

Paleofire activity in tropical America during the last 21 ka: A regional synthesis based on sedimentary charcoal

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Fire in most Neotropical systems has generally occurred during periods of reduced precipitation, and fire activity, at times, has been shown to be anti-phased between the northern and southern regions.

Understanding the linkages between past climate change and forest dynamics in the Neotropics (an area of North, South, Central America and the Caribbean from 30°N to 30°S) is a major international research challenge because of the importance of tropical biomes to global climate change. Global climate models suggest that much of Amazonia will experience increased drought and hence susceptibility to burning in the 21st century (Malhi and Phillips, 2004). Yet, large uncertainties remain for understanding the relationship between Amazonian moisture balances and future fire regimes (Cochrane and Barber, 2008). The global implications of accelerating tropical burning in the near future and the potential feedbacks between tropical deforestation and climate, makes un-

derstanding Neotropical ecosystem responses to past fire activity an important research focus.

Little is known about the frequency and spatial extent of past fires in the Neotropics since the Last Glacial Maximum (LGM; ca. 21 cal ka BP). A compilation of 56 charcoal records allowed us to compare the patterns of fire during the last 21 ka in northern (0°–30°N) and southern (0°–30°S) latitudes and to identify potential drivers of past biomass burning (Fig. 1). Published charcoal records from the Neotropics were combined to examine regional trends in biomass burning during the past 21 ka. Nearly half the records came from the tropical evergreen and semi-evergreen broadleaf biomes (48%); others were from the tropical deciduous broadleaf forests

and woodlands (18%), the warm temperate evergreen broadleaf and mixed biome (16%), and savannas (7%). Individual charcoal records were transformed and rescaled as Z-scores of charcoal influx values and composited together. Published age-depth models were used when calibrated ages were available; otherwise, radiocarbon ages were converted to calendar kiloyears before present (cal ka BP) using the calibration curve of Fairbanks et al. (2005) and new age models were created using median calibrated radiocarbon ages and a “best fit” model (see Power et al., 2008). Site-specific fire histories were also examined within the region.

Results and Discussion

Drier-than-present late-glacial climates resulting from lower-than-present sea-surface temperatures, CO₂ and sea level, resulted in decreased biomass burning across the Neotropics during the LGM (Power et al., 2008). During the late-glacial period (ca. 19 - 14 cal ka BP), most charcoal records indicate infrequent fires (Fig. 2). Late-glacial pollen, charcoal and δ¹³C evidence from Lake Titicaca (Paduano et al., 2003) suggest fires became more important as available moisture and fuel production around 15–20°S gradually increased after 17.7 cal ka BP. Regional charcoal summaries (Fig. 2) suggest fire activity in the northern Neotropics decreased to the lowest levels of the last 21 ka by 14 cal ka BP. During the early Holocene, the precessional component of insolation increased summer warmth and seasonality in the northern tropics (and reduced them in the south) and through atmospheric circulation responses, also influenced seasonal moisture and drought patterns. In both the southern and northern Neotropics, fire activity increased after ca. 14 cal ka BP and again after 11 cal ka BP, as orbital precession lengthened and intensified the dry season (Berger and Loutre, 1991). More-severe seasonal droughts were particularly evident in the northern Neotropics, with charcoal records from the Yucatan, for example, showing highest fire activity of the last 84 ka between ca. 17 and 14 cal ka BP (Bush et al., 2009).

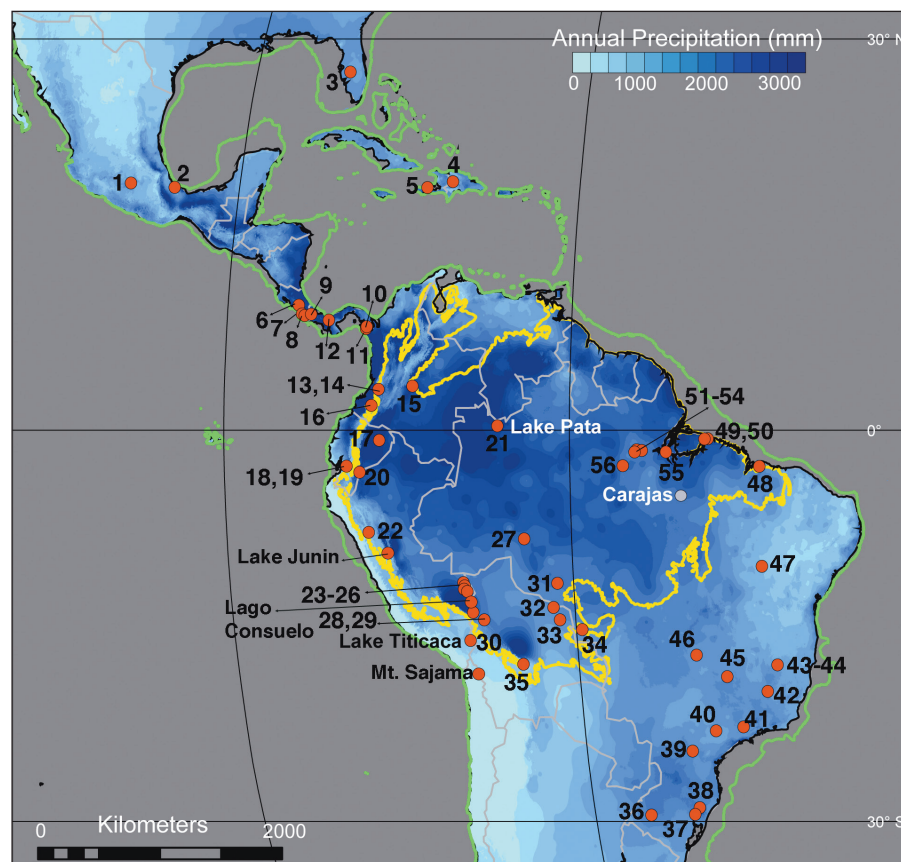


Figure 1: A regional map of tropical and subtropical America and the Caribbean showing annual average precipitation and sites mentioned in the text and figure 2 (Hijmans et al., 2005). **Yellow line** delineates the Amazon Basin, which encompasses both humid evergreen rainforests in the lowland basin and Guyana Shield, semi-deciduous Chiquitano dry forests in the south, and all forest types on the eastern flank of the Andes. **Green line** indicates Last Glacial Maximum (LGM) coastline reconstructions (Peltier, 2004); **red circles** indicate the location of charcoal records obtained from the Global Charcoal Database. A list of the oldest and youngest sample charcoal ages (following Power et al., 2008) and number of charcoal samples from each record are available at http://www.pages-igbp.org/products/newsletters/ref2010_2.html

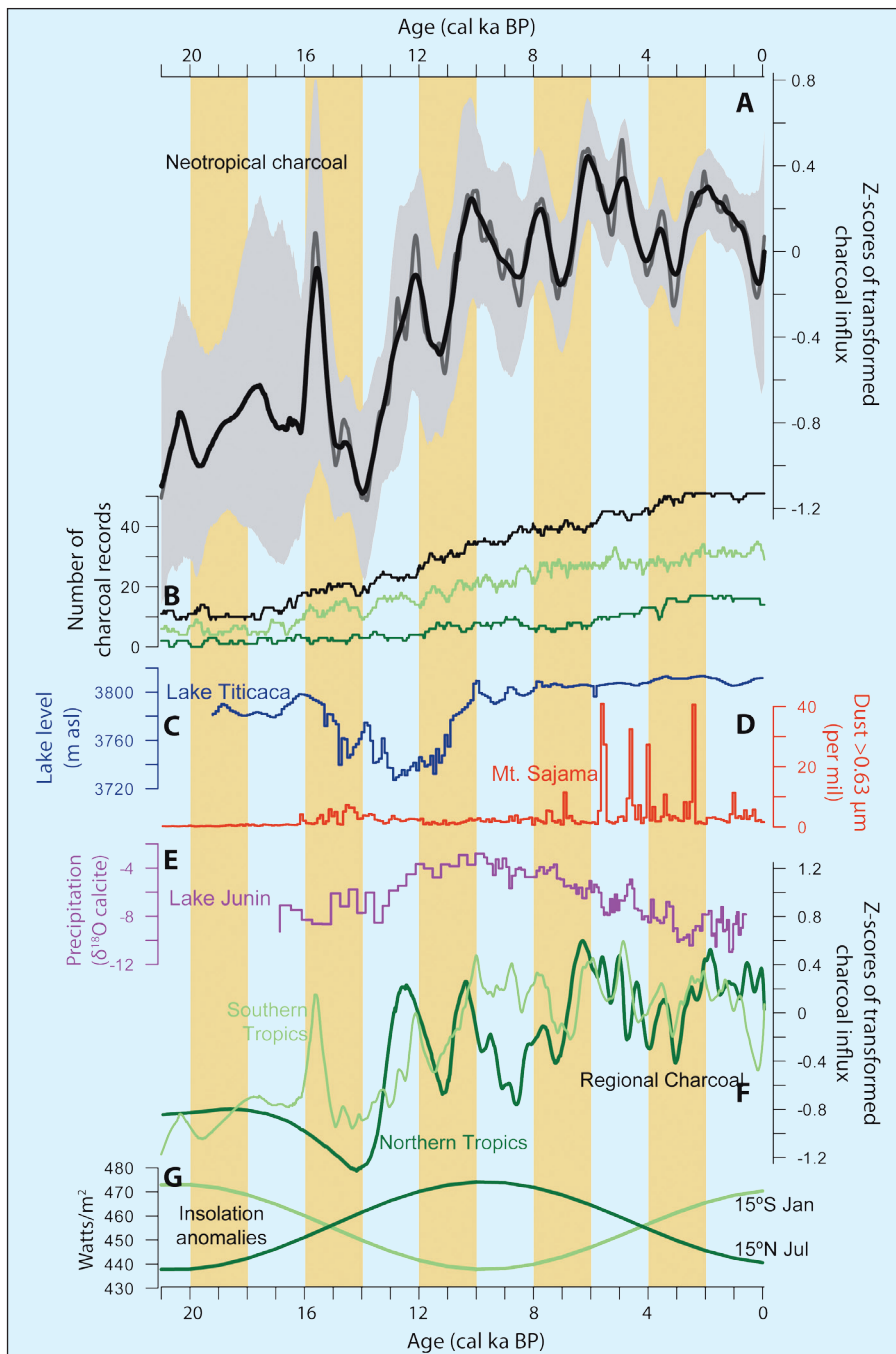


Figure 2: **A**) 21 ka composite time series from all Neotropical records (between 30°N and 30°S) of 250-a (black) and 100-a (gray) smoothed Z-score charcoal anomalies. The upper and lower 95% confidence limits from bootstrap analysis are shown in light gray. The composite charcoal curve was produced from 56 records from the Global Charcoal Database version 1, including lakes, bogs and in few instances, soil charcoal. **B**) The number of charcoal records contributing to each composite curve for Neotropics (black), northern Neotropics (0°–30°N; dark green), and southern Neotropics (0°–30°S; light green). Paleomoisture proxies are shown from selected tropical records, including **C**) Lake Titicaca elevation (m asl) inferred from $\delta^{13}\text{C}$ (Abbott et al., 2003), **D**) Mt. Sajama dust particles larger than 0.63 μm from ice cores (Thompson et al., 1998), and **E**) $\delta^{18}\text{O}$ of calcite at Lake Junin, proxy for precipitation (Seltzer et al., 2000). **F**) Northern and southern tropics composite charcoal time series using a 250-a smoothing window. The composite approach normalizes individual records in order to stabilize the variance and standardize results (Power et al., 2008, 2010). The charcoal time series was smoothed by fitting a lowess curve (Cleveland and Devlin, 1988), which prevents high-resolution records from affecting regional signals and avoids introducing, by interpolation, data into lower-resolution records. **G**) Mid-month insolation anomalies for June at 15°N and January at 15°S (Berger and Loutre, 1991). Yellow vertical bars represent 2 ka intervals.

As summer insolation decreased from 10 to 8.5 cal ka BP in the Northern Hemisphere, charcoal records from the northern Neotropics suggest decreased fire activity. Fire activity remained higher-than-present in the southern Neotropics during this time. From 8 to 6 cal ka BP, orbital-scale controls of tropical fire activity weakened. As summer insolation decreased in the Northern Hemisphere,

drought intensity and biomass burning generally decreased from 6 cal ka BP to present (Fig. 2). Increasing summer insolation in the Southern Hemisphere may have promoted more droughts and biomass burning ca. 5 cal ka BP, but both the northern and southern tropics show similar millennial-scale trends of decreasing biomass burning thereafter.

Reconstructions of tropical moisture between 6 and 3 cal ka BP suggest wetter-than-present conditions in the northern Neotropics (Hodell et al., 2000; Horn, 2007), while records from the southern Neotropics, including the tropical Andes and Amazonia, suggest drier-than-present climates. High climate variability also characterized this period, as evidenced by peak dust concentrations and snow accumulation in Andean ice cores (Thompson et al., 1998), oxygen isotope ratios from lake-sediment calcite analysis (Seltzer et al., 2000), and evidence of lake-level low stands in Lake Titicaca (Baker et al., 2001) (Fig. 2). Centennial-scale intervals of high and low biomass burning were embedded within millennial-scale trends of decreasing fire across the Neotropics. The temporal variability in biomass burning may be related to changes in Atlantic sea surface temperatures, characterized by the Atlantic thermal dipole (Hillyer et al., 2009), which reflects the seasonal and interannual changes in the position of the ITCZ and thermal equator in the tropical Atlantic Ocean (Bush et al., 2007).

Soil-charcoal records provide paleo-fire information in neotropical regions where suitable lakes and bogs are absent (Sanford and Horn, 2000). Most tropical soil charcoal records are younger than 3 cal ka BP and fire occurrence is generally considered anthropogenic in origin. Intensification of human land-use in the Neotropics during the last three millennia undoubtedly changed the geographic pattern and frequency of fire (Cochrane and Barber, 2008). In addition, radiocarbon dates on soil charcoal suggest that high fire activity in Amazonia coincided with sun-spot minima during the last 2.5 cal ka BP (Bush et al., 2008). These solar minima are possibly linked to drought events, which may have facilitated the spread of human-set fires.

Conclusions

Charcoal records from the Neotropics suggest fire activity is associated with periods of high climate variability, including changes in moisture budgets and the intensification of seasonal droughts. The direct effects of summer insolation likely explains periods of higher-than-present fire activity in the Neotropics at ca. 10 cal ka BP. Drier-than-present climates likely promoted more fires during this period, either directly by reducing humidity, lowering fuel moisture and drying soils, or indirectly by favoring more flammable vegetation. From ca. 10 to 8.5 cal ka BP, fire activity is anti-phased in the northern versus southern Neotropics. After ca. 6 cal ka

BP, biomass burning generally decreased to present across the Neotropics, with multi-centennial periods of high fire activity (e.g., 6 to 5 cal ka BP and ca. 2 cal ka BP) embedded in these long-term trends. Remarkably, records from the wettest regions of Amazonia (e.g., Lake Pata and Consuelo; Fig. 1) have no charcoal, suggesting that they remained fire-free over the last 21 ka. In contrast, Neotropical regions with high seasonality (e.g., Carajas, Brazil; Fig. 1) experienced more fires in the early to middle Holocene, when savanna replaced evergreen forest (Absy et al., 1991).

Neotropical ecosystems have experienced significant variability in biomass burning since the LGM but additional high-resolution charcoal records are needed to better establish regional fire-frequency trends. Simulating past changes in

fire regimes with global and regional Earth System models will help assess the ability of these models to predict future changes in Neotropical fire regimes. Furthermore, studies of fire history from the tropics are highly relevant to issues of climate change and biodiversity conservation and can contribute to the development of appropriate fire-management policies (Horn and Kappelle, 2009).

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http://www.pages-igbp.org/products/newsletters/ref2010_2.html



Paleofires in southern South America since the Last Glacial Maximum

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Southern South American charcoal- and tree-ring-based fire histories suggest strong linkages between climate variability and regional fire regimes, with human influences having a more localized impact on fire occurrence.

The diverse physiography, climate and biota of southern South America (SSA; 30–55°S) offer the possibility of examining the pattern and causes of paleoclimate change and paleofire activity from subtropical to subantarctic environments, including the region of maximum surface wind speeds and frontal precipitation (48–50°S) delivered by the Southern Westerly Winds (SWW). The southern Andes establishes an effective barrier to the advection of moist air masses across SSA and isolates Pacific and Atlantic moisture sources. An array of fire-history records along latitudinal and longitudinal gradients through SSA identifies the sensitivity and vulnerability of vegetation to past fire occurrence and the underlying climate and vegetation drivers of fire operating at different spatial and temporal scales.

At present, natural fire occurrence in SSA is driven primarily by tropical and extra-tropical influences on the SWW, as demonstrated by the correspondence of fires with synoptic patterns associated with El Niño-Southern Oscillation (ENSO) and the Southern Annular Mode (SAM). These modes of variability are captured by such indices as the Multivariate ENSO

Index and the Antarctic Oscillation Index (Garreaud et al., 2009; Villalba, 2007) (Fig. 1). During the positive (or warm) phase of ENSO, the southeastern Pacific subtropical high-pressure system weakens, allowing an equatorward deflection of the SWW to ~30°S. In conjunction with the development of an anomalously warm pool in the southeastern Pacific, this induces warm dry conditions in the mid latitudes (40–50°S) of western Patagonia, which promotes fire. During the positive phase of SAM, a low atmospheric pressure anomaly develops over Antarctica shifting the circumpolar vortex and subtropical high-pressure system south and deflecting the SWW to 50–60°S. The result is dry conditions conducive for fires between 35–43°S. In addition, a positive SAM is correlated with a warm South Atlantic sea-surface pool that further enhances positive temperature anomalies over the mid-latitude eastern flanks of the Andes. The varying strength of these relationships in space (the correlation indices decline north and south along the Pacific side of the Andes) and time (the relationship remains significant only for the post-1977 warm phase of the Pacific Decadal Oscillation in the

1938–2004 record from northern Patagonia) suggests modulation of signals by nonstationarities and lower-frequency climatic (Enfield et al., 2001) and fire controls (Kitzberger et al., 2007). The complexity of climate drivers at different spatial and temporal scales argues for the need for a dense network of high-resolution paleofire reconstructions on both Andean flanks between 38–55°S.

Charcoal records

The first charcoal-based fire histories in SSA were described by Calvin Heusser in Chile (Heusser, 1983) and Vera Markgraf in Argentina (Markgraf, 1983). Since then, fire history has been studied in many regions and most researchers suggest strong linkages between fire and climate, with human influences being more localized (e.g., Markgraf, 1993; Heusser, 1994; Heusser et al., 1999; Moreno, 2000; Huber and Markgraf, 2003; Haberle and Bennett, 2004; Whitlock et al., 2006; Markgraf et al., 2007; Abarzúa and Moreno, 2008). Regional syntheses of charcoal records have identified conspicuous multi-millennial trends in paleofire activity (Fig. 2) with low abundance of charcoal prior to 14 cal ka BP, an increase