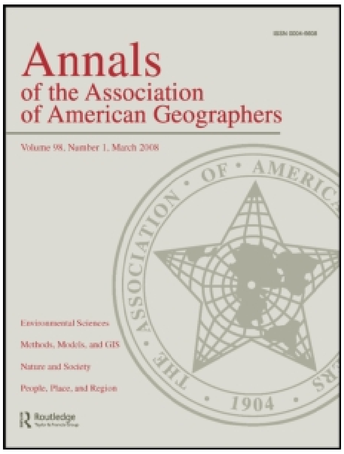

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The Columbian Encounter and the Little Ice Age: Abrupt Land Use Change, Fire, and Greenhouse Forcing

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Pre-Columbian farmers of the Neotropical lowlands numbered an estimated 25 million by 1492, with at least 80 percent living within forest biomes. It is now well established that significant areas of Neotropical forests were cleared and burned to facilitate agricultural activities before the arrival of Europeans. Paleoecological and archaeological evidence shows that demographic pressure on forest resources—facilitated by anthropogenic burning—increased steadily throughout the Late Holocene, peaking when Europeans arrived in the late fifteenth century. The introduction of Old World diseases led to recurrent epidemics and resulted in an unprecedented population crash throughout the Neotropics. The rapid demographic collapse was mostly complete by 1650, by which time it is estimated that about 95 percent of all indigenous inhabitants of the region had perished. We review fire history records from throughout the Neotropical lowlands and report new high-resolution charcoal records and demographic estimates that together support the idea that the Neotropical lowlands went from being a net source of CO_2 to the atmosphere before Columbus to a net carbon sink for several centuries following the Columbian encounter. We argue that the regrowth of Neotropical forests following the Columbian encounter led to terrestrial biospheric carbon sequestration on the order of 2 to 5 Pg C, thereby contributing to the well-documented decrease in atmospheric CO_2 recorded in Antarctic ice cores from about 1500 through 1750, a trend previously attributed exclusively to decreases in solar irradiance and an increase in global volcanic activity. We conclude that the post-Columbian carbon sequestration event was a significant forcing mechanism of Little Ice Age cooling. *Key Words: Americas, carbon dioxide, Early Anthropocene, fire history, Little Ice Age.*

1492 年的前哥伦布时代，在新热带区的低地，农民人数估计有 2500 万，其中至少有百分之八十是生活在森林生物群落里。现在人们公认，在欧洲人到来之前，为方便农业活动，新热带区内大量地区的森林被清除并焚烧。古生态和考古证据表明，人口增长对森林资源的压力（籍由人为地焚烧森林），在整个晚全新世一直稳步增加，在欧洲人到来的 15 世纪后期达到顶峰。旧世界疾病的引入导致经常性的疫病流行，造成整个新热带区前所未有的人口锐减。大约在 1650 年，人口总数的快速崩溃基本已经结束，那时，估计该地区所有原居民约有百分之九十五都已丧生。我们回顾了整个新热带区低地部分的火灾历史，总结了新的高分辨率碳记录和人口估计，这些研究共同支持下面的观点：新热带区的低地，从原来的净二氧化碳大气排放源，在遭遇哥伦布之后的几百年里，逐渐变成了净二氧化碳汇集源。我们认为，在哥伦布登陆之后，新热带区的森林再生造成了陆地生物圈的碳汇集，依次为 2 到 5 Pg C，从而支持了南极冰芯自 1500 年到 1750 年的记录，这些冰芯记录很好地展示了当时大气中二氧化碳的减少，这一减少趋势以前一直被完全归功于太阳辐射的减少和全球性火山活动的增加。我们的结论是：后哥伦布时代的碳吸存事件是小冰期变冷的一个重要影响机制。*关键词：美洲，二氧化碳，早期人类世，火的历史，小冰期。*

Hacia 1492, los cultivadores precolombinos de las tierras bajas neotropicales sumaban aproximadamente 25 millones, de los cuales por lo menos el 80 por ciento vivía dentro de los biomas de bosque. Ya se ha establecido que antes de la llegada de los europeos áreas importantes de las selvas neotropicales habían sido desbrozadas y quemadas para facilitar las actividades agrícolas. Las evidencias paleoecológica y arqueoecológica muestran que la presión demográfica sobre los recursos forestales—facilitada por la quema antropogénica—se incrementó constantemente a través del Holoceno Tardío, alcanzando el máximo cuando los europeos llegaron a finales del

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siglo XV. La introducción de enfermedades del Viejo Mundo se tradujo en epidemias recurrentes que llevaron a un colapso sin precedentes de la población en todas partes del neotrópico. La rápida catástrofe demográfica quedó concluida en gran medida para 1650, cuando se estima que cerca del 95 por ciento de todos los habitantes indígenas de la región habían perecido. Se revisaron los registros de la historia del uso del fuego en todas las tierras bajas neotropicales al tiempo que reportamos nuevos registros de alta resolución de carbón vegetal y cálculos demográficos que, conjuntamente, apoyan la idea de que las tierras bajas neotropicales pasaron de ser una fuente neta de suministro de CO_2 a la atmósfera, antes de Colón, a una caída neta de carbono durante varios siglos posteriores al encuentro colombino. Arguimos que el recrecimiento de los bosques neotropicales después del encuentro colombino condujo al secuestro del carbono biosférico terrestre del orden de 2 a 5 Pg C, contribuyendo así a la bien documentada disminución del CO_2 atmosférico registrado en núcleos de hielo antárticos, acumulados entre 1500 y 1750. Esta tendencia se le atribuyó antes exclusivamente a descensos de la irradiación solar y a un incremento del volcanismo global. Concluimos que el evento del secuestro de carbono poscolombino fue un mecanismo de forzamiento significativo en el enfriamiento global durante la Pequeña Edad del Hielo. *Palabras clave: Américas, dióxido de carbono, Antropoceno Temprano, historia del fuego, Pequeña Edad del Hielo.*

> Not even the more primitive nonagricultural folk may be considered as merely passive occupants of particular niches in their forest environment. By their continued presence and activity, they enlarged such niches against the forest.
>
> —Sauer (1958, 107)

The role of human beings in creating and expanding forest openings in the American tropics has been a topic of conjecture and debate for more than a half-century, and interest in the subject outside of academia has risen dramatically in recent years together with concerns about global warming. The Amazon rainforest in particular has widely been hailed as the "lungs of the world" due to its tremendous capacity for both oxygen production and carbon dioxide sequestration (Moran 1993). It has been estimated that the carbon flux from Neotropical forests (Figure 1) to the atmosphere totaled approximately 37 Pg from 1850 through 2000, which contributed measurably to the postindustrial CO_2 increase (Houghton 2003). Indeed, the collective roles of anthropogenic deforestation, burning (including accidental fires that are generally referred to as *leaked* or *escaped* fires), and agricultural expansion in the lowland Neotropics have been identified as major factors in both postindustrial and future global warming scenarios (Fearnside 2000; Mahli, Meir, and Brown 2002; Cramer et al. 2004; Malhi et al. 2008; Langmann et al. 2009), and yet until recently pre-Columbian land use has been considered to be negligible at the scale of global greenhouse forcing.

Widespread biomass burning and agricultural forest clearance predate the Industrial Revolution by several millennia in the Americas, Africa, Asia, Europe, and Australia, as well as on many oceanic islands (Sauer 1958; Crutzen and Andreae 1990; Goldhammer 1991; Chew 2001; Saarnak 2001; Williams 2003). The idea that preindustrial Holocene land use could have produced quantities of atmospheric CO_2 and CH_4 sufficient to impact the climate system was first outlined by Ruddiman's (2003) seminal paper, "The Anthropogenic Greenhouse Era Began Thousands of Years Ago." Although evidence mounts for a preindustrial Anthropocene (Ruddiman 2003, 2005, 2007; Faust et al. 2006; van Hoof et al. 2006; Nevle and Bird 2008; van Hoof et al. 2008; Vavrus, Ruddiman, and Kutzbach 2008), some critics maintain that human impacts in terms of climate forcing were negligible until the nineteenth century (Broecker and Stocker 2006; Olofsson and Hickler 2008; Elsig et al. 2009; Stocker, Strassmann, and Joos 2010).[1]

If preindustrial farmers did contribute measurably to the greenhouse effect via increased emissions of CO_2 and methane, only a massive and catastrophic collapse of agricultural populations could have led to significant decreases in anthropogenic emissions at any time. The post-Columbian encounter epidemics and pandemics were certainly the most rapid, thorough, and widespread to have occurred during the late Holocene (Crosby 1972; Lovell 1992), resulting in a loss of approximately 90 to 95 percent of the agricultural population throughout the Neotropics (Dobyns 1966; Lovell and Lutz 1995). The sixteenth- and seventeenth-century epidemics resulted in the abrupt abandonment of agricultural clearings in otherwise forested landscapes together with an unprecedented reduction in human fire ignitions, thus providing an ideal scenario for backcasting anthropogenic climate forcing before European contact. The widespread forest recovery that followed the native population crash after the Columbian encounter resulted in elevated biospheric sequestration of

Figure 1. Map of study area illustrating distribution of Neotropical forest biomes, geographic regions discussed in text, and sites of charcoal records used to reconstruct biomass burning histories in this study (Figures 2 and 3A) and in Nevle and Bird (2008; Figures 3B and C). Cartography by Jon Lerner, Peter Dana, and Robert Dull.

atmospheric CO_2 in plant biomass because (1) forests rapidly reoccupied abandoned cultivated landscapes via secondary succession, and (2) existing forests became more carbon dense due to a reduction in wildfires related to anthropogenic fire ignitions, both intentional and accidental.

In this article we review the evidence for prehistoric anthropogenic biomass burning in the Neotropics and provide new data supporting the thesis that the aggregate carbon footprint of Neotropical farmers was sufficient to raise global temperatures via greenhouse forcing before the Columbian encounter. Furthermore, we argue that Little Ice Age (LIA) cooling and the attendant atmospheric CO_2 decrease can be explained in part by biospheric carbon sequestration following the native population collapse. The LIA is identified in surface temperature reconstructions of the past millennium as a global thermal anomaly of about -0.1°C in which cooling was most pronounced from 1550 to 1750 AD in the Northern Hemisphere, particularly in northern Europe (Esper, Cook, and Schweingruber 2002; Jones and Mann 2004; Moberg et al. 2005). Atmospheric CO_2 concentration decreased by $\sim$7 ppm during the same period (Meure et al. 2006). Previously, the LIA thermal anomaly and concomitant decrease in atmospheric CO_2 concentrations were attributed to solar–volcanic forcing (Joos et al. 1999; Hunt and Elliott 2002; Von Storch et al. 2004). Recent analyses, however, suggest that variations in solar luminosity are insufficient to drive significant climate variations on centennial to millennial timescales (Foukal et al. 2006), and were likely a negligible climate forcing factor at the onset of the LIA (Ammann et al. 2007). We conclude that the fifteenth- and sixteenth-century arrivals of Europeans in the Americas set into motion an unprecedented anthropogenic carbon sequestration event and contributed to the LIA climate anomaly. This event represents perhaps the best example of anthropogenic influence on Earth's climate system during the preindustrial period.

Neotropical Paleoecology: Pollen and Charcoal Records

Reconstructing pre-Columbian deforestation and the net forestation in the Neotropics following the Columbian encounter requires a thorough compilation of paleoecological data. Many pollen records from the Neotropics clearly show prehistoric anthropogenic forest clearance in tandem with fire and the rise of heliophytes, cultivars, and early successional pioneers (Tsukada and Deevey 1967; Rue 1987; Byrne and Horn 1989; Goman and Byrne 1998; Clement and Horn 2001; Anchukaitis and Horn 2005; Dull 2007; Lane et al. 2008). Although the evidence for agriculture-driven late Holocene deforestation is strongest for the northern Neotropics, records have been produced from a wide variety of settings across the American tropics (Piperno 2006), including what are today remote forested regions of the Petén (Islebe et al. 1996; Wahl et al. 2006), the Darién (Bush and Colinvaux 1994), and the Amazon (Colinvaux et al. 1988; Bush, Piperno, and Colinvaux 1989; Piperno 1990; Bush and Colinvaux 1994; Bush et al. 2000). Despite this rich and growing corpus of pollen data illustrative of prehistoric agricultural forest clearance, pollen analysis alone has several inherent limitations when it comes to reconstructing changes in past forest carbon density that do not involve dramatic shifts in forest composition or structure.[2]

Modern ecological studies from tropical regions demonstrate that most human impacts on tropical forests rarely result in a wholesale transformation from dense forest to open herbaceous parkland. Instead, what has been recorded are mosaics of cleared plots and successional plots of various ages together with patches of relatively mature closed-canopy forests, all in close proximity to one another and all with varying degrees of transience with regards to carbon storage and release (Laurance 2004; Fearnside 2005). Moreover, chronic understory burning via anthropogenic fire leakage can lead gradually to total biomass reductions of 40 percent or more without the loss of the forest canopy (Cochrane and Schulze 1999). Recognizing these landscape mosaics and gradual anthropogenic reductions in biomass in the pollen record can be exceedingly difficult due to inherent uncertainties related to pollen-vegetation representation, taxonomic precision, source area, and transport (Prentice 1985; Bush 1995).

Although the pollen record is crucial to our understanding of prehistoric land use practices, as are studies of stable carbon isotopes of organic matter in sediments (Dull 2004; Lane et al. 2009), we contend that the most compelling suite of available evidence in support of the pre-Columbian Anthropocene hypothesis comes from sedimentary charcoal records and the stable carbon isotopic signatures of atmospheric methane and CO_2 (Ferretti et al. 2005; Nevle and Bird 2008; Mischler et al. 2009). The decrease in pyrogenic methane from Law Dome, Antarctica indicates a decreased global burning of biomass from about 1500 through 1700 (Ferretti et al. 2005; Mischler et al. 2009) and fire history proxies from the American Tropics corroborate this trend (Carcaillet et al. 2002; Bush et al. 2008). That biomass burning decreased in the Neotropics during the LIA is widely acknowledged (Marlon et al. 2008; Nevle and Bird 2008); however, the causes of this decrease—and the establishment of its unique geography—remain at the crux of the present debate.

Ignition by lightning is rare in tropical moist forests and tropical seasonal forests, leaving human ignition as the dominant determinant of combustion (Janzen 1988; Stott 2000; Cochrane 2003). The more people burn, whether intentionally or accidentally, the more fire prone the forest becomes and the more likely it is to burn again when drier climatic conditions prevail (Field, van der Werf, and Shen 2009). Many anthropogenic fires escape their intended confines, agricultural or other. These accidental fires play a major role in the ecology of Neotropical forests today (Middleton et al. 1997) and contribute substantially to a positive fire feedback cycle; that is, more burning leads to more forest openings, more forest edges, drier fuel loads, higher wind speeds, and greater susceptibility to future flammability (Cochrane 2003; Laurance 2003, 2004; Fearnside and Laurance 2004). Conversely, the absence of anthropogenic fire in most tropical biomes leads to rapid increases in woody biomass (Bond, Woodward, and Midgley 2005) and a "hardening" of the forest against future fire incursions.

The El Niño droughts of 1997 and 1998 provide a relevant analog scenario for this study, demonstrating how both rural land use and population density contribute significantly to the geography of fire in the tropics (Cochrane and Schulze 1999; Cochrane 2003; Field, van der Werf, and Shen 2009) and by extension the geography of carbon flux from the biosphere to the atmosphere. Between ca. 3000 and 2000 calendar year before present (BP), the widespread adoption of plant cultivation as the primary means of food production in the Neotropics resulted in larger populations and as a consequence more fire, especially in the tropical moist forest biome where the anthropogenic-fire feedback is so essential to the fire regime. Because natural ignition is limited for tropical forest fires, the increased populations of pre-Columbian farmers spread across the lowland Neotropics would have facilitated large regional conflagrations via accidental ignitions when persistent drought conditions prevailed.[3]

Data Sources and Evidence for Holocene Paleofires in the New World Tropics

Charcoal records from the Neotropics, divided here into the northern Neotropics and the southern Neotropics (Figure 1), generally fall into two broad categories: lake and wetland charcoal, both microscopic and macroscopic; and soil charcoal, usually macroscopic (Carcaillet et al. 2002; Bush et al. 2007; Marlon et al. 2008; Nevle and Bird 2008). Of these, charcoal from lake and wetland sediment cores provides the most faithful reconstructions of past fire regimes (MacDonald et al. 1991; Long et al. 1998; Conedera et al. 2009). Several published reconstructions of Neotropical fire history have been produced by aggregating all charcoal data types to create composite paleofire reconstructions (Bush et al. 2007; Marlon et al. 2008; Power et al. 2008). Despite generally low chronological sampling resolutions (i.e., many sites with fewer than ten total samples), all of these fire history reconstructions show a dramatic decline in Neotropical burning after 1500 AD. The most recent of these studies concludes that the sixteenth century decreasing charcoal trend was consistent with global patterns of fire activity and was likely forced by LIA cooling with no evidence of preindustrial anthropogenic forcing of Neotropical fire regimes (Marlon et al. 2008).

Here we present a reevaluation of extant Neotropical charcoal data together with a compilation of four new high-resolution (<10 to <50-year sampling intervals) macroscopic charcoal records that indicate a dramatic fire regime shift took place in the tropical Americas at ca. 450 cal yr BP (AD 1500; Table 1, Figures 2 and 3). We have compiled previously unpublished macroscopic charcoal data from four lake sites in the northern Neotropics—Laguna Herradura, Veracruz, Mexico; Lago Metapan, El Salvador; and Charco Verde and Lago Nicaragua, Nicaragua (Table 1, Figures 1 and 2). Volumetric samples of 1 cm^3 were disaggregated and wet sieved with a 150 μ mesh and all

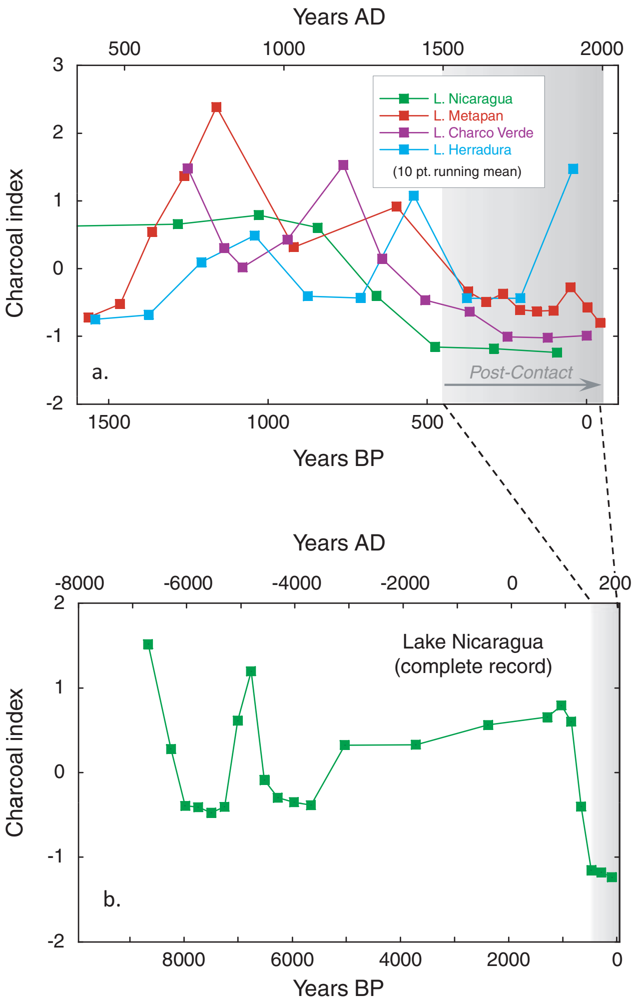

Figure 2. (A) Macroscopic (>150 μ) charcoal concentration records from four lakes in the northern Neotropics: Lago Herradura, Mexico; Lago Metapan, El Salvador; Laguna Charco Verde, Nicaragua; and Lago de Nicaragua, Nicaragua (partial record only). (B) Full charcoal concentration record for Lago de Nicaragua, Nicaragua. Data in Figures 2A and 2B reported as 10 pt. running mean of charcoal index calculated following method described by Nevle and Bird (2008). The charcoal index is a measure of the variation of the charcoal concentration, in units of standard deviation, about the mean charcoal concentration for each record. See Table 1 for characteristics of sedimentary records.

Table 1. Northern Neotropics lake sediment coring sites for macroscopic charcoal records reported in this article

Lake name	Location (latitude/ longitude)	Core length (m)	Basal age 2σ cal age	Total number of samples	Mean sampling interval (years/ sample)
Laguna Herradura, Mexico	22.01248N 98.155165W	2.00	*1677–1566 BP *AD 273–384	100	16.8
Laguna Metapan El Salvador	14.30071N 89.477829W	3.10	*1542–1414 BP *AD 408–536	155	9.8
Lake Nicaragua (LC-4), Nicaragua	11.76258N 85.872528W	4.39	*9015–8779 *7065–6829 BC	221	40.5
Charco Verde, Ometepe Island, Nicaragua	11.47615N 85.631777W	6.34	*1344–1297 BP *AD 606–653	108	12.7

Note: All ^{14}C dates calibrated with Calib 5.0 using the INTCAL 2004 data set (Reimer et al. 2004).

charcoal above that size fraction was tallied to calculate charcoal concentrations.[4] Basal ^{14}C dates are two sigma calibrated age ranges based on the calibration data set of INTCAL 2004 (Reimer et al. 2004). Data from two of these sites were reported in master's theses at the University of Texas at Austin (Lee 2006; Avnery 2007). All records are represented by at least 100 samples each, a sampling density not matched by any of the

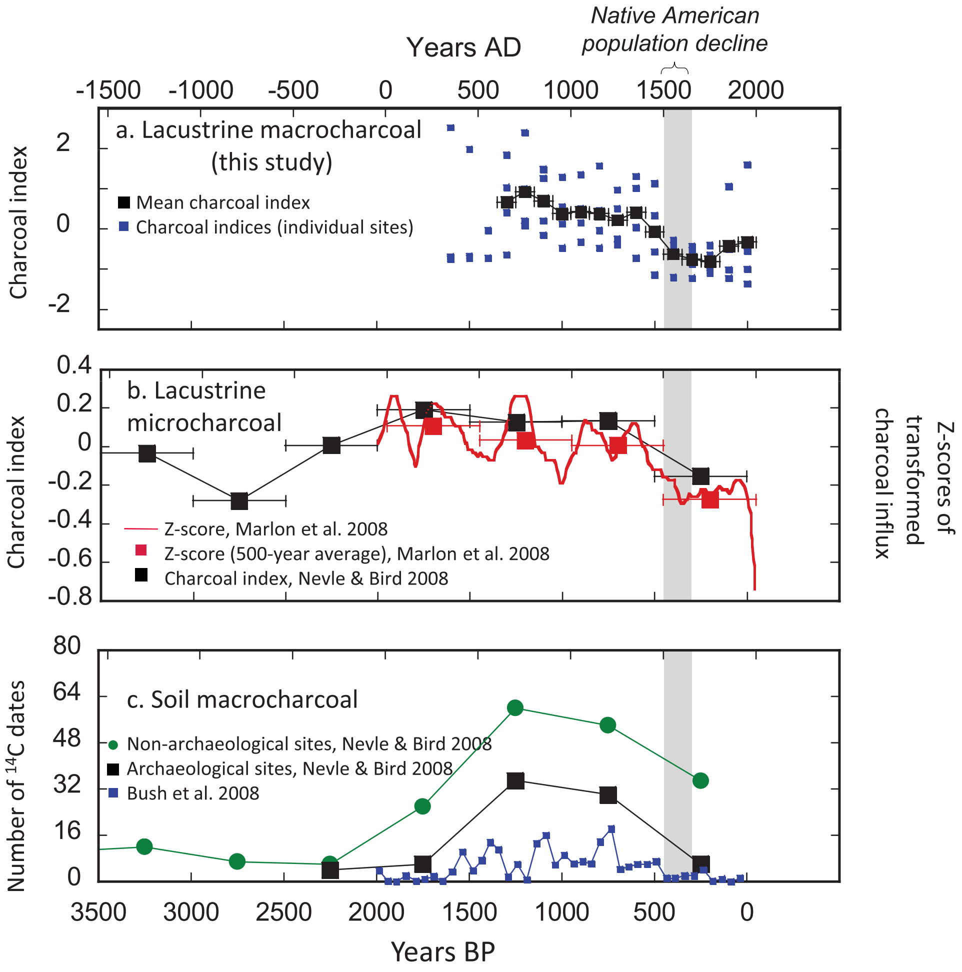

Figure 3. Comparison of Neotropical biomass-burning reconstructions. Biomass-burning reconstructions based on (A) lacustrine macroscopic charcoal records from this study (locations shown as blue/black symbols on Figure 1); (B) sedimentary charcoal records for the past 2,000 years (Marlon et al. 2008, red symbols) and 3,500 years (Nevle and Bird 2008, black symbols; locations shown as red symbols in Figure 1); and (C) soil–charcoal records (Bush et al. 2008; Nevle and Bird 2008; locations shown as pink symbols in Figure 1). Biomass-burning histories in A and B based on comparable numerical treatments of lacustrine charcoal records to reconstruct fire history. Methods used to reconstruct fire history indicate anomalies in regional variation of charcoal accumulation rates (charcoal index; black squares in A and B) and the charcoal influx (z score; red line in B), relative to their mean values for the duration of each reconstructed history. To permit direct comparison of the two fire histories based on lacustrine microscopic charcoal in B, 500-year averages of the z scores are also presented (red squares in B). Gray vertical bars represent the approximate duration of the Native American population decline (Dobyns 1966).

proxy fire data sets from the Neotropics reproduced in recent compilations (Marlon et al. 2008).

The new combined macroscopic charcoal index from the northern Neotropics (Figures 2 and 3A) is compared to several other composite fire records from the Neotropics constructed with microscopic charcoal data from lake sediments (Figure 3B) and macroscopic charcoal from terrestrial soils (Figure 3C). As evident in Figure 3C, the regional biomass burning reconstruction presented by Marlon et al. (2008) exhibits large amplitude oscillations from 2000 BP until ~500 BP and then decreases to values that remain below the minimum attained during the prior 1,500 years. The biomass burning index of Nevle and Bird (2008) is negative between 3500 and ~2500 BP and then increases and varies in a pattern nearly identical to that of the 500-year averages of the fire index from Marlon et al. 2008 (red squares). Frequencies of macroscopic soil charcoal ^{14}C dates (Bush et al. 2008; Nevle and Bird 2008)[5] obtained from both nonarchaeological and archaeological sites increase after 2500 years BP, obtain maxima after 1500 years BP, and decline markedly after 500 BP. All the biomass burning trends (Figure 3) are broadly similar despite differences in charcoal size fraction sampled, geographic distributions of sample sites, and numerical treatments of records used in each reconstruction (Bush et al. 2008; Marlon et al. 2008; Nevle and Bird 2008). The minima in the proxies of biomass burning after 500 years BP in the reconstructions shown in Figures 2 and 3 are synchronous with the absolute minimum in Holocene Neotropical charcoal accumulation in the 20,000-year reconstruction of Power et al. (2008).

Covariation between the biomass burning histories reconstructed from charcoal derived from both archaeological and nonarchaeological sites shown in Figure 3C suggests that anthropogenic activity controlled variations in the fire regime and vegetation cover in the Neotropical Lowlands prior to the Industrial Revolution. The data in Figures 2 and 3 are consistent with (1) increased biomass burning and deforestation during agricultural and population expansion in the Neotropics from ~2500 to ~500 years BP; and (2) declining anthropogenic use of fire due to pestilence-induced population collapse during the European conquest. The Late Holocene increase in biomass burning, including that indicated by the archaeological soil charcoal record (an unambiguous indicator of anthropogenic ignition), occurred as agriculture began to provide the dietary staple in the indigenous diet (Dull 2006; Rebellato, Woods, and Neves 2009; Figure 3D). These observations suggest that human–landscape interaction profoundly influenced the Late Holocene Neotropical fire regime and implicate vegetation recovery during post-Contact demographic collapse as a potentially significant carbon sink.

Food Production, Population, and Anthropogenic Landscapes of the Neotropics

Although the term *Anthropocene* was coined just ten years ago (Crutzen and Stoermer 2000), there is now a broad consensus that the post-1850 rise in atmospheric CO_2—and its attendant 1°C rise in average global temperature—occurred largely because of increases in the burning of fossil fuels together with the conversion of forested lands to agriculture (Crutzen and Steffen 2003; Doney and Schimel 2007; Zalasiewicz et al. 2008). In the Americas, food production began in the early Holocene but was not widely adopted throughout the tropical lowlands until the late Holocene (Smith 2001; Dull 2006). The advent of food production in the Americas facilitated sedentary living, the rise of urban centers with populations numbering in the tens to hundreds of thousands, and widespread anthropogenic landscapes.

Population: Southern Neotropics

Greater Amazonia is the tropical lowland interior of South America, including considerable (~20 percent) savanna (Figure 1). Until recently this region has been seen as a hostile environment characterized by low soil fertility and meager protein resources beyond the fish and other animal sources common in riparian zones. As a result, pre-European population numbers were judged to be quite low and the consequent impacts on the environment correspondingly slight. For just the Amazon Basin, Meggers (1992) estimated a density of only 0.2 persons per square kilometer and a total of 1.5 to 2.0 million indigenous inhabitants. However, accumulating evidence indicates that there was both intensive and extensive environmental management and landscape modification; that subsistence systems varied in form and intensity; and that populations were dense along the rivers, in the wet savannas, and locally in the interior, with a total population of at least 5 to 6 million (Denevan 1992a, 2001, 2003; Heckenberger et al. 2003; Erickson 2008; Oliver 2008).

Recent research has examined the extent, ecology, chemistry, productivity, and significance of exceptionally fertile prehistoric, anthropogenic Dark Earth soils (*terra preta* in Brazil; Woods et al. 2009). Three different calculations based on maize and manioc production and the physical–chemical characteristics of the deposits indicate that populations of 3.1, 3.3, and 3.7 (average 3.4) million could have been supported by these soils, which total a conservative 0.2 percent of forested Amazonia (Woods, Denevan, and Rebellato forthcoming). With at least 5 million people in the rest of the region (Denevan 1992a, 2003), the total estimated population comes to 8.4 million for greater Amazonia, with an overall density of about 0.86 per square kilometer. For Greater Amazonia (ca. 9,770,000 km^2) about 78 percent was forested (Denevan 1992a). Proportionally, this reduces the prehistoric population estimate of 8.4 million to 6.6 million for the forested area.

A population estimate of this magnitude is supported by archaeological and historical evidence for large settlements, numbering in the thousands of people in each, in upper Amazonia, along the central Amazon and major tributaries, the uplands adjacent to the Rio Tapajós, on Marajó Island, the Upper Xingu region, and the Mojos savannas of eastern Bolivia (Denevan 1966, 1996, 2003; Roosevelt 1987; Heckenberger, Petersen, and Neves 1999; Petersen, Neves, and Heckenberger 2001; Erickson 2008). Many of the settlement sites, large as well as small, contain Amazonian Dark Earths, a clear indication of at least semipermanent habitation because these soils formed over long periods of time. Anthropogenic earthworks include mounds, ditches, causeways, canals, raised fields, fish traps, moats, and embankments. Complexes of huge geometrically shaped earthern berms (geoglyphs) have been exposed by recent deforestation in western Brazil (Pärssinen, Schaan, and Ranzi 2009). All of these are indicators of numerous people and forest clearing in the past.

The forested tropical coastal areas from central Ecuador to Lake Maracaibo in Venezuela were inhabited by sophisticated gold-working chiefdoms and contained a population of possibly 1.5 million (Denevan, unpublished). This 1.5 million plus 6.6 million for greater Amazonia gives an estimated total population of 8.1 million for the forested lowland southern Neotropics.

Population: Northern Neotropics

The mostly forested lowland northern Neotropics extended from Panama through Central America through Yucatan and the southern coasts of Mexico, plus the Caribbean.[6] The pre-Columbian population numbered an estimated 11.3 million. This includes 5.1 million in the Audiencia de Guatemala (Chiapas, Soconusco [western Chiapas], El Salvador, Honduras, Nicaragua, and Costa Rica; Lovell and Lutz 1995); 2.45 million in Panama, Belize, Yucatan, and Tabasco (Denevan 1992a); 500,000 in Veracruz (Sluyter 2002); possibly 250,000 on the southwest coast of Mexico (Denevan, unpublished); and 3.0 million in the Caribbean Islands (Denevan 1992a). Thus the total estimated pre-Columbian population for the forested lowlands of the Neotropics is 19.4 million (8.1 for the south and 11.3 for the north).

Demography of the Columbian Encounter

The late fifteenth-century arrival of the Spaniards in the New World unleashed a cascade of diseases (i.e., smallpox, typhus, diphtheria, mumps, measles, influenza, etc.) that swiftly swept the Americas (Dobyns 1966; Lovell 1992), resulting in an unprecedented demographic collapse referred to by some as the American Indian Holocaust (Thornton 1990). It has been estimated by several scholars that the population of the Americas was reduced by 90 percent or more (Dobyns 1966; Denevan 1992a),[7] a loss of approximately one fifth of the Earth's human inhabitants (Mann 2005; Figure 4C). The tropical lowlands of Central and South America were particularly hard hit, where the population collapse amounted to approximately 95 percent (Dobyns 1966). The more densely populated regions of Mesoamerica were gravely affected, but so were many regions in the Amazon basin, such as the Xingu drainage, where a population estimated in the tens of thousands in the early sixteenth century was reduced to approximately 500 individuals by the mid-twentieth century (Heckenberger and Neves 2009). Populations were decimated not only by epidemics but also the ancillary effects of colonialism such as warfare, slavery, starvation, and reduced fertility.

Estimating the Pre-Columbian Carbon Footprint in the Neotropics

The thesis that post-Columbian carbon sequestration in the Neotropics was partially responsible for the rapid decrease in atmospheric CO_2 concentration during the LIA requires a significant pre-Columbian carbon footprint for the American tropics. How much

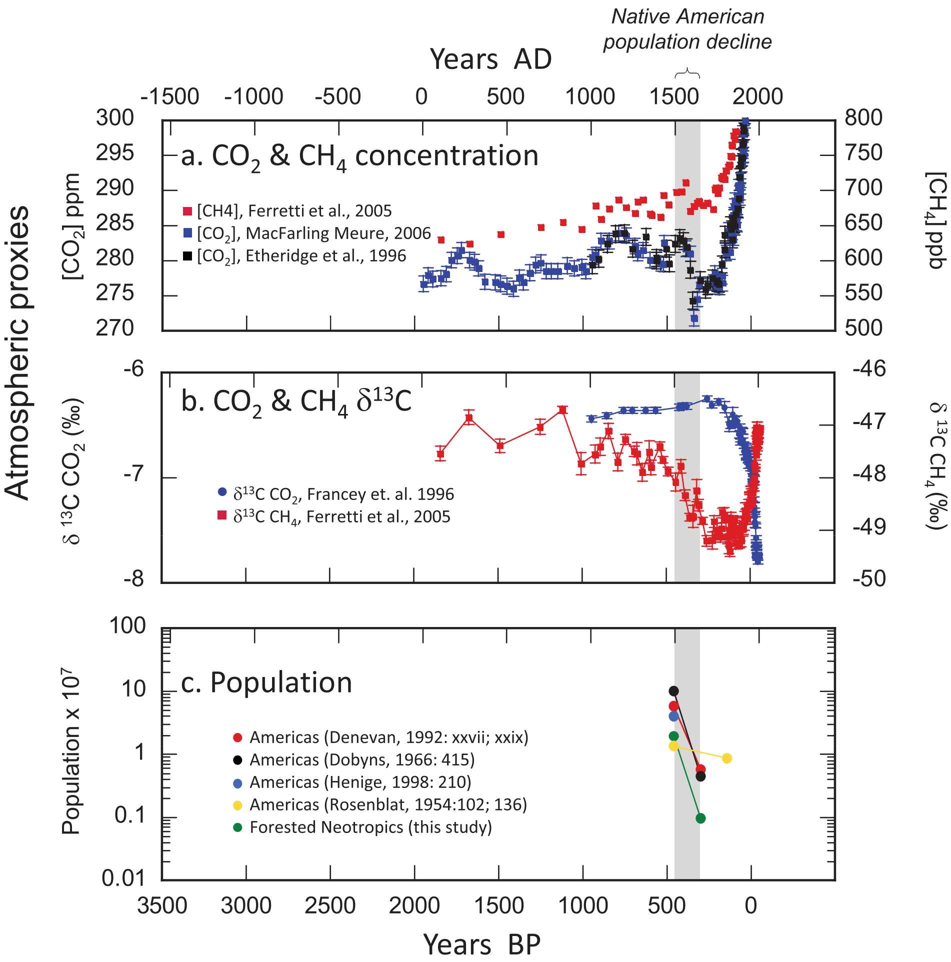

Figure 4. Comparison of atmospheric $[CO_2]$, $[CH_4]$, $\delta^{13}CCO_2$, $\delta^{13}CCH_4$, and population data for the Americas: (A) Concentration of atmospheric CO_2 (Etheridge et al. 1996; Meure et al. 2006; blue and black symbols) and CH4 (Ferretti et al. 2005; red symbols from Law Dome; (B) $\delta^{13}C$ of atmospheric CO_2 (Francey et al. 1999; blue symbols) and CH_4 (Ferretti et al. 2005; red symbols) from Law Dome; (C) population estimates for the Americas (Rosenblat 1954; Dobyns 1966; Denevan 1992a; Henige 1998) and Neotropics (this study). Gray vertical bars as in Figure 3.

biologically productive land was cleared or kept in early stages of succession by the land use practices of prehistoric Americans? The amount of land cleared for agriculture in prehistory has been estimated in several recent studies based on presumed populations (Olofsson and Hickler 2008; Pongratz et al. 2008; Pongratz et al. 2009), but the resulting maps are not at all consistent with the pollen and archaeological data, which indicate widespread cultivation and forest clearance, especially in the northern Neotropics (Whitmore and Turner 2001; Piperno 2006; Dull 2008).

The pre-Columbian carbon footprint consisted primarily of forest biomass cleared for farming and nonagricultural burning (primarily via fire leakage). Many other cultural practices, not explicit in the carbon sequestration calculations to follow, would have been common in the pre-Columbian Neotropics, such as fuel wood harvesting; establishment of habitations; weed, pest, and game management; maintenance of trails; and construction of monumental architecture, plazas, causeways, and other facilities.

The Farming Footprint

The total land area needed to provide for caloric needs varied widely across the prehistoric Americas, ranging from shifting cultivation[8] with mostly short fallows to highly productive semipermanent and permanent systems, such as those associated with Amazonian Dark Earths[9] (Denevan 2001; Whitmore and Turner 2001; Woods, Denevan, and Rebellato 2010). Per capita land needs for agricultural production in Latin America today range from approximately 0.2 to 0.3 ha $person^{-1}$ $year^{-1}$ for intensive agriculture on Amazonian Dark Earths to 2.2 ha $person^{-1}$ $year^{-1}$ in long-fallow swidden systems (Drucker and Heizer 1960; Beckerman 1987; Hecht 2003; Denevan 2004; Woods, Denevan, and Rebellato 2010; see Table 2). This range is consistent with those reported by Seiler and Crutzen (1980) of 0.4 to 0.6 ha $person^{-1}$ $year^{-1}$ for intensive agriculture and 2.0 to 3.2 ha $person^{-1}$ $year^{-1}$ for extensive long fallow systems. We estimate that a range of approximately 0.9 to 1.5 ha of land, including fallow,

Table 2. Representative agricultural land area per capita per year in the Neotropical lowlands

Crop system	Average fallow length (including ranges)	Land area needed per person/ year including fallows[a]	Sources
Long fallow, shifting cultivation (Amazonia)	15 years (10–20)[b]	2.2 ha	Beckerman (1987)[c]
Short fallow, shifting cultivation (Amazonia)	6 years (4–8)	1.0 ha	Denevan (2004)
Short fallow (Mesoamerica)	4 years (3–5)	1.5 ha	Drucker and Heizer (1960)
Semipermanent/permanent cultivation on superior soils (e.g., Amazonian Dark Earths)	2 years (0–4)	0.25 ha (0.2–0.3)	Woods, Denevan, and Rebellato (2010)
		1.2 ha (mean)	

[a] Based on average size of one family field plus the average length of fallow, divided by five, which is used here for the average size of family, which gives the amount of land needed to support one person.

[b] Long fallows can range up to fifty years or more, but most fall between ten and twenty years. Even a fifty-year fallow period would result in only about 50 percent biomass recovery.

[c] Beckerman (1987) gives field sizes for nineteen tribes, averaging 0.68 ha per field. With five people/family/field, the amount of cultivated land needed to feed one person for a year is 0.14 ha. With an additional fifteen fields in fallow, the amount needed per person for a year is 2.2 ha.

was needed per person to supply the majority of the caloric needs of the prehistoric population (Table 3).[10]

The Fire Footprint

The average global carbon emissions from fire today total amount to ~1.4 to 2.8 Pg C year^{-1}, with ~30% of global CO_2 fire emissions originating in the New World tropics (Schultz et al. 2008; Langmann et al. 2009). Even where forest regrowth and sequestration has been factored in, the "net tropical source" of CO_2 to the atmosphere during the recent era of tropical deforestation has been estimated to be as high as ~1.6 Pg C year^{-1} (Randerson et al. 1997). The association of fire with prehistoric land use and specifically agriculture in the forest biomes of the Neotropics is well established (Piperno and Pearsall 1998; Bush et al. 2008; Mayle and Power 2008). For example, Amazonian Dark Earths, which have been identified throughout the Amazon, were formed in part through repeated, intentional burning (Woods et al. 2009). This demonstrated use of fire in prehistoric agricultural systems has implications for the anthropogenic fire carbon footprint in the Prehistoric Americas.

Fire leakage is a major cause of chronic forest degradation in all tropical forests today, most notably in the Amazon (Laurance 2003; Aragão et al. 2007). For example, the 1997–1998 El Niño drought resulted in widespread fires that burned 20 million ha of tropical forests, most due to anthropogenic ignitions (Cochrane 2003), releasing ~0.7 to 0.9 Pg C to the atmosphere from the Neotropics alone, or about 20 percent of the CO_2 growth rate anomaly (van der Werf et al. 2004). Overall, roughly 2.3 to 3.0 Pg C was released from the tropics due to unintentional anthropogenic fire during the 1997–1998 El Niño, about one third from the Neotropics (Laurance 2003; van der Werf et al. 2004; Lewis 2006; Aragão et al. 2007). Unintentional fire leakage likely contributed substantially to pre-Columbian Neotropical biomass burning (Mayle and Power 2008), and consequently CO_2 flux to the atmosphere, but calculating average annual net CO_2 fluxes from this source in prehistory is nearly impossible without invoking modern fire emissions estimates from

Table 3. Summary of parameters used to calculate carbon sequestration potential of post-Contact Neotropical reforestation

Estimated pre-Contact population (millions)	Estimated 95% mortality by 1650 (millions)	Tropical forest carbon density (Mg C/ha)	Agricultural land clearance (ha/person)	Carbon sequestration potential from reforestation (Pg C)	Potential contribution to Little Ice Age CO_2 anomaly
19.4	18.4	120–190	0.9–1.5[a]	2–5	6–25%

[a] Represents average farming footprint of 1.2 ha/person/year (Table 2) ± 25 percent.

this region derived largely from remote sensing; no such explicit numbers are offered here.[11]

Postcontact Carbon Sequestration

Net primary production is highest globally in low-latitude forests, where it ranges from approximately 1,600 g m^{-2} $year^{-1}$ in tropical dry forests to 2,200 g m^{-2} $year^{-1}$ in tropical moist forests (Seiler and Crutzen 1980). Neotropical forests have played an especially crucial role in the carbon cycle because of their vast potential as a carbon sink. Several authors have suggested that the Neotropical lowlands became a massive sink for carbon following the Columbian encounter (Ruddiman 2005, 2007; Faust et al. 2006; Nevle and Bird 2008), with some suggesting that the effects of that demographic shift could still be echoing today via accelerated modern Amazon carbon sequestration rates (Phillips et al. 1998).

We calculate the carbon sequestration potential from reforestation of abandoned agricultural landscapes in the lowland Neotropics to be in the range of 2 to 5 Pg C, assuming 0.9 to 1.5 ha/person for agricultural production, 95 percent mortality of 19.4 million people, and above-ground (plant) carbon density of tropical forest of 120 to 190 Mg/ha (Prentice et al. 2001; Table 3). The 2 to 5 Pg C range represents (1) about 6 to 25 percent of terrestrial carbon sequestration (20–38 Pg; Joos et al. 1999; Faust et al. 2006) required to produce the atmospheric CO_2 anomaly of about -5 ppm from 1500 to 1750 AD; and (2) a minimum estimate for carbon sequestration associated with reforestation of humanized landscapes because indigenous people cleared land both intentionally for a variety of purposes besides agriculture and unintentionally through fire leakage.

Our order-of-magnitude calculations illustrate the potential influence of postcontact Neotropical reforestation on Earth's carbon budget and help explain anomalous variations in the concentration and $\delta^{13}C$ of greenhouse gases during the LIA. Anomalies in atmospheric [CO_2], [CH_4], $\delta^{13}C_{CO2}$, and $\delta^{13}C_{CH4}$ recorded in the Law Dome ice core (Etheridge et al. 1996; Francey et al. 1999; Ferretti et al. 2005; Meure et al. 2006; summarized in Figures 4A and B) are synchronous with Neotropical population decline (Figure 4C). The $\sim$5 ppm decrease in CO_2 from 1500 to 1800 AD and simultaneous increase in the $\delta^{13}C$ of CO_2 (Figures 4A and B) require terrestrial biospheric carbon uptake (Francey et al. 1999; Joos et al. 1999), due to the strong discrimination against ^{13}C by the C_3 photosynthetic pathway. Although models of LIA cooling have suggested that the drop in CO_2 concentration during this period is tenuously linked to solar–volcanic forcing (Hunt and Elliott 2002; Von Storch et al. 2004), it has been demonstrated more recently that solar luminosity decreases were not a significant contributor to LIA cooling (Foukal et al. 2006). Moreover, the $\delta^{13}C$ of atmospheric CO_2 began to increase as CO_2 concentrations began to decrease about a century before the solar–volcanic forcing events commonly associated with the inception of LIA cooling (the Maunder Minimum in sunspot activity, 1645–1715 AD; Rind et al. 2004; and a cluster of major volcanic eruptions toward the end of the sixteenth century). This sequence indicates that factors besides solar–volcanic forcing contributed to the sequestration of CO_2 into terrestrial biosphere, which is consistent with the observation made by Siegenthaler et al. (2005) that cooling was unlikely to have independently produced the $\sim$5 ppm decrease in atmospheric CO_2 that persisted for more than two centuries after 1500 AD (Figure 4B). Our mass balance calculations implicate Neotropical reforestation as a first-order contributor to changes in the atmospheric CO_2 concentration during the LIA.

Proxy records of atmospheric methane abundance and its carbon isotopic composition (Figures 4A and 4B) are also consistent with the hypothesis that postcontact changes in human–landscape interactions significantly influenced Earth's carbon budget. The $\delta^{13}C$ of CH_4 begins to decrease at about 1000 AD, with the rate of decrease accelerating at about 1500 AD. Ferretti et al. (2005) attributed the initial decrease in the $\delta^{13}C$ of CH_4 from 1000 to 1500 AD to natural climate change and the subsequent accelerated decrease in $\delta^{13}C$—as well as the decline in CH_4 (Figure 4B)—from 1500 to 1800 AD to reduced anthropogenic biomass burning coincident with rapid human population decline in the Americas (Figure 4C; Dobyns 1966; Henige 1998; Denevan 1992a; Dale and Adams 2003; Ruddiman 2005; Mischler et al. 2009). In summary, variations recorded by proxies of atmospheric CO_2 and CH_4 corroborate the hypothesis that preindustrial human–landscape interactions in the Neotropics influenced the regional fire regime and contributed to changes in Earth's atmospheric greenhouse gas budget.

Conclusion

The concept of anthropogenic forcing of climate before the Industrial Revolution has elicited a vigorous debate in recent years. We contend that by 1500 AD the global imprint of human land use on the carbon cycle was sufficient to produce measurable atmospheric warming and that the decrease in atmospheric CO_2 from 1500 to 1750 was in part caused by carbon sequestration in the lowland tropical forests of the Americas. We argue that the decline in atmospheric CO_2 must be evaluated not only in terms of land needed for food production but within the context of tropical fire ecology and the positive fire feedback loop created by increasingly pervasive agricultural land use and recurrent droughts during the late Holocene. The reduction in biomass burning in Neotropical regions that commenced 500 years ago cannot be explained on the basis of climatic factors alone. The sudden sixteenth-century decrease in human ignition sources contributed to an overall decrease in fire frequency—and a dramatic increase in woody biomass accumulation—in forest systems that have evolved where lightning ignition is rare.

The LIA was not caused by the Columbian encounter per se, but the evidence suggests that it was probably amplified measurably by the ecological effects of the demographic collapse. The estimates reported here of post-1500 carbon sequestration by the reforestation of lands previously cleared of tropical forests for agriculture represent a substantial terrestrial sink for CO_2 during the LIA, but these calculations only include the farming footprint with no quantification attempted of the potentially significant per capita anthropogenic fire footprint. Moreover, we have made no attempt to quantify the role of post-Conquest carbon sequestration in the Andes, the highland forests of Central America and Mexico, or the eastern deciduous forest of the United States. Future research on the climate forcing impacts of the Columbian encounter should seek to quantify a more geographically comprehensive per capita ecological footprint in the Neotropics and throughout the Americas.

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Notes

1. Also see the book review by Turner (2006), a somewhat critical and yet balanced view.
2. Interpretations of the pollen data themselves have varied widely, with two recent studies from the Maya region supporting the notion of limited prehistoric forest clearance beyond agricultural fields (Ford and Nigh 2009; McNeil, Burney, and Burney 2010).
3. In the seasonal tropical dry forest regions, these "drought" conditions would have been achieved on a near annual basis, when dry season burning would have resulted in escaped fire.
4. Samples of 1 cc were soaked overnight in 50 mL of deflocculant: a 5 percent solution of sodium hexametaphosphate. The soaking was followed by repeated warm water washes the following day. Sieved residues were transferred to standard 100 × 15 mm Petri dishes and counted with 40× magnification.
5. Periods with relatively larger numbers of ^{14}C dates from charcoal fragments correspond with periods having relatively higher mean rates of biomass burning.
6. Several million more people lived in the nonforested lowland Neotropics. Most nonforest dwellers lived in savannas and coastal scrub environments. Although there are extensive savanna regions in South America, there were much smaller patches of savannas scattered throughout the northern Neotropics (Beard 1953).
7. Although we accept the estimate of Denevan (1992a) as being the best estimate, we also include several other estimates in Figure 4C (Rosenblat 1954; Dobyns 1966; Henige 1998).
8. Long-fallow systems, although quite common in the Amazon today, are the subject of some debate in regard to prehistory. A strong case has been made that shifting cultivation was a post-Conquest adaptation in the Amazon, facilitated by the introduction of metal tools that allowed for more effective and rapid clearing of forests (Denevan 1992b). Tree cutting with stone axes would not have been a viable means of forest clearance in prehistory.
9. The productivity of Amazonian Dark Earths or *terra preta* has been shown in modern studies to be extraordinarily high with 1 ha of rich terra preta capable supporting as many as 24.5 people in a maize-based economy and 29.6 people subsisting primarily on manioc. In such a system 80 percent of the farmer's land would be in a short bush fallow rotation (about two years cropping and three to four years fallow; Woods, Denevan, and Rebellato forthcoming).

10. We consider these numbers to be representative of average agricultural land consumption patterns based on the cited literature, but we do not assign percentages of Neotropical forest land area under each fallow system.
11. Using the 1997–1998 El Niño numbers of ∼0.7 to 0.9 Pg C net Neotropical flux as an upper limit (van der Werf et al. 2004), and even if we assume average growth rate anomalies an order of magnitude or so lower than this (∼0.05–0.10 Pg year^{-1}) during prehistory, significant cumulative net CO_2 fluxes could have built up over decades and centuries (∼0.5–10+ Pg C) during the late Holocene as agricultural populations were increasing and human-mediated fire regimes were expanding.

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