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Viewpoint

Effect of per-capita land use changes on Holocene forest clearance and CO_2 emissions

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A R T I C L E I N F O

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A B S T R A C T

The centerpiece of the early anthropogenic hypothesis is the claim that humans took control of greenhouse-gas trends thousands of years ago because of emissions from early agriculture (Ruddiman, 2003, 2007). A common reaction to this claim is that too few people lived thousands of years ago to have had a major effect on either land use or greenhouse-gas concentrations. Implicit in this view is the notion that per-capita land clearance has changed little for millennia, but numerous field studies have shown that early per-capita land use was large and then declined as increasing population density led to more intensive farming. Here we explore the potential impact of changing per-capita land use in recent millennia and conclude that greater clearance by early agriculturalists could have had a disproportionately large impact on CO_2 emissions.

The central premise of the early anthropogenic (Anthropocene) hypothesis (Ruddiman, 2003, 2007) is that early deforestation by humans reversed a naturally decreasing CO_2 trend 7000 years ago and drove subsequent values upward, while early rice irrigation and livestock tending had the same effect on the methane trend beginning 5000 years ago (Fig. 1a). The shapes of these greenhouse-gas increases can be compared to late Holocene population estimates based on historical data extending as far back as 2000 years ago and extended to earlier millennia based on an assumed doubling time of 1000 years (Fig. 1b). The CH_4 rise shares some of the late-rising exponential form of the global population signal, but the CO_2 increase shows a fast rise prior to 2000 years ago and a leveling out during the historical era. This basic mismatch calls into question the proposed link between early human populations and the late-Holocene CO_2 signal.

Several modeling efforts have used relationships derived from recent populations and land-use measurements to hind cast pre-modern land use from earlier populations. Some studies assumed linear links between population and land use (e.g., Klein Goldewijk, 2001; Pongratz et al., 2008). Estimates of past land use derived from this assumption inevitably track exponential increases in global population during recent centuries. Even reconstructions based on available land-use statistics (e.g., Ramankutty and Foley, 1999) tend toward underestimates of cropped areas in early historical periods, especially where informal land ownership systems and shifting agricultural practices bias past census counts downward (Ho, 1959).

In contrast, as summarized below, several disciplines based on field evidence support a far different view of land use. Anthropological studies across a range of contemporary cultures that practice early forms of shifting cultivation, such as slash and burn farming, provide insights into farming practices used millennia ago when most agriculture in naturally forested regions was likely of this form. Studies in land-use archeology, paleoecology, paleobotany, and sedimentology provide constraints on past changes in type and extent of agriculture, in gradual transitions from natural vegetation to domesticated crops, and in enhanced erosion of slopes bared by deforestation and tilling. The common message from these field disciplines is that land use per-capita during the last 7000 years has not remained constant, but instead has decreased by a large amount. Here, we explore the possible repercussions of this decreasing per capita trend on total land clearance and net carbon emissions to the atmosphere.

Decades ago, Boserup (1965) integrated evidence from field studies and proposed that land use intensifies with increasing population (Table 1). In the earliest and least populated phase of agricultural development (the forest-fallow phase), farmers set fire to forests and planted seeds in ash-enriched soil between charred stumps. When soil nutrients became depleted after a few years, people moved on to successive plots, returning to the original one only after 20–25 years or more. Early agriculturalists often remained in the same dwellings (Startin, 1978), but rotated among

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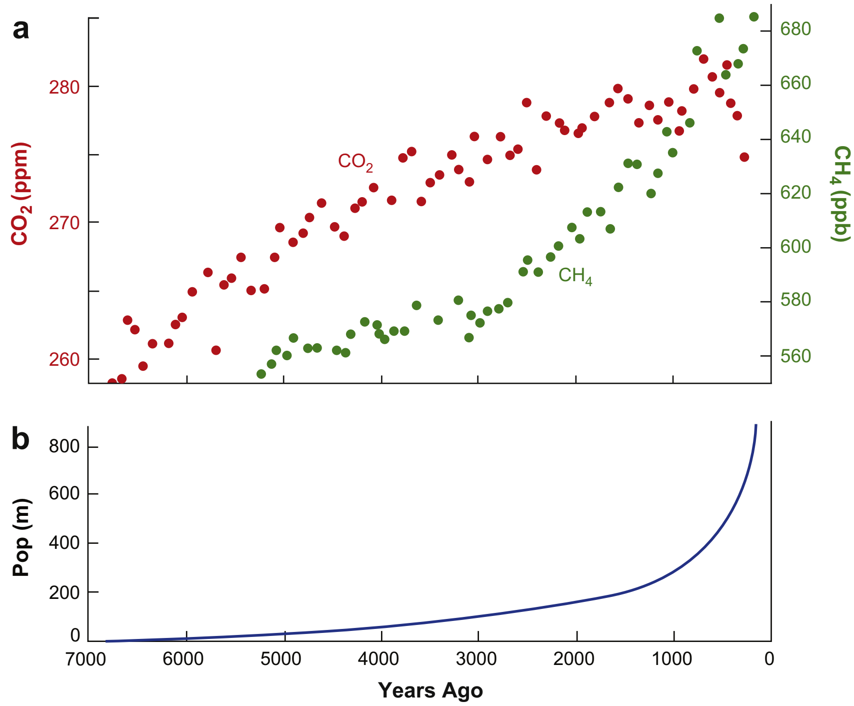

Fig. 1. (a) CO_2 and methane trends at Dome C from 7000 to 200 years ago (Luthi et al., 2008; Loulergue et al., 2008). (b) Population estimates for the same interval. For the Americas, the per-Columbian population estimate is from Denevan (1992). Other estimates for the last 2000 years are from McEvedy and Jones (1978). Populations for earlier intervals are back-extrapolated by assuming a 1000-year doubling time. Population trend passes through estimated values at 7000, 6000, 5000, 4000, 3000, 2000, 1000, and 200 years ago.

farmed plots. This kind of agriculture required little per-capita labor, but the continuing rotation among plots used a large amount of land.

Through time, as increases in population density left less land available, farmers were forced to shorten fallow periods by reusing plots more often and planting more densely. Later, they devised new technologies to increase yields per acre, such as improved plows, livestock traction, irrigation and fertilizers. Eventually, with ongoing population increases, farmers became restricted to the same plot of land every year (annual cropping) and ultimately began growing two or more crops per year in the same fields. Some regions developed sophisticated and extensive irrigation systems under centrally controlled hydraulic engineering schemes. Despite the benefit of iron tools and other innovations, this later phase of intensive farming required large amounts of labor per person to increase productivity: spreading manure and compost, tending livestock that supplied manure, eliminating weeds and insects, repairing and maintaining terraces and irrigation canals, and other efforts.

Despite four decades of debate over the long term cause-and-effect relationship between population increases and agricultural innovations, boserup's observation that land use per capita decreases as populations increase has found enduring support. Although the historical sequence of land use changes with population may differ greatly between sites and even among regions (e.g., Bogaard, 2002; Johnston, 2003), Boserup's pattern of decreasing land use per capita with increasing population remains the dominant paradigm for agricultural land use change (Grigg, 1979; Netting, 1993; Turner and Shajaat, 1996).

Here we attempt to assign numerical values to her intensification sequence based on observations (Table 1) compiled from Netting (1993, Table 9.1 after Boserup, 1981) and others (Turner et al., 1977; Seiler and Crutzen, 1980; Murdock and White, 2006). For the last century, the area cultivated per person has ranged from 0.07 to 0.35 ha/person (Ramankutty et al., 2002). These low values reflect highly intensive land use in heavily populated countries and also implicitly incorporate ongoing population shifts from rural to urban areas.

In comparison, per-capita values for the earliest (mid-Holocene) part of the sequence are not well constrained. Estimates can be obtained from studies of contemporary cultures that still use shifting cultivation methods, although these cultures face land limitations and market forces different from the conditions under which agriculture began (Boserup, 1965; Turner et al., 1977). Nevertheless, total forest clearance per capita in shifting agricultural systems can be approximated from estimates of land cultivated per person per year, typical cropping cycles (the number of years land is cultivated and then left fallow), and areas cleared for

Table 1
The Boserup land-use sequence.

	Shifting agriculture		Intensive agriculture	
Type	Long fallow	Short fallow	Annual cropping	multi-cropping
Population (persons km^{-2})	<15	5–65	65-250	>250
Cropping cycle (crops:years)	1:20–1:7	1:7–1:3	1:2–1:1	2:1–5:1
ha/person	2–6	1–2	0.3–0.6	0.05–0.3

purposes other than growing crops (pastures, woodlots, dwellings and other structures).

Given an annually cultivated land area per capita of 0.2–0.4 ha (Seiler and Crutzen, 1980) and the fallow lengths of 7–25 years typical of contemporary shifting agricultural systems that use technologies most similar to those of the first farmers (digging sticks and wooden hoes, with no metal implements; Murdock and White, 2006; Turner et al., 1977), we estimate per-capita land clearance in the range of 2–6 ha per capita for early agriculturalists (Table 1). This estimate agrees with that of Oloffson and Hickler (2008).

This range of estimates brackets the 4 ha per person calculated by Gregg (1988) based on the crop, livestock, woodlot and settlement needs of a late-Neolithic European village of 30 persons. Gregg assumed a short-fallow configuration, with a single fallow area the same size as the cropped area, although other estimates suggest that 5–10 plots could lie fallow in a long rotational sequence (Boserup, 1965; Netting, 1993). Dense stands of saplings grow back on areas left fallow for 20–25 years, but their biomass and carbon do not approach the levels typical of primary forest (Ramankutty et al., 2007). If livestock are allowed to browse on new shoots, biomass recovery is further suppressed (Boserup, 1965).

Early in the Holocene sequence (7000–6000 years ago), many people were not yet farmers. Allowance for this fact would reduce estimates of per-capita land use during the forest-fallow phase. On the other hand, early agricultural (and even pre-agricultural) people routinely used fire to clear large areas to attract game and encourage growth of berries and other natural foods (Pyne, 2000; Williams, 2003; Bliege Bird et al., 2008). Clearance by fire is not well constrained.

In addition, by 5000 years ago, the world's major crops were already being grown in the world's most populous areas; wheat and barley throughout Europe (Zohary and Hopf, 1993); millet and rice across much of China (Ruddiman et al., 2008; Fuller and Qin, 2009), and maize (corn) in Mesoamerica (Grigg, 1974; MacNeish, 1992). Because of the success of these primary food sources, populations in these areas increased rapidly and out-competed cultures still engaged in hunting and gathering.

After the early forest-fallow and later multi-cropping extremes, Boserup suggested that successive increases in population density caused shorter fallow ("bush fallow") cultivation, then annual cultivation, and finally multiple cropping on each plot (Table 1; Kates et al., 1993; Netting, 1993), although some areas may not have followed the full sequence shown in Table 1. Wet rice farming in southern China was probably relatively intensive even in its initial phase 6000–5000 years ago. By 2000 years ago, the most densely populated rice-growing areas in the river deltas of southern China and elsewhere in Asia had already reached the annual cultivation phase with 1 ha of cropland per person. Even in this region, however, further intensification (multiple cropping, manuring, weeding) caused per-capita crop area to fall to just 0.1–0.2 ha by 1800 (Chao, 1986; Ellis and Wang, 1997). Over the same interval, less densely populated areas continued to practice shifting cultivation and some may have adopted annual cropping much later (if at all).

In summary, despite considerable variations from region to region and culture to culture, average per-capita land use appears to have fallen from several ha per person in the middle Holocene to just tenths of one ha near the start of the industrial era, a drop of a full order of magnitude. Based on this evidence, hypothetical trajectories of changing per-capita land use through the Holocene are shown in Fig. 2a. For 7000 years ago, when most of those who farmed would have used the long-fallow rotation, we assume per-capita land use of 4 ha, with large uncertainties (+/−2 ha per person). At the other extreme, just before the industrial era, we assume 0.4 ha/person, a value slightly larger than the range of estimates for the last century, with estimated uncertainties of +/−0.2 ha per person.

Attempting to quantify a 'global-average' trend in per capita land use through the middle and late Holocene is obviously a complicated task that would have to take into account the very different populations, cultures and farming methods that co-existed in different regions during each interval. To reflect some of this uncertainty, we show in Fig. 2a three possible trajectories. The concave trend assumes that early per-capita reductions in land use were larger than later ones. The linear trend assumes constant rates of land-use reduction through time. The convex trend assumes greater land-use reductions later in the sequence. This latter trend is consistent with evidence for accelerated agricultural intensification during the historical era (Boserup, 1965; Grubler, 1994).

The product of global population (Fig. 1b) and the three possible trajectories of average per-capita land use (Fig. 2a) leads to three estimates of global land clearance (Fig. 2b). Given the uncertainties described above, these trends are not meant as literal estimates of the amount of pre-industrial deforestation. Instead, they are intended to provide an assessment of the extent to which land-use intensification could have altered estimates of global land use relative to estimates based on linear links to population (dotted line in Fig. 2b).

All three estimated trends of total land clearance rise rapidly until 2000 years ago (Fig. 2b). Subsequently, the trends from the linear and concave cases remain level from 2000 to 1000 years ago and then turn upward in response to the large acceleration of population in the centuries just before the industrial era. The trend based on the convex trajectory shows a small but persistent reduction in total clearance since 2000–1500 years ago.

Two factors contribute to the slowing in estimated land use since 2000 years ago in these scenarios. The loss of tens of millions of people during major pandemics and times of civil strife plays a role. During the most severe of these episodes (200–600 AD and 1200–1700 AD), 'excess' mortality amounted to ~12 to ~18% of the prior global population (McEvedy and Jones, 1978; Denevan, 1992).

The major factor controlling these trends is the decrease in per-capita land use (Fig. 2a). For both the concave and linear cases, this decrease is sufficient to offset the increase in population between 2000 and 1000 years ago, but not afterwards. For the convex case, the exponential decrease in land use more than counteracts the exponential population rise in recent centuries.

As large-scale cultivation of prairie-steppe grasslands did not occur prior to the early 1800s, most land cleared for agriculture in pre-industrial times was forested. Clearance of forests was the major anthropogenic source of CO_2 prior to the combustion of industrial-era fossil fuels (Houghton, 1999). Although the late exponential increase in global population (Fig. 1b) bears little relation to the early rise of the CO_2 signal (Fig. 1a), allowance for the Holocene trend toward smaller per-capita land use (Fig. 2a) produces estimates of total land use (Fig. 2b) that look more similar to the CO_2 signal (Fig. 1a).

Because atmospheric CO_2 concentrations depend on the rate of clearance rather than on total clearance, changes in land use per millennium calculated from the trends in Fig. 2b are shown in Fig. 2c. Similar to the CO_2 trend (Fig. 1a), the three rates of clearance show faster rises prior to 2000 years ago, followed by a leveling out and then a decrease. In addition, because early farming was concentrated in well-watered valleys with fertile soils, forests cleared from those areas would likely have been more carbon-dense than those on hillsides and mountain slopes cleared later in historical times. Allowance for changing carbon density in calculations of carbon emission rates would further enhance CO_2 emissions earlier in the Holocene.

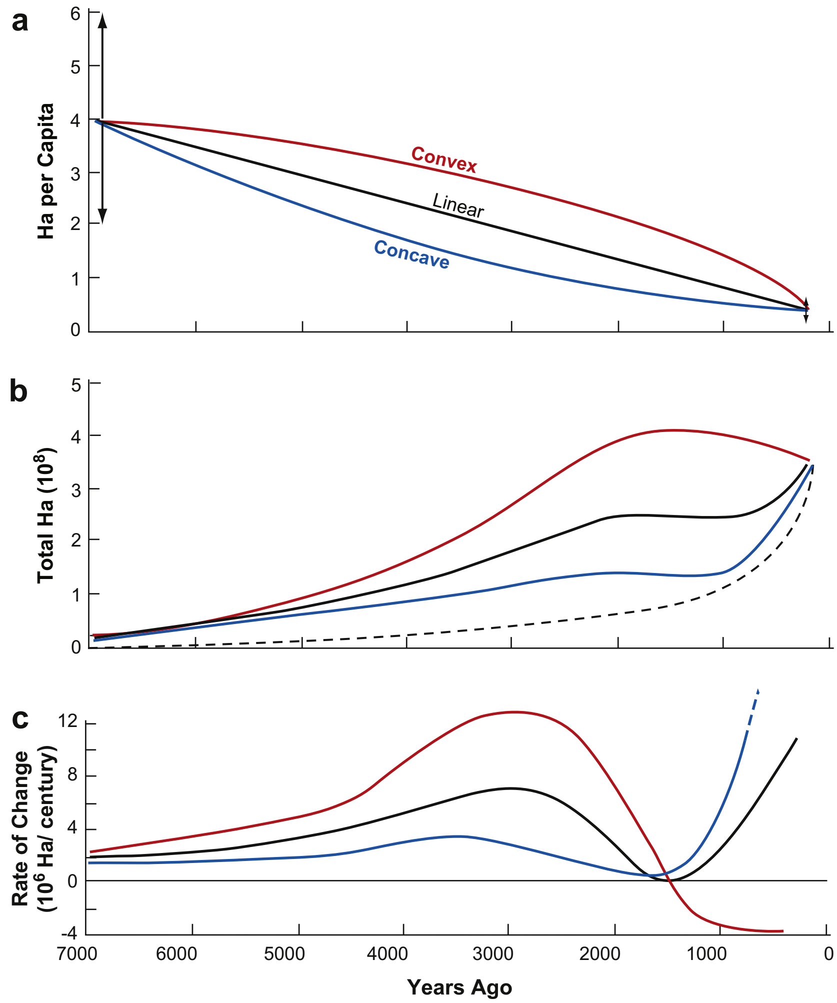

Fig. 2. (a) Estimated trend of changes in per-capita land use from 7000 to 200 years ago based on studies cited in text and in Table 1. (b) Total land use from 7000 to 200 years ago (in 10^8 ha) calculated as the product of global population (Fig. 1b) and per-capita land use (Fig. 2a). Light dashed line shows total land clearance based on assuming a constant value of 0.4 ha per person. (c) Long-term rate of change of land use in 10^6 ha/century based on trends in Figure 2b.

A fully quantitative comparison with late Holocene CO_2 trends will require a global compilation of regionally specific estimates of land-use change like those of Kaplan et al. (in press) for Europe. Such compilations will also require careful assessments of the links between pre-industrial population densities and land clearance (and recovery), regional factors such as climate, soil quality, and topography (floodplains versus hillslopes), cultural factors such as livestock preferences, and historical factors such as exchanges of crop varieties and technologies stemming from early colonial encounters. In addition, fully quantitative attempts to convert land-use changes into estimates of CO_2 emissions and atmospheric CO_2 concentrations need to take into account the long residence time of CO_2 in the atmosphere (Joos et al., 2004; Archer, 2008).

In summary, attempts to hind cast pre-industrial land clearance based on assuming linear or near-linear links to past populations are likely to underestimate early deforestation. Estimates of past clearance need to incorporate the large and ongoing decrease in per-capita land use prior to the pre-industrial era. Based on our results, forest clearance histories that incorporate land use intensification processes will bring estimates of early land clearance (and CO_2 emissions) into closer agreement with the observed trajectory of pre-industrial CO_2 in the atmosphere.

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References

Archer, D.A., 2008. The Long Thaw: How Humans are Changing the Next 100,000 years of Earth's Climate. Princeton University Press, Princeton, NJ.
Bliege Bird, R., Bird, D.W., Codding, B.F., Parker, C.H., Jones, J.H., 2008. The "fire stick farming" hypothesis: Australian Aboriginal foraging strategies, biodiversity, and anthropogenic fire mosaics. Proceedings of the National Academy of Sciences of the United States of America 105. doi:10.1073/pnas0804757105.
Bogaard, A., 2002. Questioning the relevance of shifting cultivation to Neolithic farming in the loess belt of Europe: evidence from the Hambach Forest experiment. Vegetation History and Archaeobotany 11, 155–168.
Boserup, E., 1965. The Conditions of Agricultural Growth. Aldine, NY.
Boserup, E., 1981. Population and Technological Change: A Study of Long Term Trends. University of Chicago Press, Chicago.
Chao, K., 1986. Man and Land in Chinese History: An Economic Analysis. Stanford University Press, Stanford.
Denevan, W.M., 1992. The Native Population of the Americas in 1492. University of Wisconsin Press, Madison.
Ellis, E.C., Wang, S.M., 1997. Sustainable traditional agriculture in the Tai Lake region of China. Agriculture, Ecosystems and Environment 61, 177–193.
Fuller, D.Q., Qin, L., 2009. Water management and labor in the origins and dispersal of Asian rice. World Archaeology 41, 88–111. doi:10.1080/00438240802668321.
Gregg, S.A., 1988. Foragers and Farmers: Population Interaction and Agricultural Expansion in Pre-historic Europe. University of Chicago Press, Chicago.

Grigg, D.B., 1974. The Agricultural Systems of the World: an Evolutionary Approach. Cambridge University Press, Cambridge.

Grigg, D., 1979. Ester Boserup's theory of agrarian change: a critical review. Progress in Human Geography 3, 64–84. doi:10.1177/030913257900300103.

Grubler, A., 1994. Technology. In: Meyer, W.B., Turner, B.L. (Eds.), Changes in Land Use and Land Cover. Cambridge University Press, Cambridge, pp. 287–328.

Ho, P.T., 1959. Studies on the Population of China, 1363–1953. Harvard University Press, Cambridge.

Houghton, R.A., 1999. The annual net flux of carbon to the atmosphere from changes in land use 1850–1990. Tellus B 51, 298–313.

Johnston, K.J., 2003. The intensification of per-industrial cereal agriculture in the tropics: Boserup, cultivation lengthening, and the Classic Maya. Journal of Anthropological Archaeology 22, 126–161. doi:10.1016/S0278-4165(03)00013-8.

Joos, F., Gerber, S., Prentice, I.C., Otto-Bliesner, B.L., Valdes, P.J., 2004. Transient simulations of Holocene atmospheric carbon dioxide and terrestrial carbon since the Last Glacial Maximum. Global Biogeochemical Cycles 18. doi:10.1029/2003GB002156.

Kaplan, J.O., Krumhardt, K., Zimmerman, N.E. The prehistoric and preindustrial deforestation of Europe. Quaternary Sciences Reviews, in press.

Kates, R.W., Hydâen, G., Turner II, B.L., 1993. Theory, evidence, study design. In: Turner II, B.L., Hydâen, G., Kates, R.W. (Eds.), Population Growth and Agricultural Change in Africa. University Press of Florida, Gainesville, pp. 1–40.

Klein Goldewijk, K., 2001. Estimating global land use change over the past 300 years: the HYDE database. Global Biogeochemical Cycles 15, 417–433.

Loulergue, L., et al., 2008. Orbital and millennial-scale features of atmospheric CH_4 over the past 800,000 years. Nature 453, 383–386. doi:10.1038/nature06950.

Luthi, D., et al., 2008. High-resolution carbon dioxide concentration record 650,000–800,000 years before present. Nature 453, 379–382. doi:10.1038/nature06949.

MacNeish, R., 1992. The Origins of Agriculture and Settled Life. University of Oklahoma Press, Norman.

McEvedy, C., Jones, R., 1978. Atlas of World Population History. Penguin, New York.

Murdock, G.P., White, D.R., 2006. Standard cross-cultural sample: on-line edition (July 19, 2006). Social Dynamics and Complexity. Working papers Series: Paper Stand-ard_Cross_Cultural_Sample. Variables 858: Subsistence Type - Ecological Classification, 1128: Cropping Index http//repositories.cdlib.org./lmbs/socdyn/wp/Standard_Cross_cultural_Sample (accessed 20.04.2009).

Netting, R.M., 1993. Smallholders, Householders: Farm Families and the Ecology of Intensive Sustainable Agriculture. Stanford University Press, Stanford, CA.

Oloffson, J., Hickler, T., 2008. Effects of human land-use on the global carbon cycle during the last 6000 years. Vegetation History Archeobotany 17, 605–615. doi:10.1007/s00334-007-0126-6.

Pongratz, J., Reick, C., Raddatz, T., Claussen, M., 2008. A reconstruction of global agricultural areas and land cover for the last millennium. Global Biogeochemical Cycles 22, GB3018. doi:10.1029/2007GB003153.

Pyne, S.J., 2000. Vestal Fire: An Environmental History, Told Through Fire, of Europe and Europe's Encounter with the World. University of Washington Press, Seattle.

Ramankutty, N., Foley, J.A., 1999. Estimating historical changes in global land cover: croplands from 1700 to 1992. Global Biogeochemical Cycles 13, 997–1027.

Ramankutty, N., et al., 2002. People on the land: changes in global population and croplands during the 20th century. AMBIO 31 (3), 251–257.

Ramankutty, N., et al., 2007. Challenges to estimating carbon emissions from tropical deforestation. Global Change Biology 13, 51–66.

Ruddiman, W.F., 2003. The anthropogenic greenhouse era began thousands of years ago. Climatic Change 61, 261–293.

Ruddiman, W.F., 2007. The early anthropogenic hypothesis: challenges and responses. Reviews of Geophysics 45 2006RG000207R.

Ruddiman, W.F., Guo, Z., Zhou, X., Wu, H., Yu, Y., 2008. Rice farming and anomalous methane trends. Quaternary Science Reviews 27, 1291–1295. 10.10.16/j.quascirev.2008.03.007.

Seiler, W., Crutzen, P.J., 1980. Estimates of gross and net fluxes of carbon between the biosphere and the atmosphere from biomass burning. Climatic Change 2, 207–247.

Startin, W., 1978. Linear pottery culture houses: reconstruction and manpower. Proceedings of the Prehistoric Society 44, 143–159.

Turner II, B.L., Shajaat, A., 1996. Induced intensification: agricultural change in Bangladesh with implications for Malthus and Boserup. Proceedings of the National Academy of Sciences of the United States of America 93, 1484–1491.

Turner II, B.L., Hanham, R.Q., Portararo, A.V., 1977. Population pressure and agricultural intensity. Annals of the Association of American Geographers 67, 384–396.

Williams, M., 2003. Deforesting the Earth. University of Chicago Press, Chicago.

Zohary, D., Hopf, M., 1993. Domestication of Plants in the Old World. Oxford University Press, Oxford.