2   **Continuous human presence without extensive reductions in forest**

3   **cover over the past 2500 years in an aseasonal Amazonian**

4   **rainforest**

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18 **Abstract**

19 The impact of pre-Columbian indigenous communities on forest cover in Amazonia is highly

20 contentious, particularly for the wettest forests. To contribute to this debate, we studied the

21 vegetation and fire history of a site, Quistococha, which lies within the aseasonal forests of the

22 northern Peruvian Amazon and is associated with independently dated pre-Columbian and

23 recent human occupation. Paired cores from swamp and lake environments were used to

24 distinguish landscape-scale changes in vegetation from local-scale succession. An increased

25 abundance of disturbance-adapted taxa in the pollen record from the lake, but not swamp, since

26 c. AD 1860 likely reflects extensive deforestation related to the expansion of the nearby city

27 of Iquitos. However, previous persistent occupation of the site by pre-Columbian indigenous

28 communities, indicated by the charcoal record from the lake site, is not associated with

29 evidence for similarly extensive disturbance of the landscape. The unique features of this site

30 therefore demonstrate that occupation by indigenous communities over thousands of years was

31 not associated with large-scale deforestation. These results support an emerging model of

32 persistent but localised impacts by pre-Columbian indigenous communities on aseasonal

33 Amazonian forests.

34 **Keywords:** Holocene; charcoal; paleoecology; palynology; disturbance; peatland

35 **Introduction**

36 Convincing evidence from archaeology and palaeoecology clearly indicates that forest cover

37 in at least some parts of Amazonia was strongly affected by prehistoric societies, particularly

38 where climate is strongly seasonal, and along navigable rivers (Bush et al., 2015). These

39 impacts include forest clearance and burning, and construction of earthworks and field systems,

40 often on a landscape scale (e.g. Balée and Erickson, 2006; McMichael et al., 2012, 2015;

41 Carson et al., 2014; Bush et al., 2015; Watling et al., 2017). However, the magnitude of past

42 impacts in comparison to modern deforestation remains unclear.

43 The growing evidence for manipulation of some Amazonian landscapes also raises the issue of

44 their spatial variability (e.g. McMichael et al., 2011, 2012, 2015). In particular, aseasonal

45 forests – those that occur where there is no strong dry season – were probably more difficult to

46 clear by burning or felling than the less dense, periodically dry vegetation of seasonal forests.

47 Aseasonal forests are therefore, in general, likely to have been less heavily affected than more

48 seasonal forests, and this inference appears to match the broad spatial distribution of the current

49 evidence for impacts of prehistoric societies (McMichael et al., 2015). However, the

50 palaeoecology of aseasonal forests has been relatively understudied compared with drier parts

51 of the Amazon. A better understanding of spatial variation in the magnitude of past impacts is

52 needed to assess their relationship with current patterns of forest dynamics and diversity,

53 particularly whether the high biodiversity of aseasonal tropical forests (ter Steege et al., 2003)

54 occurs despite, or as a result of, high levels of pre-Columbian human impact.

55 Addressing this problem requires paired archaeological and paleoenvironmental studies where

56 evidence for settlement and environmental change can be compared directly, and an

57 understanding of how deforestation within the historic period is represented in these records

58 (Mayle and Iriarte, 2014). Here we present a new palaeoenvironmental dataset from a lake,

59 Quistococha, in NE Peru (Fig. 1). We compare the new record from the lake to a published

60 palaeoecological record from a peat swamp forest adjacent to the lake (Roucoux et al., 2013)

61 and to the timing of independent records of pre-Columbian settlements. Uniquely for an

62 Amazonian site, our interpretations of the pollen and charcoal data from the new lake sediment

63 sequence are constrained by (a) comparisons with the pollen record from the adjacent swamp,

64 which helps us to separate local from regional pollen inputs, and (b) the signature of significant

65 19th–21st century forest clearance, which provides a benchmark against which to measure the

66 evidence for human impact related to both horticulturalists and hunter-gatherers recorded in

67 earlier parts of the sequence.

68 **Study site**

69 Our study site, Quistococha, is located on the outskirts of the city of Iquitos. Quistococha is a

70 small, shallow lake ('-cocha'), c. 1 km^2 in area and up to c. 3 m deep, occupying an abandoned

71 channel of the Amazon River (Räsänen et al., 1991; Roucoux et al., 2013), which has since

72 migrated c. 10 km to the east. The lake is bounded to the south and east by a c. 5 km^2 palm

73 swamp containing up to 4 m of peat (Lähteenoja et al., 2009a). To the north the lake is bounded

74 by a shallow levee, and to the west by the edge of a c. 15 m fluvial terrace incised into Miocene-

75 Pliocene sands, thought to mark the western extremity of the Holocene floodplain of the

76 Amazon.

77 The climate, as measured at Iquitos, is hot and wet all year round (Marengo, 1998). Annual

78 precipitation is 3087 mm and relative humidity is typically 80-90%. There is only a weakly-

79 defined dry season; monthly precipitation varies between c. 165 mm (in August) and 295 mm

80 (in March and April). Mean monthly temperatures vary between 25 and 27°C.

81 The present-day vegetation in one forest census plot in the peat swamp was described by
82 Roucoux et al. (2013). Three species, *Mauritia flexuosa, Mauritiella armata* (Mart.) Burret
83 (both Arecaceae) and *Tabebuia insignis* Sandwith (Bignoniaceae), together represent 82% of
84 the individuals. The aquatic plants on the lake itself occupy small patches mostly within 10 m
85 of the shore line. There are small (c. 5 x 5 m) floating mats of Cyperaceae and Poaceae near to
86 the eastern shore line, and larger patches of floating Nymphaeaceae around the lake margin
87 (aff. *Nymphaea amazonum*). A small artificial beach has been constructed on the western
88 margin of the lake.

89 Several previous studies have investigated both the lake of Quistococha, and the adjacent
90 peatland. Räsänen et al. (1991) dated a core from the lake and estimated its age at c. 6000 cal
91 a BP (calendar years before present, i.e. AD 1950). From a more detailed sedimentological
92 study of three cores from the lake, Aniceto et al. (2014a, b) concluded that an apparent hiatus
93 from 4600–2000 cal a BP implied a period of climatic drying. In the peat swamp forest adjacent
94 to the lake, Lähteenoja et al. (2009a, b) showed that the peats were up to 2320–2350 cal a BP
95 at the base, and that the peatland is likely fed by a mixture of rainwater and groundwater.
96 Roucoux et al. (2013) and Lawson et al. (2014) presented a detailed study of the palynology
97 and geochemistry of a 6 m core from the peatland, QT-2010-1, which will be discussed further
98 below. Kelly et al. (2014) and Teh et al. (2017) have additionally studied the hydrology and
99 trace gas exchange in the peatland.

100 Archaeological investigations began near Quistococha in 2005 with the discovery by A.
101 Ovuela-Caycedo and colleagues of cultural soils and artefacts on the terrace immediately above
102 the western margin of the lake (Fig. 1d). Archaeological excavations extending to the very edge
103 of the terrace have produced abundant fragments of pottery, charcoal, phytoliths of palms and
104 grasses, and cobs of corn (*Zea mays*), dating to two periods, 1740–1880 and 2350–2690 cal a
105 BP (Rivas Panduro, 2006; Rivas Panduro et al., 2006). These finds make Quistococha a
106 regionally important archaeological site, being one of the few in Western Amazonia to contain
107 *terra preta* or *terra mulata* (black or dark brown) soils (Rivas Panduro, 2006). *Terra preta* and
108 *terra mulata* soils, which are more widespread in Eastern Amazonia, are considered to be
109 anthropogenic, amended by additions of manure, charcoal and refuse, and indicative of human
110 occupation and horticulture (Glaser and Woods, 2004). Below the strata containing ceramics
111 was a further, undated, c. 50 cm thick stratum with its base up to 2.45 m below the modern
112 surface. This stratum consisted of black earth with charcoal, but without ceramics or stone
113 tools; it was interpreted as the first archaeological evidence for hunter-gatherer populations

discovered from a floodplain-edge terrace of the Peruvian Amazon (Rivas Panduro, 2006). A similar deposit, this time with stone tools, has subsequently been discovered in the Cachiyacu River basin, closer to the eastern slope of the Andes (S. Rivas Panduro, unpublished data).

Since the 19th century, the landscape surrounding Quistococha has been substantially deforested to accommodate the growth of Iquitos, which grew to international prominence during the rubber boom of 1890–1920. Currently, Iquitos has approximately 600,000 inhabitants. However, expansion of Iquitos has always been limited by its location on a peninsula of land locked between three rivers, and it is not connected to the national road network. The only road that leaves Iquitos, passing close to Quistococha and continuing south to the river port of Nauta 100 km away, was only paved in the 2000s. There has never been extensive deforestation for commercial agriculture, as for example, in the southern Brazilian Amazon. As a result, present-day deforestation in the area around Quistococha is moderate, at <50% within 10 km of the lake, which is important for interpreting the signal of this disturbance in the palaeoecological record.

Materials and Methods

Core sampling

A 364 cm core from the lake at Quistococha was collected using a Russian-type corer (Jowsey, 1966) operated from a floating platform. Core sections were wrapped in cling-film and placed into protective plastic gutters before being wrapped in a further layer of thick plastic sheeting. The top 30 cm of the lake sediments, which were poorly consolidated, were collected using a kajak-type gravity corer (Renberg, 1991) into polythene sample bags at 5 cm intervals. The sampling location (03.8297°S, 073.3200°W, 94 m above sea level) was recorded using a Garmin handheld GPS. The core was transported to the UK under license and stored at 4°C until analysis.

Dating

Twelve samples 1–2 cm^3 in volume were chosen for radiocarbon dating. Only a single plant macrofossil (an unidentified leaf) was recovered from the core for radiocarbon dating in the gyttja above 148 cm. Bulk organic lake gyttja samples were therefore used to obtain dates in this part of the core. In the lower, mineral-rich sediments, a comparison of bulk samples and picked samples of (unidentified) plant macrofossils was made to establish whether there was an old carbon offset. Samples were pre-treated in 2M HCl for 4 h before being washed in deionised water, and their δ^{14}C and δ^{13}C content was determined through accelerator mass

spectrometry (AMS) by the NERC Radiocarbon Facility in East Kilbride, UK. An age model for the lake core was produced using the BACON package (Blaauw and Christen, 2011) in R (R Core Team, 2015).

Pollen and charcoal analysis

Sample preparation followed standard methods (Faegri and Iverson, 1989), including acetolysis, and digestion in hydrofluoric acid where necessary. Samples were mounted in silicone oil. Pollen and charcoal analysis was undertaken using a Leica DMLS binocular microscope, routinely at 1000x. A minimum total of 300 total land pollen (TLP) was counted. The pollen sum excluded spores of the Pteridophyta and the pollen of the aquatic plant *Pistia stratiotes*. Unknown pollen types were included in the pollen sum. Microcharcoal fragments in the pollen slides between 5 and 180 μm in size were counted.

Pollen identifications were based on pollen reference slides, pollen atlases (Roubik and Moreno, 1991; Colinvaux et al., 1999), the Neotropical Pollen Database (Bush and Weng, 2006) and other literature (Absy, 1979; Walker and Walker, 1979; Weber et al., 1999; van Geel, 2001; Nowicke and Takahashi, 2002; Dias Saba, 2007; Burn and Mayle, 2008). *Mauritia* type pollen grains were measured to help separate *Mauritia* from *Mauritiella* (Kelly et al., 2017). Optimal splitting by sum of squares was applied to produce a pollen zonation scheme in Psimpoll (Bennett, 2007). Only pollen taxa that exceeded 5% in one or more samples were included; spores and aquatic taxa were excluded.

Sedimentological analysis

Sediment descriptions were made in the field following Troels-Smith (1955), and checked in the laboratory. Volumetric magnetic susceptibility (MS) was measured using a Bartington MS2 meter and MS2c loop sensor at 2 cm intervals prior to subsampling. No magnetic susceptibility measurements were made on the poorly-consolidated material in the top 30 cm of the sequence. Loss-on-ignition (LOI) was carried out on 1 cm^3 sub-samples at 4 cm intervals (or on subsamples of the 5 cm thick samples from the top 30 cm) at 550°C for four hours (Heiri et al., 2001). For carbon and nitrogen analyses, 1 cm^3 sub-samples were dried at 105˚C and milled to homogenize the sub-sample. Each sub-sample was then weighed into a tin cap prior to analysis with a Eurovector Turboflash CNS combustion analyser. Vanadium pentoxide was used as a catalyst. The peat standard NJV942 was used with all sample batches, and experimental values for carbon and nitrogen were within 95% of the certified value for all sample runs.

Results

In this section we describe the new radiocarbon dates (Table 1) and sedimentological (Fig. 2) and palynological data (Fig. 3) for core QT-2010-3, using the pollen zonation as a framework and with reference only to depths down-core; the construction of an age-depth model for the core is described in the next section. A complete pollen diagram showing all taxa recorded is presented as Fig. S1 (Supplementary Information). The interpretation of the data in terms of past environments is discussed later.

The pollen diagram is divided into five zones, A (at the base) to E (see Table 2 for detailed descriptions). The clearest division in the pollen dataset is between zone A and zones B–E; a large number of significant indicator taxa (Table 3) collectively make zone A very distinctive compared with the others. This fundamental division of the sequence is also very clear in the sedimentology, e.g. in the loss-on-ignition data. Pollen zones B–E are comparatively alike in terms of palynology and sedimentology, and the zonation reflects gradual changes (e.g. a more or less steady increase in *Mauritia* t. throughout zones B–D) as well as sharper boundaries (e.g. the increase in *Cecropia* sp. across the zone D–E boundary).

Pollen Zone A

From 364–156 cm, which equates to Pollen Zone A, the core consists of sandy and clayey silts, characterised by high magnetic susceptibility, low organic carbon concentrations, and low C/N ratios. Their pollen assemblages are dominated by *Cecropia* sp., and Cyperaceae and Poaceae are also important. Pollen concentrations are low and preservation is less good than in overlying zones. Charcoal abundance is very low. The six radiocarbon dates from this part of the sequence have calibrated ranges between 5603 and 2748 cal a BP, and are not all in stratigraphic sequence.

Transition between Pollen Zones A and B–E

The boundary between pollen zones A and B is gradational rather than abrupt, spanning much of the interval between 180 and 148 cm, and many taxa or variables begin to change well below the formal zone boundary (at 156 cm). The sediments gradually transition upwards from sandy and clayey silts to lake gyttjas similar to those being deposited today, with much lower magnetic susceptibility and higher carbon concentrations and C/N ratios. Different proxies change at different rates and at different depths in the sequence: in particular, the main increase in pollen and charcoal concentrations and C/N ratios occurs some 20 cm below the main increase in loss-on-ignition values. Within the pollen assemblages, the major compositional

209 change occurs at the zone boundary, but percentages of e.g. *Cecropia* sp., Moraceae undiff.,
210 and *Brosimum* sp. begin to change c. 20 cm below the boundary and continue to change for
211 several centimetres above it.

212 *Pollen Zones B–E*

213 The six radiocarbon dates that fall within Zones B–E are in stratigraphic sequence and have
214 calibrated ranges between 2299 and 560 cal a BP. In general, Pollen Zones B–E contrast with
215 Zone A in having lower proportions of *Cecropia* sp. (except for Zone E), Cyperaceae and
216 Poaceae, and increased proportions of a range of tree and shrub taxa including *Ilex* sp.,
217 Melastomataceae/Combretaceae, *Brosimum* sp., *Alchornea* sp., *Euterpe* t. and *Mauritia* t.

218 Pollen Zone B is characterized by a number of indicator taxa including types typically found
219 in wetland forest settings, including *Symmeria paniculata*, *Ilex* sp., and Myrtaceae undiff.; ferns
220 are also abundant, and *Mauritia* t. begins to expand. In Zone C ferns decline, and *Mauritia* t.
221 becomes consistently abundant at around 15%, accompanied by an increase in *Euterpe* t. Zone
222 D is marked mainly by another increase in *Mauritia* t. to around 25%, at the expense of *Euterpe*
223 t. Zone E is characterized by a renewed increase of *Cecropia* sp. For more detail, see Table 2.

224 Charcoal concentrations in Zones B–D are typically high by comparison with the
225 concentrations in the lower part of Zone A, but with substantial variations; they are lower again
226 in Zone E. The sediment is gyttja throughout Zones B–D, with minor and gradual variations in
227 composition, the most marked of which as a decline in C/N ratios from the middle of Zone C
228 upwards, and an increase in loss-on-ignition in the upper half of Zone D.

229 **Age model**

230 In the clay-rich sediments below 148 cm, some of the radiocarbon dates are out of stratigraphic
231 sequence (Table 1). The sample from 280–282 cm (SUERC-46369) returned a calibrated age
232 of 5333–5603 cal a BP, significantly older than the basal sample (357–360 cm, 4833–4967 cal
233 a BP, SUERC-37523). Sample SUERC-46369 was composed of small picked fragments and,
234 despite best efforts to extract as much material as possible from the core section, the sample
235 size available for ^{14}C determination was <300 μg C, meaning that it may be unreliable.
236 Accordingly, we chose not to include it in our age model.

237 Three further dates were also rejected. Two samples of picked plant fragments from the clayey
238 silts, SUERC-37524 and SUERC-37521, produced radiocarbon dates which were at least 1000
239 years younger than bulk dates obtained from the same levels. An offset between macrofossil

240 and bulk dates was anticipated by Räsänen et al. (1991), who argued that bulk dates on Amazon
241 floodplain sediments were likely to contain old carbon introduced by fluvial inwash. The
242 confirmation of an old carbon offset in the mineral-rich sediments calls into question the
243 chronologies recently developed for three cores from Quistococha by Aniceto et al. (2014a, b).
244 They inferred a hiatus in deposition between 4900 and 2600 cal yr BP, but this coincides with
245 the transition from clayey silts to gyttja at the top of their cores. In our view, the old carbon
246 offset in the mineral-rich sediments is sufficient to account for this 'hiatus'. There is no
247 sedimentological indication of a hiatus in QT-2010-3, which instead shows a gradual change
248 from inorganic to organic sediments. The very low C/N ratio of organic matter in the clayey
249 silts was interpreted by Aniceto et al. (2014a) as indicating that the organic matter had largely
250 been reworked from soils, consistent with our interpretation of the dates. The age model for
251 QT-2010-3 presented here consequently relies only on picked macrofossil samples in the lower
252 part of the sequence, and the bulk samples SUERC-37522 and SUERC-37524 were rejected.

253 One other macrofossil date was rejected: the sample from 229–231 cm (2751–2842 cal a BP,
254 SUERC-37523) returned an age almost identical to that from 196–198 cm (2748–2838 cal a
255 BP, SUERC-37521). Given no strong indication of which of these two macrofossil dates was
256 more reliable, the one most in keeping with the rest of the dates (SUERC-37521) was retained.

257 Although we took these decisions to exclude four dates on the basis of the arguments presented
258 here, a run of BACON using all of the dates treated the same four dates as outliers, which
259 provides an independent line of support for our age model based on a different set of priorities
260 (i.e. a preference for avoiding large changes in sedimentation rate, rather than taking into
261 account the composition and size of individual samples).

262 In total therefore, eight of the twelve radiocarbon dates were used to produce an age model for
263 the lake core (Figure 2). The age model appears to be reliable in the gyttjas above 148 cm, but
264 should be treated with more caution in the mineral-rich sediments below.

265 **Palaeoenvironmental reconstruction**
266 Here we interpret the new palaeoenvironmental dataset from the lake core QT-2010-3 in terms
267 of palaeoenvironments, taking into account the published data from the peatland core QT-2010-
268 1 (Fig. 4; Roucoux et al., 2013; Lawson et al., 2014).

269 *Zone A (c. 4490–2180 cal a BP)*
270 In QT-2010-3 the sedimentology of Zone A, dominated by sands and silts, is interpreted as
271 representing a combination of lake sediments and the sediment-laden flood deposits of a

272   channel of the Amazon. The pollen assemblages should be interpreted cautiously, as they likely
273   represent a mixture of pollen blown in from around the lake, and fluvially-transported pollen
274   deposited during floods. The domination of pollen assemblages by *Cecropia* sp. is typical of
275   river-influenced sediments; *Cecropia* species are pioneer trees found in abundance on
276   riverbanks and disturbed floodplains (Pennington et al., 2004). Sedges (Cyperaceae) and
277   grasses (Poaceae), two other indicator taxa in this zone, are also typically abundant plants in
278   disturbed riparian environments. Within this zone the evidence for a gradual change in
279   conditions, with magnetic susceptibility generally declining and loss-on-ignition slowly
280   increasing, probably reflects a gradual decline in the influence of the River Amazon on the site,
281   i.e. a reduction in the frequency and volume of sediment-laden floodwaters reaching the
282   western edge of the floodplain, as the main river channel migrated eastwards.

283   *Zone B (c. 2180–1660 cal a BP)*
284   Beginning around 24 cm below (~300 years before) the base of Zone B, a faster transition to
285   much more organic sediments takes place. We interpret this transition as marking the effective
286   isolation of the basin from regular flooding by sediment-laden waters from the Amazon. At the
287   present day the peatland around the lake floods in exceptional years but there is very little
288   mineral material in the peats (Lawson et al., 2014), indicating that the floodwater originates
289   primarily from groundwater and/or rainfall on the floodplain. Unlike the previous studies of
290   Aniceto et al. (2014a, b), we find no evidence to suggest that sediment accumulation in the lake
291   was discontinuous. This is important because it implies that this Amazonian floodplain lake, at
292   least, contains a reliable record of environmental change, and that its hydrological balance has
293   not been as strongly affected by past climatic change as has previously been argued. From this
294   point on we interpret the QT-2010-3 pollen record as representing the vegetation growing in
295   and around the lake, including on the terrace as well as in the peat swamp, which was beginning
296   to accumulate peats around the same time (Lähteenoja et al., 2009a; Roucoux et al., 2013).

297   The sequence of vegetation communities reconstructed from the peatland record QT-2010-1 is
298   echoed in the new QT-2010-3 pollen record, but as might be expected from a lake record with
299   a wider source area integrating over a somewhat heterogenous environment, changes appear
300   more gradual and the pollen zones less distinct than in the peat core. Small-grained pollen types
301   such as *Cecropia* sp. and Moraceae are always much more abundant in the lake core, while
302   insect-pollinated taxa such as *Symmeria paniculata* and *Ilex* sp. are less abundant. These
303   discrepancies are consistent with the usual taphonomic bias of lake sites towards well-
304   transported anemophilous pollen types; *Cecropia*-type pollen typically occurs at 15–20% in

305   lake sequences, even where *Cecropia* is not locally dominant (Bush and Colinvaux, 1988; Bush

306   and Rivera, 1998, 2001; Weng et al., 2002; Gosling et al., 2009).

307   The peat core pollen record indicates that at its location, the vegetation in the first century of

308   peat accumulation was open with abundant Cyperaceae. The lake record suggests that this was

309   the case widely across the basin; not only are Cyperaceae abundant at the start of Zone B, but

310   the high abundance of Melastomataceae/Combretaceae (many members of which are shrubs)

311   and several fern taxa such as *Nephrolepis* sp. and *Polypodium* t. is strongly indicative of open

312   conditions. Myrtaceae, typically shrubs of deeply-flooded environments (in similar floodplain

313   settings), are also relatively abundant in this zone. Whereas the record from the peatland

314   indicates little presence of *Mauritia/Mauritiella* in the early period of peat accumulation, the

315   lake record suggests that suitable habitat for these palms (and others such as *Euterpe*) was

316   present somewhere in the pollen catchment from the outset.

317   Charcoal is continuously present and much more abundant in Zones B–D than in Zone A,

318   indicating that the vegetation was subjected to burning. The substantial variations in the

319   charcoal concentration throughout this period suggest variations in the fire regime over time.

320   Charcoal was all but absent in pollen slides from core QT-2010-1 so, unless QT-2010-1 was

321   an exceptional location within the peatland, the charcoal in QT-2010-3 is very likely to

322   originate from outside the permanently-wet peatland, most likely on the drier terrace above the

323   lake.

324   *Zone C (1660–680 cal a BP)*

325   In Zone C the pollen evidence indicates a further step-like expansion of the palms

326   *Mauritia/Mauritiella*, accompanied by a sharp decline in the abundance of ferns, which

327   indicate open environments, and taxa such as Myrtaceae that are indicative of deeply-flooded

328   hardwood communities. This shift in assemblages probably reflects the gradual lessening of

329   the depth and/or frequency of flooding (due to the infilling of the basin with peat and the

330   continued migration of the Amazon away from the site) and the closing up of the palm swamp

331   forest canopy.

332   *Zone D (680–90 cal a BP)*

333   Zone D is marked by a further small step-expansion of *Mauritia/Mauritiella* at the expense of

334   tree diversity in general, and Melastomataceae/Combretaceae and *Euterpe* in particular. This

335   decline in diversity was also found in the peatland pollen record, which was taken to indicate

336   that the very low tree diversity recorded at the peatland core site today is of relatively recent

origin (Roucoux et al., 2013). The new lake record suggests that this was a general pattern across the Quistococha basin. It remains unclear whether this decline in diversity is the result of environmental changes such as homogenization of the peat swamp environment due to infilling, or the outcome of centuries of inter-specific competition.

Zone E (90 to -60 cal a BP, i.e. AD 1860–2010)

The key characteristic of this uppermost zone is a renewed expansion of the disturbance indicator *Cecropia* sp. This likely reflects recent human activities around the lake, presumably focused on the western shore and the terrace above where much of the land has been cleared of forest (Fig. 1c). Perhaps counter-intuitively, charcoal concentrations are lower in Zone E than is typical in Zones B and C (Zone D being transitional), which suggests that the rate of burning (in terms of biomass per year) was higher in the more distant past than in recent decades.

Discussion

Although they are typically rich in pottery, few archaeological sites in Western Amazonia contain stone tools (Lathrap, 1970; Rivas Panduro et al., 2008). Without stone tools it would have been very difficult for people to substantially alter or clear forests without using fire (Bush et al., 2015). The majority of soil cores taken in interfluvial areas in Western Amazonia by McMichael et al. (2012) did not contain any charcoal, which indicates that natural fires are extremely rare and small-scale; Mayle and Power (2008) separately estimated the natural fire return interval in Western Amazonia at 900 years. We therefore interpret the microcharcoal record from Quistococha as an important indicator of human presence and environmental impact (Bush et al., 2015).

The first increase in microcharcoal in the new lake record at c. 2450 cal a BP coincides with the change from minerogenic sediment to organic sediment in the sequence. It possibly indicates a taphonomic change rather than the arrival of people at Quistococha. However, this date coincides with the earliest known ceramics on the adjacent terrace, dated to 2350–2690 cal a BP (Rivas Panduro, 2006; Rivas Panduro et al., 2006). Charcoal is thereafter present in quantity in every sample in the lake record and it seems likely that, despite an apparent gap in the direct archaeological evidence, people were present in the area near Quistococha persistently up to the present day.

There is no clear indication in the Quistococha lake sequence (beyond its charcoal record) for a substantial impact by people on the surrounding *terra firme* forest until modern times. The

369 main structural changes in the pollen assemblages are explainable in terms of changes in the

370 peat swamp forest, which Roucoux et al. (2013) accounted for by a combination of a changing

371 degree of influence from the River Amazon as it migrated away from Quistococha, and

372 autogenic succession. *Mauritia* t. appears to have become generally more abundant over the

373 last 2000 years in many parts of Amazonia, and this expansion has been linked to the use of

374 fire, suggesting that humans may have been involved (Rull and Montoya, 2014). However,

375 Roucoux et al. (2013) did not find it necessary to invoke human activities to explain the

376 vegetation changes reconstructed from their peatland record, and they found no evidence to

377 suggest *in situ* burning.

378 Given the strong and varying representation of peatland taxa in the lake sediment pollen record,

379 a very detailed reconstruction of the history of *terra firme* forest would not be justifiable, but

380 some important inferences can nevertheless be made. The strongest palynological indicator of

381 human impact in the new lake sediment record is the record of the key disturbance indicator

382 *Cecropia* sp. It expands several times in Zones C and D, but never to the levels reached since

383 the 19th century (Zone E), which still represent less than total deforestation: even today, most

384 of the land around Quistococha remains covered in forest (Fig. 1). Pollen of the Moraceae

385 family, typical of *terra firme* rainforest (Gosling et al., 2005), remains abundant throughout the

386 last c. 2200 years. The pollen data are therefore consistent with, at most, small-scale clearances,

387 and not landscape-scale deforestation.

388 This interpretation is consistent with the results of a previous study of soil cores from the region

389 around Iquitos (McMichael et al., 2012, 2015), which found no evidence for deforestation (in

390 three soil cores sampled for phytoliths) and much less evidence for past burning than in other

391 parts of Amazonia (charcoal was present in nine out of 40 soil cores, a much lower proportion

392 than in most other parts of Amazonia studied by McMichael et al. [2012, 2015]). By contrast,

393 in many drier parts of Amazonia there is evidence for very extensive clearance of forest in pre-

394 Columbian times. Networks of fields and geoglyphs from e.g. the Beni basin/Llanos de Mojos,

395 Bolivia (Erickson and Balée, 2006), eastern Acre (Mann, 2008), or the upper River Xingu

396 (Heckenberger et al., 2003), may imply largely unforested landscapes. A benchmark for the

397 palaeoecological expression of this type of landscape is provided by Carson et al. (2014), who

398 studied two lake sediment sequences (Lagunas Granja and Orícore, Fig. 1) close to a complex

399 of geometric earthworks in the seasonally-dry Beni region of NE Bolivia. Their pollen data

400 indicate that the vegetation was substantially more open than it is today, both before and during

401 the period of earthwork construction, with >50% Poaceae (grass) pollen and <30% tree pollen

13

402 in their sequences. Forest cover has expanded only in the last few centuries, possibly due to a
403 combination of land abandonment and climatic change. However, such extensive maintenance
404 of open environments was not ubiquitous, even in seasonally-dry regions: for example, in the
405 Upper Beni, two lake records have been produced which indicate little reduction of the forest
406 cover by pre-Columbian people (Lakes Chalalán and Santa Rosa: Urrego et al., 2013), while
407 in Acre State, Brazil, there is compelling palaeoecological evidence that geoglyphs were
408 constructed in landscapes that were only ever partly cleared of trees at any one time (Watling
409 et al., 2017).

410 Another point of comparison is provided by palaeoecological research on lakes and soils in
411 aseasonal, densely forested regions of Ecuador and SE Peru. Here Bush et al. (2007) and
412 McMichael et al. (2011, 2012, 2015), in studies of five lakes (Ayauchi, Gentry, Parker, Vargas,
413 Werth) and numerous soil sequences in interfluvial settings which were not associated with
414 archaeological sites, showed that past human impact (crop pollen and charcoal) was patchy,
415 with three out of five lakes producing temporally discontinuous charcoal records, and two lakes
416 and many soil cores producing no charcoal at all; nowhere did they find indications of
417 landscape-scale forest clearance (Bush et al., 2007a; McMichael et al., 2011, 2012, 2015).
418 Continuity of forest cover over the past c. 5000 years was also inferred at Lake Kumpaka in
419 the Andean foothills of eastern Ecuador (Liu and Colinvaux, 1988) and, in the lowlands, at
420 Maxus 5, despite a continuous charcoal record (Athens and Ward, 1999).

421 Our dataset thus fits into an emerging pattern, whereby pre-Columbian landscapes in the wetter
422 climatic regions of Amazonia were typically less likely to be deforested than those in
423 seasonally dry climatic regions. Importantly, our dataset makes it clear that, even where there
424 is direct archaeological evidence for human settlement adjacent to the palaeoecological record,
425 forest cover could remain largely intact.

426 It is highly likely that people used forest and wetland resources in ways that are palynologically
427 and archaeologically invisible, but there is no direct evidence in the new dataset, nor from the
428 peatland pollen records from Quistococha (Roucoux et al., 2013) and San Jorge (Kelly et al.,
429 2017), of human activities in the peatlands themselves. Phytoliths of palms which may have
430 originated in the swamp were recovered from the archaeological site, although remains of the
431 dominant palm *Mauritia flexuosa* were not observed (Rivas Panduro, 2006).

432 Our dating evidence indicates that hunter-gatherer communities were already living close to
433 Quistococha before the lake became fully isolated from the Amazon. This is consistent with

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the so-called 'bluff model' of pre-Columbian settlement (Denevan, 1996), whereby settlements in the interior of the Amazon basin tend to occur on high, rarely-flooded terraces adjacent to navigable rivers. The later horticultural, ceramic-using occupations attested in the Quistococha archaeological record were likely living in a different landscape context, with less direct access to the main-stem Amazon, but still able to rely on the lake and wetland for important resources such as fish. Our palaeoenvironmental reconstruction confirms that in this region of Amazonian Peru, pre-Columbian settlement was not restricted to the immediate shores of navigable rivers, but could extend at least to the edge of the active floodplain, which can be very wide: today Quistococha is separated from the main channel of the Amazon by 10 km of forested floodplain.

Conclusions

The palaeoenvironmental record from Quistococha and its associated archaeological dataset together provide an important piece of information that helps us to judge the extent of past human impact in this aseasonal region of Amazonia. The new pollen record from the lake provides evidence for prehistoric human activity in the form of a charcoal record which indicates continuous human activity since before the lake was isolated from Amazon floodwaters. This indicates that gaps in the archaeological record from the site adjacent to the lake do not imply an absence of human populations from the wider area. Occupation apparently persisted throughout the last c. 2500 years, even after the Amazon abandoned the Quistococha basin and the site became set back from the main navigable waterway. Crucially, throughout this period the relative abundance of the key forest disturbance indicator *Cecropia* remained low, before increasing sharply over the last 100 years. This indicates that pre-Colombian societies did not substantially deforest this landscape, and that the present, moderate extent of forest disturbance around Quistococha is without precedent in the last 2500 years.

Small floodplain lakes occur frequently in the region south and west of Iquitos, and those that occur far from the present channel may well hold sediment records as old, continuous, and well-resolved as that at Quistococha. They provide an excellent opportunity for further investigation of the spatial variation in past human interaction with forests in Peruvian Amazonia, especially if integrated into regional archaeological research programmes.

Supplementary Information

Additional supporting information can be found in the online version of this article:

Figure S1 Full pollen percentage diagram for core QT-2010-3.

15

466 **Acknowledgements**

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Figure captions

Figure 1: Location of sites discussed in the text. (a) Location of the main study area. Published records referred to in the Discussion: 1, Ayauchi; 2, L. Kumpaka; 3, Lakes Werth, Gentry, Parker and Vargas; 4, Lakes Chalalán and Santa Rosa; 5, Lagunas Granja and Orícore. (b) Map indicating the context of Quistococha on the Amazon floodplain. The paleoecological site of San Jorge (open circle; Kelly et al., 2017) and the town of Tamshiyacu and city of Iquitos (filled circles) are shown for reference. Darker shading indicates land over 120 m above sea level, inferred from Shuttle Radar Topography Mission (SRTM) data (http://srtm.csi.cgiar.org). (c) False-colour Landsat TM image of the study site, covering the same area as panel d. Colours follow Draper et al. (2014): red and dark green indicate forest; black, open water; white and light blue, bare or open ground. (d) Key features of the area shown in panel c, including the location of cores QT-2010-1 and QT-2010-3.

Figure 2: Bayesian age-depth model for core QT-2010-3. The shaded area indicates the 95% probability interval of the model, given the assumptions underlying it (i.e. the prior information specified). The red line indicates the best-fit (most probable) age-depth relationship. For the key to lithological symbols see Figure 3.

Figure 3: Selected palynological and sedimentological data for core QT-2010-3. For the full pollen dataset, see Figure S1 (Supplementary Information). The dashed vertical line in the plot of *Mauritia* t. grain diameter indicates the approximate division between samples that are richer in *Mauritiella* (typically <40 μm) and samples that are richer in *Mauritia* (typically >40 μm). Measurements are indicated with a dot where only one measurement was possible, and with a horizontal bar indicating the 95% confidence interval of the mean where more than one measurement was made. Abbreviations: *Dal.*/*Mach.*, *Dalbergia*/*Machaerium*; Mela.Comb., Melastomataceae/Combretaceae; part., particles; t., type..

Figure 4: Selected pollen taxa from cores QT-2010-3 (lake: this study) and QT-2010-1 (peat: Roucoux et al., 2013) plotted against age.

Table 1: Results of radiocarbon dating analyses undertaken on samples from the lake core at Quistococha (QT-2010-3). Analytical uncertainty is shown to 1 standard deviation (s.d.). Samples were analysed at the NERC facility at East Kilbride. (Note that sample marked ‡ contained <300 μgC). * denotes sample rejected from age model.

Laboratory code	Depth (cm)	Material	^{14}C age (a BP)	s.d.	δ^{13}C	Calibrated age (cal a BP)
SUERC-44979	40–41	Bulk gyttja	703	37	-25.9	560–710
SUERC-44980	60–61	Bulk gyttja	927	35	-26.2	765–927
SUERC-44981	88–89	Plant macrofossil	1357	37	-31.6	1182–1357
SUERC-38477	95–96	Bulk gyttja	1710	37	-29.0	1540–1705
SUERC-37520	127–128	Bulk gyttja	1942	37	-32.3	1830–1930
SUERC-44982	152–153	Bulk gyttja	2117	37	-31.3	1992–2299
SUERC-37521	196–198	Picked plant fragments	2669	37	-21.8	2748–2838
SUERC-37522*	196–198	Bulk	3728	35	-22.9	3914–4070
SUERC-37523*	229–231	Picked plant fragments	2678	37	-16.3	2751–2842
SUERC-37524*	229–231	Bulk	3667	35	-21.2	3926–4082
SUERC-46369*	280–282	Picked plant fragments ‡	4792	78	-37.1	5333–5603
SUERC-44986	357–360	Picked plant fragments	4311	36	-28.2	4833–4967

Table 2: Pollen assemblage zone descriptions for core QT-2010-3.

Zone (depths, age)	Pollen assemblage zone characteristics
E (1–10 cm, 90 to -60 cal a BP)	*Cecropia* sp. increases towards the top of this zone where it reaches 40%. *Mauritia* t. remains abundant (max. 22%); *Alchornea* sp. (max. 10%) and Moraceae (max. 17%) remain moderately abundant; *Euterpe* t. becomes rare (max. 2.5%). All fern spore types are rare, with many <1% in most samples.
D (10–44 cm, 680–90 cal a BP)	*Mauritia* t. increases to >20% for the first time and peaks at the top of this zone (38%). *Euterpe* t. declines to 3% at the top of this zone, and Cyperaceae and Poaceae decline further, dropping to <1% at the top of this zone. *Alchornea* sp. (max. 13%) and *Cecropia* sp. (max. 25%) remain abundant, and *Brosimum* sp. continues to be moderately abundant (max. 7%). Amongst the minor types, *Amanoa* sp. peaks towards the top of this zone (2%).
C (44–108 cm, 1660–680 cal a BP)	Moraceae, *Alchornea* sp. and *Cecropia* sp. remain abundant. *Mauritia* t. is moderately abundant in this zone (max. 16%), as is *Euterpe* t. which peaks at 72 cm (12%). Cyperaceae declines to <5%. Amongst the minor types, *Ilex* sp. declines from its values in the zone below, and is mostly <1% in this zone. Asteraceae declines to <1%. *Tapirira* t. peaks towards the top of this zone (max. 2.6%). *Trema* t. is most abundant in this zone (max. 3.5%).
B (108–156 cm, 2180–1660 cal a BP)	*Cecropia* sp. declines to <20%. Moraceae peaks in this zone at 128 cm (28%). Cyperaceae remains moderately abundant (max. 11.5%), and Poaceae declines to <5%. *Brosimum* sp. increases to >5% for the first time, and *Alchornea* sp. increases towards the top of this zone (max. 10%). *Mauritia* t. and *Euterpe* t. both increase to >5% for the first time. Amongst the minor types, *Ilex* sp*.,* Asteraceae and Myrtaceae are consistently present. Several fern spore types are moderately abundant; *Nephrolepis* sp. (max. 10%), *Polypodium* t. (max. 6%), and Monolete spores (max. 14%) all peak in this zone.
A (156–330 cm, 4490–2180 cal a BP)	*Cecropia* sp. is dominant (max. 67%), with Moraceae, Poaceae, Cyperaceae and *Alchornea* sp. also abundant. Amongst the minor types, *Piper* sp., Mel./Comb., Asteraceae, and *Iriartea deltoidea* are all consistently present. Fern spore types never exceed 10%.

Table 3: Statistically significant indicator species ($p < 0.05$) identified for each pollen assemblage zone in core QT-2010-3.

Taxon	Zone	Indicator value	Probability
Pouzolzia	E	0.4578	0.012
Pourouma	E	0.4631	0.011
Euterpe t.	C	0.3691	0.047
Symmeria	B	0.4563	0.026
Moraceae	B	0.2879	0.020
Ilex	B	0.4480	0.011
Myrtaceae	B	0.4153	0.004
Melastomataceae/Comb.	B	0.3580	0.002
Asteraceae	A	0.3527	0.028
Cyperaceae	A	0.4234	0.013
Piper	A	0.5249	0.009
Cecropia	A	0.3450	0.003
Poaceae	A	0.6166	0.001

Supplementary information

Figure S1: Full pollen percentage diagram for core QT-2010-3.