1 **A 6900-year history of landscape modification by humans in lowland Amazonia.**

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Abstract

A sedimentary record from the Peruvian Amazon provided evidence of climate and vegetation change for the last 6900 years. Piston cores collected from the center of Lake Sauce, a 20 m deep lake at 600 m elevation, were 19.7 m in length. The fossil pollen record showed a continuously forested catchment within the period of the record, although substantial changes in forest composition were apparent. Fossil charcoal, found throughout the record, was probably associated with humans setting fires. Two fires, at c. 6700 cal BP and 4270 cal BP, appear to have been stand-replacing events possibly associated with megadroughts. The fire event at 4270 cal BP followed a drought that caused lowered lake levels for several centuries. The successional trajectories of forest recovery following these large fires were prolonged by smaller fire events. Fossil pollen of *Zea mays* (cultivated maize) provided evidence of agricultural activity at the site since c. 6320 cal BP. About 5150 years ago, the lake deepened and started to deposit laminated sediments. Maize agriculture reached a peak of intensity between c. 3380 and 700 cal BP. Fossil diatom data provided a proxy for lake nutrient status and productivity, both of which peaked during the period of maize cultivation. A marked change in land use was evident after c. 700 cal BP when maize agriculture was apparently abandoned at this site. *Iriarteia*, a hyperdominant of riparian settings in western Amazonia, increased in abundance within the last 1100 years, but declined markedly at c. 1070 cal BP and again between c. 80 and - 10 cal BP.

Keywords: Agriculture, Fossil charcoal, Fossil Pollen, Fossil diatoms, Human disturbance, *Iriarteia*, Maize, *Mauritia*, Forest enrichment, Pre-Columbian

Introduction

Climate change and human activity have had profound influences on forests in many regions of Amazonia. The early- to mid-Holocene was drier than the modern Amazonian climate (Mayle et al., 2000). Since the mid-Holocene, however, there has been an overall tendency toward wetter environments and an increase in the spatial extensiveness and temporal frequency of human disturbance (Mayle et al., 2000; Mayle and Power, 2008; Neves and Petersen, 2006). The arrival of Europeans and their diseases in the 1500s led to a >90% reduction in Amazonian populations (Denevan, 2003; Dobyns, 1966; Newson, 1996), though there is little agreement on pre-European population estimates (e.g. Bush et al., 2015a; Bush and Silman, 2007; Clement et al., 2015). After the population collapse, a new wave of settlers arrived in Amazonia during the Rubber Boom from 1850-1920 A.D. (e.g. Weinstein, 1983). Over the last century, transmigration policies have further increased environmental impacts (Hecht and Cockburn, 1989).

At finer spatial and temporal scales, the development of ancient Amazonian cultures has been seen to be heterogeneous, as have the impacts of climate change. It has been suggested that indigenous cultures were influenced by a c. 200-year periodicity of climatic events (Meggers, 1994; Schimmelman et al., 2003). Regardless of whether such a periodicity exists, the potential for unusually large climatic events to occur is evident by two ‘droughts of the century’ (2005 and 2010) that occurred within a decade (e.g. Aragão et al., 2007; Marengo et al., 2011). It is also apparent from those events that the influence of large climatic pulses may also be heterogeneous in their effect across the Amazon Basin. The full ecological impact of such large climate events is poorly understood. It is

clear, however, that tree mortality in fragmented habitats is greater than in intact ones (Asner and Alencar, 2010; Laurance and Williamson, 2001; Nepstad et al., 2007), and that if fire results, it induces long-lasting changes that reverberate through the ecosystem far longer than the duration of the event itself (Barlow and Peres, 2008; Cochrane and Laurance, 2002).

The successional recovery post-disturbance depends on the magnitude of the disturbance and also the conditions under which recovery is taking place. Successional chronosequences from new succession, e.g. regrowth along newly accreted river shorelines appear to take c. 200-300 years to reach maturity (Foster, 1990). All forests experience natural disturbance, such that a mosaic of regrowth stages exists within an old growth terra firme forest (Chambers et al., 2013; Richards, 1996). Most of the loss of above ground biomass comes in small disturbances, e.g. $>20\text{m}^2$ canopy gaps, with very little occurring as a result of large disturbance events, e.g. 5 - >30 ha blow downs (Espírito-Santo et al., 2014). These smallest gaps do not allow enough light to reach the forest floor to start a new succession (Hubbell et al., 1999), hence it is the rarer larger gaps that could influence the composition of a forest. Succession in such large gaps or following fire would be expected to follow the classic sequence of pioneers and light-demanding species progressively giving way to shade-tolerant competitors.

Amazonian climatic variability and human activity in the Mid- and Late-Holocene

Human colonization of the Andes and Amazonia approximately coincided with the onset of the Holocene (Dillehay et al., 2008; Roosevelt et al., 1996). Across the span of the Holocene, Amazonian and Andean climates were strongly influenced by precessional forcing (Baker et al., 2001; Bush et al., 2002), such that, on a millennial

scale, at the nadir of wet season insolation lake levels tended to be low (Baker et al., 2001; Bird et al., 2011). For the tropical southern hemispheric Andes and western Amazonia, a drought-prone period began c. 9000 cal BP, peaked at c. 5500 cal BP, and ended c. 4000 cal BP (Abbott et al., 1997; Ekdahl et al., 2008). A complex series of droughts formed what has become known as the ‘Mid-Holocene dry event’. In Bolivia and Peru, lake levels began rising c. 4000 cal BP, and continued to rise until c. 3300 cal BP or 2500 cal BP, according to location (Abbott et al., 1997; Hillyer et al., 2009; Mosblech et al., 2012). This pattern was reproduced in the speleothem calcite record from the Tigre Perdido Cave (van Breukelen et al., 2008), which revealed the last 3000 years to have been considerably wetter than the mid-Holocene, with slight fluctuations at multi-centennial to millennial scales.

A basic trajectory of human occupation of western Amazonia

Humans have lived within lowland Amazonia for the entire Holocene (Roosevelt et al., 1996), although their role in shaping the forest is contentious (Bush et al., 2015a; Clement et al., 2015; Roosevelt, 2013). In western Amazonia, the earliest evidence of human occupation is the presence of shell middens at c. 10,000 cal BP in the Bolivian Llanos (Lombardo et al., 2013), while the earliest known agriculture is the occurrence of maize pollen in the sediments of the Llanos de Moxos at c. 6500 cal BP (Brugger et al., 2016) (Fig. 1). After that time, there is increasing evidence of people occupying western Amazonia, especially in riverine and lakeside settings (Bush et al., 2007a; Bush and Silman, 2007; Denevan, 1996; Urrego et al., 2013).

Between 3000 and 2000 cal BP agricultural activity expanded in many parts of Amazonia (Piperno, 2006). This expansion was a manifestation of a longer-term shift from hunter-gatherer to increasingly settled communities. Intensified agricultural effort coincided with the formation of anthropogenic soils, known as *terras pretas* or Amazonian black earths, in central and eastern Amazonia (Glaser and Birk, 2012; Glaser and Woods, 2004; Neves et al., 2004), the development of complex societies in the upper Xingu and Marajó Island (Heckenberger et al., 2008; Roosevelt, 1991), geoglyph construction in southwestern Amazonia (Pärssinen et al., 2009; Schaaf et al., 2012), and large-scale landscape transformation in the seasonal wetlands of Bolivian Amazonia (Erickson, 2000). Although the scale of human disturbance of Amazonian landscapes is actively debated (Balée, 2010; Bush et al., 2015a; Clement et al., 2015; McMichael et al., 2015), long-term human occupation and landscape modification was most likely to occur besides lakes and rivers (Denevan, 1996).

A lack of reliable historical accounts of Amazonian populations and landscape at the time of European contact has allowed a range of hypotheses to co-exist regarding the environmental impact of pre-Columbian populations. The extent to which these pre-Columbian populations influenced Amazonian ecology, particularly patterns of alpha and beta diversity, is contentious. Meggers (1954, 2007) argued that Amazonian peoples were environmentally determined, due to harsh climatic conditions and poor soil quality, to remain socially and technologically primitive. This view of small hunter-gatherer groups suggested that the pre-Columbian occupants of Amazonia had almost no impact on the forests. The discovery of complex village structures representing organized societies who engaged in agriculture (Heckenberger et al., 2008; Heckenberger et al., 1999; Roosevelt,

1991), aquaculture (Erickson, 2000) and hundreds of geoglyphs in the Bolivian Amazon (Pärssinen et al., 2009; Schaan et al., 2012), undermined the generality of Meggers' argument. On the opposite extreme from Meggers, some have argued that all of Amazonia was transformed by human activity, and as we are just one tree generation away from the population collapse associated with human arrival, Amazonia is not a natural wilderness, but an abandoned parkland (Balée, 2010; Clement et al., 2015; Roosevelt, 2013). One of the key suggestions of the parkland advocates is that forests were enriched with useful species as a result of generations of people encouraging trees that bear edible fruits and removing species deemed useless (Balée, 1989; Clement, 2006).

Here, we present a high-resolution 6900-year paleoecological reconstruction from lacustrine sediments collected beneath Lake Sauce in the lowland Amazonian forests of Peru. We employed a combination of sediment descriptions, pollen, charcoal, and diatom data to 1) identify major climatic events present at the lake setting, 2) identify the timing and intensity of human activity around the lake, and 3) assess the vegetation response to major climatic events under increasing and decreasing human pressures through the time series.

Material and Methods

Site description

Lake Sauce lies at 600 m elevation ($6^{\circ} 42' 17''$ S, $76^{\circ} 13' 04''$ W) within a seasonally dry region of Amazonia at the base of the Andes (Fig. 1a). The origin of the lake is unknown, but it may have been formed by tectonic activity. The lake is shaped like a tadpole with the tail and the body connecting across a ledge that is about 16 m deep (Fig. 1b). The main basin of the lake is c. 2.7 km x 1.5 km, with a flat-bottom that is c. 20 m deep, while the 2 km x 0.5 km tail is steep sided and 40 m deep. The main basin has small inlet streams arriving on the eastern shore, and an outlet to the north. The lake is accessible by road and is currently used for recreation and aquaculture.

Insert Fig. 1

Annual precipitation to the site is c. 1475 mm, with March-April as the wettest bimester averaging 320 mm of precipitation. The other wet season peak occurs between September and October with 285 mm. The driest time of the year occurs between November and December with an average of 180 mm (monthly data from 1964 to 2002 for Sauce meteorological station, Servicio Nacional de Meteorología e Hidrología, Perú).

The vegetation surrounding Lake Sauce is heavily disturbed, but remnants of a diverse seasonal tropical forest were evident on the steep-sided sections flanking the tail of the lake. Under natural conditions the landscape would be expected to support a closed-canopy forest rich in Anacardiaceae, Annonaceae, Euphorbiaceae, Fabaceae, Meliaceae, Moraceae, Rubiaceae, and Sapotaceae (Gentry, 1988). Disturbance events

such as tree fall gaps would support pioneering taxa such as *Cecropia*, *Miconia*, and members of the Araliaceae. Poaceae could have occurred either in disturbance gaps or in marshland around the lake along with Cyperaceae, Asteraceae and semi-aquatics such as Onagraceae, Alismataceae, and Amaranthaceae.

Field and analytical methods

In May 2003, a series of cores were raised from the deepest point of the main basin of Lake Sauce in 20 m of water. A pontoon raft was built on site with two 6 m Maravia Cataraft hulls providing buoyancy. A tripod supported a 1-tonne come-along winch for core extraction. Coring was conducted using a 50 mm-diameter Colinvaux-Vohnout piston sampler (Colinvaux et al., 1999) to a sediment depth of 10 m, and then using a 30 mm-diameter core barrel to obtain the next 9.7 m. Two parallel cores were obtained, with a third core to capture the mud-water interface. Cores were sealed in the field and shipped to the Florida Institute of Technology. In 2009 and 2015, a team revisited the lake to collect limnological data using a YSI multimeter and mud-water interface cores.

Total carbon and nitrogen were measure in the Department of Geological Sciences, University of Florida, using a Carlo Erba NA1500 CNHS elemental analyzer. Dried samples were combusted and a thermal conductivity detector measured the size of the pulses of N₂ and CO₂.

Sediment subsamples of 0.5 cm³ were removed for pollen analysis at every 20 cm of core depth, and at every 1 cm for charcoal analyses. Processing of pollen samples followed standard protocols (Faegri and Iversen, 1989) with the addition of exotic

Lycopodium spores (Stockmarr, 1972) allowing calculation of concentration of the subfossils. Pollen counts were made to a sum of 300 grains, although Cyperaceae and other aquatics were excluded from the pollen sum. Extended counts were made to find maize pollen in every sample. The residues of already –counted samples were filtered at 60 μm , then mounted on a slide and scanned for *Zea* or *Manihot* grains. *Zea* pollen was identified by its size (88-100 μm in water) and surface pattern (Holst et al., 2007).

Zonations for fossil pollen and diatom data were drawn based on a CONISS constrained clustering analysis performed using the R package ‘rioja’ (Juggins, 2012). Multivariate analysis using both Detrended Correspondence Analysis (DCA) (Hill, 1979) and Non-metric Multidimensional Scaling (NMDS) (Kruskal, 1964) were also employed on the fossil pollen data using the ‘vegan’ package (Oksanen et al., 2013) in R.

Samples for charcoal analysis (0.5 cm^3) were gently disaggregated in 10% KOH, and then sieved at 60 and 180 μm . The retained fraction was placed in a petri dish and charcoal identified and quantified under a stereomicroscope. Image J software was used to calculate area of charcoal in each sample (Clark and Royall, 1996).

Samples (0.25 cm^3) for diatom analysis were oxidized using H_2O_2 prior to dilution to 10 ml with distilled water. Battarbee techniques were followed to allow calculation of diatom concentrations and influx (Battarbee, 1986). Samples were mounted in naphrax and counts of 500 valves made at x1000 magnification. Diatoms were identified using (De Oliveira and Steinitz-Kannan, 1993; De Oliveira et al., 1986; Lange Bertalot, 1998, 2000) and the online databases of algaebase.org and westerndiatoms.colorado.edu.

Samples for ^{14}C dating were based on macrofossils where they could be isolated, otherwise on bulk samples. Accelerator Mass Spectrometry (AMS) dating of samples was conducted at the Lawrence Livermore National Laboratories. Ages were calibrated using the IntCal 13SH calibration curve (Hogg et al., 2013) and a chronology, based on 13 of those ages, was constructed using *Bacon* R-code, which uses Bayesian statistics to reconstruct accumulation histories for sedimentary deposits (Blaauw and Christen, 2011).

Results

Limnology

The modern lake is c. 27 °C at the surface and 25 °C at its base, showing no strong thermal stratification. Oxygen concentrations decline from 7 mg l⁻¹ at the surface to 0.2 mg l⁻¹ between 7 and 8 m water depth. Salinity was constant throughout the vertical profile at 0.3 ppt. The presence of aquaculture pens that may have contributed to recent eutrophication, and local people told us of repeated fish kills damaging their business; suggesting that periodically the lake becomes anoxic from top to bottom. Our observation of modern anoxia in the bottom waters, probably also applied to the past as the recovered sediments smelled strongly of H₂S, and copious amounts of gas bubbled from the bore-hole for at least 3 days post-drilling.

Core description and chronology

The stratigraphy showed no sign of slumping or perturbation, and for much of the sequence exhibited fine laminations. The broad flat-bottom of the lake reduced the probability of dealing with slumped material. The ^{14}C AMS ages were broadly consistent,

suggesting a rapid rate of sediment accumulation. Three of the 14 AMS dates were ‘too young’ for their stratigraphic position, but in two of the cases, the reversals were not sufficient to warrant exclusion from the Bacon-derived chronology. Only one date was rejected, that of the lowermost sample, which was based on a very small sample size. The age-depth plot and the inferred chronology (Fig. 2) showed an approximate doubling of the sedimentation rate between c. 10.9 m (2200 cal BP) and 6.8 m (1500 cal BP) depth. Sample 102755 was incorrectly reported as having a depth of 17.82 m in Correa et al. (2010) and this has been corrected to 18.82 m.

Insert Fig. 2

Rates of sedimentation in the basal 3000 years of the record were roughly constant at 1- 2 mm per year, but these rates accelerated after c. 3400 cal BP reaching a peak depositional rate of c. 7.5 mm per yr at c. 1600 cal BP (Fig. 2). Thereafter, rates declined back to c. 2 mm per annum at c. 500 cal BP prior to a surge of deposition in the last century, where rates could have been as high as 16 mm per year.

The total length of the core recovered from Lake Sauce was 19.7 m, with an inferred basal age of c. 6900 cal BP (Fig. 3). The basal meter of sediment was coarsely laminated with approximately one band per 2-5 mm. Between c. 18.7 m and 18.5 m depth, laminations were evident, but were distorted by turbidite flows. Between c. 18.5 m and 16.8 m depth the sediment comprised a massive gray gyttja. A transitional zone between 16.8 and 16.7 m depth showed more structure, but a marked change was evident at 16.7 m (c. 5100 cal BP) depth when the sediment transitioned to laminated gyttja. In

the lower 10 m of the core most of the laminations were dark green or gray gyttja alternating with mid-green gyttja. Occasional rust-red bands also occurred. Above c. 9 m core depth (c. 1850 cal BP) the laminations generally consisted of varying shades of green or gray alternating with pale green or pink-white bands. The pink and the white bands appear to be clay-rich layers, while the green bands derive their color from algal content. The sediment above c. 1.1 m (c. 130 cal BP) was a dark green-black gyttja with some banding, but not the highly resolved structure of most of the core. Near the surface the core was very loose and semi-liquid. During transit the top 10-15 cm of the core were so sloppy that they became mixed. We consider the portion below 20 cm depth to be intact, but to err on the side of caution the uppermost sediment included in this analysis lay at 30 cm core depth. A mud-water interface sample collected from very close to the original coring site in 2015 is provided in both the pollen and diatom data.

Carbon and nitrogen and nitrogen curves appeared to be broadly coupled with the strongest divergence being a peak of carbon at c. 4320-4130 cal BP that had no corresponding peak of nitrogen (Fig. 3). This anomaly reflected samples rich in charcoal.

Insert Fig 3 stratigraphy C,N, etc

The fossil pollen data

The fossil pollen samples were rich in pollen from lowland seasonal forest taxa. Asteraceae, *Brosimum*, *Caesalpinia*, *Cecropia*, *Celtis*, Melastomataceae, Moraceae, *Paullinea*, Poaceae, *Trema*, were abundant in most samples and distinct peaks of *Iriarte*, Meliaceae, Lecythydaceae, and Cyperaceae, were documented. *Zea mays* was identified

consistently in samples aged between 750 and 3380 cal BP and in more scattered samples back as far as 6320 cal BP (Fig. 4). Micro- and macro- charcoal fragments were found in almost all samples. Three zones for fossil pollen and four for diatoms were recognized.

Insert Fig. 4

The multivariate analysis of both pollen and diatom data was inconclusive. The NMDS of the pollen data had cut-levels that were only marginally acceptable, and the ordination failed to produce clear patterns (SOM Fig. 1). The NMDS of the diatom data produced unacceptable cut-levels. The DCA analysis (SOM Fig.1) of the fossil pollen data was similar to that of the NMDS, but provided prioritized axes. Axis 1 showed a steady trend of increasingly positive values (Fig. 4).

The basal zone SAP-1 (19.7-18.5 m; c. 6860-6200 cal BP) in the fossil pollen record, started with a large peak of disturbance taxa and a fire event. This zone had the highest values of the entire record for Poaceae, weed taxa (Amaranthaceae, Apiaceae, Asteraceae, Lamiaceae, and Polemoniaceae), and Cyperaceae. Spores were also very abundant in the basal samples. *Zea mays* pollen was first documented by the presence of two grains (88 μ m in length) at 6320 cal BP.

Pollen zone SAP-2 (18.9-11 m; c. 6450-2200 cal BP) spanned a major change in the appearance of sediments as they transitioned from massive to laminated sediments at c. 16 m (c. 5000 cal BP), but there was no pronounced shift in the pollen signature at that time. Between c. 6450 and 4500 cal BP the pollen reflected a transition from fast growing trees, e.g. *Virola* and members of the Urticaceae/Moraceae, Poaceae, Cyperaceae and

weedy species, giving way to *Iriartea*, other Arecaceae, *Hyeronima*, *Connarus*, *Alchornea*, Lecythidaceae, Melastomataceae, Meliaceae and *Brosimum*. This same progression apparently repeated after another large fire event at c. 4500 cal BP.

Zea mays pollen occurred sporadically throughout the base of zone with grains as large as 100 μm (measured in water prior to mounting). The proportion of samples that included *Zea* doubled after c. 3380 cal BP.

The third pollen zone was from 11 m - 0 m depth (c. 2200 - 0 cal BP), and occurred where there was a doubling in the sedimentation rate of the core (Figure 2 and 3). Many woody taxa, e.g. *Brosimum*, Moraceae/Urticaceae, *Cecropia* and *Alchornea* exhibited some of their lowest values in the sequence at this time. Contrastingly, *Vismia* and *Socratea* became relatively abundant, and Cyperaceae and spore types exhibited strong peaks of abundance between 2000 and 1000 cal BP. An unknown pollen type (a small, psilate, tricolporate listed as *Begonia*-type) showed an initial spike of abundance (12-18%) between c. 1700-1650 cal BP, and an even higher spike of c. 30% between 1410 and 1380 cal BP. *Zea mays* was recorded regularly from 3200 BP until c. 750 cal BP, but only rarely thereafter. Herbaceous and weedy taxa reached their highest values of the record with > 20% of the pollen sum at c. 1170 cal BP, although *Zea mays* was not recorded in that sample. A spike of small charcoal particles was evident at c. 900 cal BP, but overall the period c. 1100 – 500 cal BP had the lowest charcoal abundances of the entire sequence. After c. 700 cal BP few samples contained *Zea mays* and *Cecropia* and other forest taxa increased in abundance.

Fossil diatoms

No diatoms were recovered from the basal sediments of this core (19.7-19 m depth). Above this depth, however, diatoms were generally abundant and well-preserved. Diatom assemblages were frequently dominated by *Discostella* spp., *Ulnaria* spp., and *Nitzschia cf amphibia* (Fig. 5). *Aulacoseira* spp., which generally thrive in well-mixed lakes (Haberyan et al., 1997), tended to occur in pulses.

Insert Fig. 5

In the basal zone, SAD-1, a sequence of *Aulacoseira granulata*, *Fragilaria tenera*, *Nitzschia frustulum* and *Cyclotella meneghiniana* gave way to *Discostella stelligera*. *D. stelligera/pseudostelligera* represented about 80% of frustules for the remainder of this zone. At c. 5200 yr BP, zone SAD- 2 began with an abrupt decline in *D. stelligera/pseudostelligera* and increases in *Encyonema minutum var. pseudogracilis* and *Ulnaria delicatissima*. Toward the top of this zone, subaerial or benthic taxa diatoms, e.g. *Hantzschia amphioxys*, *Luticola mutica*, *Planothidium rostratum*, *Cocconeis placentula*, *Diadesmis contenta*, and *Nitzschia fruticosa*, increase in abundance as most of the planktonic species decline in abundance. These peaks of benthic diatoms coincided with strong decreases in diatom concentration (two orders of magnitude).

Diatom zone SAD-3, begins at c. 3600 cal BP and was marked by the return of *Nitzschia cf amphibia*, shortly followed by a decline of the subaerial or benthic taxa. Isolated peaks of *Nitzschia frustulum*, *Fragilaria capucina* and *F. tenera* occurred as there was a more general oscillation between *Nitzschia cf amphibia* and *Ulnaria delicatissima*.

The boundary between SAD-3 and SAD-4 is marked by a spike of *Aulacoseira granulata* at 1690 cal BP, followed by an increase in the abundance of *Discostella stelligera*, attaining values of >90%. Brief spikes of other planktonic diatoms, e.g. *Cyclotella meneghiniana* at 725 cal BP, and *A. granulata* at c. 100 BP, occurred. The penultimate samples from the core were dominated by *Fragilaria radians* and had sizable spikes of charcoal. The modern mud-water interface sample was once again dominated by *Discostella stelligera/pseudostelligera* (hereafter *Discostella* spp.).

Discussion

Sediment depositional rates that averaged 3 mm per year at Lake Sauce provided an exceptional opportunity to analyze fine-scale paleoecological changes and human activity in the basin over the last 6900 years (Fig. 3). The 20-cm sampling interval provided c. 30-40 year sample interval for much of this record, while the 2-cm sampling for charcoal provided decadal to subdecadal resolution throughout the record. The modern lake may occupy an ancient basin, but this sediment core had a basal age of c. 6900 cal BP. The basal sediments were unusually rich in Poaceae and Cyperaceae pollen, which could represent either the termination of a drier, grassier landscape, human activity, or the initial filling of the basin to form the modern lake. The shallow lake that existed prior to c. 6500 cal BP did not support silica preservation, a common phenomenon in lowland shallow lowland Amazonian lakes (Bush et al., 2000; Velez et al., 2005). Overall, this catchment illustrated a continuous history of forest cover, albeit heavily modified by human activity.

Climate change

Isotopic records from Caverna Tigre Perdido (c. 153 km from Sauce) suggest a transition to wetter climates at c. 5000 BP (van Breukelen et al., 2008), which is consistent with evidence from multiple Amazonian sites suggesting that the mid-Holocene (c. 8000-5000 cal BP) was dry relative to the late Holocene (Bush et al., 2007c; Mayle et al., 2000; Mayle and Power, 2008). In the Sauce record, Cyperaceae is the most abundant pollen type that could reflect changes in lake level (Correa-Metrio et al., 2010), and its peak abundances broadly coincide with wettest signals in the Tigre Perdidos data. Although Poaceae can be both a wetland plant and a disturbance indicator (Bush, 2002), it appears negatively related to the wetter isotopic values at both Tigre Perdidos and Huagapo caves (Kanner et al., 2013). A Cyperaceae:Poaceae (Cyp:Poa) ratio can be used to indicate wet versus dry times (Turney et al., 2004). Burrows et al. (2014) found that in the humid tropics of northern Australia a ratio >3 indicated wet events. At Sauce, Cyp:Poa ratios were commonly 1-5 throughout the period from the onset of sedimentation until 1700 cal BP; thereafter values were commonly >10 . The transition to markedly wetter conditions at 1700 BP coincided with the boundary between SAD-3 and SAD-4 as *Ulnaria delicatissima* gave way to *Discostella* spp. The highest Cyp:Poa ratios (25 to 84), occurred between c. 1030 and 700 cal BP. This period overlapped, within radiocarbon dating error, the estimate of Colinvaux et al. (1985) for highstands of western Amazonian rivers in Ecuador (c. 1200-770 $\pm$ 100 cal BP) and wet events in the Quelccaya ice cap (Thompson et al., 2013) that have been linked to the Mediaeval Climate Anomaly (c. 1000-700 cal BP).

Crops and forest modification

Paleoecological data indicate that fires in western Amazonia are strongly indicative of human presence. Indeed lake sediments, where humans have no known history of presence contain no charcoal (Bush et al., 2007a). The presence of both fire and crop pollen can be taken as firm evidence of human activity in the landscape (Bush et al., 2007b; Carson et al., 2015; Iriarte et al., 2012). Both of these factors are evident through the majority of the Lake Sauce record. The presence of charcoal, with a major spike of fire activity at 6700 cal BP is consistent with human presence and provides a similar age to the onset of fire at Lake Ayauchⁱ (450 km north of Lake Sauce), Ecuador, where charcoal was recorded at c. 5900 cal BP and was suggested to have been a result of human activity (Bush and Colinvaux, 1988) (Figure 5). Sediments from Lakes Gentry and Parker, Peru (1100 km to the southeast of Lake Sauce), and soils adjacent to those lakes also recorded frequent fires from 7500-5500 cal BP, though the onset of agriculture was not evident until 4000 cal BP (Bush et al., 2007a; McMichael et al., 2012) (Figure 5).

The only portion of the Sauce record to show signs of turbidite activity follows the first peak of fire activity in the record and could represent increased inflow activity as the landscape was opened. Human settlers would probably have used fires on a daily basis to cook, and more sporadically to clear land (Smith, 1980). The great majority of fires used to clear land or reduce vegetation density near habitation would have died out as they encountered mature forest (Nepstad et al. 2001). Nevertheless, the presence of human-induced fire in the catchment greatly increased the probability that during strong droughts these local uses of fire could have escaped to form wildfires (Cochrane and Laurance, 2008; Nepstad et al., 2001). A single fire escaping into the forest would have

caused some tree mortality (Barlow et al., 2003), but probably not enough to register in the pollen record of a 3-km diameter lake (although the charcoal might still be found). Under strong drought conditions, fires may have repeatedly burned the landscape, and these induced enough alteration of forest composition (Barlow and Peres, 2008; Barlow et al., 2003), to be seen in the pollen record. Crown fires are exceptionally rare in Amazonian systems, but repeated fires coinciding with strong droughts may have created the conditions where stand-replacing fire events could have occurred on a landscape scale, i.e. the lake catchment area. Such intense fires would have damaged soils and would have been consistent with the kind of disturbance documented at Lake Sauce at 6700 and between 4500 and 4270 cal BP. We cannot rule out the possibility that these were large, deliberately-induced fires, by indigenous people. Given, however, that these actions were not repeated during the succeeding 4000 years of landuse, we find an explanation based on climatic extremes to be more parsimonious.

In prior studies in Amazonia and Central America, the inferred initiation of human action is often marked by a large spike in charcoal, e.g. at Lakes Ayauchⁱ (Bush and Colinvaux, 1988), Gentry, and Geral (Bush et al., 2007b), Granja, (Carson et al. 2014), and La Yeguada (Bush et al., 1992). Intriguingly, that charcoal spike is almost always followed by a lag of hundreds of years before the first crops are recorded in the sedimentary sequence. Furthermore, although people are growing crops, the lake records do not show corresponding peaks of charcoal, just a consistent low presence. Several competing hypotheses can be raised to explain the charcoal pattern and the agricultural lag. The first is that people managed a landscape by burning and hunting, with each fire leading to a more open forest until patches became farmable. This explanation, however,

does not explain the decreasing trend in charcoal after an initial event. A second is that different groups managed the land. Hunter-gatherers produced more charcoal in game drives or opening the forest for improved hunting than agriculturalists who used fire, but also practiced fire suppression. Again this hypothesis, does not account for the long decline in charcoal. A third explanation is a modified Signor-Lipps effect (Signor and Lipps, 1982) in which the first occurrence of a rare taxon, in this case the poorly-dispersed pollen of a crop such as *Zea* (Kennedy and Horn, 1997; Lane et al., 2010), is hard to detect. If some critical mass of land clearance, particularly connecting the lake edge to field systems, has to be achieved before the crops are detectable, this could account for fire preceding the agricultural signal. This hypothesis needs to be tested further.

Two further hypotheses could be combined with any of the preceding ones, but aim to answer why charcoal abundance declines progressively after a major fire event. The first is that droughts follow a pattern of an immense megadrought, followed at decadal-scale intervals by droughts that diminish in intensity through time. Bond Cycles (Bond et al., 1997) in the Atlantic Ocean could perhaps induce such a rhythm, but the timing of events at Sauce does not match the pattern of hypothesized Bond Cycles. Further work is needed to evaluate the drought history of Amazonia and how it relates to possible forcing mechanisms (Wanner et al., 2011). The last hypothesis offered here, which is not mutually exclusive with any of the foregoing, is that forest succession leads to less flammable forests. After an initial giant, drought-induced, fire (probably sparked by human activity), the biomass of fallen wood on the forest floor is greatly reduced, the recovering forest is more prone to fire than a mature forest (Barlow and Peres, 2008;

Barlow et al., 2003). If fire intervals are far enough apart that succession continues, the forest becomes cooler, more humid, and composed of species less likely to burn (note this is not the same as fire tolerant) (Holdsworth and Uhl, 1997). The less intense fires do not consume fallen, moist, woody biomass, but rather it is likely to decay due to high temperature and moisture. A drought, however, would induce mortality, increase coarse woody debris and reduce decay, substantially increasing fuel on the forest floor. Thus temporal pattern to obtain large charcoal signatures may reflect the time needed for succession coupled with periodic, unusually intense, drought. These are preliminary observations about an emerging pattern, but ones that may lead to a deeper assessment of the interaction between people, climate, forests and fire in Amazonia.

Maize agriculture at Sauce

At Sauce the lag between the first large fire and evidence of maize cultivation is almost 400 years, enough time for a forest to regrow. The occurrence of maize microfossils provides indisputable evidence of human presence. The pollen sample from 6320 cal BP includes two Poaceae pollen grains (88 μm in length) that are identified as maize. These grains provide some of the earliest evidence of maize yet documented from the Amazon Basin. The ages of maize microfossils at Lakes Sauce, Lake Ayauchⁱ, Ecuador (Bush et al., 1989) and the and the Llanos de Moxos, Bolivia (Brugger et al., 2016) overlap (given two standard deviation ranges), and are c. 400 years younger than maize cobs recovered from coastal Peru (Grobman et al., 2012).

Insert Fig. 5

497

498 Although the very low abundance of maize precludes a statistical demonstration
499 of increased intensity of agriculture, we infer this to be the case based on cumulative
500 evidence. Maize agriculture is sporadically evident in the lower section of the Sauce core
501 (Figs. 4 & 6), but the proportion of samples containing maize pollen increased in
502 frequency around c. 3380 cal BP. Between c. 3380 and 700 cal BP (n=54), c. 60% of
503 samples contained *Zea* pollen, compared with c. 30% of samples prior to 3380 (n=31). A
504 shift toward diatoms indicative of more nutrient-rich conditions than before or after the
505 peak of *Zea* pollen occurrence (below) is evident (Fig. 5). Evidence of increased erosion
506 is seen in a quadrupling of sedimentation between c. 3380 and 2000 cal BP as rates rose
507 from c. 0.13 to 0.55 cm per year (Fig. 3). Taken together, we see the maize, diatoms, and
508 phytoliths and sedimentation records as strongly indicative of intensification of landuse
509 after 3380 cal. BP.

510 Whether humans responded to climate change through changing landuse, or
511 whether landuse changes came about because of social change is actively (e.g. Binford et
512 al. 1997; Erickson 1999). The inferred pattern of an increase in intensification of landuse
513 or adoption of maize agriculture between c. 3500-3000 cal BP is suggested by similar
514 metrics at lowland sites such as Lakes Ayauchⁱ (Bush et al., 1989), and Gentry (Bush et
515 al., 2007c), the mid-elevation site of Lake Pomacochas (Bush et al., 2015b) and the
516 montane sites of Lakes Marcacocha (Chepstow-Lusty et al., 1998), Pacucha, and Huaypo
517 (Mosblech et al., 2012). The adoption of maize agriculture across 1000s of meters of
518 elevation, and from coastal semi-desert to Amazonian forested settings, strongly suggests

that rather than being purely climatically driven, this was a technological adoption, perhaps fostered by climatic events.

The peak intensity of maize agriculture at Lake Sauce seems to have been between c. 2000 and 1600 cal BP with multiple maize pollen grains found in most samples. In contrast to this pattern, after c. 700 cal BP a single grain of maize was found (at c. 480 cal BP) in the next eight samples. It appears that maize agriculture, if not abandoned, was being practiced differently prior to the time of European contact (c. 400 cal BP). A purely local explanation could be that maize agriculture was being practiced on seasonally flooded wetlands prior to c. 700 BP, and that the proximity of the crops and water draining from the fields promoted dispersal of these large heavy pollen grains to the coring site. Thereafter, a cultural shift caused maize to either be replaced or for maize agriculture to be moved further back from the lake onto drier sites. The timing of this apparent societal change at c. 700 cal BP (1250 AD) is within the period of the rise of organized Andean cultures, such as the Wari (Isbell, 2008) and the Chachapoyas (Church, 1994). It is possible that increasingly sophisticated societies prompted trade and led to local specialization that did not include maize agriculture in this setting. Although abundant evidence exists in paleoecological records to demonstrate the collapse of human populations at the time of European conflict, (e.g. Bush and Colinvaux, 1994; Carson et al., 2015; Carson et al., 2014) some records show a cultural change of apparent abandonment of maize agriculture considerably earlier. Pomacochas, Peru, which lies almost immediately upslope from Lake Sauce at 2050 m a.s.-l., provided a record of at least 3000 years of maize agriculture that ended c. 1200 cal BP (Bush et al., 2015b). At Lake Ayauchⁱ, Ecuador, a long history of maize agriculture ended at c. 1100 cal BP

(Bush et al. 1989). Thus the apparent cultural change at c. 700 cal BP to move away from maize agriculture at Lake Sauce was not unique, but remains unexplained. One avenue that is worth investigating is to determine the influence on local cultures of climate change during and immediately following the Mediaeval Climate Anomaly.

Ecological impacts of disturbance in the lake

One effect of human activity may have been to increase erosion and thereby elevate silica content in the water column and the sediment, allowing diatoms to preserve. The most noticeable transitions in the diatom record occurred when *Discostella* spp. were replaced by other taxa. As *Discostella stelligera* was characteristic of open water habitats in oligotrophic systems (Rühland et al., 2015; Saros and Anderson, 2015), the transition to *Fragilaria* and *Nitzschia* species was consistent with eutrophication (Gaiser et al., 2006; Patrick and Reimer, 1966) and broadly coincided with increased human activity in the catchment. Peaks of erosion were marked by increased abundances of benthic species. The uptick in benthic species, however did not appear to correspond to lowered lake levels as their increase coincides with regionally rising lake levels (Abbott et al., 2003; Baker et al., 2001; Burbridge et al., 2004; Mayle et al., 2000; Tapia et al., 2003). Equally, however, it seems unlikely that the signal was solely due to flooding new shallow regions. If the system was simply adding more marginal habitat it might be expected that the benthic diatoms would be additive, increasing the total diatom concentration. Instead, as the benthic species enter the record, diatom concentrations fell by two orders of magnitude (Fig. 4). To reduce lake productivity this much, the most plausible scenario was that the benthic diatoms reflected inwashed marginal peats and soils that clouded the

water column. Non-siliceous algae or simply turbidity could have reduced the photic zone and hence led to the observed reductions in diatom concentration. The strongest peaks of benthic diatoms were aligned to fire and maize agriculture in the lake, supporting the hypothesis that they represented periods of land clearance or erosion.

The charcoal peaks generally tracked the abundance of the diatom *Ulnaria delicatissima*. In modern systems, *Ulnaria* spp. were strongly positively correlated with increasing nitrogen to phosphorus ratios (Interlandi et al., 1999), while *Discostella stelligera* were sensitive to attenuation of light as nutrient availability increased (Saros et al., 2013). In this system, *Ulnaria* and *Nitzschia amphibia* peaks were consistent with elevated nutrient availability that may have reflected a combination of erosion and local agricultural activity. Around 1700 cal BP, consistent with the wet signature from the Cyp:Poa pollen ratio, large spikes of *Aulacoseira* appeared in the record, consistent with large pulses of water that induced strengthened circulation. This system did not sustain such strong circulation and the characteristic taxon of the wet phases at Lake Sauce were *Discostella* spp..

Nitzschia amphibia disappeared from the record about 700 BP, strongly suggestive of reduced eutrophication, and consistent with less agriculture causing erosion. *Discostella* spp. remained the dominant diatom until modern times apart from brief spikes of *Aulacoseira* and *Fragilaria radians* within the last century. These spikes of abundance followed the highest accumulation rates of the entire sequence, presumably flow and nutrient pulses resulting from recent deforestation and disturbance of the catchment (Suttle et al., 1987).

588 *Ecological impacts of disturbance on land*

589 Although we zoned the diagram to aid in its description, the Sauce record was
590 comprised of strong directional change rather than stasis within zones. Moreover, the
591 sequence of taxa forming the directional change in the pollen record was preceded by a
592 major disturbance, and the entire pattern was repeated within the sequence. Two large
593 fires, one at c. 6700 cal BP and the other at 4270 cal BP, provided the disturbance that
594 appear to have ‘reset’ the successional system, and triggered long-term change.

595 Natural fires are very rare in western Amazonian forests and usually burn out
596 within a few tens of meters (Barlow et al., 2012; Ray et al., 2005). Even in the drier
597 forests of the western Amazon, the driest month receives c. 85 mm of precipitation
598 making it unlikely to burn. Consequently, these forests are not comprised of fire-tolerant
599 species (Barlow and Peres, 2008). The arrival of humans would be expected to create
600 positive feedbacks between the occurrence of fire and forest alteration as fire-adapted
601 species replaced fire-sensitive ones (Cochrane and Laurance, 2008).

602 The fire near the base of this record, at c. 6700 cal BP, coincided with increased
603 fire activity across Amazonia (McMichael et al., 2012; Power et al., 2008). Lying within
604 the period known as the mid-Holocene dry event, this fire could have been natural, but a
605 human ignition source cannot be ruled out. Both the local signature of fire derived from
606 particles >180 µm and the regional fire signature (particles 60-179 µm) (Clark and
607 Royall, 1996) indicate a massive input of charcoal relative to the rest of the record, only
608 matched at one other time in the last 6900 years. The effect of the fire on the pollen
609 assemblage was also much stronger than normally documented following a single burn
610 (e.g. 2006; Barlow and Peres, 2008; Bush et al., 2007a).

A successional sequence in forest composition following the 6700 cal BP fire event followed a trajectory similar to those documented as the forest matures around an Amazonian floodplain lake (Foster, 1990). Early in the successional sequence, *Virola*, *Iriartea* and *Connarus* were important components, but over time these taxa were successively replaced by taxa such as *Arecaceae*, *Hyeronima*, *Alchornea*, *Melastomataceae*/*Combretaceae* and *Meliaceae*. What makes this observation even more noteworthy is that a parallel sequence of forest succession and recovery was observed after the other large fire-prone period, which began c. 4500 cal BP and built to a peak at c. 4270 cal BP. The second successional sequence may have progressed further than the first and appears to have culminated in a peak of *Brosimum* at c. 2260 cal BP. A normal succession in Amazonia leads to forest recovery such that it is hard to distinguish from mature forest within 200-300 years (Foster, 1990). In this record, however, the transition took about 2000 years.

A closer inspection of the pollen data reveals many smaller fire events taking place, but an overall trajectory of decreasing charcoal representation between 6700 – 4800 cal BP and 4200 – 2000 cal BP. Each of these lesser fire events appears to have impacted the forest, but the post-fire recovery is led by a different taxon from that impacted by the fire. We suggest that these sequences represent an overall succession pattern that was repeatedly being disrupted. These minor disruptions did not reset the system, but rather provided a small setback. In other words, the system was taking two steps forward during a recovery phase, and one step backwards with each fire event. The recovery after each small fire was from a more mature flora than existed after the

previous fire, hence there was a progression. In this way the recovery was prolonged, taking almost two millennia to reach what appeared to be a mature state.

Decadal-scale megadroughts have been suggested based on ice-core and lake records in the Andes and have been related to cultural turnover (Chepstow-Lusty et al., 2002; Shimada et al., 1991). This is the first record from the lowland Amazon that shows such a profound vegetation response to fire events, and suggests that this system climatically, edaphically or because of human land use, may have been especially prone to such intense fires.

Forest enrichment

It has been suggested that indigenous peoples had long traditions of enhancing the proportions of ‘useful’ taxa in the forest (Clement, 2006; Levis et al., 2012). Such an enhancement would lead to the expectation that such species would not suffer population declines, but rather have a growing representation. We saw no evidence to support this hypothesis for *Iriarte*, or *Mauritia*, which are potential candidates for anthropogenic species enrichment (Kahn and De Granville, 2012; Rull and Montoya, 2014). A further taxon that is often cited as being manipulated by humans is the Brazil nut, *Bertholletia* (Lecythidaceae) (Clement et al., 2015). Peaks of Lecythidaceae pollen occurrence did appear to coincide with those of *Zea*, but *Bertholletia* has not been collected from this section of the Amazon (GBIF.org) and other members of this large-tree genus are unlikely to have been cultivated. Two palm taxa, *Iriarte* and *Mauritia*, which were probably used by indigenous people for food and construction materials, appeared to

have peaks of abundance that were similar, but slightly offset from one another, and broadly antiphased to the *Zea* - *Lecythidaceae* peak abundances (Fig. 5).

In this heavily modified setting it was likely that humans influenced the abundance of all forest trees, but we did not see evidence of a deliberate enrichment of forest with palms. Sustained peaks of palm abundance appeared between c. 1200 and 1000 BP and again in the last 300 years of the record. Both periods corresponded to less frequent detection of maize pollen. It was not possible on present evidence to determine whether these palms were part of forest recovery as land was abandoned, or that their abundance was manipulated. The latest peak of *Iriartea* at c. 1880 was more than double any prior abundance and declined markedly (from 14% to <1%) between c. 1880 and c. 1960 AD. During this phase forest taxa decline in abundance and weedy species such as *Cecropia* and *Virola* increase; patterns consistent with deforestation. *Iriartea*, in addition to being a potential thatch palm, was favored by settlers for its heart-of-palm. As heart-of-palm entailed destructive harvesting, we hypothesized that C20th deforestation around Lake Sauce may have left *Iriartea* trees standing, but they were subsequently exploited unsustainably.

Conclusions

A high-resolution record from Lake Sauce in the Peruvian Amazon provided a 6300-year history of maize agriculture. Maize pollen occurred intermittently prior to c. cal BP, but became a regular component of the record between c. 3200 and 700 cal BP. Maize agriculture appears to have been abandoned at this site long before the decline of populations associated with European arrival in the Americas. No evidence was found to

support extensive forest enrichment with useful species by pre-Colombian peoples despite a >6000-year history of occupation.

The impacts of human activities on this watershed were profound, with diatom communities altered by eroding sediment and eutrophication. Even the low intensity agriculture that took place between c. 6900 and 4000 cal BP, apparently induced changes from a *Discostella stelligera*-dominated community toward one rich in *Ulnaria* species. Fires, almost certainly promoted by human action, were a regular component of the landscape around Lake Sauce for the last 6900 years. Two especially large events at c. 6700 and between 4500 and 4230 BP may have been amplified by periods of very strong drought, where the effect of fire was atypically pronounced. The successional recovery following each of these large-scale events was repeatedly setback by smaller fires, so that instead of taking a few hundreds of years, the successional recovery was still evident after 2000 years.

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Figure legends

Fig. 1: Sketchmap showing the location and bathymetry of Lake Sauce, Peru. Coring location is marked with a star. Numbers refer to Peruvian and southern Ecuadorian locations mentioned in the text: 1 = Lakes Ayauchⁱ and Kumpak^a, 2 = Caverna Tigre Perdido, 3 = Lake Pomacochas, 4 = Lake Sauce, 5 = Lake Pacucha, 6 = Lake Huaypo, 7 = Lake Gentry; 8= Huagapo Cave.

Fig. 2: The stratigraphy and chronology developed for the sediments of Lake Sauce. Upper left panel depicts the Markov Chain Monte Carlo iterations for the Bayesian Bacon model. Also shown are the prior (green curves) and posterior (grey histograms) distributions for the accumulation rate (middle panel) and memory (right panel). The lower panel shows the calibrated ¹⁴C dates (transparent blue) and the age-depth model (darker greys indicate more likely calendar ages; grey stippled lines show 95% confidence intervals; red curve shows single 'best' model based on the weighted mean age for each depth) (Blaauw & Christen 2011; p6). The Chronology is derived from Bacon using the IntCal 13SH calibration curve.

Fig. 3: Sedimentary characteristics of the core raised from Lake Sauce, Peru, showing a 20-cm long core section, the overall stratigraphy, rate of sedimentation, Total C, Total N, and the ratio of C:N.

Fig. 4: Percentage occurrence of the most abundant fossil pollen taxa recovered from the sediments of Lake Sauce, Peru, plotted against time. Panel a shows arboreal taxa, whereas panel B shows herbaceous taxa, spores, concentration values and two charcoal size fractions. The values of the DCA Axis 1 sample scores are also plotted against time.

Fig. 5: Percentage occurrence of the most abundant fossil diatom taxa recovered from the sediments of Lake Sauce, Peru, plotted against time.

Fig. 6: A comparison of the history of maize agriculture at Andean and Amazonian sites, contrasted with species potentially enriched by human activity at Lake Sauce in the context of changing moisture availability inferred from the isotopic record from Tigre Perdido Cave, Peru (van Breukelen et al. 2010). From top to bottom: Pomacochas *Zea* data are from Bush et al. (Bush et al., 2015b) with grey circles indicating *Zea* presence from Lake Ayauchⁱ, a lowland lake in Ecuador (Bush et al. 1989), Huaypo *Zea* data are from Mosblech et al. (2012), and black circles indicate *Zea* presence at the nearby Lake Pacucha (Valencia et al., 2010). Sauce *Zea* (this record) showing solid line for within pollen sum percentages and '+'s for *Zea* found in extended counts. Hollow circles indicate *Zea* presence from Lake Gentry, a lowland lake in Peru (Bush et al. 2007a). Sauce *Iriarte*a, *Mauritia*, Lecythidaceae, and Poaceae were from this study. Tigre Perdido (van Breukelen et al. 2009) and Huagapo Cave (Kanner et al. 2013) isotopic reconstruction reflected moisture conditions through the Holocene for sites in Peru. All ages were recalibrated using Intcal 13 (Reimer et al., 2013).

Fig.1

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1125 Fig.2

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Fig 3

Fig. 4

Fig. 5

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cal yr BP

1143 Fig. 6

Fig. SOM 1. Detrended correspondence Analysis samples output for Axis 1 versus Axis 2 of the fossil pollen data from Lake Sauce, Peru. Adjacent samples have been linked and the ordination divided into time-blocks to maximize separation of temporal groups.

1150 SOM Table of ^{14}C data from the Lake Sauce record. The basal date with an asterisk was
 1151 clearly too young and was excluded from calculating the Bacon –derived chronology.

1152

CAMS #	Depth (m)	Material	^{14}C age	$\pm$	Calibrated Ages		
					2-sigma	1 sigma	Midpoint
					Age cal BP	Age cal BP	Age cal BP
102748	2.87	BS	1295	40	1072-1270	1094-1267	1177
102757	4.87	BS	1685	45	1416-1698	1434-1593	1510
102749	6.83	BS	1935	40	1730-1925	1749-1891	1830
102750	8.26	BS	1580	40	1324-1530	1368-1477	1420
130093	8.43	MF	1750	40	1537-1707	1569-1699	1530
130094	9.98	MF	2770	110	2497-3163	2744-2967	2860
102751	10.69	BS	1275	40	1062-1269	1071-1256	1160
109896	10.9	MF	2040	35	1844-2043	1924-2000	1960
109897	12.51	MF	2515	35	2379-2718	2473-2705	2590
102752	14.36	BS	3225	50	3252-3559	3354-3462	3400
102753	16.37	BS	4435	45	4850-5275	4870-5038	5010
102754	17.62	BS	3435	40	3484-3823	3579-3692	3630
102755	18.82	BS	5665	40	6307-6489	6321-6445	6390
102756*	19.43	BS-MF	2540	35	2492-2750	2539-2744	2630

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