



Holocene patterns of peat accumulation in Peruvian Amazonia

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ABSTRACT

Peatlands accumulate and store carbon over centuries to tens of millennia. Analysing the age structure of peatlands helps us to understand their genesis, development, and stability as carbon stores, and informs peatland management. Here we analyse new and previously published radiocarbon dates from peatlands in the Pastaza-Marañón Basin in Peru, the largest known peatland complex in Amazonia. We show that peatlands here are younger (< c. 8900 and frequently <2500 years old) than in many other parts of the tropics. Basal peat ages in extant peatlands vary depending on the geomorphological stability of the landscape, with younger basal dates typically occurring close to active river floodplains and older basal dates in more stable contexts. The data indicate that within individual peatlands, peat initiation may occur synchronously across a basin, or peat may spread laterally from one or more nucleation sites. Only two out of seven well-dated records show clear hiatuses in past peat accumulation, suggesting that carbon sequestration in some, but not all peatlands has been vulnerable to landscape hydrological change or climate change. Peatland ecosystems in the region are economically important sources of non-timber forest products, which it may be possible to harvest sustainably without biomass loss or drainage, but our analysis indicates that the peat itself accumulates too slowly to be considered as a renewable resource on economically meaningful timescales.

1. Introduction

Peatlands are valued for many reasons, including their contribution to biodiversity, ecosystem services and resources, and their role as important reservoirs of carbon. Peats typically accumulate over time-scales of centuries to millennia and preserve in their stratigraphy a record of change over time. Understanding the age structure of peatlands can help us to understand how they formed, how carbon has accumulated in them, and how vulnerable they may be to future climate change and human activities (e.g. Roucoux et al. 2017; Lawson et al., 2022). For example, different models of peatland development and expansion can

be tested using basal dates from multiple cores (e.g. Juselius-Rajamäki et al., 2023); evidence for past hiatuses in peat accumulation, or net peat mineralization, can (together with palaeoclimatic data) give insights into the stability of carbon storage in the past (e.g. Garcin et al., 2022); and age-depth models are important for validating the process-based peat accumulation models (e.g. Kurnianto et al., 2015; Young et al., 2023) which are increasingly used to explain and predict peatland responses to environmental (including climatic) change.

Beyond these specialised research agendas, understanding the age structure of peatland ecosystems makes an important contribution to tropical ecology because other opportunities for reconstructing long-

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term ecosystem dynamics (e.g. palynology, environmental history, dendrochronology) are scarce in the lowland tropics, at least by comparison with many temperate environments. Reconstructing the history of peatland development gives a rare and valuable insight into, for example, the rates and processes of ecological community assembly in tropical forests, and a means of assessing the role of past disturbances such as climate change and human impact. For example, palaeoecological research has shown that peatland pole forests, an important target for conservation due to their distinctive habitat (Honorio Coronado et al., 2021), are sometimes only a century or two old and may still be undergoing natural successional change (Kelly et al., 2017). Robust information on the age of peat carbon is also relevant to policy-making: peat is still being ‘harvested’ for power generation and horticulture in some parts of the world despite a strong case for the view that peat accumulates too slowly to be considered a renewable resource within a sustainable development/net zero framework (Cole, 2017).

This study presents 66 previously unpublished radiocarbon dates, including eight from a PhD thesis (Draper, 2015), on peats from the Pastaza-Marañón Foreland Basin (PMFB), the largest peat-forming wetland complex known in Amazonia (Hastie et al., 2024; cf. Winton et al., 2025). The new dates substantially increase the total available from peatlands in the PMFB to 155, allowing a reappraisal of earlier interpretations drawn by Lähteenoja et al. (2009a, 2009b) and Lähteenoja and Page (2011). This study has three aims:

1. To investigate the timing of peat initiation, including testing the hypothesis that peat initiation was favoured during discrete periods of particularly wet climate;
2. To analyse the geography of peat accumulation, including testing the hypothesis that older peats are restricted to the more stable geomorphological areas north of the Marañón river, and the floodplains of black-water rivers;
3. To test whether peat accumulation has been affected by past climatic change.

Aim 1 stems from previous indications that PMFB peatlands are typically very young compared with those in other parts of the tropics, often only 2000–3000 years old, with only a handful of older dates up to a maximum of c. 8900 cal BP (calendar years before present). By contrast, there are dates older than 40,000 cal BP from SE Asia (Ruwaimana et al., 2024) and central Africa (Dargie et al., 2025), while many peatlands in the temperate and boreal zones began to form shortly after local deglaciation during the Lateglacial or early Holocene (e.g. Gorham et al., 2007; Liu et al., 2025). In many parts of the world, the timing of initiation of new peatlands and/or their lateral expansion has been shown to relate to periods of enhanced climatic wetness, e.g. a climatic shift at the start of the Holocene (e.g. Ruppel et al., 2013; Liu et al., 2025) or a response to changing monsoon strength (e.g. Zhao et al., 2014). Through further dating, we aim to test whether the extant PMFB peatlands are indeed anomalously young, and whether there is evidence for greater frequency of peat initiation and/or expansion at particular times.

Aim 2 builds on earlier work by Lähteenoja et al. (2009a, 2009b) and Lähteenoja and Page (2011), testing the hypothesis that the distribution of older peats within the PMFB can be explained by the contrasting geomorphological stability of floodplains in different parts of the basin. Floodplain stability varies partly according to the tectonic history of the basin (Dumont, 1996), and partly depending on whether a river originates in the Andes (and is thus rich in suspended mineral sediment, a ‘white water’ river), or within the basin itself (‘black water’ rivers, usually dark in colour due to high concentrations of dissolved organic carbon: see ‘Study Region’ below for further discussion). The expanded dataset also gives insights into the process of peat initiation and lateral expansion at the scale of individual peatlands, contributing to the emerging conceptual model of peatland development in the PMFB.

Aim 3 seeks to understand the sensitivity of PMFB peatlands to past

climatic change. Research in many different environments has linked peat accumulation or other peat properties to climatic change, particularly to changes in climatic wetness and/or seasonality. For example, in the central Congo Basin, palaeoenvironmental research recently demonstrated that a Mid to Late Holocene drought event, culminating around 2000 cal BP, caused extensive peat decomposition and return of stored carbon to the atmosphere (Garcin et al., 2022). This evidence for past sensitivity to climatic change suggests that Congo Basin peatlands may also be sensitive to future climatic drying (ibid.). There are indications of similar variations in peat carbon accumulation related to climate change e.g. in high Andean peats (Perez and Loisel, 2023). Studies on two separate peat sequences in the PMFB (Kelly et al., 2017; Swindles et al., 2018) have identified hiatuses in peat accumulation that may also be caused by climatic change (discussed further below). This study aims, by detailed dating of further sequences, to test whether such hiatuses are widespread, and therefore to assess how susceptible PMFB peatland carbon storage has been to interruption in the past.

2. Study region

The PMFB is now one of the best-studied peat-forming regions in the tropics despite only having been recognized as a peatland complex in the scientific literature within the last twenty years (Freitas et al., 2006; Lähteenoja et al., 2009a; Baker et al., 2019). The region is a tectonic basin, sometimes called the Ucayali Depression, approximately 400 km across its longest (east-west) axis (Fig. 1). The basin is at least Mesozoic in age, with subsidence continuing into the Quaternary (Dumont, 1996). The basin is traversed by two major rivers, the Marañón and the Ucayali, both of which originate in the Andes and which join to form the Amazon towards the eastern edge of the basin. The basin's climate is tropical ever-wet, with an annual average temperature of 26 °C and ~ 3000 mm of rainfall measured at the regional capital, Iquitos, with two minor dry seasons (Marengo, 1998). The level of the main rivers responds strongly to the Andean snow-melt cycle, with high water between February and May (Roucoux et al., 2023). The vegetation varies between terra firme (permanently unflooded) forest on higher land, to a mosaic of seasonally flooded forest, palm swamp, herbaceous fen, and peatland pole (thin-stemmed) forest in low-lying areas (Fig. 2; Honorio Coronado et al., 2021; Hastie et al., 2022, 2024). About 100,000 people live in the basin, including indigenous communities; subsistence livelihoods are dominated by fishing, hunting and collection of non-timber forest products such as fruit of the palm *Mauritia flexuosa* (Schulz et al., 2019a, 2019b), and therefore are highly dependent on the peatlands.

In detail, the geomorphology of the basin has a complex history (e.g. Dumont, 1996; Rojas et al., 2023), meaning that although it is legitimate to view the PMFB as a distinct hydrologically-interconnected wetland complex, its character varies substantially from place to place. Major landscape units include the gently southwards-sloping Pastaza Fan, which occupies the north-western part of the basin; the Pacaya-Samiria region or Central Ucayali Depression between the Marañón and Ucayali, where small ‘scavenger’ rivers today occupy fossil channels and floodplains of the Ucayali (Rojas et al., 2023); and the floodplains of the sediment-laden Ucayali and Amazon, which are highly geomorphologically active (e.g. Quintana-Cobo et al., 2018; Abad et al., 2022). The catchments of major tributaries, such as the blackwater Tigre and the whitewater Tapiche Blanco, have different characteristics again in terms of water chemistry, hydroperiod, geological structure, and vegetation, meaning that the present, still limited, sampling of peatlands in the PMFB is unlikely to be fully representative of the total variation in their form and function.

3. Methods

The dates analysed here are presented in Tables S1 and S2. Previously published dates were obtained for a range of purposes reflecting changes in research questions and methods since work began in this

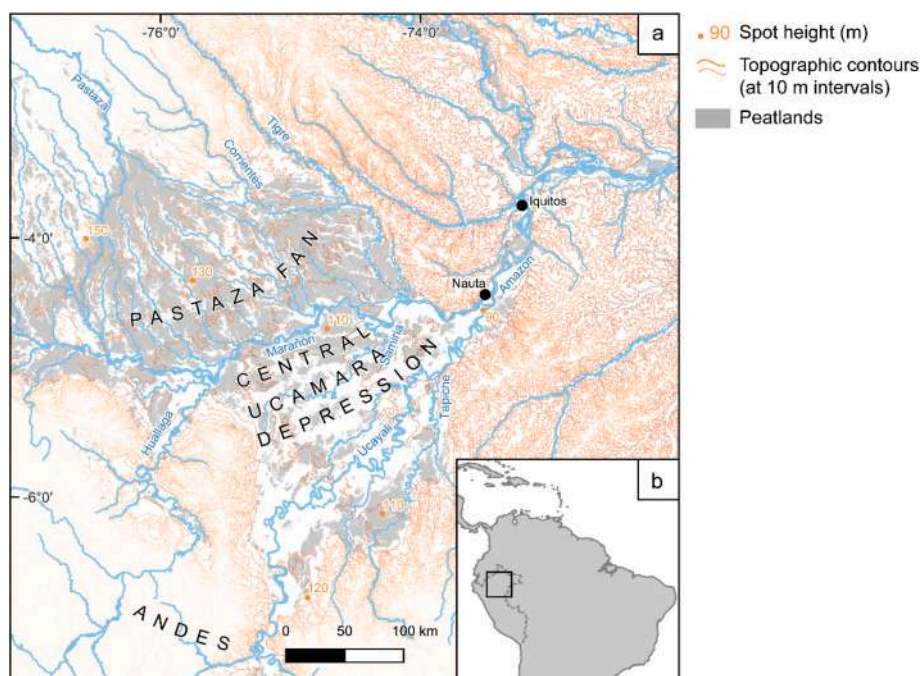


Fig. 1. (a) Map of the study region with features mentioned in the text. Contours and spot heights (in metres above WGS84 geoid) based on FABDEM 1.2 (Forest And Buildings removed Copernicus Digital Elevation Model, [Hawker et al., 2021](#); [Hastie et al., 2022, 2024](#)); peatland distribution from [Hastie et al. \(2022, 2024\)](#). (b) Context map showing the location of panel a within South America; outline of Peru shown as a dotted line.

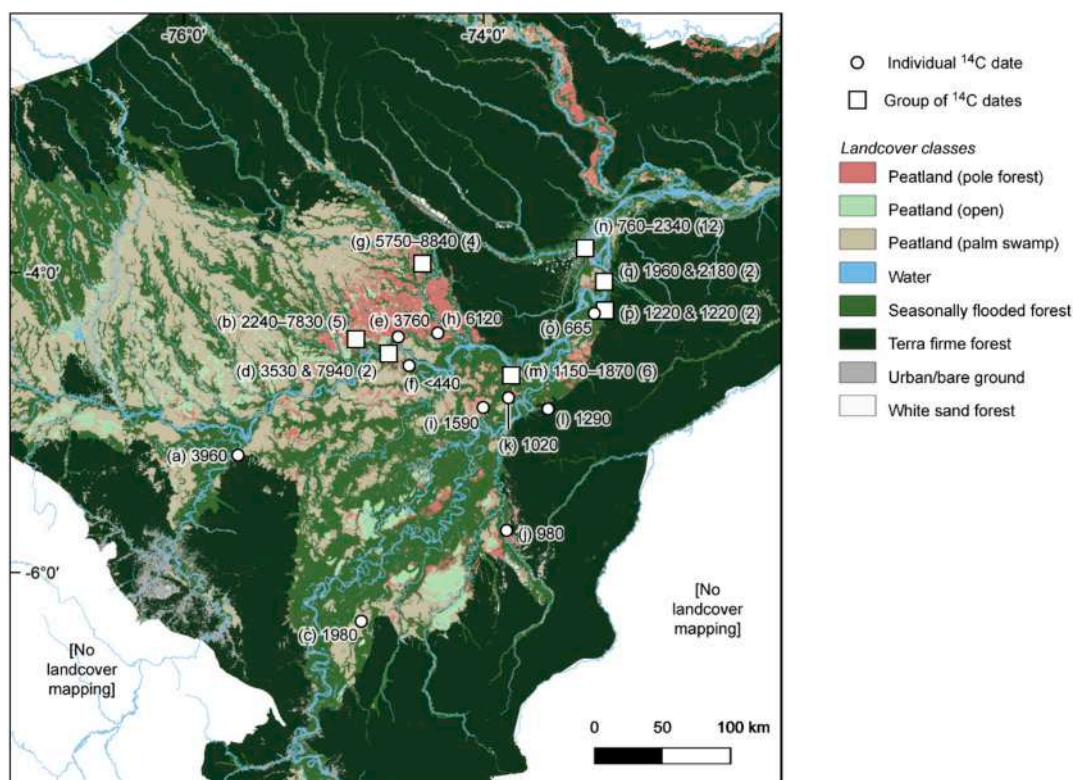


Fig. 2. Basal peat ages in calendar years before present (cal yr BP), summarized as the median of the calibrated age range of individual dates, or the range of dates where there are more than two dates from the same peatland. Landcover mapping is from [Hastie et al. \(2022, 2024\)](#). Letters indicate sites as follows: (a) Lagunas; (b) Ollanta/Roca Fuerte; (c) Maquia; (d) San Roque (SRQ_01_2018 and SR5); (e) San Roque (SAR_T3_03_B); (f) Parinari; (g) Aucayacu; (h) Nueva York; (i) Riñon; (j) Tapiche Blanco; (k) Jenaro Herrera (JEN_14_2018); (l) Jenaro Herrera (JH_2011_4); (m) Veinte de Enero; (n) Quistococha; (o) Charo; (p) Buena Vista; (q) San Jorge. Figures in parentheses indicate the number of dates within an individual peatland.

region. Peat dating began as part of exploratory work by [Lähteenoja et al. \(2009a, 2012: 42 dates\)](#) and was followed by a series of

palaeoecological studies on peat sequences which aimed to understand the changes in vegetation and environmental conditions through the history of the peatlands (Roucoux et al., 2013; Kelly et al., 2017, 2020; Swindles et al., 2018; Sassoon et al., 2024: 46 dates). More recently, complete peat sequences have been collected and dated principally to address the questions presented in this paper, i.e. the spatio-temporal patterning of peat initiation and the sensitivity of the peatlands to past climate change. Sampling in all cases (both the new and the previously published dates) has been purposive, not random; fieldwork in the region's peatlands is constrained by problems of access to sites which are often remote, hazardous, and/or legally inaccessible. This means that sites close to rivers and in the eastern half of the Pastaza-Marañón Basin, within relatively easy reach of the main regional city Iquitos, are disproportionately represented in the dataset. On the other hand, the dataset covers all of the major types of peatlands known to occur; these peatland types are classified mainly by the present-day vegetation at the coring site as palm swamp forest, pole forest, open herbaceous mire, and seasonally flooded forest (Draper, 2015; Draper et al., 2014; Honorio Coronado et al., 2021). The dataset now also includes 20 cores with multiple down-core dates, some of them very thoroughly dated with up to 20 dates per core. There are also now four discrete 'peatlands' (i.e. distinct bodies of peat, bounded by rivers or mineral soils) where more than one core has been dated, giving insights into the pattern and process of peat emplacement within these individual peatlands.

Peats in the study region are typically highly organic and well humified with few visible macrofossils other than roots, and are clearly distinct from the fluvial or floodplain silts and clays that they overlie (e.g. Roucoux et al., 2013; Swindles et al., 2018; Kelly et al., 2020). Layers of silt-sized inorganic sediment are rarely present within the peat body, and at sites where thin layers do occur they likely represent occasional flooding by sediment-laden river water (e.g. San Roque SAR_T3_03_B; Sassoon et al., 2024). Two exceptional sites are San Roque SR5, reported by Lähenteenoja et al. (2012) as containing an interval of several metres where "the dominating sediment was minerogenic", and Parinari PAR-2018-01, which barely qualifies as a peat sequence by our definition as its LOI values rarely exceed 65% (see below). These two palm swamp sites are close to the sediment-laden Marañón river, suggesting that the high proportion of minerogenic material in these sequences is due to regular flooding from the river. These records are nonetheless of interest because they represent an understudied type of site that lies between the end-members of 'pure' peatlands on the one hand, and wholly fluvial depositional settings on the other (Lähenteenoja et al., 2012). In this paper we consider SR5 and PRN-2018-01 separately from the more clearly defined peat sequences.

All of the peat sequences included in this study were obtained in the field using a hand-operated Russian-type (enclosed chamber) peat corer (Jowsey, 1966). Coring always continued to the silt or clay deposits underlying the peat. In early work by Lähenteenoja et al. (2009a, 2012) and Draper (2015), the base of the peat was identified visually in the field, and cores were also subsampled in the field with a resolution of 10 or 16 cm (see Table S1 and S2 for details). Given the typical peat accumulation rate of about 1 m per millennium, this introduces an uncertainty on the order of one to two centuries, in addition to analytical uncertainty which is of a similar magnitude. In more recent work, including the new dates presented here, at least the lowermost core section was returned intact to the laboratory and 'basal' samples were obtained for dating from each sequence at the lowest point where organic matter content measured by loss-on-ignition (Heiri et al., 2001) at 4 cm resolution exceeded 65% (Lawson et al., 2014, 2015; Dargie et al., 2017). The lowermost peat samples are underlain by, and sometimes intercalated on a centimetre scale with, grey and buff inorganic silts and clays; the stratigraphic transition from mineral sediment to peat may be gradational over a few centimetres (Figs. S1 and S2; cf. Quirk et al., 2022). In our discussion we do not place any weight on differences in age that are smaller than the uncertainty in basal age estimates which arise from issues of low resolution or analytical error.

Palaeoecological and geochemical studies (e.g. Roucoux et al., 2013; Lawson et al., 2014; Kelly et al., 2020) indicate that peat formation is often preceded by a period of low-energy deposition of silts and clays in lacustrine or over-bank depositional environments; at some sites silt/clay inputs gradually decreased over several centuries, whereas at other sites the change in depositional environment was more abrupt. Thus in dating the lowermost samples that are visibly peat or (more objectively) >65% OM, we obtain an estimate of the maximum age of peat at that location. This measurement also represents, albeit necessarily less precisely, an estimate of the date at which the core site transitioned from being dominated by fluvial or floodplain processes, to functioning as a peatland.

In addition to the lowermost peat sample (the 'basal' sample), further samples for dating were taken at intervals throughout selected cores, informed by other palaeoecological data (Åkesson et al. in prep) and in some cases extending into the underlying mineral sediments.

For the new dates presented here, bulk peat samples were processed by sieving at 180 µm and removing visible roots by hand, then by standard acid-base-acid pretreatment and AMS dating at the NERC Radiocarbon Facility, East Kilbride, UK. This treatment method was chosen on grounds of reliability, minimizing the risk of contamination by younger root material (Wüst et al., 2008) and for consistency with the large majority of published peat dates from the PMFB. An exception is the published set of dates from core AUC1.4 km, where some samples consisted of unidentified wood or leaf material and the remainder consisted of bulk peat sieved at 63 µm (Swindles et al., 2018).

For this analysis, all published and unpublished dates were calibrated in R version 4.4.0 (R Core Team, 2024) and the *rintcal* package (version 0.6.4; Blaauw, 2023) using a mixed calibration curve (50,50 IntCal20 and SHCal20; Reimer et al., 2020; Hogg et al., 2020) to account for the study region's location close to the Inter-Tropical Convergence Zone (Hogg et al., 2020). For young dates, the calibration curve was extended using the SH3 post-Bomb curve (Hua et al., 2021). Where samples had been dated in duplicate and the results were within error (three out of four cases), the dates were pooled before calibration following Scott et al. (2007). In the one case where two duplicate dates were substantially different, the younger was rejected on the grounds that it is more likely in these environments that a date is too young (e.g. due to root penetration or contamination during coring) than that it is too old.

Where more than two dates were available from separate levels within a core, age models were constructed using the *rbacon* package in R (version 3.2.0; Blaauw and Christen, 2011), with starting parameters adjusted to allow for abrupt changes in the age-depth gradient (i.e. low memory: $\text{mem.mean} = 0.1$, $\text{mem.strength} = 2$), as is appropriate for peats. The top of each core was assigned the date that the core was taken since there is no evidence of any disturbance, such as peat cutting or natural erosion, having removed the uppermost layers of peat at any of the sites. Overall peat accumulation rates were calculated for each core using the calibrated basal date and the date that the core was taken. Confidence intervals for the peat accumulation rates were calculated using the 95% confidence interval for the calibrated date, assuming that any uncertainty in the sample depth is negligible.

4. Results and discussion

The location of all sites is shown in Fig. 2, which summarizes the geographical distribution of dated peatland. Details of the new dates are listed in Table S1. There is presently very little direct evidence for pre-historic human impacts on the ecosystems of the PMFB, although palaeoenvironmental data remain sparse and many possible forms of past activity (e.g. drainage, deliberate forest management) would be difficult to identify in such records (see e.g. Rull and Montoya, 2014; Kelly et al., 2018). Consequently, our discussion focuses on natural processes of climate and ecosystem change.

4.1. Basal dates

After pooling of replicates, 43 cores from 17 separate peatlands have basal peat age determinations (Figs. 2 and 3). The 17 dates (including those from Draper, 2015) that have not previously been published include six dates from a palm swamp/open peatland complex close to the village of Veinte de Enero, near the confluence of the Marañón and Ucayali rivers; four dates from a peatland north of the Marañón named informally as Ollanta, which appears in remote sensing imagery to be contiguous with the peatland called Roca Fuerte by Lähteenoja and Page (2011); a date from Nueva York, a peatland pole forest by the blackwater Rio Tigre; two samples close to the town of Jenaro Herrera, one (core JEN_14_2018) from a palm swamp on the Ucayali floodplain, the other (JH-2011-4) from a 100 m wide patch of palm swamp within white sand forest on a low terrace above the present floodplain; a date from the exceptional site of Parinari discussed above, a palm swamp just south of the Marañón with organic sediments that barely qualify as peats; a date from a nearby open peatland at San Roque, core SRQ_01_2018; a date from a peat sequence developed in seasonally flooded forest at Buena Vista, on the banks of the blackwater Rio Tahuayo; and a date from Tapiche Blanco, from a pole forest peatland on the floodplain of the river of that name.

Notably, despite this additional sampling effort, sites in the south-eastern part of the PMFB, including on the present or former floodplains of the Ucayali and Amazon, have not returned dates older than ~3000 cal BP, while the oldest dates are in stable areas that are drained by blackwater rivers (e.g. the Tigre and minor tributaries of the Marañón). The oldest reported peat age from the PMFB remains that of Lähteenoja and Page (2011) of 8645–8990 cal BP at Aucayacu AU8, which is a pooled calibration based on two almost identical dates (7949 ± 50 and 7976 ± 50 uncal. BP; *ibid.*).

Fig. 3a plots all available basal age estimates, indicating that a large majority (30 out of 43) are younger than ~2300 cal BP. However, this result is partly an artifact of the concentrated dating effort at two sites, Quistococha and Veinte de Enero, both of which happen to have formed within the last 2300 cal yrs. (see below). Fig. 3b, which shows only the oldest date per peatland, indicates a more even spread of peatland formation dates through the last ~9000 years. Statistically, there is no indication that the dates are more clustered in time than would be expected by random sampling from a uniform distribution (nearest neighbour test, $p > 0.05$). There is also no statistically significant difference between vegetation types (H-test on the data shown in Fig. 3b, $p = 0.266$), although the sample size is small meaning that the power of this test is weak. At face value, one of the new dates, a young date of 930–1060 cal BP from a pole forest at Tapiche Blanco, is surprising given that pole forest peatlands have been associated with ombrotrophic, domed mires which are expected to take a long time to form (Lähteenoja et al., 2009b; Kelly et al., 2017). However, the site at Tapiche Blanco is not obviously domed, the peat thickness being only 120 cm. The presence of pole forest there may be due to other reasons e.g. low nutrient concentrations in the local groundwater. Open peatlands had until recently only presented young basal dates, but the record from San Roque SAR_T3_03_B (Sassoon et al., 2024), close to the Marañón, gave a date of 3650–3870 cal BP. This site has been classed as an open peatland, with abundant grasses and sedges, although there are scattered *Mauritia* palms at the site today. The persistence of more or less open vegetation at the site since its inception has been interpreted, based on several palaeoenvironmental proxies, to be due to repeated disturbance by flooding (*ibid.*).

Overall, the spatiotemporal pattern of basal dates likely reflects several different processes. Taken at face value, the absence of pre-Holocene dates (by contrast with similar datasets from e.g. the Congo Basin or SE Asia) suggests that the drier climates of the last glacial interval may have been generally unsuitable for peatland formation, though it is certainly possible that older peats have been overlooked. However, a reasonable explanation for the comparatively young dates is

that the PMFB (at least, those parts that have been well sampled) appears to be more geomorphologically active than many other tropical peatland regions, reducing the probability that older, pre-Holocene peat sequences would survive to the present day (as argued by Lähteenoja et al., 2009a and Lähteenoja and Page, 2011). Most of the major rivers crossing the PMFB, including the Marañón and Ucayali which join to form the Amazon, have their headwaters in the Andes and carry large quantities of sediment, which results in high rates of lateral erosion and deposition across the gently sloping landscape (Bernal et al., 2011; Rojas et al., 2023). Most peatlands close to these actively meandering or anastomosing rivers are probably only able to persist for up to a few thousand years. A field observation (T. Kelly) of a peat section in an eroding riverbank provides direct evidence that sites are being destroyed by erosion today, and large-scale creation and destruction of floodplain features in the PMFB has been documented using historical Landsat imagery (Quintana-Cobo et al., 2018). Reworking of old peat thus likely contributes to the flux of carbon transported by the Amazon and its tributaries (e.g. Moreira-Turcq et al., 2003). By contrast, older sites like Aucayacu and Ollanta are situated in less geomorphologically active parts of the landscape, particularly the north-eastern part of the basin around the Rio Tigre (Bernal et al., 2011), where remote sensing indicates abundant pole forest. This area is difficult to access but future sampling here would help to establish just how widespread such deep, old peats may be.

At four locations, dates obtained in multiple cores now give insights into patterns of peat initiation within individual peatlands. The most thoroughly studied peatland is Quistococha (Kelly et al., 2020; Fig. 4a) with 12 basal dates. All but one indicate peat initiation around 2000–2300 cal BP; peat initiation was very nearly synchronous across the whole peatland. Kelly et al. (2020) argued that the pattern in the basal dates, supported by palynology and other palaeoecological proxy data, was consistent with the peatland having originated in a channel abandoned by the Amazon. The only substantially younger date (SUERC-44988, 690–900 cal BP) came from an atypically shallow peat core close to the centre of the site, midway along a transect surrounded by older dates. This site presumably occupies a high point on the palaeo-floodplain which must have persisted as an inlier of mineral soil for more than a millennium until peat accumulation eventually overwhelmed it.

By contrast, the dates from Aucayacu (Fig. 4b), arranged along a transect from the edge towards the centre of the peatland, vary by about 3000 years in age and are in chronological order, oldest (and deepest) towards the centre. Swindles et al. (2018) interpreted these dates as indicating that peat first formed close to the centre of the present-day peatland, then expanded laterally. Similar lateral expansion is familiar in temperate and boreal settings (e.g. Ruppel et al., 2013) and has been reported in the tropics (e.g. at Ekolongouma, Congo: Dargie et al., 2017).

There is a similarly strong spatial pattern in the dates at Veinte de Enero (Fig. 4c). The six basal dates, arranged along a 2.4 km transect, all lie within 1000 years of one another: the youngest calibrates to 1020–1270 cal BP, the oldest to 1750–1990 cal BP. The oldest dates are in the central part of the peatland, which today has a high water table even during the dry season and is occupied by herbaceous vegetation. The dates become younger towards the northern margin of the peatland, suggesting lateral expansion as at Aucayacu, but the three northernmost dates overlap one another, implying rapid emplacement of peat towards the modern margin of the site, reminiscent of Quistococha.

At Ollanta/Roca Fuerte (Fig. 4d) there are five basal dates, ranging from 2150 to 2350 to 7680–7990 cal BP, widely spaced along a line 5.5 km long. However, here there is no obvious spatial trend in the dates. The oldest date comes from the westernmost, deepest peat sequence, perhaps occupying a former river channel towards the edge of the modern peatland. The lack of a spatial pattern in the remaining dates suggests that peat initiated in several locations independently, then later coalesced. The underlying topography of much of the PMFB is thought to consist of a ridge-and-swale surface (Kalliola et al., 1991; Rojas et al., 2023), and it is plausible that the lowest sites were most conducive to

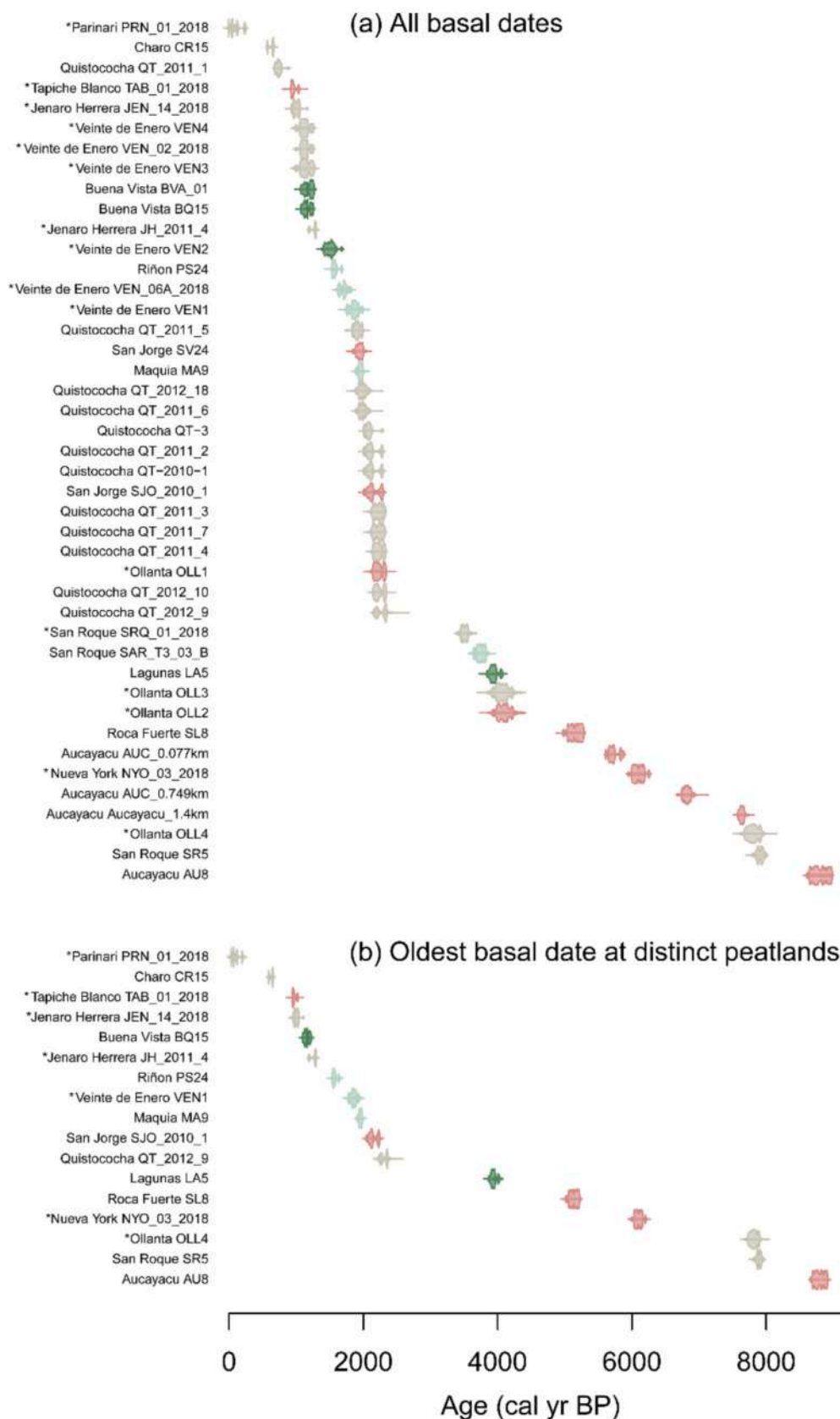


Fig. 3. (a) Oldest basal age per core (i.e. all 43 basal dates); (b) oldest basal age per peatland (a subset of the basal dates). Colours indicate present-day vegetation, based on field data and/or descriptions in publications: red, pole forest; green, seasonally flooded forest; brown, palm swamp; turquoise, open (herbaceous) vegetation. Dates marked with an asterisk are previously unpublished. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

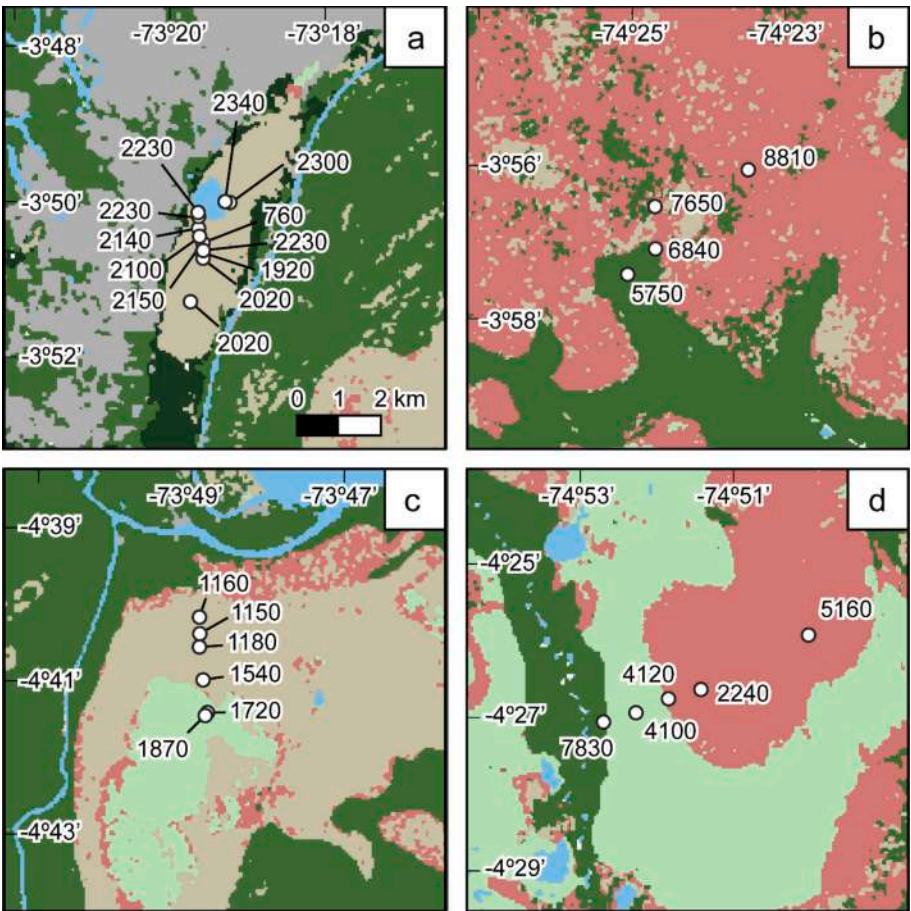


Fig. 4. Spatial configuration of basal dates at peatlands with multiple dates: (a) Quistococha, (b) Aucayacu, (c) Veinte de Enero, (d) Ollanta/Roca Fuerte. Colours follow Fig. 1; the scale bar in (a) applies to all panels. Land cover variations are indicative, based on modelling using remote sensing data and ground reference data (Hastie et al., 2022, 2024).

peat initiation, with peat later spreading by paludification. A similar pattern, of peat formation in small, separate basins and ultimately

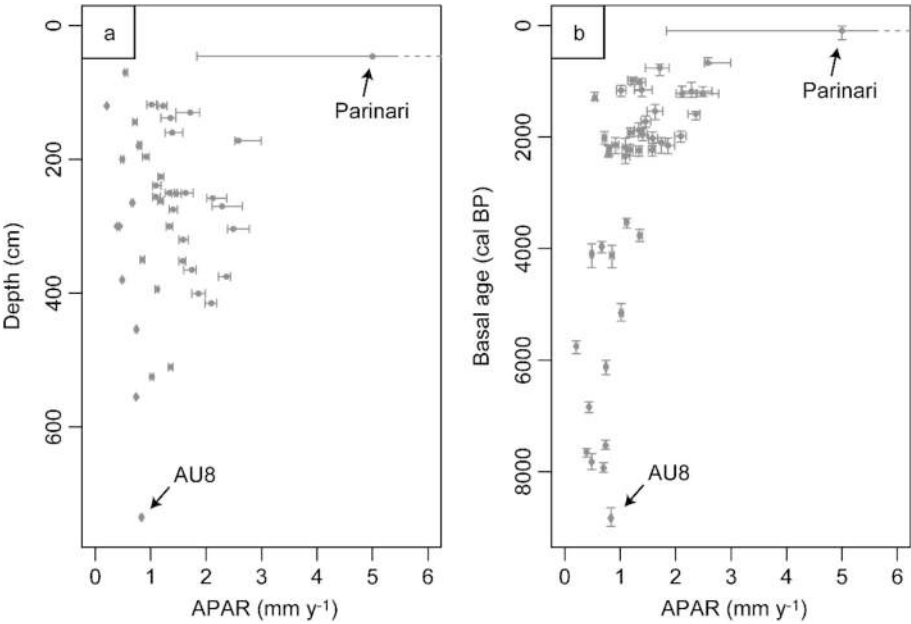


Fig. 5. Apparent peat accumulation rates (APAR) averaged over each core, vs (a) peat thickness (i.e. depth to peat base) and (b) basal age; uncertainty estimates are 2-sigma, calculated from the probability density functions of the calibrated basal dates, assuming no uncertainty in the depth measurements. The right-hand bar for Parinari extends to 65.7 mm y⁻¹.

coalescing, has also been documented in a peatland area in the south of Peru, in the Madre de Dios Basin (Householder et al., 2012).

In summary, the evidence available suggests that some peatlands occupying individual abandoned channels may have formed nearly synchronously throughout their basins, but others have more complex histories involving lateral spread of peat, over the course of centuries to millennia, from one or more nucleation sites located in low-lying parts of the palaeo-landscape.

4.2. Age-depth relationships

Apparent peat accumulation rates (APAR) are plotted against peat thickness in Fig. 5a and against basal age in Fig. 5b, using only the basal ages to calculate the apparent peat accumulation rate over the whole of each sequence (recognizing that it is not strictly possible to reconstruct past instantaneous peat accumulation rates using radiocarbon dates alone: Young et al., 2021). Disregarding the shallowest date (from the sediment-rich Parinari core PRN_2018_01, where the very young age of 58 ± 37 ^{14}C years at 46 cm depth yields a wide calibrated estimate of 5–250 cal BP), the sites show overall peat accumulation rates varying between 0.21 and 2.58 mm y^{-1} . Directly comparing APAR between sequences of widely differing ages can be problematic but in general, APAR in the PMFB appears to be high relative to many other regions. For example, Beilman et al. (2009) reported a median value of 0.72 m of peat accumulation since 2000 cal BP from 23 Siberian peats, with an absolute maximum of 2.72 m; by contrast, several sites in the PMFB have accumulated more than 3 m of peat over a similar period. Age-depth models have only so far been published from a handful of sites in the central Congo Basin but they likewise indicate much lower rates of peat accumulation than in the PMFB (Garcin et al., 2022). Inland peats in parts of SE Asia have also returned low peat accumulation rates, but several coastal peat domes in high-rainfall regions of Borneo and Sumatra have yielded age-depth curves that are similarly steep to those from the PMFB, with whole-Holocene average APAR of 1.77 mm y^{-1} (Dommain et al., 2014).

The maximum thickness of peat yet observed in the Pastaza-Marañón Basin is 8.10 m, an undated measurement from a palm swamp in Datem del Marañón in the northwestern PMFB (Del Castillo et al., 2024); this is thinner than some south-east Asian peat domes (which are frequently over 10 m thick: Dommain et al., 2014) but thicker than those reported from the Congo Basin (up to 5.99 m: Hawthorne et al., 2023). Most peats in our study area are much shallower, with a median recorded thickness of 2.8 m ($n = 77$ including undated sites reported by Hastie et al., 2022, 2024), likely reflecting a combination of their origins in shallow floodplain channels and a lack of time for sufficient peat to build up to form thick ombrotrophic domes.

There is no significant relationship between APAR and peat thickness, but (even excluding Parinari) there is a highly significant correlation between APAR and basal age ($\rho = -0.76$, $p < 0.001$, Spearman's rank), suggesting that younger sites tend to hold thick peats for their age. The relationship appears to be slightly curved, although this could be due to over-representation of young sites in the dataset. There are at least three plausible explanations for this correlation between PAR and basal age:

- (1) Peat accumulation is expected to slow down over time, as decomposition throughout the increasingly thick peat sequence comes into balance with the input of fresh litter (Clymo, 1984);
- (2) Old sites may be more likely to have passed through one or more periods of adverse environmental conditions (e.g. drought), causing intervals of slow accumulation and/or a depositional or erosional hiatus (cf. Swindles et al., 2018; Kelly et al., 2017; Garcin et al., 2022);
- (3) Old sites are more likely to have become domed, ombrotrophic and nutrient-depleted over time (Lähteenoja and Page, 2011), in

which circumstances plant litter production (and hence peat accumulation) is likely to be relatively low (Dargie et al., 2024).

Starting with the first of these explanations, the age-depth relationships in the 20 cores where we have additional chronostratigraphic information (Fig. 6) indicate that while Clymo's (1984) model of the changing long-term balance between litter deposition and peat decay may well apply to the PMFB peatlands, it is unlikely to be the only factor determining the relationship between apparent peat accumulation rate and basal age. Fig. 6 shows that individual age-depth curves may be concave-upwards, as predicted by Clymo's model, but may also be straight or convex-upwards. This variety of patterns probably reflects a combination of the young age of many sites, which are therefore not 'mature' in the sense of Clymo's model; possible ongoing tectonic subsidence, creating additional accommodation space (e.g. Dumont, 1996); and external influences such as changing climate or hydrology, discussed below.

Turning to the second explanation above for the relationship between apparent peat accumulation rate and basal age (that older sites are more likely to have experienced hiatuses), several cores show one or more plateaux in the age-depth relationship (Fig. 6). In some cases (Aucuyacu_1.4 km, NYO_03_2018, TAB_01_2019, and possibly JEN_14_2018 and SAR_T3_03_B) a plateau occurs at or close to the beginning of peat accumulation, which would be consistent with either slow accumulation and/or high rates of decomposition in what may frequently be open-water and/or seasonally-flooded early-successional environments, based on palaeoecological data (e.g. Roucoux et al., 2013; Swindles et al., 2018; Kelly et al., 2020; Sassoon et al., 2024). However, in two cases (Aucuyacu_1.4 km and SJO-2010-1) there are additional, later plateaux in the age-depth relationship (at 1800–3900 and 4900–6100 cal BP, and 400–1300 cal BP respectively). According to the original authors, these changes may indicate responses to changing climatic wetness for which there is independent evidence (for example, see Fig. 7), although they were interpreted (based on supporting palaeoenvironmental evidence) in different ways: as indicating periods of reduced litter production brought on by a wetter climate by Swindles et al. (2018), and as indicating periods of increased decomposition rates brought on by a drier climate by Kelly et al. (2017). Uncertainties in the age models of the peat records mean that it is not clear whether the events registered are genuinely synchronous nor how they relate in time to regional palaeoclimatology (Fig. 7). It is possible that the two records represent opposing, site-specific responses to the same, regional climatic history: stable isotope records from two sites just outside the PMFB (Fig. 7) are reasonably consistent in suggesting that the climate was becoming generally wetter from around 4000 years ago and more variable on interannual to decadal timescales although there are discrepancies between them in detail (Van Breukelen et al., 2008; Bird et al., 2011a, 2011b).

In order to test whether such multi-centennial interruptions or slow-downs in peat accumulation were widespread, and recognizing that the dating resolution of published sites is often insufficient to provide an effective test, we undertook detailed dating of additional cores (including JEN-14, NYO-03, TAB-03, and VEN-02, presented here for the first time: Fig. 6). These new age-depth curves did not identify any substantial hiatuses: in all of these sequences (and indeed in other reasonably well-dated cores, e.g. QT-2010-1 and SAR_T3_03_B), once the site has stabilized and peat has begun to accumulate, the age-depth gradient shows little subsequent change over time. This suggests that either (a) the peatlands at Aucuyacu and San Jorge, which are ombrotrophic at the present day, have been particularly sensitive to changing climate in the past, or (b) the plateaux in their age-depth profiles have different, local, and therefore probably non-climatic causes, such as reorganisation of local hydrology caused by local river channel migration. Thus the present data suggest that past episodes of climatic change may have affected peat accumulation at some locations but there is no evidence yet for a widespread, substantial effect on peat accumulation

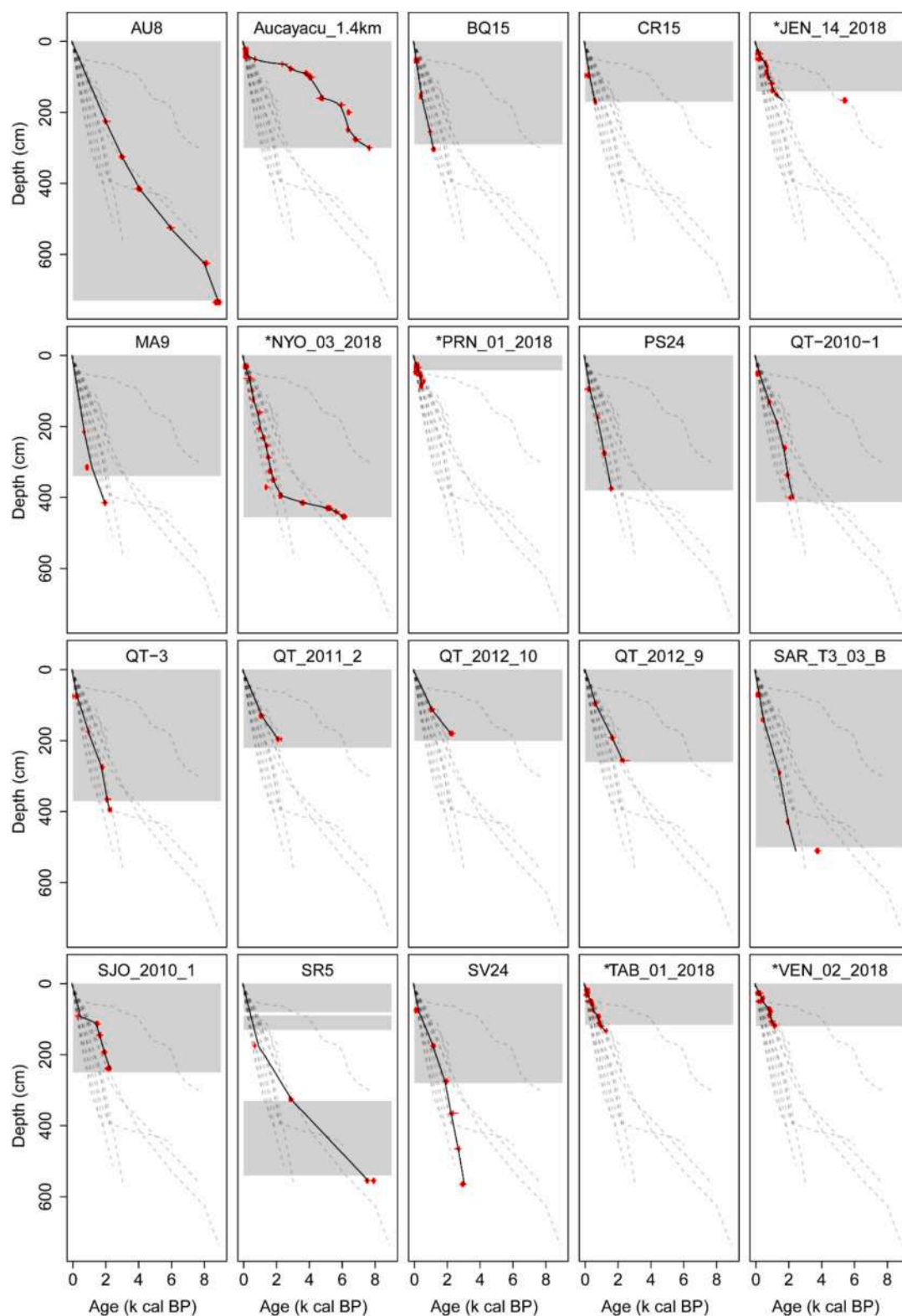


Fig. 6. Age-depth curves for every core with at least two dates (red markers) spaced >50 cm apart. Grey rectangle indicates depth(s) of peat (>65% organic matter, Lawson et al., 2015; Dargie et al., 2017) reported at each core location; some chronologies extend into the underlying mineral sediment. All of the curves are shown as dashed grey lines in the background, for context. Cores marked with an asterisk are presented for the first time here. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

rates in the Pastaza-Marañón Basin to match that seen (for example) in the central Congo Basin (Garcin et al., 2022). Further study of peat sequences using more sensitive proxies for palaeohydrology and peat decomposition (e.g. leaf-wax deuterium, thermogravimetric analysis)

could help to test more fully whether, and how, PMFB peatland ecosystems have responded to past climatic change (cf. Garcin et al., 2022).

The third possible explanation of the relationship between apparent peat accumulation rate and basal age is that older sites are more likely to

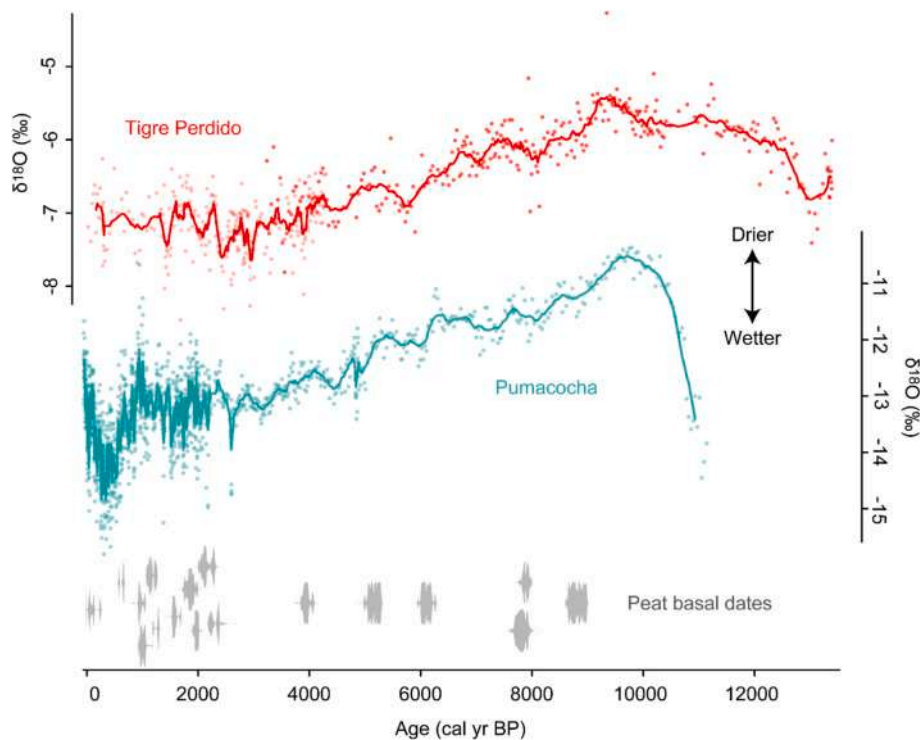


Fig. 7. Climate proxy curves from Tigre Perdido (Van Breukelen et al., 2008) and Laguna Pumacocha (Bird et al., 2011a, 2011b). Points indicate original $\delta^{18}\text{O}$ values; lines show an 11-point rolling mean. The Tigre Perdido record is spliced from two separate speleothems (pale and dark points); see Van Breukelen et al. (2008) for details. Peat basal dates (oldest date per peatland) from Fig. 3b are shown for context, vertically offset for clarity.

have become ombrotrophic, and that peat accumulation rate would be expected to slow under nutrient-poor conditions. Sites in the PMFB, like peatlands elsewhere, may pass through a classic ‘fen-bog transition’ and become ombrotrophic as a domed peat mound accumulates above the regular reach of flood waters. A second process may also be important on PMFB floodplains: Mertes (1997) showed that the wide floodplains in the wetter parts of the Amazon function as a mixing zone between rainwater, groundwater, and river water, such that the chemistry of floodwater affecting a site may become more or less nutrient-rich as the river migrates laterally across the floodplain. This scenario has been proposed to apply to peatlands such as Quistococha, which is thought to occupy a former channel of the Amazon, which has since moved several kilometres eastwards; Quistococha is therefore likely to have experienced reduced nutrient inputs over time, even though the peatland is still occasionally flooded today (Kelly et al., 2020). Either or both processes could account for the tendency towards ombrotrophy first observed in the PMFB by Lähenteenoja and Page (2011). If nutrient depletion leads to reduced plant litter production, and if the rate of decomposition of litter remains unchanged (an untested assumption), then a trend to ombrotrophy should result in a reduction in peat accumulation rate.

Many of the older peatlands in the PMFB today support a thin-stemmed ‘peatland pole forest’ associated with ombrotrophy, and in some cases there is supporting geochemical evidence for ombrotrophy. However, the strength of any relationship between ombrotrophy and peat accumulation rate is unclear. Dargie et al. (2024) found that total litter productivity in a palm swamp (at Veinte de Enero) and a pole forest (at Nueva York) was similar, though the partitioning of that productivity between different components (stem, leaves, roots) was markedly different. Measured litter decomposition rates were also similar at the two sites, albeit that the experiment used standardized samples (*Mauritia flexuosa* leaves, roots and stems) at both sites, which may not reflect the differing botanical composition of the litter in the two ecosystems (ibid.). Thus it is not yet clear whether there is an

empirical link between PAR and ombrotrophy in the PMFB. Furthermore, some palm swamps, assumed to be minerotrophic, have returned very old basal dates (e.g. San Roque SR5), and some pole forests have returned much younger basal dates (San Jorge, OLL1). Palynology and geochemistry indicate that sites that are ombrotrophic today may have spent most of their history in a minerotrophic state (Lähenteenoja et al., 2009a, 2009b; Kelly et al., 2017). Therefore, on present evidence, it is still uncertain whether changes in nutrient supply alone can account for the observed relationship between peat accumulation rate and basal age in the PMFB. Further research is needed to better understand how nutrient supply affects PMFB peatland ecosystem function.

5. Conclusion

This paper has substantially increased the number of reported radiocarbon dates from the peatlands of the Pastaza-Marañón Basin, the largest known peatland complex in Amazonia. All of the sampled peat sequences are Holocene in age. However, it is very possible that older Holocene or even Pleistocene peats remain to be discovered, most likely around the Tigre and its confluence with the Marañón, a relatively geomorphologically stable area with abundant peatland pole forest (Honorio Coronado et al., 2021; Hastie et al., 2022, 2024).

There is little evidence that peat initiation during the Holocene has been controlled directly by climate or other external events, as has been argued for other parts of the world (e.g. following Lateglacial/early Holocene deglaciation and affected by the 8.2 cal ka cooling in North America: Gorham et al., 2007; alongside early Holocene climatic wetting in Congo: Dargie et al., 2017; during the mid-Holocene insolation peak in the Hengduan Mountains, China: Liu et al., 2020). By contrast, peat initiation dates from the PMFB are distributed throughout the last c. 8900 cal years with no evidence of clustering around particular climatic events.

Peats older than c. 2300 cal BP appear to be absent from the floodplains of the Ucayali and Amazon, suggesting that peatlands on these

geomorphologically-active floodplains are ephemeral phenomena on Holocene timescales. Peat carbon storage on these floodplains is likely to be a dynamic but possibly steady-state process, with river migration creating new sites for peat accumulation in abandoned channels and meander scrolls, balancing out the erosion of existing peatlands. The young age of these peatlands and their frequent origins in abandoned channels distinguish them from the often older, larger, domed peatlands typical of e.g. the central Congo Basin (Dargie et al., 2017) and Kalimantan (Dommmain et al., 2014).

Apparent peat accumulation rates in the Pastaza-Marañón Basin are variable but typically high by global standards, which may be linked to high litter production in the two main peat swamp forest types, palm swamp and pole forest (Dargie et al., 2024). With our additional dating, there are now at least seven cores from the PMFB that are sufficiently well dated to test effectively for past hiatuses, slow-downs or reversals in peat accumulation. However, only two of these cores (both of them previously published) provide evidence for such events, and these events may not have been synchronous. This finding suggests that many, perhaps most peatlands in the PMFB have not been greatly affected by climatic change during the past few millennia. This does not necessarily mean that the peatland complex will be resilient to future climatic change, which is expected to involve increasing seasonality and increasingly severe droughts and floods (Gloor et al., 2013, 2015; Ranasinghe et al., 2021; Roucoux et al., 2023) and which could conceivably exceed the envelope of Holocene climatic variations.

Our analysis of the substantial body of radiocarbon dates from the PMFB holds two key implications for management of the peatland complex. The first is that the process of peat accumulation is slow in relation to the timescales of policy and management: all but one of the sampled peat sequences began to form before the arrival of Europeans in South America. From a management point of view, peatlands should be viewed as ancient and irreplaceable, underlining the need for careful conservation and management of the carbon, biodiversity, and ecosystem services that they provide to the great benefit of local communities (Roucoux et al., 2017; Schulz et al., 2019a, 2019b). It is likely possible to harvest some forest resources, such as *Mauritia* palm fruits, sustainably in the long term (Honorio Coronado et al., 2025), but the peat itself accumulates too slowly to be considered a renewable resource on economically meaningful timescales. The second point is that the peatland complex is a dynamic landscape. We can expect peatlands occasionally to be destroyed by natural processes of channel migration, but these losses are likely to be balanced by the creation of new sites. Newly-abandoned channels may become significant carbon stores over the course of decades to centuries. Therefore, preserving the carbon storage function of the PMFB peatland complex requires careful management of the hydrology and ecology of the whole of the landscape, not just those parts that presently contain peat.

CRedit authorship contribution statement

I.T. Lawson: Writing – original draft, Visualization, Supervision, Software, Project administration, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **C.M. Åkesson:** Writing – review & editing, Investigation. **G.C. Dargie:** Writing – review & editing, Investigation. **J. del Aguila Pasquel:** Investigation. **F.C. Draper:** Writing – review & editing, Investigation. **A. Hastie:** Writing – review & editing, Investigation. **T.J. Kelly:** Writing – review & editing, Investigation. **D. Sassoon:** Writing – review & editing, Investigation. **V. Abraham:** Writing – review & editing. **T.R. Baker:** Writing – review & editing, Investigation, Funding acquisition, Conceptualization. **D. Fabel:** Resources, Investigation. **P. Gulliver:** Writing – review & editing, Methodology, Investigation. **E.N. Honorio Coronado:** Writing – review & editing, Investigation, Conceptualization. **K.H. Roucoux:** Writing – review & editing, Supervision, Funding acquisition, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.palaeo.2026.113579>.

Data availability

Full details of the new dates reported here are listed in Table S1. Dates funded under NERC project NE/R000751/1 are also available at the NERC Environmental Information Data Centre (Lawson et al., 2023).

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