of CH_4 inputs at AD 1700 for the early anthropogenic CH_4 hypothesis (Table 2).

What combination of the five early anthropogenic sources listed in Table 1 could account for a CH_4 input of between 32 and 60 tg/year at AD 1700 ? A "bottom-up" approach used to address this kind of problem requires synthesizing estimates of all individual CH_4 inputs, but such estimates can vary by almost an order of magnitude for the centuries just prior to industrialization (Kammen and Marino, 1993; Subak, 1994). Such an approach is inherently difficult because of the large uncertainties involved in compiling specific estimates of past human activities in many regions across the world.

A reasonable alternative is to assume that the annual methane inputs from all early anthropogenic sources at any time in the past were proportional to the number of humans alive (as in Quay et al., 1988, for example). The number of humans on Earth at AD 1700 was about 650 million, or roughly 13% of the 1990 population of 5 billion. If we multiply the modern-day CH_4 input of 230 tg/yr from "early anthropogenic" sources in Table 1 by 0.13, we derive a scaled-down CH_4 input in AD 1700 of 28.3 tg/yr, almost enough to meet the "minimum-case" requirement of 32 tg/yr (Table 2), but still less than half of the maximum-case requirement of 60 tg/yr.

Clearly, meeting the maximum-case early anthropogenic requirement requires a source of methane disproportionately large compared to the population living at AD 1700. Which of the "early anthropogenic" sources listed in Table 1 emitted a disproportionate amount of CH_4?.

Three of the five sources listed are not promising, because they probably were closely tied to the number of humans alive: human sewerage, livestock emissions, and animal waste. Because livestock were kept mainly for food, their numbers (or mass) would not likely have departed much from the size of the human populations at that time.

Subak (1994) argued that a fourth factor, biomass burning, emitted 26 tg/year of methane in the pre-industrial era (AD 1500), equivalent to 65% of the modern estimate of 40 tg/yr. If this estimate is correct, biomass burning could provide most or all of the extra (disproportionate) CH_4 we seek. But this proposal can be rejected: carbon-isotopic evidence from Quay et al. (1988) rules out a disproportionate pre-industrial contribution from biomass burning. By examining the $\delta^{13}C$ composition of ice-core methane dating to AD 1650–1700, they found that the primary sources of CH_4 at that time had a mean $\delta^{13}C$ value of -60%. They concluded that this carbon-isotopic value rules out a major AD 1700 contribution from biomass burning, which yields CH_4 with $\delta^{13}C$ values of just -27%.

Quay et al. (1988) inferred that the bulk of the CH_4 input at AD 1700 must have come mainly from natural wetlands, which yield methane with $\delta^{13}C$ values near $-60‰$. However, they failed to consider another possible source of methane with this same $\delta^{13}C$ value: rice paddy farming, the last of the "early anthropogenic" factors listed in Table 1. Methane emissions from rice paddies also yield $\delta^{13}C$ values averaging near $-60‰$. As a result, this source could also satisfy the $\delta^{13}C$ analyses.

6. Disproportionate early anthropogenic input of methane from rice farming

We propose that the inefficiency inherent in primitive rice farming is a plausible source of a disproportionately large early anthropogenic input of CH_4. Our premise is that early attempts at rice farming required relatively extensive flooding of weed-infested fields to produce small amounts of rice, so that the methane emissions would have been disproportionately large compared to the actual amount of rice produced and population fed.

Late AD 1900 trends support our argument that early rice farming was inefficient. In Fig. 3 we plot the ratio of the population of Asia (including India) versus the area under cultivation for rice farming, with the vertical axis scaled to a value of 1.0 in the year AD 1991. Population and rice farming data from IRRI (1991) indicate that this same ratio in 1950 AD had a value of just 0.7. Populations grew faster than the area farmed between 1950 and 1991: more efficient farming required less area to feed each person.

The decline in rice-farming efficiency back through this well-quantified interval has the right sense to provide independent support for our maximum-case estimate of early anthropogenic CH_4 inputs, if two simplifying assumptions are met: (1) the area irrigated for rice farming must be a valid proxy for all rice farming; and (2) the amount of CH_4 emitted through time must be proportional to the area flooded for rice irrigation.

The first assumption is basically (although not precisely) validated by Minami and Neue (1994), who found that more than 70% of the rice produced comes from irrigated lands, with an additional amount from naturally flooded regions. Drier upland regions that produce little rice produce little CH_4. This establishes a close link between rice production and irrigation.

The second assumption would be invalidated if the use of fertilizers and pesticides caused increased methane emissions along with increased rice yields. However, Bodelier et al. (2000) showed that increased fertilizer use in recent decades improved rice yields without increasing CH_4 emissions per area irrigated. And while improved agricultural management and increased use of herbicides have no doubt reduced the impact of weeds in irrigated areas, weeds generate at least as much CH_4 as rice (Yamane and Sato, 1963). This finding implies that increased rice production has been accompanied by little change in CH_4 emission per area irrigated, and perhaps even a small reduction. In

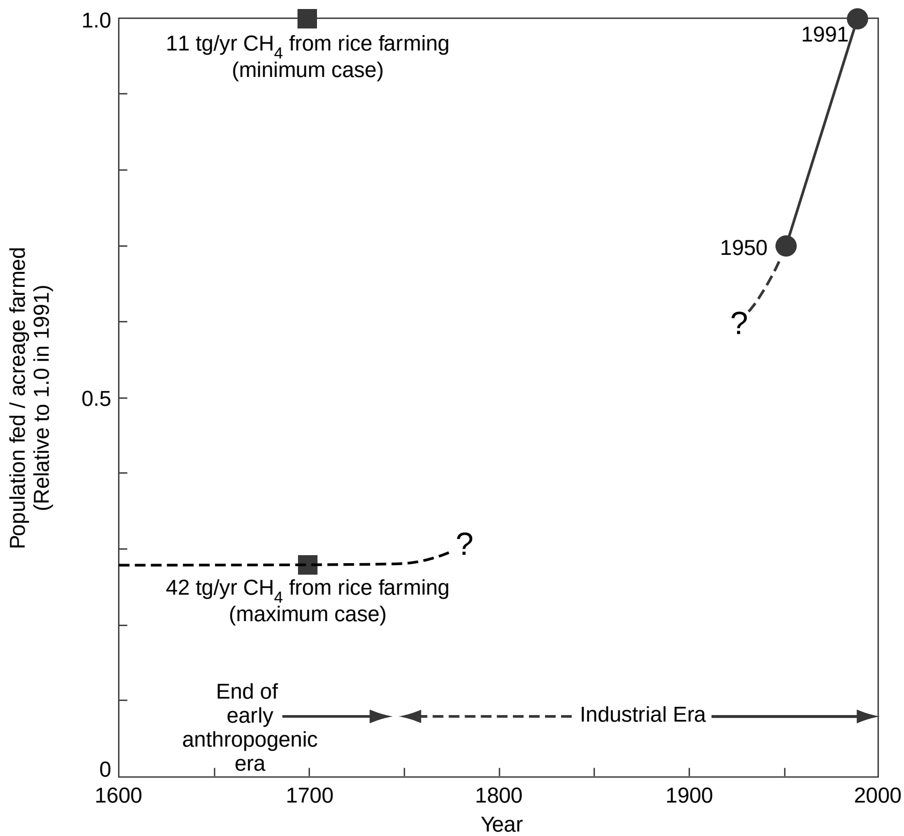

Fig. 3. The amount of population fed per acre farmed ("farming efficiency") through time can be compared to an arbitrary value of 1.0 (100% efficiency) in 1991. The well-defined late 1900s trend (IRRI, 1991) shows a lower farming efficiency in 1950 than in 1991. Projection of this trend backward in time implies a still lower rice farming inefficiency in AD 1700. This projection supports the "maximum-case" requirements of the early anthropogenic CH_4 hypothesis: inefficient early rice farming would have produced disproportionately large amounts of methane relative to the size of the human population.

summary, increased rice yields of the last half-century were probably not accompanied by extra emissions of methane.

How much methane input is needed from inefficient rice farming in AD 1700 to satisfy the maximum-case requirements of our hypothesis? First, we again assume that the four other early anthropogenic factors (including biomass burning) are linearly related to global population and total 18 tg/yr (Table 2). This leaves unsatisfied a requirement for another 42 tg/yr from inefficient rice farming to meet the maximum-case estimate of 60 tg/yr of CH_4 input.

We know of no credible way to reconstruct the level of farming efficiency in AD 1700, but we can shed some light on this factor by testing two assumptions. We start with the simple but unlikely assumption that rice farming in AD 1700 followed exactly the same practices as in 1991. If this assumption is valid, a linear relationship would have existed between human population, rice produced, area farmed for rice, and CH_4 emitted. We can again use population changes from AD 1700–1991 as a basis for linearly scaling back to the estimated CH_4 emissions from rice paddies in AD 1700. In this case, we use population changes in Indo-Asia (Lamb, 1977), where rice is the major food staple. We derive an estimate of 12 tg/yr of CH_4 emitted from rice paddies in AD 1700.

But a farming efficiency of 100% in AD 1700 makes no sense when considered by comparison to the AD 1950–1991 trend plotted in Fig. 3. It would require that farming was far *more* efficient in 1700 than in AD 1950, a reversal of the trend measured in the late-1900s.

An alternative assumption is to derive the level of farming efficiency that would be necessary to satisfy the maximum-case requirements of our hypothesis. By comparing the 42 tg/yr input of CH_4 input needed to match this requirement against the 12 tg/yr input derived by assuming a farming efficiency of 100%, we calculate that an efficiency of 0.28 (12 divided by 42) would satisfy our hypothesis. This lower efficiency value lies along a reasonable backward extrapolation of the late-AD 1900s trend (Fig. 3). Although any such extrapolation is obviously speculative, we argue that it at least makes sense that rice farming efficiency in AD 1700 would have been considerably lower than in the mid-1900s.

In summary, highly inefficient farming is a plausible source of the disproportionately large CH_4 input needed to verify the maximum-case requirements of our hypothesis. In effect, the extensive areas flooded in the 1700s emitted disproportionately large amounts of CH_4 compared to the food needs of the small populations living at the time.

If our maximum-case estimate of anthropogenic CH_4 input (60 tg/yr) is correct for AD 1700, it would have supported an atmospheric CH_4 level of 192 ppb, or more than 1/4 of the 725 ppb value observed. This contribution in AD 1700 represents a continuation of human CH_4 inputs that had begun slowly and at much smaller levels by 5000 years ago and grown in size during the intervening centuries.

This large an anthropogenic CH_4 contribution in AD 1700 would help to resolve a discrepancy that bothered Quay et al. (1988): their calculations implied that late pre-industrial CH_4 inputs from natural sources (primarily wetlands) were at least twice as large as today. Methane input from rice paddies would reduce the need for extra pre-industrial methane input from natural wetlands.

How can our hypothesis be tested by future work?. One challenging possibility would be to find reliable records of the area of rice farmed during recent centuries in historical archives in Asia. Another approach would be to find a chemical tracer that can distinguish rice-paddy CH_4 from that emitted by natural wetlands.

7. Climatic implications of an early anthropogenic CH_4 increase

What effect would a human-induced CH_4 increase of 192 ppb have had on global temperature? Lower greenhouse gas concentrations at the Last Glacial Maximum (LGM) are thought responsible for 40% (1.25–2.1°C) of the estimated 3–5°C global cooling (Raynaud et al., 1992). The uncertainty in the size of this global cooling centers mainly on tropical temperature responses (CLIMAP, 1981; Rind and Peteet, 1985), but the range of climate sensitivity to greenhouse gases at the LGM inferred from these data lies within the range indicated by general circulation models (Schlesinger and Mitchell, 1987). Approximately 25% (0.3–0.5°C) of the estimated greenhouse-gas cooling is attributed to the lowering of glacial methane levels by 350 ppb, and the rest mainly to lower CO_2 (Raynaud et al., 1992). Scaled similarly, a 192 ppb increase in methane levels due to early anthropogenic inputs could have caused a global warming of 0.2°C (0.16–0.28°C) between 5000 cal BP and AD 1700.

This temperature overprint would probably have been larger at high latitudes, where climatic changes are typically intensified by a factor of 2–3 near seasonal snow and ice boundaries. Poleward intensification of the early anthropogenic CH_4 effect would translate into a mean annual warming of 0.5°C (0.3–0.8°C) at high northern latitudes from 5000 years ago to AD 1700.

Modeling experiments indicate that the 5% drop in summer insolation at high northern latitudes during the last 6000 years should have driven a summer cooling of 2–3°C, along with a small warming in winter (TEMPO Project Members, 1996; Kutzbach et al., 1997). These estimates are broadly consistent with records from climatic proxies sensitive to summer temperatures at high northern latitudes, including ocean temperatures, glacier ablation, and northern tree limits (Koc et al., 1993; Lubinski et al., 1999). The warming effect caused by anthropogenic methane could have countered a small part of this natural cooling and to at least this small extent would have opposed the onset of the next glaciation at high northern latitudes.

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