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Viewpoint

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

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ABSTRACT

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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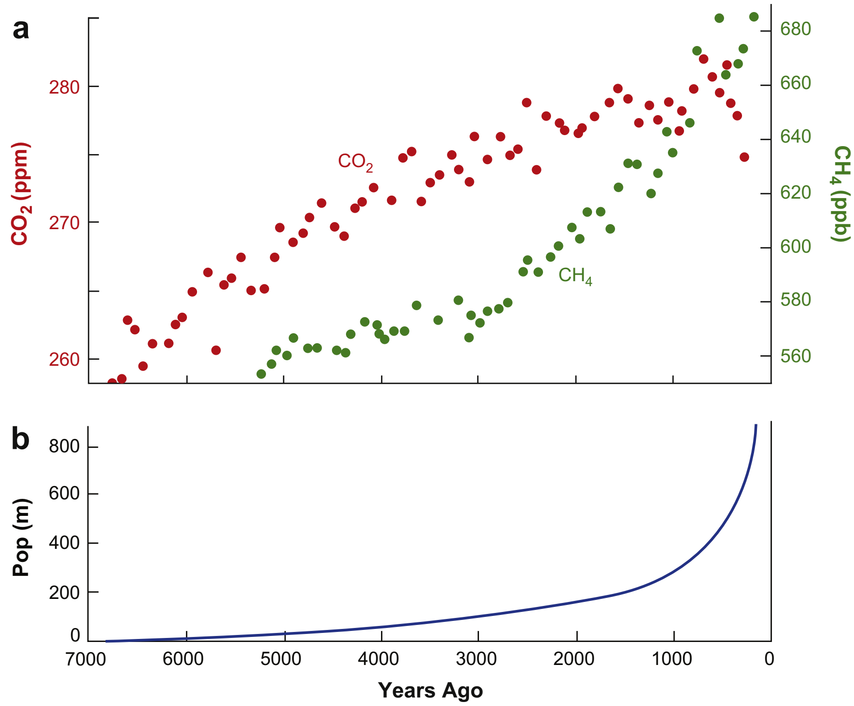

Fig. 1. (a) CO_2 and methane trends at Dome C from 7000 to 200 years ago (Luthi et al., 2008; Loulergue et al., 2008). (b) Population estimates for the same interval. For the Americas, the per-Columbian population estimate is from Denevan (1992). Other estimates for the last 2000 years are from McEvedy 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