Quaternary International xxx (2017) 1–14

Contents lists available at ScienceDirect

Quaternary International

journal homepage: www.elsevier.com/locate/quaint

# Reassessing climate and pre-Columbian drivers of paleofire activity in the Bolivian Amazon

S. Yoshi Maezumi [a, *], Bronwen S. Whitney [b], Francis E. Mayle [c], Jonas Gregorio de Souza [a], Jose Iriarte [a]

[a] Department of Archaeology, College of Humanities, University of Exeter, Laver Building, North Park Road, Exeter EX4 4QE, UK
[b] Department of Geography and Environment Sciences, Northumbria University, Ellison Place, Newcastle-upon-Tyne, NE1 8ST Drummond Street, UK
[c] Department of Geography and Environmental Science, University of Reading, Whiteknights, PO Box 227, Reading RG6, UK

A R T I C L E I N F O

*Article history:*
Received 28 December 2016
Received in revised form
3 October 2017
Accepted 30 November 2017
Available online xxx

*Keywords:*
Paleofire
Charcoal
Pre-Columbian
Fire management
Maize cultivation
Bolivian Amazon

A B S T R A C T

A 50,000-year-old sediment core record from Laguna Chaplin is reanalyzed to explore potential paleoecological methods to detect the extent of pre-Columbian disturbance in the Bolivian Amazon. High-resolution (sub-centennial) macrocharcoal data are analyzed using statistical algorithm software including Regime Shift Detection and CHAR Analysis to detect changes in past fire regimes. These data are compared with existing charcoal records from throughout the Bolivian lowlands to provide a regional scale context of past biomass burning. During the mid-Holocene, changes in precipitation are the dominant driver of fire activity and biomass burning at Laguna Chaplin and across the Bolivian lowlands. During the late Holocene, increased fire activity across ecosystems ranging from fire-adapted to fire-intolerant forests is attributed to the apex of pre-Columbian activity. These data suggest human-caused ignitions during the late Holocene are the driving factor of regional scale fire activity in the Bolivian lowlands. After ca. 650 cal yr BP, there is an increase in biomass burning and fire frequency synchronous with the expansion of Moraceae/Urticaceae pollen (>50%) at Laguna Chaplin. This occurs during the time-transgressive southward expansion of the rainforest boundary, during the apex of pre-Columbian activity in the region. The increase in biomass burning at Laguna Chaplin is reflected at other sites in the region with known human occupation histories. The presence of *Zea mays* ca. 970 to 170 cal yr BP indicates maize cultivation is practiced in the immediate vicinity surrounding Laguna Chaplin. The simultaneous increase in fire activity with the expansion of the less flammable humid rainforest vegetation suggests human fire management practices. These data are interpreted as the use of frequent, low severity, human-caused fires to clear the croplands from encroaching rainforest vegetation. Despite evidence of pre-Columbian fire management during the late Holocene, vegetation and fire data indicate the extent of human-landscape modification and fire management at Laguna Chaplin, is not enough to inhibit the climate-driven regional forest expansion of the savanna-rainforest ecotonal boundary to its most southern extent in the last 50,000 years. This study demonstrates the utility of applying a multi-proxy, high-resolution paleoecological method to disentangle climate and pre-Columbian disturbance in the Bolivian Amazon.



## 1. Introduction

Recent evidence of pre-Columbian (before AD 1492) landscape modifications in Amazonia including earthen mounds, canals, causeways and geometric earthworks (Erickson, 2010, 2001; Erickson and Balée, 2006; Heckenberger and Neves, 2009; Heckenberger, 2008; Lombardo et al., 2011; Mann, 2008; Pärssinen and Schaan, 2009), has heightened scientific interest in the extent of past deforestation and burning in a region once viewed as 'pristine' (Heckenberger et al., 2003; Willis et al., 2005). Disentangling the extent of anthropogenic impact on fire and vegetation in the paleoecological record is complicated by the synchroneity of human occupation and climate-driven ecosystem change (i.e., Carson et al., 2014). For example, the late Holocene increase in precipitation (ca. 3000 cal yr BP) resulted in a time-

* Corresponding author.
*E-mail address:* s.y.maezumi@exeter.ac.uk (S.Y. Maezumi).

https://doi.org/10.1016/j.quaint.2017.11.053

transgressive southward expansion of the rainforest-savanna ecotone in the Bolivian Amazon (Burbridge et al., 2004; Mayle et al., 2000). The period of highest pre-Columbian occupation in the Bolivian Amazon (Heckenberger and Neves, 2009; Lombardo et al., 2011; Pärssinen and Schaan, 2009) is thus set against a backdrop of transitional climate and vegetation change (Mayle et al., 2000). Additionally, a growing number of studies suggest there is a high degree of spatial and temporal heterogeneity in pre-Columbian land-use throughout different regions of Amazonia (Bush et al., 2007; Carson et al., 2014; Iriarte, 2003; Mayle and Iriarte, 2012; McMichael et al., 2011; Piperno et al., 2015; Whitney et al., 2014). The synchroneity of potential natural and anthropogenic drivers of ecological change, coupled with the high degree of spatial and temporal heterogeneity in pre-Columbian land-use has resulted in considerable debate over the extent of pre-Columbian ecosystem disturbance (Bush et al., 2007; Carson et al., 2014; Clement et al., 2010; Iriarte et al., 2012; Mayle and Iriarte, 2012; McMichael et al., 2012; Piperno et al., 2015; Thomas et al., 2015; Whitney et al., 2014) and the potential long-term legacy of past land-use practices on the composition, structure and spatial patterning of modern Amazonian ecosystems (Carson et al., 2016; Whitney et al., 2014).

The difficulties in disentangling climate- and human-driven fire and vegetation change in the paleorecord is compounded by conventional sampling methods used in Amazonian paleo-studies which have been largely focused on detecting orbital-scale climate and vegetation change (Burbridge et al., 2004; Mayle et al., 2000; Urrego et al., 2010; Valencia et al., 2010). However, it is difficult to detect short-term (sub-centennial), highly localized (ca. $<10^6$ $m^2$) human impacts with the coarse temporal and spatial resolution of these studies. It has become evident that to decipher the effects of late Holocene climate-driven and human-driven impacts on fire and vegetation change requires a different methodological approach to those typically applied to study longer-term orbital-scale transitions. To address these issues, this study explores the comparison of conventional sampling techniques with high-temporal sampling resolution on modified pollen and charcoal methods and statistical algorithms. These data are compared with existing charcoal records to provide a regional context for paleofire activity across a range of ecosystems in an attempt to disentangle climate- and human-drivers of fire and vegetation change in the Bolivian Amazonian during the Holocene.

### 1.1. Emerging methods to disentangle climate and pre-Columbian paleofire activity

To date, there is no direct way to distinguish human-caused wildfires from climate-driven wildfires in the paleo-record (Marlon et al., 2013). To establish an empirical link between changes in past fire regimes and human land-use practices depends on the ability to demonstrate synchroneity of fire activity and human impact in the paleorecord. This link is dependent on having archaeological evidence (e.g. AMS-dated archaeological sites) or vegetation data (e.g. crop pollen) to establish a human presence. Additionally, fire records need sufficient sampling resolution and appropriate chronological control that correspond to the period of human occupation in a region (Berglund, 2003). Conventionally, paleoecological studies have focused on long-term climate-driven forest dynamics. Sampling sediment charcoal records with low resolution (LR) pollen sampling (ca. 5–10 cm or multi-centennial to millennial scale) has been sufficient to address the temporal range of these questions (Burbridge et al., 2004; Bush et al., 2000; Mayle et al., 2000; Urrego et al., 2005, 2013a,b). Subsequently, LR sampling combined with chronological uncertainties has led to ambiguity and debate in the nature of the fire-human-climate linkages in South America (Heusser, 1994; Whitlock et al., 2007).

Alternatively, high-resolution (HR) (0.5–1 cm or sub-centennial to centennial scale) sampling enables a more detailed exploration of natural and human impacts within the period of human occupation (sub-centennial to millennial). Recently, the combination of interdisciplinary archaeological and (HR) paleoecological methods at large and small lake basins in the Bolivian Amazon have differentiated local human-driven versus regional climate-driven controls on vegetation dynamics and fire activity (Carson et al., 2014). However, in the present study, only a large lake basin is available, and archaeological survey data has not been conducted around the lake. Hence, an alternative method to explore potential pre-Columbian impacts implements use of modified pollen sieving techniques to detect human occupation (Whitney et al., 2012) and statistical algorithm software including regime shift index (RSI) (Rodionov, 2004) and CHAR Analysis (Higuera et al., 2010) on HR macrocharcoal data (>125 μm, henceforth "charcoal") to explore natural and human impacts on fire activity. HR charcoal and statistical algorithms are used to explore changes in past fire regimes including changes in *fire severity* (total biomass burned indicated by influx) and *fire frequency* (how often fires occur) before, during and after the period of human occupation. These data are compared with dated archaeological sites across the Bolivian lowlands (Fig. 1) to provide a regional context for pre-Columbian activity and past paleofire activity.

With the application of this modified pollen and HR charcoal method in conjunction with existing charcoal, vegetation, climate, and compiled regional archaeological data, it is possible to begin to disentangle potential drivers of past fire activity. For example, in Amazonian ecosystems precipitation is the most important effect of climate on wildfire as it governs the abundance of fuel moisture (Brown and Power, 2013; Marlon et al., 2013; Mistry, 1998). Fire responds differently to increases in precipitation depending on whether fuel moisture is initially abundant or limited in the ecosystem (Marlon et al., 2013; Mistry, 1998). In dry and semi-dry environments such as *cerrado* savanna grasslands, increases in precipitation tend to increase fire through a buildup of available fuel (Maezumi et al., 2015; Marlon et al., 2013), whereas increased precipitation in humid environments, such as humid tropical rainforests, can reduce fire through increases in available fuel moisture (Bush et al., 2008; Cochrane, 2003; Marlon et al., 2013). In the paleoecological record, independent climate records indicating wet conditions coupled with vegetation data dominated by moist, fire-intolerant, fire-adverse vegetation with high-fuel moisture, natural fire activity is expected to be rare unless under extreme conditions (e.g. severe drought stress) (Bush et al., 2004; Cochrane, 2009). If fire activity is high during this period, an alternative scenario including human-caused ignitions may be applicable. Archaeological and ethnographic evidence from the Amazon indicates a wide range of human uses of fire including burning for land-clearing, food, and resource procurement, and as a means to promote soil nutrient availability for crop cultivation (Glaser et al., 2002; Kato, 1998; Oguntunde et al., 2004; Steiner et al., 2007). If human occupation or the use of crop cultivation are established through independent lines of evidence and the paleoecological record indicates biomass burning and fire frequency is high in vegetation not prone to natural ignitions, it follows that humans were likely utilizing fire as a tool to manage the landscape (Bush et al., 2016).

An additional line of evidence to support the interpretation of fire activity and human-caused ignitions can be established by examining the synchroneity of fire activity at widely-separated sites (i.e., hundreds or thousands of kilometers apart) across a range of ecosystems (Ali et al., 2009; Gavin et al., 2006). Existing charcoal records are used to create regional charcoal curves

Please cite this article in press as: Maezumi, S.Y., et al., Reassessing climate and pre-Columbian drivers of paleofire activity in the Bolivian Amazon, Quaternary International (2017), https://doi.org/10.1016/j.quaint.2017.11.053

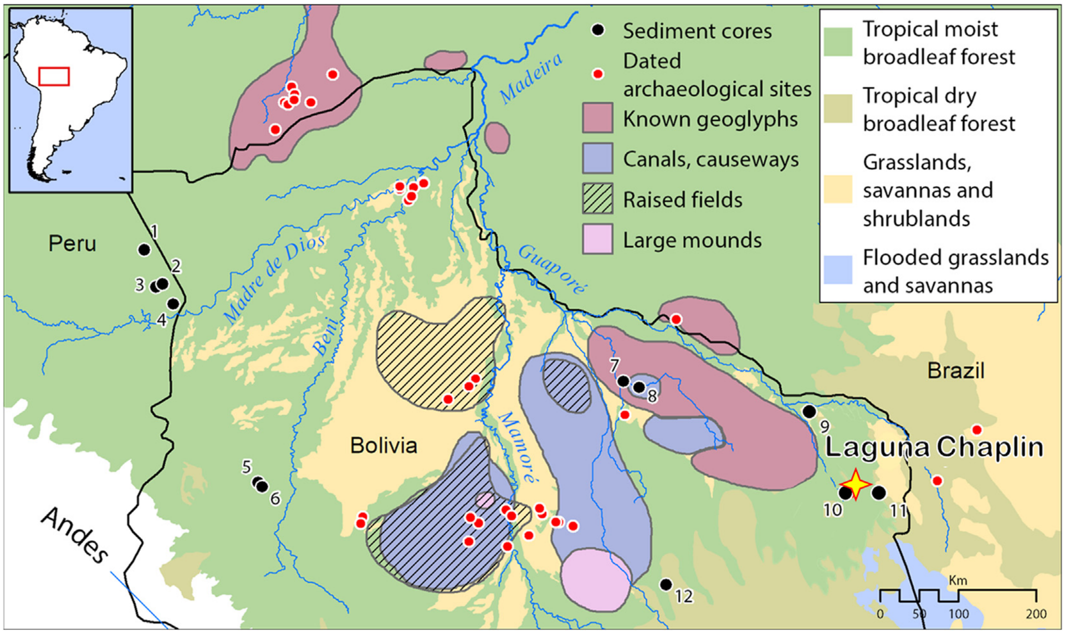


**Fig. 1.** Regional Map of Study Site: Estimated extent of documented archaeological sites and vegetation boundaries. Laguna Chaplin indicated by a yellow star. Modified from (Mann, 2008). Existing charcoal records included in this study indicated by numbered black dots: 1) Werth; 2) Parker; 3) Vargas; 4) Gentry; 5) Laguna Chalalán; 6) Laguna Santa Rosa; 7) Laguna Oricore; 8) Laguna Granja; 9) Laguna Bella Vista; 10) Cuatro Vientos, 11) Huanchaca Mesetta, 12) Laguna Yaguarú. Red dots indicate dated archaeological sites included in SPD curve (see Table 3 for site details). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(henceforth "RCC") or averages in past biomass burning across ca. $>10^{10}$ $m^2$ area and Gridded Time Maps (henceforth "GTMs") of transformed charcoal values to examine spatial and temporal patterns of paleofire activity (Blarquez et al., 2014; Marlon et al., 2013; Power et al., 2010a,b). Composite charcoal curves extracted from a range of spatial scales and across an array of biomes have been used to explore regional mechanistic drivers of past fire activity including climatic and anthropogenic effects on fire at local ($1\ m^2$–$10^6\ m^2$) and regional ($>10^{10}\ m^2$) scales (Brown and Power, 2013; Marlon et al., 2013; Power et al., 2010a, 2010b). Sites that have different ecological and human histories are unlikely to have synchronous changes in fire regimes unless they are driven by similar regional-scale factors (e.g. climate change; regional depopulation following the Columbian encounter) (Ali et al., 2009; Gavin et al., 2006; Turner, 1995). If an individual charcoal record exhibits an asynchronous change to the regional patterns of biomass burning, and human occupation is established based on independent lines of evidence, these data support the interpretation of a localized human impact on biomass burning at that site (Bush et al., 2016; Marlon et al., 2013).

### 1.2. Aims and approach

The primary aim of this research is to explore suitable paleoecological methods to disentangle climate and pre-Columbian disturbance on past vegetation and fire activity in the Bolivian Amazon. This study is based on the reanalysis of pollen and charcoal from the existing sediment record from Laguna Chaplin (LCH). The scope of the previous analysis of LCH focused on orbital-scale climate forcing of ecosystem change over the past 50,000 years (Burbridge et al., 2004; Mayle et al., 2000), for which conventional pollen and macrocharcoal techniques with low temporal resolution (ca. 4–10 cm or ca. 650–1650 years respectively) were sufficient for the research questions. Archaeological investigations are lacking in the area around LCH and the surrounding vegetation, within the Noel Kempff Mercado National Park, is assumed by most ecologists to be old-growth and largely pristine (Killeen, 1998). Therefore, the authors of the original publication assumed that pre-Columbian peoples had no significant impact on the vegetation near LCH (Burbridge et al., 2004). LCH is selected for reanalysis because it has long been recognized, together with the neighboring site of Laguna Bella Vista (ca. 70 km north), as providing strong evidence for the late Holocene climate-driven expansion of the Amazon rainforest ecotone to its southernmost extent in the past 50,000 years (Mayle et al., 2000). This regional rainforest expansion is broadly in phase with lake level rise at Lake Titicaca (Baker et al., 2001a,b), hence is consistent with a precipitation driven explanation of vegetation change at these sites. The increased evidence of human impact in the Bolivian lowlands since the original publication of this site (Carson et al., 2014; Dickau et al., 2013; Whitney et al., 2013, 2012) raises the possibility that humans may have played a more significant role in the vegetation and fire dynamics at LCH than hitherto assumed.

## 2. Methods

### 2.1. Study site

Laguna Chaplin (LCH) (14°28′S, 61°04′W), is a shallow (2.0–2.5 m during the dry season), flat-bottomed lake, formed by subsidence of the underlying rocks along fault lines of the Pre-Cambrian Shield (Burbridge et al., 2004) (Fig. 1). The lake is currently surrounded by humid tropical rainforest (Burbridge et al., 2004; Killeen and Schulenberg, 1998; Mayle et al., 2000). The climate of this region is characterized by a seasonal tropical climate (DaSilva Meneses and Bates, 2002). The mean annual precipitation is ca. 1400–1500 mm per year, with mean annual temperatures between 25 and 26 °C (Hanagarth, 1993; Montes de Oca, 1982; Roche and Rocha, 1985). There is a 3- to 5-month dry season during the Southern Hemisphere winter (May to September–October) when the mean monthly precipitation is less than 30 mm (Killeen, 1990). Precipitation falls mainly during the austral summer

**Table 1**
All samples are carbonate-free bulk sediment. Radiocarbon ages less than 21,000 14C yr B.P. were calibrated into years before present (cal yr BP) (McCormac et al., 2004; Stuiver et al., 1998). The radiocarbon dates have been calibrated by a simple intercept with a linear interpolation of the calibration data points. The 1σ cal age ranges are shown, with the cal age intercepts in parentheses. All ages were rounded to the nearest 10 years (Burbridge et al., 2004). * excluded from original age model.

| Lab Code | Depth (cm) | AMS 14C yr B.P. ± 1σ | Calibrated yr B.P. 1σ |
|---|---|---|---|
| Bet-13757 | 36.5 | 710 ± 50 | 670 (660) 570 |
| AA39700 | 51.5 | 2240 ± 40 | 2320 (2,300, 2,240, 2170) 2150 |
| AA39701 | 69.5 | 2740 ± 40 | 2850 (2790) 2770 |
| AA39702 | 85 | 3870 ± 50 | 4350 (4250) 4160 |
| AA39703 | 100 | 4330 ± 80 | 4960 (4850) 4830 |
| AA39704 | 125 | 6040 ± 50 | 6900 (6,860, 6,830, 6800) 6750 |
| AA39705 | 135 | 9000 ± 100 | 10,230 (10,180) 9930 |
| AA39706 | 155 | 17,820 ± 140 | 21,470 (21,210) 20,960 |
| AA39707 | 175 | 31,060 ± 440 | |
| AA39708 | 195 | 34,820 ± 700 | |
| AA39709 | 213 | 37,750 ± 970 | |
| AA39710 | 250 | 43,400 ± 1900 | |
| AA39711 | 285 | 41,200 ± 1400* | |
| AA39712 | 296 | 38,100 ± 1000* | |

(December to March), originating from a combination of deep-cell convective activity in the Amazon Basin from the South American summer monsoon (SASM) (Vuille et al., 2012).

### 2.2. Sediment core

LCH was cored in August 1998, using a Geocore “drop-hammer” piston corer (Colinvaux et al., 1999) ca. 80 m from the southern shore of the lake. The uppermost surface sediments were recovered with a clear Perspex plastic tube and piston (Burbridge et al., 2004). Detailed methods of the original analysis of charcoal and pollen can be found in Burbridge et al. (2004).

### 2.3. Chronology

The chronological framework for LCH is established with 14 AMS radiocarbon dates from non-calcareous bulk sediment (Table 1, Fig. 2). The uncalibrated radiometric ages are given in radiocarbon years before 1950 AD (years ‘before present’, yr BP). Errors are quoted at one standard deviation and reflect both statistical and experimental errors. Radiocarbon ages were originally calibrated by a simple intercept with a linear interpolation of the calibration data points (Burbridge et al., 2004; Stuiver et al., 1998). The 2σ cal age ranges are shown, with the calibrated age intercepts in parentheses. All ages were rounded to the nearest 10 years (Burbridge et al., 2004). In this reanalysis, ages are calibrated using CALIB 7.0 and the IntCal13 calibration dataset (McCormac et al., 2004). Date ranges are reported with 95% confidence intervals. The reanalyzed age model for this study is created through linear interpolation between calibrated $^{14}C$ dates and an assumed modern age for the core top (sediment-water interface) using classical age-depth modeling in the package CLAM (Blaauw, 2010) within the open-source statistical software R. Age estimates are rounded to the nearest 10 years.

### 2.4. Cultigen pollen

Pollen reanalysis to concentrate large crop pollen is performed at 4 cm resolution. Samples measuring 1 $cm^3$ are prepared following the standard chemical digestion protocol (Bennett and Willis, 2002; Faegri and Iversen, 1989), including an additional sieving stage to concentrate large cultigen pollen types, such as *Z. mays* (Whitney et al., 2012). Large pollen grains (>53 μm), concentrated through the fine-sieving methodology are scanned for *Z. mays* and other crop taxa producing large pollen, such as *Manihot esculenta* and *Ipomoea batatas*. *Z. mays* pollen grains (>70 μm) are identified using the criteria outlined in Holst et al. (2007), which is based on both maize grain size (>53 μm) and a uniform distribution of intertectile columellae as viewed under phase contrast at 1000× magnification to distinguish them from the large pollen grains of the wild grass *Tripsacum* spp. All grains displayed the diagnostic patterning (Holst et al., 2007), measuring 62–80 μm (most grains measured 75 μm and above). Three slides are counted per sample.

### 2.5. Charcoal analysis

Sediment samples are analyzed for charcoal pieces greater than 125 μm using a modified macroscopic sieving method (Brown and

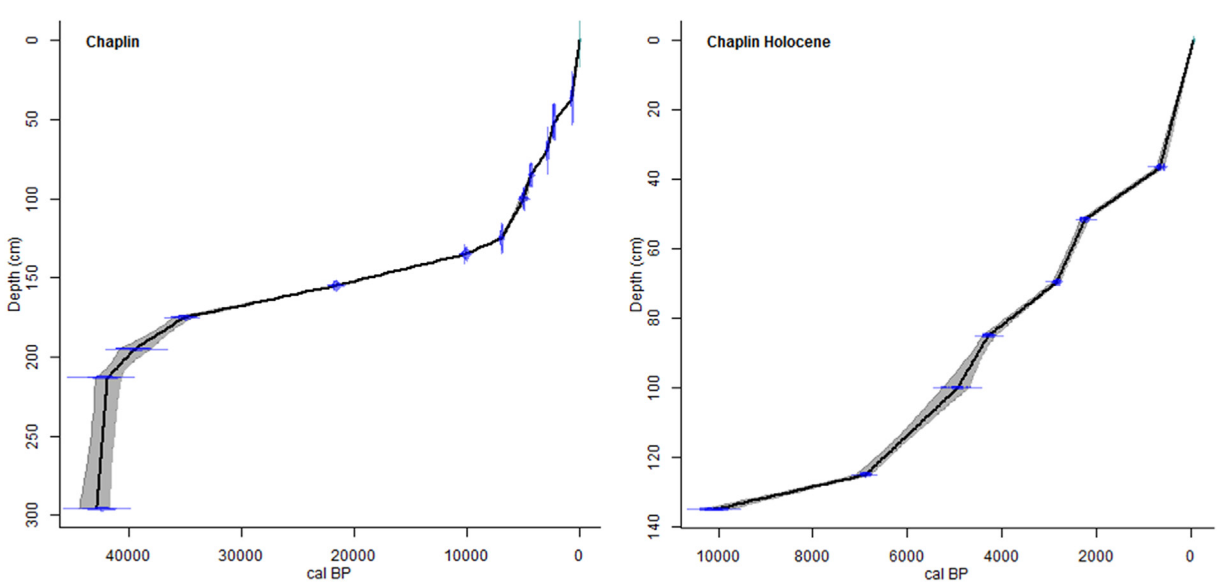


**Fig. 2.** New age-model created for LCH using the IntCal13 calibration curve. The mean age value of the largest probability at 2 sigmas is used to create the linearly interpolated age model using classical age-depth modeling, in the package CLAM (Blaauw, 2010) within the open-source statistical software R.

Please cite this article in press as: Maezumi, S.Y., et al., Reassessing climate and pre-Columbian drivers of paleofire activity in the Bolivian Amazon, Quaternary International (2017), https://doi.org/10.1016/j.quaint.2017.11.053

**Table 2**
Existing regional sediment charcoal records used in regional charcoal curve (RCC) from the Global Charcoal Database (GCD) Version 2.0. Vegetation types abbreviated: Seasonally dry tropical forest (SDTF), Mesic evergreen forest (MEF), Humid evergreen rainforest (HERF), cerrado savanna (SAVN).

| Regional charcoal composite sites | | | | |
|---|---|---|---|---|
| Site | Latitude | Longitude | Holocene vegetation | # Holocene samples |
| Laguna Bella vista | −13.6167 | −61.55 | SDTF/HERF | 19 |
| Lago Chalalán | −14.4278 | −67.9208 | MEF | 39 |
| Laguna Chaplin | −14.4667 | −61.0667 | SDTF/HERF | 134 |
| Cuatro Vientos | −14.5322 | −61.1307 | SDTF/HERF | 154 |
| Gentry | −12.1773 | −69.0977 | HERF | 137 |
| Lagoa Granja | −13.2626 | −63.7099 | SDTF/HERF | 205 |
| Laguna Oricore | −13.3363 | −63.5238 | SDTF/HERF | 81 |
| Huanchaca Mesetta | −14.5549 | −60.7431 | SAVN | 800 |
| Laguna Yaguaru | −15.6000 | −63.2167 | SDTF | 50 |
| Parker | −12.1406 | −69.0215 | HERF | 224 |
| Santa Rosa | −14.4769 | −67.8747 | MEF | 68 |
| Vargas | −12.3725 | −68.8992 | HERF | 26 |
| Werth | −11.747 | −69.2336 | HERF | 86 |

Power, 2013; Whitlock and Larsen, 2001). Charcoal is analyzed in contiguous 1 cm intervals for the entire length of the sediment core at 1 $cm^3$ volume. Samples are treated with 5% potassium hydroxide in a hot water bath for 15 min. The residue is sieved through a 125 μm sieve. Macroscopic charcoal (particles >125 μm in minimum diameter) is counted in a gridded petri dish at 40 × magnification under a dissecting microscope. Charcoal counts are converted to charcoal influx (number of charcoal particles $cm^{-2}$ $yr^{-1}$) and charcoal accumulation rates by dividing by the deposition time (yr $cm^{-1}$). Charcoal influx data (particles per $cm^{-2}$ $yr^{-1}$) is used as an indicator of *fire severity* (the amount of biomass consumed during a fire episode or period of increased burning).

### 2.6. Statistical methods

To aid in the interpretation of charcoal influx data, a regime shift detection algorithm (RSI) based on a sequential t-test is applied to determine where statistically significant shifts in the charcoal influx data occur (Rodionov and Overland, 2005; Rodionov, 2005, 2004). Shifts are detected in both the mean fluctuations and the variance of raw charcoal counts. The algorithm for the variance is similar to that for the mean but based on a sequential F-test (Rodionov, 2005). RSI values are plotted against charcoal influx data to identify statistically significant changes in past fire regimes and interpreted as an indicator of changes in fire severity.

CHAR statistical software (Higuera et al., 2009) is used to decompose charcoal data to identify distinct charcoal peaks based on a standard set of threshold criteria. The background component reflected the low-frequency portion of the CHAR series that varied in response to changes in the rate of total charcoal production and secondary charcoal transport (Higuera et al., 2007). Background charcoal is modeled using a curve-fitting algorithm (Higuera et al., 2010). If charcoal influxes exceed the background threshold, they are considered a peak. Charcoal peaks are interpreted as a *fire episode* (a period of increased burning) because they cannot unambiguously be related to a single fire event (Brown and Power, 2013). The time difference between peaks is reflected in the fire return interval (*fire frequency*) for every 800 years. Estimates of fire frequency are obtained by summing and smoothing the peak series over a specified window width (Higuera et al., 2010).

Additionally, charcoal records are compiled from the Global Charcoal Database (GCD version 2.0) and analyzed using the paleofire R package software (version 1.1.8) (Blarquez et al., 2014). Twelve charcoal records between 16ºS and 11ºS and 61ºW to 70ºW that have greater than 20 charcoal samples are included in this analysis to create a RCC (Table 2, Fig. 1). The sites selected include a range of forest types from the Bolivian and Peruvian lowlands including savanna swamps, *cerrado* savannas, seasonally dry tropical forests, and humid tropical rainforests to provide an average of regional biomass burning during the Holocene. To facilitate intersite comparison, the twelve records are pretreated using standard protocol (Marlon et al., 2008; Power et al., 2008) for transforming and standardizing of individual records that includes: (1) transforming non-influx data (e.g. concentration particles $cm^{-3}$) to influx values (particle $cm^{-2}$ $yr^{-1}$), (2) homogenizing the variance using the Box-Cox transformation, (3) rescaling the values using a minimax transformation to allow comparisons among sites, and (4) rescaling the values to z-scores using a base period of 200 years. Sites are smoothed with a 300-year half width smoothing window and a bootstrap of 100 years (Blarquez et al., 2014). The GTMs are calculated using weighted spatiotemporal interpolation of transformed charcoal values at a defined distance from the grid cell center. Spatial grids are used to interpolate transformed charcoal values for key time periods with a 200-year time buffer with time grids at 10,000, 8,000, 6,000, 3,000, 2,000, 1,200, 700 and 200 cal yr BP with a cell size of 15,000 m and distance buffer of 50,000 m.

### 2.7. Compiled regional archaeology data from the Bolivian lowlands

The sum of the calibrated probability distributions (SPDs) can be a reliable method to assess relative population dynamics in the past (Shennan et al., 2013). SPDs are a standard method for representing chronological trends in radiocarbon datasets. They are produced by calibrating each independent date in the sample and adding the results to produce a single density distribution. This has the advantage of including the full range of probabilities associated with calibrated dates, instead of using single point estimates (Downey et al., 2016; Goldberg et al., 2016; >Shennan et al., 2013; Timpson et al., 2014; Zahid et al., 2016). Here, a total of 271 AMS dates are compiled from 38 archaeological sites (Table 3, SI) from the Bolivian lowlands (ca. 69° to 58° W, 9° S to 16° S). SPDs are built in OxCal and the IntCal13 calibration curve (Bronk Ramsey and Lee, 2013; Hogg et al., 2013). A binning procedure is applied to account for sites that have multiple dates within a phase (Goldberg et al., 2016; Shennan et al., 2013; Timpson et al., 2014). Dates within sites are ordered and those occurring within 100 years of each other are grouped into bins and merged. Each bin has a maximum width of 200 years. Timpson et al. (2014) found that different values for the bin-width did not affect the final shape of the SPD. The binning procedure is necessary to account for sampling bias across sites that have multiple dates obtained for a phase (bin window), as a sum of

Please cite this article in press as: Maezumi, S.Y., et al., Reassessing climate and pre-Columbian drivers of paleofire activity in the Bolivian Amazon, Quaternary International (2017), https://doi.org/10.1016/j.quaint.2017.11.053

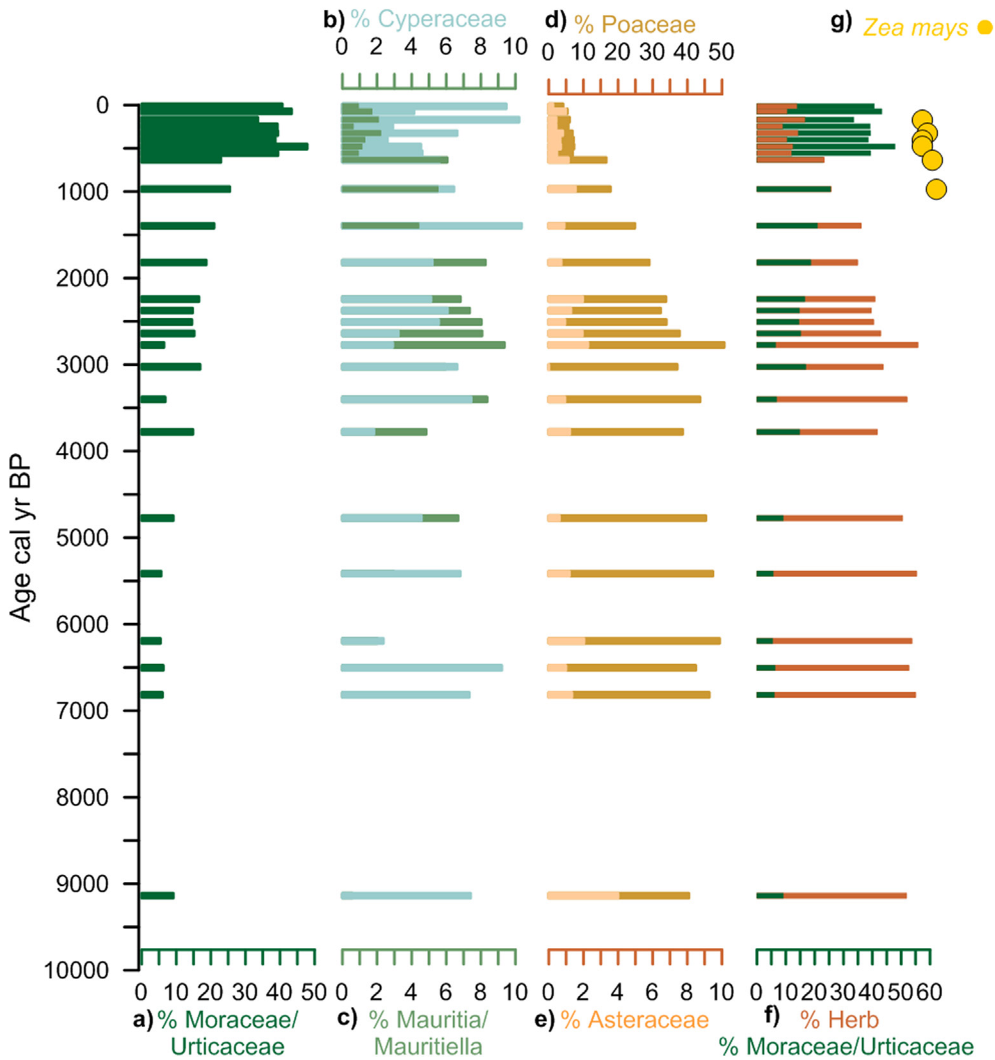


**Fig. 3.** Laguna Chaplin summary pollen percentage diagram showing herbs, palms and pollen indicative of rainforest (Moraceae/Urticaceae): a) % Moraceae/Urticaceae, b) % Mauritia/Mauritiella, c) % Cyperaceae, d) % Poaceae, e) % Asteraceae, f) % herb brown & % Moraceae/Urticaceae green, g) yellow circles indicate individual counts of *Zea mays*. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the calibrated dates assumes that observations are independent. Following the binning procedure, the final filtered dataset contains 150 dates. Despite the decrease in sample size, the filtered SPD is highly correlated with an SPD built with all radiocarbon dates ($r_s = 0.991$, $p < 0.001$). In addition to the SPD, a histogram of the number of occupied sites (site frequencies) is used as an additional proxy for human activity, based on the medians of the calibrated dates per 200-year intervals.

## 3. Results and interpretation

### 3.1. Crop cultivation at Laguna Chaplin

Pollen types from the original analysis are grouped into vegetation types and replotted using the new age model (Fig. 3). There is a time-transgressive ecotonal expansion of rainforest vegetation that replaces seasonally dry forest and savanna swamps after ca. 2000 cal yr BP ay LCH. Modern rainforest vegetation establishes at LCH ca. 650 cal yr BP (Burbridge et al., 2004) in response to increased precipitation during the late Holocene (Baker et al., 2001a,b; Mayle et al., 2000). *Z. mays* pollen is present between ca. 970 cal yr BP and ca. 170 cal yr BP but is absent in the uppermost two samples. Concentrations are very low throughout, thus are reported as the number of grains found in each sample. The presence of *Z. mays* indicates pre-Columbian maize cultivation is being practiced on the lake shore for at least the last ca. 1000 years.

### 3.2. Distinguishing local and regional fire signals

High resolution (HR) and low resolution (LR) charcoal influx data (number of charcoal particles cm $^{-2}$ yr $^{-1}$) are compared with the same core to evaluate the effects of sample resolution in reconstructing past biomass burning (Fig. 4). In this comparison, HR sampling more than doubled the number of particles at any given depth. This is likely the result of the inherent variability between the measurement methods and between the measurement biases made between different analysts, or a combination of both. During the middle-late Holocene (ca. 7000–5000 cal yr BP), the LR charcoal sampling conducted in the original analysis (Burbridge et al., 2004) identifies a slight increase in fire activity ca. 7000 cal yr BP. LR RSI values indicate higher fire activity than present. HR charcoal values indicate an increase ca. 5500 cal yr BP along with RSI values indicative of higher severity fire regimes. The lack of data points in the original LR sampling ca. 5000–1000 cal yr BP results in a shift in

Please cite this article in press as: Maezumi, S.Y., et al., Reassessing climate and pre-Columbian drivers of paleofire activity in the Bolivian Amazon, Quaternary International (2017), https://doi.org/10.1016/j.quaint.2017.11.053

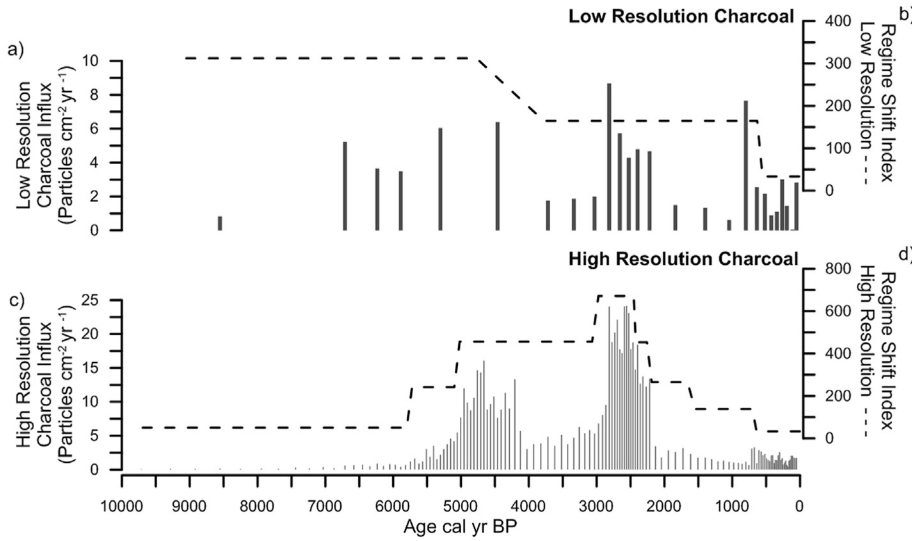


**Fig. 4.** Laguna Chaplin Low and High-Resolution Charcoal Influx: a) original low-resolution charcoal influx, b) low-resolution regime shift index, c) high-resolution charcoal influx, d) high-resolution regime shift index.

the RSI values towards less severe fire regimes ca. 5000 cal yr BP, whereas HR sampling indicates maximum charcoal influx (ca. 5000–2000 cal yr BP) with increasingly severe fire regime shifts at ca. 5000 and 3000 cal yr BP. This increase is captured in the LR record (ca. 2500 cal yr BP) but since there is only one data point in the LR sampling that reflected an increase during this period, the RSI values did not register a change in the fire regime. After ca. 2000 cal yr BP, HR influx values and RSI values decreased to lower severity fire regimes. The step changes that occur during the past two millennia are in phase with the expansion in rainforest pollen taxa associated with the non-fire adapted, less flammable humid rainforest vegetation. At ca. 700 cal yr BP both LR and HR charcoal records indicate decreased biomass burning and lower severity fire regimes, although charcoal is still present in both records.

HR Charcoal influx values reach highest values between ca. 5000 and 4000 cal yr BP and ca. 3000 to 2000 cal yr BP (Fig. 5). HR CHAR Analysis indicates the largest peak magnitude episodes occur ca. 5000 (ca. 5000 $cm^{-2}$ $peak^{-1}$) and 3000 cal yr BP (ca. ca. 9000 $cm^{-2}$ $peak^{-1}$; figures cropped from plotting). These episodes are synchronous with the onset of major increases charcoal influx data and are interpreted as increased fire severity. Fire frequency began increasing ca. 6000 cal yr BP and reached its highest point (2–3 episodes/1000 yrs) ca. 4000 cal yr BP. Combined with low charcoal influx values (ca. 4–8) and low peak magnitude, these data are interpreted as frequent, low-severity fire activity.

From ca. 2000–1000 cal yr BP charcoal influx decreases coupled with a decrease fire frequency (0–1 episodes/1000 yrs), synchronous with the decrease in seasonally dry forest vegetation and expansion of fire adverse, fire-intolerant humid rainforest vegetation. SPD values and archaeological site frequency data indicate an increase in human activity starting ca. 2000 cal yr BP reaching its apex ca. 600 cal yr BP. The data corroborate with *Z. mays* pollen that is first identified ca. 970 cal yr BP and continues to ca. 170 cal yr BP. After ca. 600 cal yr BP there is an increase in charcoal influx values and fire frequency (0–2 episodes/1000 yrs) that is synchronous with a compositional shift toward higher abundance of less flammable rainforest taxa shown by the increase Moraceae/Urticaceae pollen (>40%) indicating the complete establishment of humid rainforest vegetation around LCH.

The RCC (Fig. 5) indicates decreased regional biomass burning from ca. 10,000 to 6500 cal yr BP (ca. 1.5 to −1). There is an increase in RCC values ca. 6500 cal yr BP (ca. −1 to 0.5), synchronous with the decrease in regional precipitation (Fig. 5). These data correspond with the GTMs after ca. 6000 cal yr BP that indicate all sites across all forest types experience increased biomass burning at this time with the exception of Laguna Yaguarú and Huanchaca Mesetta (Fig. 6). The RCC indicates burning increased (ca. −0.5 to 0.5) until ca. 1500 cal yr BP, followed by a decrease in values (to ca. −0.5) to 1000 cal yr BP. There is an increase to ca. 0.4 at ca. 700 cal yr BP followed by a decrease in regional biomass burning to present. After ca. 700 cal yr BP the RCC correlates with the GTMs indicating decreased biomass burning across the region to present.

### 3.3. Regional pre-Columbian activity in the Bolivian lowlands

The 150 AMS-dates compiled from archaeological sites from the Bolivian lowlands indicate low human activity during the early Holocene (SPD values <0.009 and site frequency < 2). There is a slight increase ca. 6500 cal yr BP in SPDs (ca. 0.01) and site frequencies (ca. 3) that corresponds to a regional increase in burning indicated by the RCC values and a slight increase in charcoal influx values at LCH. Human activity and site frequencies begin to increase ca. 2000 to 1000 year ago (SPD values ca. 0.2, site frequency ca. 8), synchronous with the earliest documented evidence of *Z. mays* pollen at LCH. SPD values (ca. 0.3), indicate pre-Columbian activity reached its apex ca. 700 to 500 cal yr BP, coupled with the highest level of sites frequencies in the record (ca. 14). Maximum human activity corresponds to the expansion of Moraceae/Urticaceae pollen, the presence of *Z. mays* pollen, and increased fire activity at LCH coupled with the increase in RCC values indicating increased regional burning.

## 4. Discussion

### 4.1. Climate drivers of regional biomass burning

During the middle Holocene, the RCC and GTMs indicate increased fire across the Bolivian lowland across a range of vegetation types including savanna swamps, seasonally dry tropical forests and humid tropical rainforests. This synchronous increase in biomass burning after ca. 7500 cal yr BP suggests a common mechanism causing regionally consistent responses. The mid-

Please cite this article in press as: Maezumi, S.Y., et al., Reassessing climate and pre-Columbian drivers of paleofire activity in the Bolivian Amazon, Quaternary International (2017), https://doi.org/10.1016/j.quaint.2017.11.053

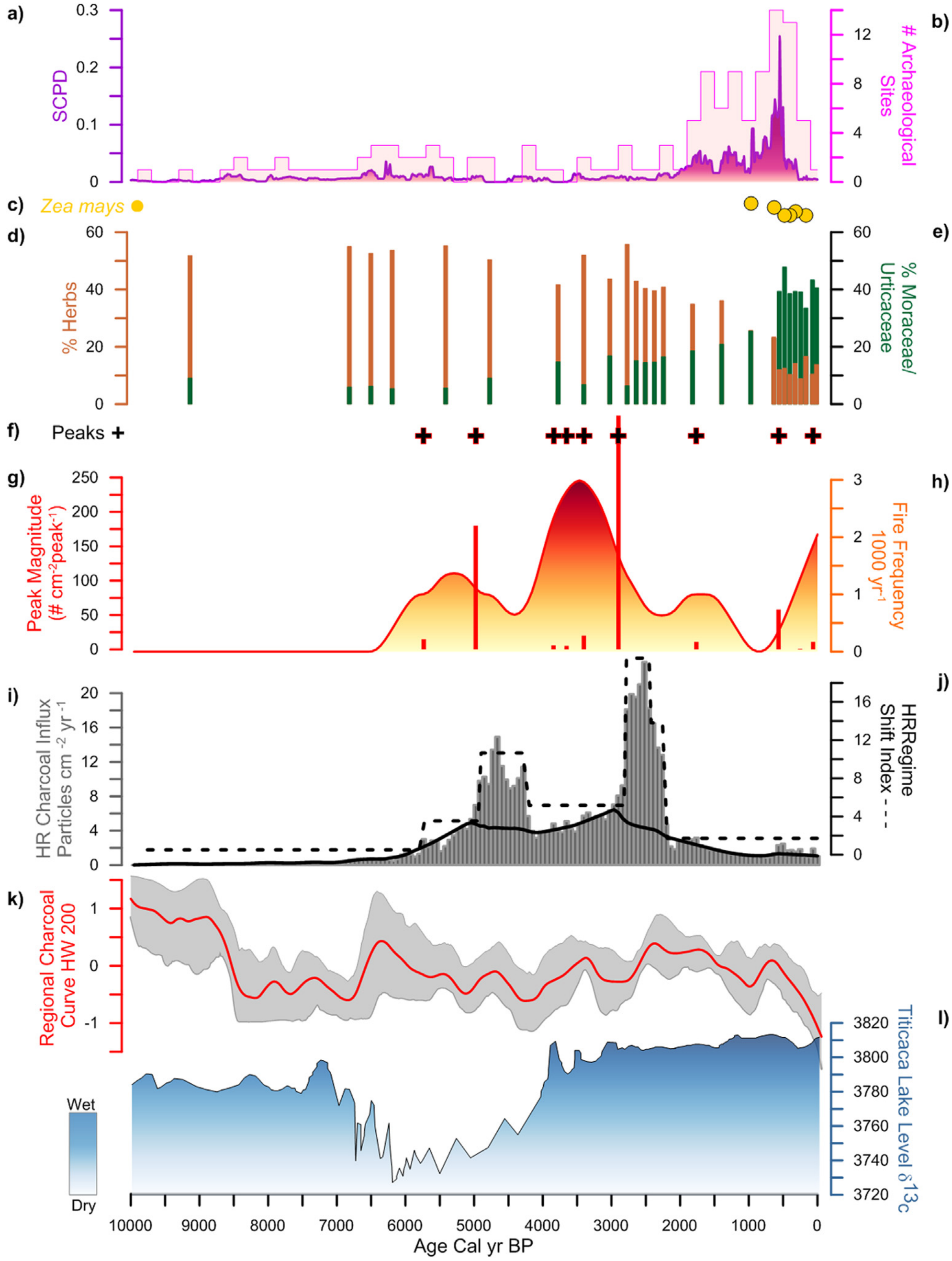


**Fig. 5.** Laguna Chaplin Holocene Summary: a) regional SPD curve, b) number of archaeological sites, c) individual *Zea mays* counts, d) % herbs in brown, e) % Moraceae/Urticaceae in green, f) CHAR peaks, g) peak magnitude (values at ca. 5000 and 3000 cal yr BP cropped for plotting (ca. 9000 and 5000 cm-2 peak-1 respectively), h) fire frequency, i) high-resolution charcoal influx, background black line is background, j) high-resolution regime shift index, k) regional charcoal curve (RCC) comprised from 12 records in the Global Charcoal Database, l) Titicaca δ13C lake level (Baker et al., 2001a,b). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Holocene dry event (MHDE, ca. 7000–4000 cal yr BP) has been well documented in the Peruvian and Bolivian lowlands (Abbott et al., 2003; Baker et al., 2001a,b; Cruz et al., 2005; Hanselman et al., 2005; Hillyer et al., 2009; Urrego et al., 2010; Valencia et al., 2010; Whitney et al., 2011). Previous studies correlate the decrease mid-Holocene precipitation with decreased Austral Summer Mean insolation which impacts the position of the South American low-pressure and convective systems (Abbott et al., 2003; Mayle et al., 2000; Seltzer et al., 2002). This results in an increase in the length and severity of the dry season. Existing sedimentary charcoal records from the Neotropics suggest that increased regional scale fire activity is associated with periods of high climate variability, including changes in moisture budgets and the intensification of seasonal droughts (Power et al., 2010a,b). Additionally, decreased dry-season precipitation (July–September) has recently been identified as a key factor in increased forest flammability during the 2005 and 2010 droughts in Amazonia (Brando et al., 2014). Similar decreases in precipitation are likely present during the MHDE driven by the increased length of the dry season (Urrego et al., 2013a,b). Longer, more severe dry seasons likely promoted the accumulation of dry fuels and increased fuel flammability in vegetation types including savanna swamps,

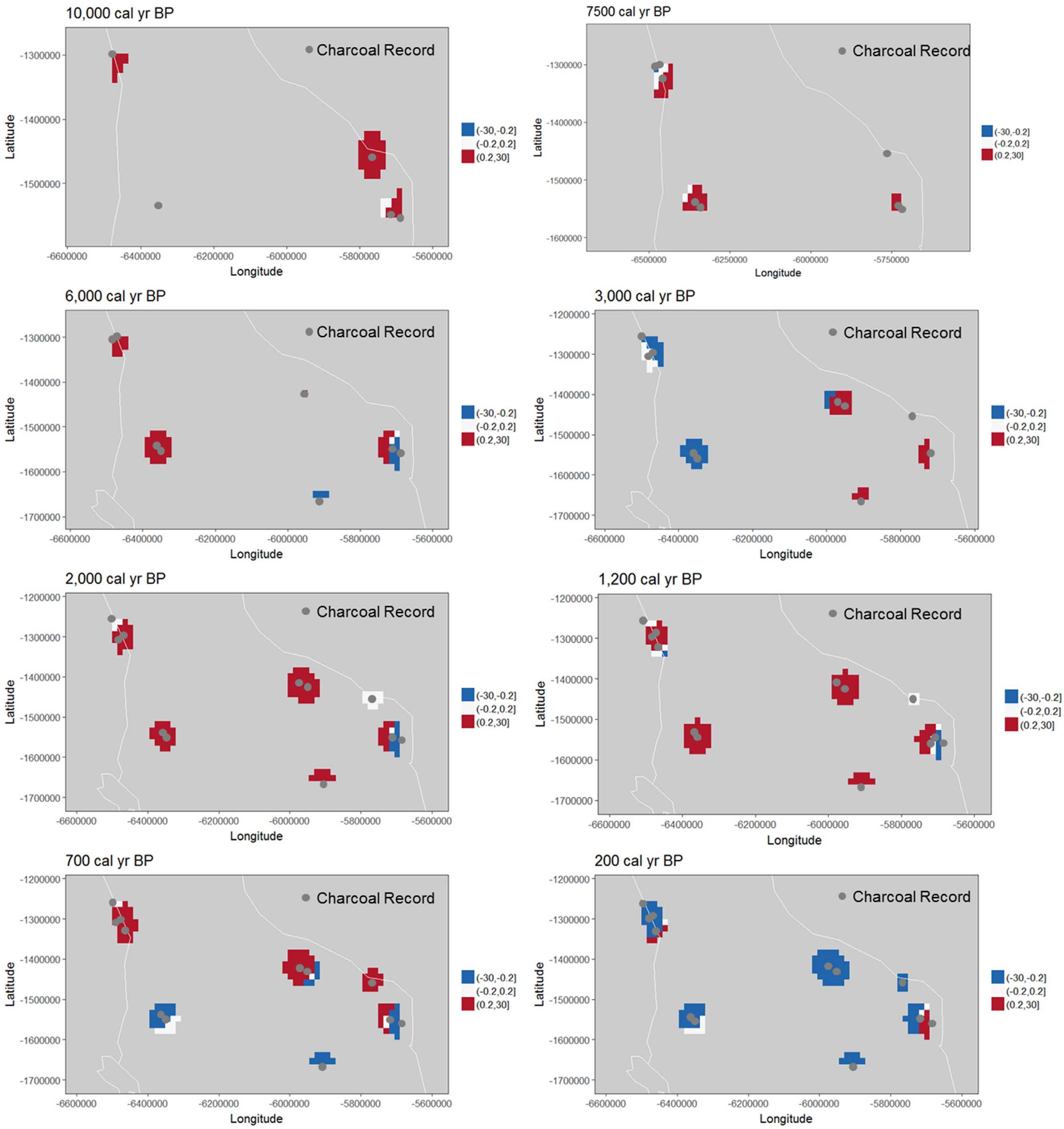


**Fig. 6.** Gridded Time Maps (GTMs) of Regional Biomass Burning. Charcoal records indicated by grey dots. Red indicates positive anomalies, blue indicates negative anomalies. The cell size is 15,000 m with a distance buffer of 50,000 m and time buffer is 200 years for selected time intervals. Existing charcoal records included in this study indicated by grey dots: Werth, Parker, Vargas, Gentry, Laguna Chalalán, Laguna Santa Rosa, Laguna Oricore, Laguna Granja, Laguna Bella Vista, Laguna Chaplin, Cuatro Vientos, Huanchaca Mesetta, and Laguna Yaguarú. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

seasonally dry tropical forest and humid tropical rainforests. The availability of abundant dry fuels likely contributed to increased lightning-caused fires during early wet-season convective thunderstorms (Ramos-Neto and Pivello, 2000). This period also corresponds with early evidence of *Z. mays* cultivation (ca. 6500 cal yr BP) in the *Llanos de Moxos*, ca.550 km NW of LCH (Brugger et al., 2016). SPD values and site frequencies indicate low levels of human activity in the region, thus it is not possible to rule out that these ignitions are human-caused. However, the synchronous regional response of fire coupled with the low levels of human activity, suggests the increase in the length and severity of the dry season is likely the first order driving mechanism for the increase in regional scale biomass burning in the Peruvian and Bolivian lowlands during the MHDE.

### 4.2. Human drivers of regional scale paleofire activity

After ca. 2000 cal yr BP, there is a regional increased biomass burning indicated by the RCC values and GTMs at all sites with the exception of Laguna Bella Vista and Huanchaca Mesetta (Figs. 6 and 7). Given its more northerly location, Laguna Bella Vista experienced an earlier vegetation transition (ca. 1500 cal yr BP) from seasonally dry tropical forest to humid tropical rainforest (Baker et al., 2001a,b; Burbridge et al., 2004; Mayle et al., 2000). The turnover from fire-tolerant, fire-adapted dry forest vegetation to fire-intolerant, fire-adverse rainforest vegetation likely results in decreased biomass burning first at Laguna Bella Vista and later at LCH (Fig. 6). It is difficult, however, to detect sub-millennial changes in fire and human activity at Laguna Bella Vista because of the low charcoal sample resolution (Table 2), and the lack human indicators. Huanchaca Mesetta (Maezumi et al., 2015) is located in the *cerrado* savanna on the remote Huanchaca Mesetta Plateau (ca. 40 km east of LCH, 1000 m a.s.l.). Throughout the past 15,000 years, the plateau has no evidence for human activity or indicators of crop cultivation, thus provides an example of a natural, climate-driven fire regime to compare with existing charcoal records with known human land-use histories. Previous interpretations from the Bolivian lowlands attribute the increase in late Holocene fire activity to human-caused ignitions at sites ranging from fire-tolerant, fire-adapted seasonally dry tropical forest (Laguna Chalalán, Laguna Santa Rosa; Urrego et al., 2013a,b) and mixed seasonally dry tropical forest-savanna swamps (Oricore and Granja; Carson et al., 2014), to fire-intolerant, fire-adverse humid tropical rainforests (Gentry, Parker, Vargas and Werth; Bush et al., 2007). Fire activity at Huanchaca Mesetta is asynchronous with the lowland sites, exhibiting low fire activity in tune with the wet, stable climate conditions during this period (Fig. 6). After ca. 2000 cal yr BP, 10 of the 12 sites included in this study attribute the increased fire activity to human-caused ignitions (Bush et al., 2007; Carson et al., 2014; Urrego et al., 2013a,b).

After ca. 700 cal yr BP, increased spatial variability in regional biomass burning (Fig. 6) corresponds to increased climate variability and the apex of pre-Columbian activity in the region (Fig. 7). Superimposed upon the progressively wet late Holocene climate trend are two brief climate events that occurred in NW Europe: the Medieval Climate Anomaly (MCA, ca. 900–1100 cal yr BP) and the Little Ice Age (LIA, ca. 200–400 cal yr BP). The MCA and LIA have been well documented in northern latitudes, but uncertainty remains as to the expression and spatial patterning of these climate events around the globe (Mann et al., 2009). New evidence of potential climate teleconnections between these high latitude events and the lowland southern hemisphere Neotropics has emerged from a new speleothem record from Mato Grosso (ca. 470 km east of LCH) (Novello et al., 2016). These data are interpreted by Novello et al. (2016) as anomalously dry MCA conditions and anomalously wet LIA conditions in the region. The onset of the MCA precedes the increase in regional biomass burning indicated by RCC values by ca. 400 years (Fig. 7). The increase in regional burning indicated by RCC values occurs during the transition between the MCA and LIA climate anomalies. This period also corresponds with a steady rise in SPD values and site frequencies indicating increased pre-Columbian activity that reaches its apex ca. 600 cal yr BP (Fig. 7). Fire activity remains high at sites with established histories of human land-use and fire management (e.g. Oricore, Granja, Gentry, Parker, Vargas and Werth, Fig. 7). Fire activity decreases at Laguna Chalalán, Laguna Santa Rosa, and Laguna Yaguarú, in tune with the progressive late Holocene expansion in fire adverse, fire-intolerant vegetation in response to the southward migration of the rainforest ecotone (Mayle et al., 2000; Taylor et al., 2010) and decrease in human activity around these sites. During the LIA, there is a synchronous decrease in biomass burning at all lowland sites that is likely the result of the combined factors of wetter than average climate conditions associated with the LIA (Novello et al., 2016) that would have increased fuel moisture and decreased fuel flammability, coupled with the pre-Columbian population decline following European contact due to disease (Denevan, 2012) that would have resulted in fewer human-caused ignitions (Fig. 7). Together these data provide a regional perspective of paleofire activity that suggests human-caused ignitions are the first order driving mechanism of increased regional scale fire activity in the Bolivian lowlands during the late Holocene.

### 4.3. Drivers of paleofire severity

Fire severity (i.e. the amount of biomass burned) is interpreted from the charcoal influx data as an approximation of the amount of biomass burned during a fire episode. Two severe fire episodes occur at LCH ca. 5000 and 3000 cal yr BP indicated by the highest influx and peak magnitude values in the record (Fig. 5). LCH is dominated by fire-adapted, fire-tolerant seasonally dry tropical forest vegetation when the first major episode occurs during the prolonged MHDE drought conditions. This extended dry period likely created conditions conducive for a major, stand-replacing fire episode on the landscape. Although low levels of human activity are documented in the region during this time, climate is more likely the driver of increased fire severity at LCH during the MHDE. The second major episode occurs ca. 3000 cal yr BP, (ca. 1000 years after the end of the MHDE) during relatively wet, stable climate conditions (Fig. 5). LCH continues to be dominated by fire-adapted, fire-tolerant seasonally dry tropical forest vegetation. The peak magnitude value (>ca. 9000 $cm^{-2}$ $peak^{-1}$; cropped for plotting) associated with this episode represents an anomalously large input of charcoal relative to the rest of the record. The relatively wet and stable climate conditions during this time, suggests a different mechanism driving such a significant increase in fire severity. The onset of human activity in the Amazon is often marked by a large spike in lake sediment charcoal (Bush et al., 2016). This pattern has been demonstrated at Lakes Ayauch (Bush and Colinvaux, 1988; McMichael et al., 2011), Gentry and Geral (Bush et al., 2007), Granja, (Carson et al., 2014), and La Yeguada (Bush et al., 1992). The initial increase in charcoal at LCH corresponds with the onset of increased human activity in the region indicated by the SPD values and site frequency data. Thus, it cannot be ruled out that this event is a large, deliberate, human-induced fire. Furthermore, the presence of both fire and crop pollen have been interpreted as firm evidence of human activity in the landscape (Bush et al., 2016, 2007; Carson et al., 2015; Iriarte et al., 2012). Although evidence for *Z. mays* cultivation is documented at numerous sites in the region during this period (Brugger et al., 2016; Bush et al., 2007; Bush and Colinvaux, 1988; McMichael et al., 2011), there is an absence of *Z. mays* pollen that dates to this second major fire episode at LCH. More data are needed to confirm the presence of human activity at LCH during this period to definitively attribute this major fire event to human ignitions. Given, however the relatively wet, stable climatic conditions, an explanation based on human-induced fire is more parsimonious.

### 4.4. Local scale paleofire management

It is important to note that there are uncertainties with regard to the temporal resolution of the age model from LCH ca. 2000 cal yr BP to present (only 2 AMS dates available, Table 2), resulting in some uncertainty over the temporal resolution that is possible to achieve. However, an AMS date at ca. 700 cal yr BP enables this period to be addressed with greater temporal resolution. At ca.

Please cite this article in press as: Maezumi, S.Y., et al., Reassessing climate and pre-Columbian drivers of paleofire activity in the Bolivian Amazon, Quaternary International (2017), https://doi.org/10.1016/j.quaint.2017.11.053

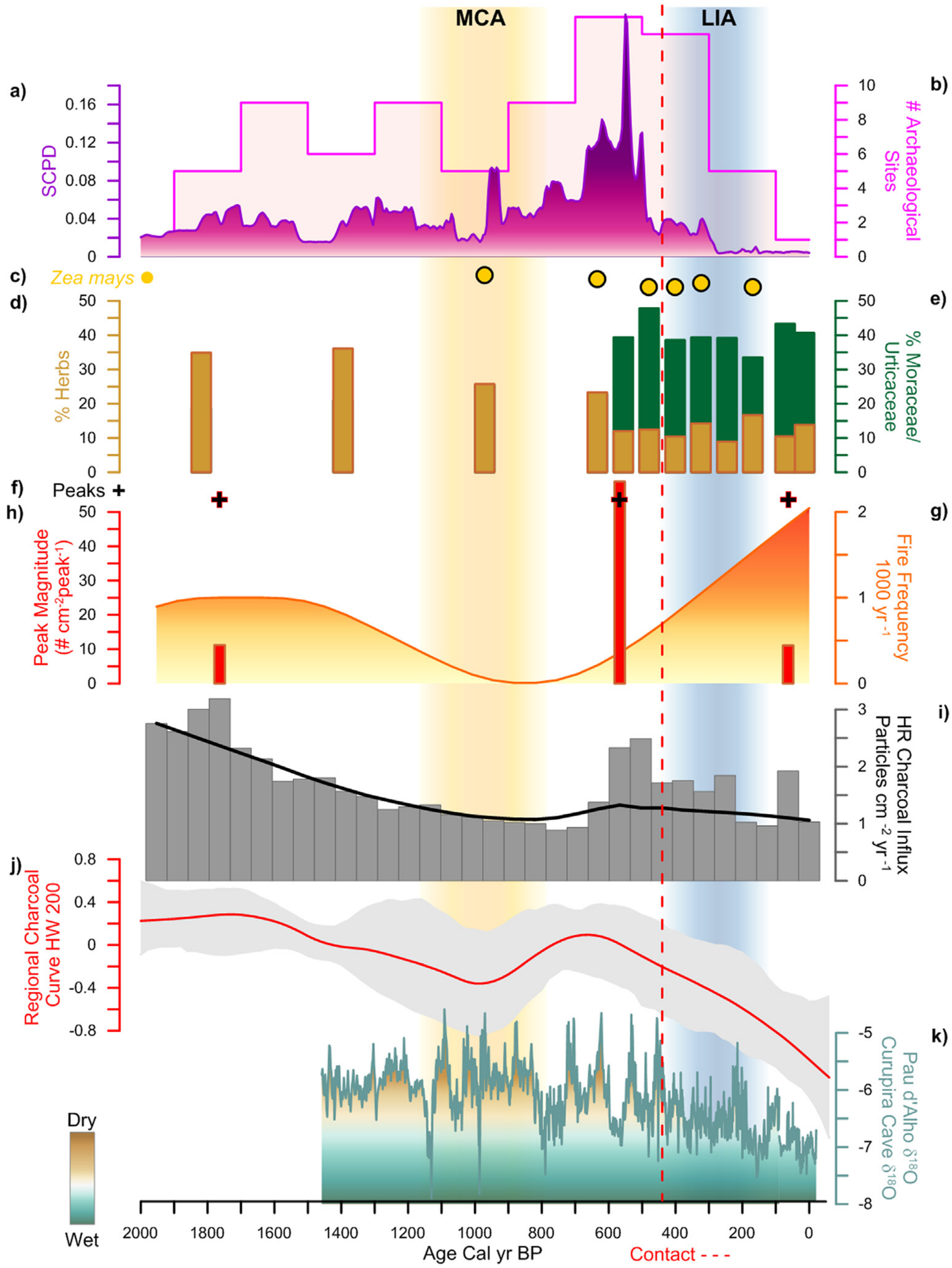


**Fig. 7.** Laguna Chaplin Late Holocene Summary: a) regional SPD curve, b) number of archaeological sites, c) individual *Zea mays* counts, d) % herbs in brown, e) % Moraceae/ Urticaceae in green, f) CHAR peaks, g) fire frequency, h) peak magnitude, i) high-resolution charcoal influx, background black line is background, j) regional charcoal curve (RCC) comprised from records in the Global Charcoal Database, k) Pau d'Alho Cave δ18O and Curupira Cave δ18O (Novello et al., 2016). Orange vertical shading represents the MCA and blue represents the LIA. Red dashed line indicates European contact (ca. 1492). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

700 cal yr BP, there is an increase in charcoal influx and fire frequency (fire episodes per 1000 yrs), and the highest peak magnitude event in the past 2000 years, simultaneous with a sharp increase in less flammable vegetation signaled by the increased in Moraceae/Urticaceae pollen (>50%) (Fig. 7). The increase in charcoal influx and peak magnitude values at LCH are not as substantial as the increases that occur during the middle Holocene; indicating a fire regime characterized by higher frequency (more fires per 1000 years), lower severity (less biomass burned) fire activity. The conversion from seasonally dry tropical forest to humid tropical rainforest vegetation at LCH is the result of the time-transgressive southward expansion of the rainforest ecotone driven by increased late Holocene precipitation (Baker et al., 2001a,b; Burbridge et al., 2004; Mayle et al., 2000). Today, natural fires are rare in humid rainforests unless under extended, extreme drought conditions due to high fuel moisture present in the rainforest vegetation (Bush et al., 2016; Cochrane, 2009). Fires in these forests are most often the result of human intervention for burning (Bush et al., 2007). Thus, the transition towards less fire-adapted rainforest vegetation should result in decreased biomass burning and

Please cite this article in press as: Maezumi, S.Y., et al., Reassessing climate and pre-Columbian drivers of paleofire activity in the Bolivian Amazon, Quaternary International (2017), https://doi.org/10.1016/j.quaint.2017.11.053

decreased fire frequency at LCH. However, the presence of *Z. mays* pollen ca. 970 cal yr BP to ca. 170 cal yr BP indicates pre-Columbians are present on the landscape, cultivating maize in the immediate vicinity of LCH. The use of low severity burning in slash and burn agriculture has been well documented in the ethnographic and archaeological record as a tool to clear land for agriculture and crop cultivation (Kleinman et al., 1995; Uhl, 1987). As vegetation begins to transition from more open seasonally dry forest to less open closed canopy humid rainforests ca. 500 cal yr BP, human-caused, low-severity fires are likely implemented to keep crop fields clear from encroaching rainforest vegetation. During this period, the pre-Columbian application of fire to manage the southward expansion of rainforest vegetation to clear land for crop cultivation is previously documented at Laguna Granja (ca. 370 km west of LCH) (Carson et al., 2014).

The continued presence of *Z. mays* at LCH until ca. 170 cal yr BP (Fig. 7), suggests that pre-Columbian populations did not immediately abandon maize cultivation at LCH following European contact (ca. 1492). The continued presence of *Z. mays* indicates this area does not experience immediate depopulation following the arrival of European settlers. Maize cultivation persists around LCH for a few centuries following European contact despite regional pre-Columbian population declines indicated from the SPD values and site frequency data. The interpretation of the continued pre-Columbian presence at LCH is supported by corroborating evidence of occupation following contact from Laguna San Jose (Whitney et al., 2013) and Laguna El Cerrito (Whitney et al., 2014) along with extensive archaeological evidence in the Bolivian lowlands (Carson et al., 2015; Dickau et al., 2012; Walker, 2011).

### 4.5. Extent of pre-Columbian disturbance in the Bolivian Amazon

During the last millennium, the data presented in this study indicate pre-Columbian fire management practices and *Z. mays* agriculture occur locally around LCH. It is important to note, however, that the use of fire management for *Z. mays* agriculture is only one type of pre-Columbian land-use practice that is readily detectable by the methods presented in this study. Alternative scenarios of pre-Columbian land-use modification involving the selection and enrichment of economically important native tree species over others have been suggested (Clement et al., 2015; Levis et al., 2017; Roosevelt, 2013). However, these types of land-use modifications are more difficult to detect using conventional paleoecological methods and the floristic changes associated with this type of selective forest management are not detectable using the available pollen data. Additionally, this type of forest enrichment does not necessitate the use of fire; therefore charcoal data are not necessarily indicative of human disturbance. More research is needed to interpret the broader scale regional impacts of the pre-Columbian populations including improved methodologies to detect enrichment economically important species coupled with archaeological surveys in the area. Irrespective of the type or duration of anthropogenic forest disturbance, it is not sufficient to prevent the climate-driven regional expansion of the humid evergreen rainforest ecotonal boundary to its most southern extent in the last 50,000 years (Burbridge et al., 2004; Mayle et al., 2000). This interpretation is supported by the neighboring sites of Laguna Granja and Laguna Oricore which demonstrate strong evidence of local-scale human disturbance against the backdrop of regional-scale climate-driven rainforest expansion (Carson et al., 2014).

## 5. Conclusions

Increased anthropogenic impacts in Amazonia have stimulated interest in the legacy of long-term (multi-millennial) pre-Columbian land-use practices in the Amazon. It has become evident that the investigation of pre-Columbian land-use practices necessitates different methodological approaches than conventional paleoecological studies. The reanalysis of LCH validates the use of a modified, high-resolution sampling methodology to disentangle climate versus human drivers of paleoecological change in the Bolivian Amazon. During the MHDE, increased fire activity at sites across a range of forest types suggests a common mechanism driving regionally consistent responses. Decreased precipitation associated with the MHDE is likely the first order driving mechanism of increased burning across the Bolivian lowlands. During the late Holocene, there is a regional increase biomass burning in tune with relatively wet, stable climate conditions across fire-tolerant to fire-intolerant sites with established histories of human land-use. These data suggest human-caused ignitions are the driving mechanism of regional scale fire activity across the Bolivian lowlands during the late Holocene. After ca. 650 cal yr BP, there is an increase in charcoal influx and fire frequency at LCH that is synchronous with the expansion of Moraceae/Urticaceae pollen (>50%) indicating the vegetation transition from flammable seasonally dry tropical forest to less flammable humid rainforest vegetation. The presence to *Z. mays* pollen indicates maize cultivation is being practiced around the lake ca. 970 cal yr BP to ca. 170 cal yr BP. It is likely that as vegetation begins to transition from more open, seasonally dry forest to closed canopy humid rainforests ca. 500 cal yr BP, human-caused, low-severity fires are used to keep crop fields clear from encroaching rainforest vegetation. Additionally, the presence of *Z. mays* at LCH until ca. 170 cal yr BP, suggests that pre-Columbian populations did not immediately abandon maize cultivation at LCH following European contact (ca. 1492). The continued presence of *Z. mays* potentially indicates this area did not experience immediate depopulation following contact or despite population declines, *Z. mays* cultivation persists around the lake. It is important to note that the pre-Columbian use of fire for agriculture is only one type of land-use. It is possible alternative methods such as agroforestry and forest enrichment were being practiced prior to the adoption of *Z. mays* agriculture; however, this type of forest modification is not detectable with the available pollen data. Regardless, the late Holocene establishment of humid rainforest vegetation coupled with the local and regional decease in biomass burning indicate the extent of pre-Columbian landscape modification and land-clearing for agriculture did not hinder the climate-driven regional decrease in biomass burning and expansion of the humid rainforest to its most southern extent in the last 50,000 years.

## Acknowledgements

Funding for research is supported in part by the ERC-PAST (Pre-Columbian Amazon-Scale Transformations) European Research Council (616179) awarded to JI. We thank Jonas Gregorio de Souza for the regional map. Special thanks to Tom Thompson and Chase Adams for their editorial assistance and to the anonymous reviewers for their comments and suggestions. Funding for FM to core Laguna Chaplin in 1998 is provided by a Royal Society Research Grant and a Royal Society Study Visit grant. We thank Tim Killeen and the Museo de Historia Natural "Noel Kempff Mercado", Santa Cruz, Bolivia, for providing logistical support, and in particular Lupita Sanchez and local guides (e.g., Juan Surubi) from the village of Florida for assistance with coring the site.

## Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.quaint.2017.11.053.

Please cite this article in press as: Maezumi, S.Y., et al., Reassessing climate and pre-Columbian drivers of paleofire activity in the Bolivian Amazon, Quaternary International (2017), https://doi.org/10.1016/j.quaint.2017.11.053

## References


Abbott, M.B., Wolfe, B.B., Wolfe, A.P., Seltzer, G.O., Aravena, R., Mark, B.G., Polissar, P.J., Rodbell, D.T., Rowe, H.D., Vuille, M., 2003. Holocene paleohydrology and glacial history of the central Andes using multiproxy lake sediment studies. Palaeogeogr. Palaeoclimatol. Palaeoecol. 194, 123–138.

Ali, A.A., Higuera, P.E., Bergeron, Y., Carcaillet, C., 2009. Comparing fire-history interpretations based on area, number and estimated volume of macroscopic charcoal in lake sediments. Quat. Res. 72, 462–468. https://doi.org/10.1016/j.yqres.2009.07.002.

Baker, P.A., Rigsby, C.A., Seltzer, G.O., Fritz, S.C., Lowenstein, T.K., Bacher, N.P., Veliz, C., 2001a. Tropical climate changes at millennial and orbital timescales on the Bolivian Altiplano. Nature 409, 698–701.

Baker, P.A., Seltzer, G.O., Fritz, S.C., Dunbar, R.B., Grove, M.J., Tapia, P.M., Cross, S.L., Rowe, H.D., Broda, J.P., 2001b. The history of South American tropical precipitation for the past 25,000 years. Science 291, 640–643.

Bennett, K.D., Willis, K.J., 2002. Pollen. In: Smol, J.P., Birks, H.J.B., Last, W.M. (Eds.), Tracking Environmental Change Using Lake Sediments: Terrestrial, Algal, and Siliceous Indicators. Kluwer Academic, Dordrecht, The Netherlands, pp. 5–32.

Berglund, B.E., 2003. Human impact and climate changes—synchronous events and a causal link? Quat. Int. 105, 7–12.

Blaauw, M., 2010. Methods and code for “classical” age-modelling of radiocarbon sequences. Quat. Geochronol. 5, 512–518.

Blarquez, O., Vannière, B., Marlon, J.R., Daniau, A.-L., Power, M.J., Brewer, S., Bartlein, P.J., 2014. Paleofire: an R package to analyse sedimentary charcoal records from the Global Charcoal Database to reconstruct past biomass burning. Comput. Geosci. 72, 255–261.

Brando, P.M., Balch, J.K., Nepstad, D.C., Morton, D.C., Putz, F.E., Coe, M.T., Silvério, D., Macedo, M.N., Davidson, E.A., Nóbrega, C.C., 2014. Abrupt increases in Amazonian tree mortality due to drought–fire interactions. Proc. Natl. Acad. Sci. 111, 6347–6352.

Brown, K.J., Power, M.J., 2013. Charred particle analyses. In: The Encyclopedia of Quaternary Science. Elsevier, Amsterdam, The Netherlands, pp. 716–729.

Brugger, S.O., Gobet, E., van Leeuwen, J.F.N., Ledru, M.-P., Colombaroli, D., van der Knaap, W.O., Lombardo, U., Escobar-Torrez, K., Finsinger, W., Rodrigues, L., 2016. Long-term man–environment interactions in the Bolivian Amazon: 8000 years of vegetation dynamics. Quat. Sci. Rev. 132, 114–128.

Burbridge, R.E., Mayle, F.E., Killeen, T.J., 2004. Fifty-thousand-year vegetation and climate history of Noel Kempff Mercado National Park, Bolivian Amazon. Quat. Res. 61, 215–230.

Bush, M.B., Colinvaux, P.A., 1988. A 7000-year pollen record from the Amazon lowlands. Ecuad. Plant Ecol. 76, 141–154.

Bush, M.B., Correa-Metrio, A., McMichael, C.H., Sully, S., Shadik, C.R., Valencia, B.G., Guilderson, T., Steinitz-Kannan, M., Overpeck, J.T., 2016. A 6900-year history of landscape modification by humans in lowland Amazonia. Quat. Sci. Rev. 141, 52–64.

Bush, M.B., De Oliveira, P.E., Colinvaux, P.a., Miller, M.C., Moreno, J.E., 2004. Amazonian paleoecological histories: one hill, three watersheds. Palaeogeogr. Palaeoclimatol. Palaeoecol. 214, 359–393.

Bush, M.B., Miller, M.C., Oliveira, P.E., De Colinvaux, P.A., 2000. Two Histories of Environmental Change and Human Disturbance in Eastern Lowland Amazonia, Vol. 5, pp. 543–553.

Bush, M.B., Piperno, D.R., Colinvaux, P.A., De Oliveira, P.E., Krissek, L.A., Miller, M.C., Rowe, W.E., 1992. A 14 300 Yr paleoecological profile of a lowland tropical lake in Panama. Ecol. Monogr. 62, 251–275.

Bush, M.B., Silman, M.R., de Toledo, M.B., Listopad, C., Gosling, W.D., Williams, C., de Oliveira, P.E., Krisel, C., 2007. Holocene fire and occupation in Amazonia: records from two lake districts. Philos. Trans. R. Soc. Lond. B. Biol. Sci. 362, 209–218.

Bush, M.B., Silman, M.R., McMichael, C., Saatchi, S., 2008. Fire, climate change and biodiversity in Amazonia: a Late-Holocene perspective. Philos. Trans. R. Soc. Lond. B. Biol. Sci. 363, 1795–1802. https://doi.org/10.1098/rstb.2007.0014.

Carson, J.F., Mayle, F.E., Whitney, B.S., Iriarte, J., Soto, J.D., 2016. Pre-Columbian ring ditch construction and land use on a “chocolate forest island”in the Bolivian Amazon. J. Quat. Sci. 31, 337–347.

Carson, J.F., Watling, J., Mayle, F.E., Whitney, B.S., Iriarte, J., Prümers, H., Soto, J.D., 2015. Pre-Columbian land use in the ring-ditch region of the Bolivian Amazon. The Holocene 25, 1285–1300.

Carson, J.F., Whitney, B.S., Mayle, F.E., Iriarte, J., Prümers, H., Soto, J.D., Watling, J., 2014. Environmental impact of geometric earthwork construction in pre-Columbian Amazonia. Proc. Natl. Acad. Sci. U. S. A. 111, 1–6.

Clement, C.R., de Cristo-Araújo, M., Coppens D'Eeckenbrugge, G., Alves Pereira, A., Picanço-Rodrigues, D., 2010. Origin and domestication of native Amazonian crops. Diversity 2, 72–106.

Clement, C.R., Denevan, W.M., Heckenberger, M.J., Junqueira, A.B., Neves, E.G., Teixeira, W.G., Woods, W.I., 2015. The domestication of Amazonia before European conquest. Proc. R. Soc. Lond. B Biol. Sci. 282.

Cochrane, M.A., 2009. Fire in the tropics. In: Tropical Fire Ecology. Springer, pp. 1–23.

Cochrane, M.A., 2003. Fire science for rainforests. Nature 421, 913–919.

Colinvaux, P.A., De Oliveira, P.E., Moreno, E., 1999. Amazon: Pollen Manual and Atlas. CRC Press.

Cruz, F.W., Karmann, I., Viana, O., Burns, S.J., Ferrari, J.a., Vuille, M., Sial, A.N., Moreira, M.Z., 2005. Stable isotope study of cave percolation waters in subtropical Brazil: implications for paleoclimate inferences from speleothems. Chem. Geol. 220, 245–262.

DaSilva Meneses, J.M.C., Bates, J.M., 2002. Biogeographic patterns and conservation in the South American cerrado: a tropical savanna hotspot. Bioscience 52, 225–234.

Denevan, W.M., 2012. Rewriting the late pre-European history of Amazonia. J. Lat. Am. Geogr. 11, 9–24.

Dickau, R., Bruno, M., Iriarte, J., 2012. Diversity of cultivars and other plant resources used at habitation sites in the Llanos de Mojos, Beni, Bolivia: evidence from macrobotanical remains, starch grains, and phytoliths. J. Archaeol. Sci. 39, 357–370.

Dickau, R., Whitney, B.S., Iriarte, J., Mayle, F.E., Soto, J.D., Metcalfe, P., Street-Perrott, F.A., Loader, N.J., Ficken, K.J., Killeen, T.J., 2013. Differentiation of neotropical ecosystems by modern soil phytolith assemblages and its implications for palaeoenvironmental and archaeological reconstructions. Rev. Palaeobot. Palynol. 193, 15–37.

Downey, S.S., Haas, W.R., Shennan, S.J., 2016. European Neolithic societies showed early warning signals of population collapse. Proc. Natl. Acad. Sci. 113 (35), 9751–9756.

Erickson, C.L., 2010. The transformation of environment into landscape: the historical ecology of monumental earthwork construction in the Bolivian Amazon. Diversity 2, 618–652.

Erickson, C.L., 2001. Pre-Columbian roads of the Amazon. Expedition 43, 21–30.

Erickson, C.L., Balée, W., 2006. The historical ecology of a complex landscape in Bolivia. In: Balee, W., Erickson, C.L. (Eds.), Time and Complexity in Historical Ecology: Studies in the Neotropical Lowlands. Columbia University Press, New York, NY, pp. 187–233.

Faegri, K., Iversen, J., 1989. Textbook of Pollen Analysis, Revised by Faegri K, Kaland PE. Krzywinski K. J Wiley, New York.

Gavin, D.G., Hu, F.S., Lertzman, K., Corbett, P., 2006. Weak climatic control of stand-scale fire history during the late holocene. Ecology 87, 1722–1732.

Glaser, B., Lehmann, J., Zech, W., 2002. Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal–a review. Biol. Fertil. Soils 35, 219–230.

Goldberg, A., Mychajliw, A.M., Hadly, E.A., 2016. Post-invasion demography of prehistoric humans in South America. Nature 532 (7598), 232–235.

Hanagarth, W., 1993. Acerca de la geoecología de las sabanas del Beni en el noreste de Bolivia. Instituto de Ecología, La Paz, Bolivia.

Hanselman, J.A., Gosling, W.D., Paduano, G.M., Bush, M.B., 2005. Contrasting pollen histories of MIS 5e and the Holocene from Lake Titicaca (Bolivia/Peru). J. Quat. Sci. 20, 663–670.

Heckenberger, M., Neves, E.G., 2009. Amazonian archaeology. Annu. Rev. Anthropol. 38, 251–266.

Heckenberger, M.J., 2008. The western Amazon's “Garden Cities”. Science 321, 1151–1151.

Heckenberger, M.J., Kuikuro, A., Kuikuro, U.T., Russell, J.C., Schmidt, M., Fausto, C., Franchetto, B., 2003. Amazonia 1492: pristine forest or cultural parkland? Science 301, 1710–1714.

Heusser, C.J., 1994. Paleoindians and fire during the late Quaternary in southern South America. Rev. Chil. Hist. Nat. 67, 435–443.

Higuera, P., Peters, M., Brubaker, L., Gavin, D., 2007. Understanding the origin and analysis of sediment-charcoal records with a simulation model. Quat. Sci. Rev. 26, 1790–1809.

Higuera, P.E., Brubaker, L.B., Anderson, P.M., Feng, S.H., Brown, Thomas, A., 2009. Vegetation mediated the impacts of postglacial climate change on fire regimes in the south-central Brooks Range, Alaska. Ecol. Monogr. 79, 201–219.

Higuera, P.E., Gavin, D.G., Bartlein, P.J., Hallett, D.J., 2010. Peak detection in sediment–charcoal records: impacts of alternative data analysis methods on fire-history interpretations. Int. J. Wildl. Fire 19, 996.

Hillyer, R., Valencia, B.G., Bush, M.B., Silman, M.R., Steinitz-Kannan, M., 2009. A 24,700-yr paleolimnological history from the Peruvian Andes. Quat. Res. 71, 71–82.

Hogg, A.G., Hua, Q., Blackwell, P.G., Niu, M., Buck, C.E., Guilderson, T.P., …, Reimer, R.W., 2013. SHCal13 Southern Hemisphere calibration, 0–50,000 years cal BP. Radiocarbon 55 (4), 1889–1903.

Holst, I., Moreno, J.E., Piperno, D.R., 2007. Identification of teosinte, maize, and Tripsacum in Mesoamerica by using pollen, starch grains, and phytoliths. Proc. Natl. Acad. Sci. U. S. A. 104, 17608–17613.

Iriarte, J., 2003. Assessing the feasibility of identifying maize through the analysis of cross-shaped size and three-dimensional morphology of phytoliths in the grasslands of southeastern South America. J. Archaeol. Sci. 30, 1085–1094.

Iriarte, J., Power, M.J., Rostain, S., Mayle, F.E., Jones, H., Watling, J., Whitney, B.S., McKey, D.B., 2012. Fire-free land use in pre-1492 Amazonian savannas. Proc. Natl. Acad. Sci. 109, 6473–6478.

Kato, M., 1998. Fire-free Land Preparation as an Alternative to Slash-and-burn Agriculture in the Bragantina Region, Eastern Amazon: Crop Performance and Phosphorus Dynamics. Cuvillier Verlag.

Killeen, T.J., 1998. Vegetation and flora of Parque Nacional Noel Kempff Mercado. In: Killeen, T.J., Schulenberg, T.S. (Eds.), A Biological Assessment of Parque Nacional Noel Kempff Mercado, Bolivia. Conservation International, Washington, DC, pp. 61–85.

Killeen, T.J., 1990. The grasses of Chiquitanía, Santa Cruz, Bolivia. Ann. Mo. Bot. Gard. 1, 125–201.

Killeen, T.J., Schulenberg, T.S., 1998. Vegetation and Flora of Noel Kempff Mercado National Park. A Biological Assessment of Parque Nacional Noel Kempff Mercado, Bolivia. RAP working papers 10. Conservation International, Washington,

DC.
Kleinman, P.J.A., Pimentel, D., Bryant, R.B., 1995. The ecological sustainability of slash-and-burn agriculture. Agric. Ecosyst. Environ. 52, 235–249.
Levis, C., Costa, F.R.C., Bongers, F., Peña-Claros, M., Clement, C.R., Junqueira, A.B., Neves, E.G., Tamanaha, E.K., Figueiredo, F.O.G., Salomão, R.P., 2017. Persistent effects of pre-Columbian plant domestication on Amazonian forest composition. Science 355, 925–931.
Lombardo, U., Canal-Beeby, E., Fehr, S., Veit, H., 2011. Raised fields in the Bolivian Amazonia: a prehistoric green revolution or a flood risk mitigation strategy? J. Archaeol. Sci. 38, 502–512.
Maezumi, S.Y., Power, M.J., Mayle, F.E., McLauchlan, K., Iriarte, J., 2015. The effects of past climate variability on fire and vegetation in the cerrãdo savanna ecosystem of the Huanchaca Mesetta, Noel Kempff Mercado National Park, NE Bolivia. Clim. Past. Discuss. 11, 135–180.
Mann, C.C., 2008. Ancient earthmovers of the Amazon. Science 321, 1148–1152.
Mann, M.E., Zhang, Z., Rutherford, S., Bradley, R.S., Hughes, M.K., Shindell, D., Ammann, C., Faluvegi, G., Ni, F., 2009. Global signatures and dynamical origins of the Little ice age and medieval climate anomaly. Science 326, 1256–1260.
Marlon, J.R., Bartlein, P.J., Carcaillet, C., Gavin, D.G., Harrison, S.P., Higuera, P.E., Joos, F., Power, M.J., Prentice, I.C., 2008. Climate and human influences on global biomass burning over the past two millennia. Nat. Geosci. 1, 697–702.
Marlon, J.R., Bartlein, P.J., Daniau, A., Harrison, S.P., Maezumi, S.Y., Power, M.J., Tinner, W., Vanniére, B., 2013. Global biomass burning: a synthesis and review of Holocene paleofire records and their controls. Quat. Sci. Rev. 65, 5–25.
Mayle, F.E., Burbridge, R.E., Killeen, T.J., 2000. Millennial-scale dynamics of southern Amazonian rain forests. Science 290, 2291–2294.
Mayle, F.E., Iriarte, J., 2012. Integrated palaeoecology and archaeology – a powerful approach for understanding pre-Columbian Amazonia. J. Archaeol. Sci. 1–11.
McCormac, F.G., Hogg, A.G., Blackwell, P.G., Buck, C.E., Higham, T.F.G., Reimer, P.J., 2004. SHCAL04 southern hemisphere calibration, 0-11.0 cal KYR BP. Radiocarbon 46, 1087–1092.
McMichael, C.H., Bush, M.B., Piperno, D.R., Silman, M.R., Zimmerman, A.R., Anderson, C., 2011. Spatial and temporal scales of pre-Columbian disturbance associated with western Amazonian lakes. The Holocene 22, 131–141.
McMichael, C.H., Piperno, D.R., Bush, M.B., Silman, M.R., Zimmerman, A.R., Raczka, M.F., Lobato, L.C., 2012. Sparse pre-Columbian human habitation in western Amazonia. Science 336, 1429–1431.
Mistry, J., 1998. Fire in the Cerrado (savannas) of Brazil: an ecological review. Prog. Phys. Geogr. 22, 425–448.
Montes de Oca, I., 1982. Geografía y recursos naturales de Bolivia, third ed. Edobol, La Paz, Bolivia.
Novello, V.F., Vuille, M., Cruz, F.W., Stríkis, N.M., de Paula, M.S., Edwards, R.L., Cheng, H., Karmann, I., Jaqueto, P.F., Trindade, R.I.F., 2016. Centennial-scale solar forcing of the south american monsoon system recorded in stalagmites. Sci. Rep. 6.
Oguntunde, P.G., Fosu, M., Ajayi, A.E., Van De Giesen, N., 2004. Effects of charcoal production on maize yield, chemical properties and texture of soil. Biol. Fertil. Soils 39, 295–299.
Pärssinen, M., Schaan, D., 2009. Pre-Columbian geometric earthworks in the upper Purus: a complex society in western Amazonia. Antiquity 83, 1084–1095.
Piperno, D.R., McMichael, C., Bush, M.B., 2015. Amazonia and the Anthropocene: what was the spatial extent and intensity of human landscape modification in the Amazon Basin at the end of prehistory? The Holocene 25, 1588–1597.
Power, M.J., Bush, M.B., Behling, H., Horn, S.P., Mayle, F.E., Urrego, D.H., 2010a. Paleofire activity in tropical America during the last 21 ka: a regional synthesis based on sedimentary charcoal. Pages 18, 4–6.
Power, M.J., Marlon, J., Ortiz, N., Bartlein, P.J., Harrison, S.P., Mayle, F.E., Ballouche, A., Bradshaw, R.H.W., Carcaillet, C., Cordova, C., Mooney, S., Moreno, P.I., Prentice, I.C., Thonicke, K., Tinner, W., Whitlock, C., Zhang, Y., Zhao, Y., Ali, A.A., Anderson, R.S., Beer, R., Behling, H., Briles, C., Brown, K.J., Brunelle, A., Bush, M., Camill, P., Chu, G.Q., Clark, J., Colombaroli, D., Connor, S., Daniau, A.-L., Daniels, M., Dodson, J., Doughty, E., Edwards, M.E., Finsinger, W., Foster, D., Frechette, J., Gaillard, M.-J., Gavin, D.G., Gobet, E., Haberle, S., Hallett, D.J., Higuera, P., Hope, G., Horn, S., Inoue, J., Kaltenrieder, P., Kennedy, L., Kong, Z.C., Larsen, C., Long, C.J., Lynch, J., Lynch, E. a., McGlone, M., Meeks, S., Mensing, S., Meyer, G., Minckley, T., Mohr, J., Nelson, D.M., New, J., Newnham, R., Noti, R., Oswald, W., Pierce, J., Richard, P.J.H., Rowe, C., Sanchez Goñi, M.F., Shuman, B.N., Takahara, H., Toney, J., Turney, C., Urrego-Sanchez, D.H., Umbanhowar, C., Vandergoes, M., Vanniere, B., Vescovi, E., Walsh, M., Wang, X., Williams, N., Wilmshurst, J., Zhang, J.H., 2008. Changes in fire regimes since the Last Glacial Maximum: an assessment based on a global synthesis and analysis of charcoal data. Clim. Dyn. 30, 887–907.
Power, M.J., Marlon, J.R., Bartlein, P.J., Harrison, S.P., 2010b. Fire history and the Global Charcoal Database: a new tool for hypothesis testing and data exploration. Palaeogeogr. Palaeoclimatol. Palaeoecol. 291, 52–59.
Ramos-Neto, M.B., Pivello, V.R., 2000. Lightning fires in a Brazilian savanna National Park: Rethinking management strategies. Environ. Manag. 26, 675–684.
Ramsey, C.B., Lee, S., 2013. Recent and planned developments of the program OxCal. Radiocarbon 55 (2–3), 720–730.
Roche, M.A., Rocha, N., 1985. Precipitacioes anuales. Programa climatólogico e hidrológico de la Cuenca Amazónica Boliviana (PHICAB). Servicio Nacional de Meteologia e Hidrologia (SENAHMHI), La Paz, Bolivia.
Rodionov, S., Overland, J.E., 2005. Application of a sequential regime shift detection method to the Bering Sea ecosystem. ICES J. Mar. Sci. J. Du. Cons. 62, 328–332.
Rodionov, S.N., 2005. A sequential method for detecting regime shifts in the mean and variance. Large-Scale Disturbances (Regime Shifts) Recover. Aquat. Ecosyst. Challenges Manag. Towar. Sustain. 68–72.
Rodionov, S.N., 2004. A sequential algorithm for testing climate regime shifts. Geophys. Res. Lett. 31.
Roosevelt, A.C., 2013. The Amazon and the Anthropocene: 13,000 years of human influence in a tropical rainforest. Anthropocene 4, 69–87.
Seltzer, G.O., Rodbell, D.T., Baker, P.A., Fritz, S.C., Tapia, P.M., Rowe, H.D., Dunbar, R.B., 2002. Early warming of tropical South America at the last glacial-interglacial transition. Science 296, 1685–1686.
Shennan, S., Downey, S.S., Timpson, A., Edinborough, K., Colledge, S., Kerig, T., Manning, K., Thomas, M.G., 2013. Regional population collapse followed initial agriculture booms in mid-Holocene Europe. Nat. Commun. 4.
Steiner, C., Teixeira, W.G., Lehmann, J., Nehls, T., de Macêdo, J.L.V., Blum, W.E.H., Zech, W., 2007. Long term effects of manure, charcoal and mineral fertilization on crop production and fertility on a highly weathered Central Amazonian upland soil. Plant Soil 291, 275–290.
Stuiver, M., Reimer, P.J., Bard, E., Beck, J.W., Burr, C.S., Hughen, K.A., Kromer, B., McCormac, G., Plicht, J., van der Spurk, M., 1998. ARTICLES-INTCAL98 radiocarbon age calibration, 24,000-0 cal BP. Radiocarbon Int. J. Cosmogenic Isot. Res. 40, 1041–1084.
Taylor, Z.P., Horn, S.P., Mora, C.I., Orvis, K.H., Cooper, L.W., 2010. A multi-proxy palaeoecological record of late-Holocene forest expansion in lowland Bolivia. Palaeogeogr. Palaeoclimatol. Palaeoecol. 293, 98–107. https://doi.org/10.1016/j.palaeo.2010.05.004.
Timpson, A., Colledge, S., Crema, E., Edinborough, K., Kerig, T., Manning, K., …, Shennan, S., 2014. Reconstructing regional population fluctuations in the European Neolithic using radiocarbon dates: a new case-study using an improved method. J. Archaeol. Sci. 52, 549–557.
Thomas, E., Alcázar Caicedo, C., McMichael, C.H., Corvera, R., Loo, J., 2015. Uncovering spatial patterns in the natural and human history of Brazil nut (Bertholletia excelsa) across the Amazon Basin. J. Biogeogr. 42, 1367–1382.
Turner, B.L., 1995. Global Land Use Change: a Perspective from the Columbian Encounter. Editorial CSIC-CSIC Press.
Uhl, C., 1987. Factors controlling succession following slash-and-burn agriculture in Amazonia. J. Ecol. 377–407.
Urrego, D.H., Bush, M.B., Silman, M.R., 2010. A long history of cloud and forest migration from Lake Consuelo, Peru. Quat. Res. 73, 364–373. https://doi.org/10.1016/j.yqres.2009.10.005.
Urrego, D.H., Bush, M.B., Silman, M.R., Niccum, B.A., De La Rosa, P., McMichael, C.H., Hagen, S., Palace, M., 2013a. Holocene fires, forest stability and human occupation in south-western Amazonia. J. Biogeogr. 40, 521–533.
Urrego, D.H., Bush, M.B., Silman, M.R., Niccum, B.A., La Rosa, P., McMichael, C.H., Hagen, S., Palace, M., 2013b. Holocene fires, forest stability and human occupation in south-western Amazonia. J. Biogeogr. 40, 521–533.
Urrego, D.H., Silman, M.R., Bush, M.B., 2005. The Last Glacial Maximum: stability and change in a western Amazonian cloud forest. J. Quat. Sci. 20, 693–701.
Valencia, B.G., Urrego, D.H., Silman, M.R., Bush, M.B., 2010. From ice age to modern: a record of landscape change in an Andean cloud forest. J. Biogeogr. 37, 1637–1647.
Vuille, M., Burns, S.J., Taylor, B.L., Cruz, F.W., Bird, B.W., Abbott, M.B., Kanner, L.C., Cheng, H., Novello, V.F., 2012. A review of the South American monsoon history as recorded in stable isotopic proxies over the past two millennia. Clim. Past. 8, 1309–1321.
Walker, J.H., 2011. Amazonian Dark Earth and Ring Ditches in the Central Llanos de Mojos, Bolivia. Cult. Agric. Food Environ. 33, 2–14.
Whitlock, C., Larsen, C., 2001. Charcoal as a fire proxy. In: Tracking Environmental Change Using Lake Sediments. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 75–97.
Whitlock, C., Moreno, P.I., Bartlein, P., 2007. Climatic controls of Holocene fire patterns in southern South America. Quat. Res. 68, 28–36.
Whitney, B.S., Dickau, R., Mayle, F.E., Soto, J.D., Iriarte, J., 2013. Pre-Columbian landscape impact and agriculture in the Monumental Mound region of the Llanos de Moxos, lowland Bolivia. Quat. Res. 80, 207–217.
Whitney, B.S., Dickau, R., Mayle, F.E., Walker, J.H., Soto, J.D., Iriarte, J., 2014. Pre-Columbian raised-field agriculture and land use in the Bolivian Amazon. The Holocene 24, 231–241.
Whitney, B.S., Mayle, F.E., Punyasena, S.W., Fitzpatrick, K.A., Burn, M.J., Guillen, R., Chavez, E., Mann, D., Pennington, R.T., Metcalfe, S.E., 2011. A 45kyr palaeoclimate record from the lowland interior of tropical South America. Palaeogeogr. Palaeoclimatol. Palaeoecol. 307, 177–192.
Whitney, B.S., Rushton, E.A., Carson, J.F., Iriarte, J., Mayle, F.E., 2012. An improved methodology for the recovery of Zea mays and other large crop pollen, with implications for environmental archaeology in the Neotropics. The Holocene 22, 1087–1096.
Willis, K.J., Gillson, L., Brncic, T.M., 2005. How "virgin" is virgin rainforest?, vol. 826, pp. 2003–2004.
Zahid, H.J., Robinson, E., Kelly, R.L., 2016. Agriculture, population growth, and statistical analysis of the radiocarbon record. Proc. Natl. Acad. Sci. 113 (4), 931–935.

Please cite this article in press as: Maezumi, S.Y., et al., Reassessing climate and pre-Columbian drivers of paleofire activity in the Bolivian Amazon, Quaternary International (2017), https://doi.org/10.1016/j.quaint.2017.11.053