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LETTER

Timing of peat initiation across the central Congo Basin

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Abstract

The central Congo Basin contains the world's most extensive tropical peatland complex, spanning 16.7 million hectares. Until now, radiocarbon dating of basal peats has been limited to 14 samples with poor spatial coverage, and suggested that peat typically initiated during the Holocene. We present 38 new basal dates, improving spatial coverage across the region. Some of the new basal dates are much older than any previous dates, indicating that peat initiated in the central Congo Basin at multiple locations in the Late Pleistocene. Our oldest basal date is 42 300 (41 200–43 800) calibrated years before present, making this one of the world's oldest extant tropical peatlands, and twice as old as previously believed. The temporal distribution of basal dates suggests that changing climatic wetness has played a role in peat initiation in the region; numerous basal dates correspond with climatically wet phases, whilst few basal dates correspond with dry phases such as the Last Glacial Maximum (LGM). Today we find the central Congo Basin peatlands on wide interfluves between rivers, and on floodplains (mostly of the dendritic left-bank tributaries of the Congo River). We find the oldest basal dates on the floodplains of these left-bank tributaries, indicating a surprisingly high degree of channel stability over many millennia. This contrasts with, for example, peatlands on Amazonian floodplains, which are typically just a few thousand years old.

The persistence of peat in the central Congo Basin since before the LGM, likely the most climatically dry period during the last 42 000 yr in this region, suggests that these areas may have played an important biogeographical role as forest refugia during glacial-interglacial cycles.

1. Introduction

It has only recently been revealed that the wetlands of the central Congo Basin are predominantly peat-forming and represent the most extensive known tropical peatland complex [1]. Recent estimates [2] give a peatland spatial extent of 167 600 km^2. The central Congo Basin peatlands are some of the most carbon-dense ecosystems on Earth, storing an average of 1712 Mg C ha^{-1}, with a total of 29 Pg C^{-1} stored in the peat [2]. However, research into the establishment and development of this large carbon stock, including the spatiotemporal dynamics of peat initiation and expansion across the basin, is in its early stages.

The use of peat radiocarbon basal ages to identify patterns in peat initiation and expansion at regional [3–10], continental [11, 12] and even global [13, 14] scales, is well established. Basal date compilations provide information on carbon dynamics [15] and landscape evolution through time [12]. By identifying any patterns in peatland development, inferences can be made about factors controlling peat formation across a region [3, 10, 16], which can also be useful for understanding how a peatland landscape might respond to future environmental changes.

Here we analyse 52 basal radiocarbon dates obtained through accelerator mass spectrometry (AMS) with the aim of improving our understanding of the dynamics and drivers of peat initiation and peatland expansion in the central Congo Basin. The dataset comprises 38 new dates from basal peat samples across the central Congo Basin, and 14 previously published basal dates [1, 17]. The previously published dates are mostly from the northwestern part of the peatland complex in the Republic of the Congo (DRC), and are mostly Early Holocene in age [1, 17], with two dated slightly earlier at 16 950–17 300 calibrated years before present (cal yr^{-1} BP) and 19 100–19 450 cal yr^{-1} BP, during the last deglaciation. Twenty of the new basal dates are from the DRC, which accounts for two-thirds of the region's peatland area and was represented by just two dates in previous studies. We combine the radiocarbon dates with a newly extended reconstruction of Congo River palaeo-discharge [18], to provide a regional hydrological context within which to interpret the dates.

2. Methods

2.1. Site description

The central Congo Basin straddles the equator, containing ∼360 000 km^2 of wetland [19] that is shared between the Republic of the Congo (ROC) and the DRC. Of this wetland area, an estimated 167 600 km^2 is swamp forest underlain by peat deposits, with a median thickness of 1.7 m [2]. Annual rainfall across the region ranges from ∼1700 to 2200 mm [20] and has a bimodal distribution, reflecting the annual north-south migration of the tropical rain belt. The mean annual temperature is ∼25 °C [21, 22].

2.2. Field sampling

Field sampling was carried out along transects, widely dispersed across the peatland area, during seven field campaigns between 2012 and 2022. Our 52 peat cores used for basal dating come from 21 transects (figure 1). Transect length (varying from 2.5 to 20 km) and location were selected to assess peat initiation alongside mapping the extent of peat in the region, the amount of carbon stored in peat [1, 2], and palaeoecological studies [17, 23].

Peat cores were collected using a 50 cm long closed chamber Russian-type corer (manufacturer: Eijkelkamp [24]). Peat cores were collected for two purposes—palaeoecological work and carbon stock estimates—and this determined how they were subsampled. Peat cores that were collected for carbon stock estimates were predominantly subsampled into 10 cm long sections in the field (with some subsampled into 3 cm long sections during the first field expedition) before being transported out in sealed plastic (n = 29), whilst cores for palaeoecological studies were transported out of the field in 50 cm long intact segments in rigid plastic half-cylinders. All samples were transported to the UK and stored under licence at 4 °C before analysis.

The peat cores selected for basal dating always included the thickest peat core recovered from each transect. Preference was given to palaeoecological cores for dating, as these could be subsampled in the laboratory at a 1 cm resolution, but as these were not taken along every transect, or were not always the deepest core to have been sampled along a transect, cores taken for carbon stock estimates were also dated. For ten transects, multiple cores (between two and six; table 1) were chosen for radiocarbon dating to allow for more detailed palaeoecological research.

In this paper we use all peat basal dates available for the central Congo Basin region, including dates from the same transect, and dates from different transects but which sample the same peatland expanse. Some previous studies of peat initiation have only considered the oldest basal age from individual peatlands. This approach would tell us when peat first initiated, but not necessarily when the majority

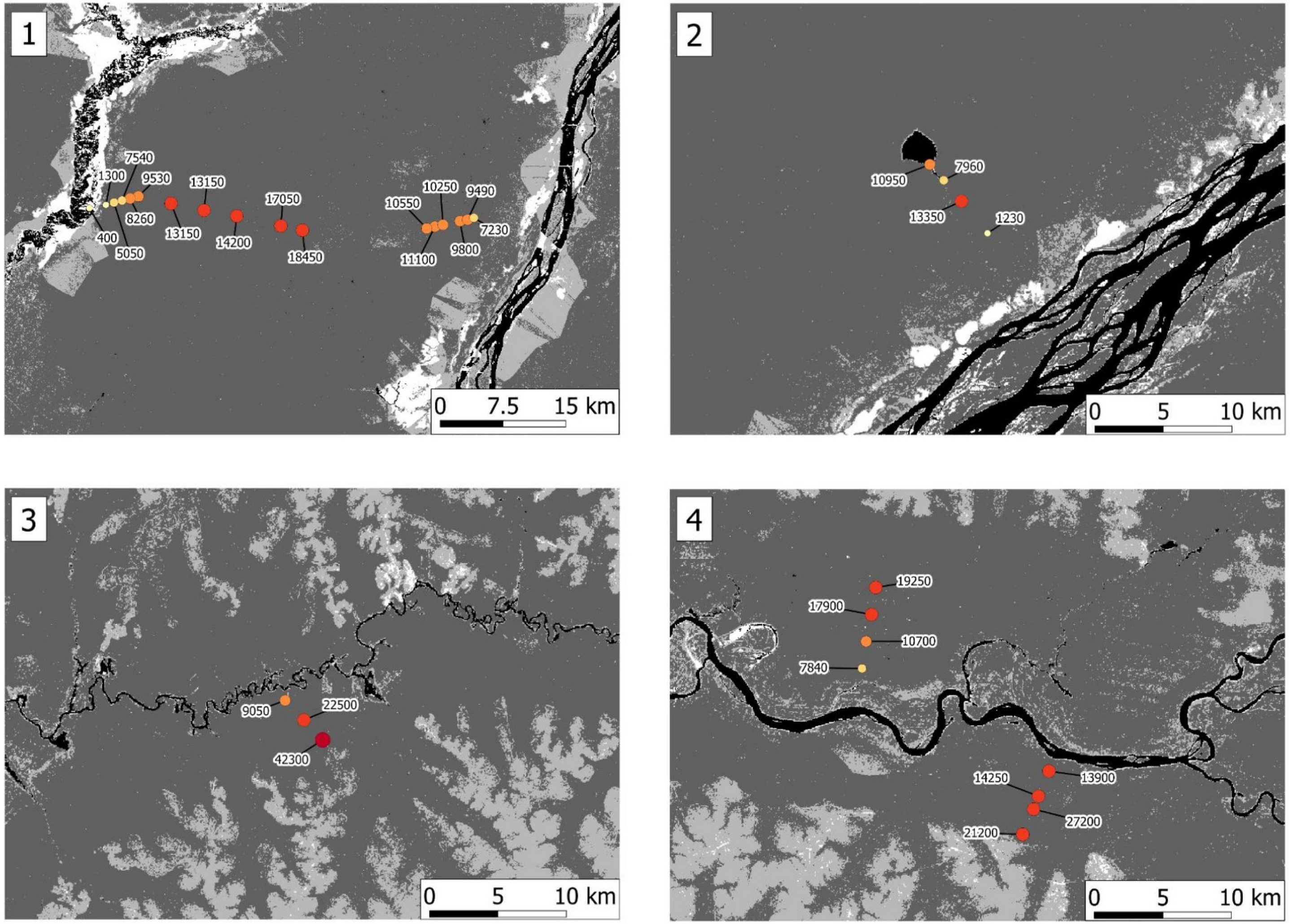

Figure 1. The spatial distribution of basal dates in this study, with the oldest date of each transect, shown against a land cover classification of the region [2]. The colour scale corresponds to the geochronological time period the basal date belongs to. Dates represent the median of the 2-sigma calibrated age range. Red rectangles represent insets 1–8, which show transects with multiple dates at a larger scale. The black dashed line encompasses the sites located along the Congo River left-bank tributaries. The top left inset shows the African continent; black outlines for the Republic of the Congo and Democratic Republic of the Congo; the dashed line with hatching infill shows the study region. The figure was created using the free and open source software QGIS [25].

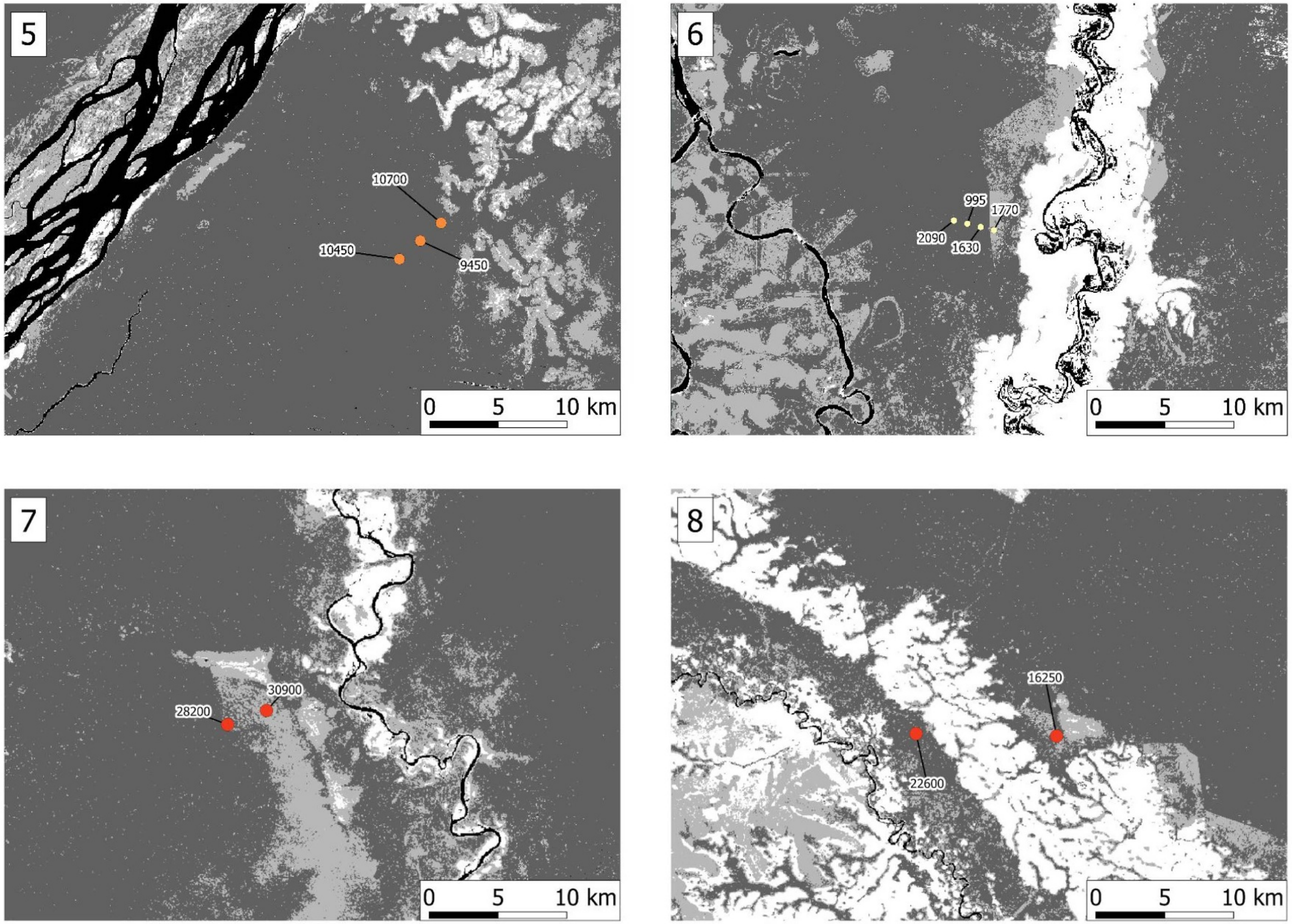

Figure 1. (Continued.)

of peat formed, either within an individual peatland or within a region, which is our interest here; in other words, our sampling captures not just the deepest/oldest part of each peatland, but also the dynamics of lateral expansion of individual peatlands [15].

It is possible that peat first appeared in the landscape earlier than the oldest date we report, as although we have greatly increased the number of basal dates from the central Congo Basin peatlands, sampling density remains low. Therefore, we may not have sampled the oldest peats across the region. It is also possible that the oldest carbon has already been lost through peat decomposition, particularly if the peat remained shallow over millennia and droughts could lower the water table to the basal peat, making it susceptible to oxidation.

2.3. Laboratory methods

We define peat as a soil with an organic matter (OM) content of at least 65% and a minimum thickness of 30 cm [1]. The basal dates were therefore taken at the stratigraphic level at which the OM content first rose above 65% (i.e. later mineral-rich layers, which often form during the early stages of floodplain peat accumulation, were ignored). The OM content was determined through loss on ignition (LOI; 4 h at 550 °C [26]). Sampling for LOI was carried out at 1 cm resolution and radiocarbon samples were 1 cm thick (palaeoecological cores) or carried out at 3–10 cm resolution and radiocarbon samples were 3–10 cm thick using homogenised subsamples from the field (carbon stock cores). The use of the 3–10 cm samples will reduce the resolution of the measured basal age, compared to the 1 cm sections, with the effect that the true basal ages from these larger sections could be older than we report.

For the radiocarbon dating, we used bulk peat samples, owing to a lack of well-preserved macrofossils in the peat. Bulk basal peat radiocarbon ages may not always accurately represent the timing of peat initiation at a location. Bioturbation, the inclusion of root material [6], and contamination during sampling could all result in a younger radiocarbon age being returned. Samples were sieved at 180 μm to remove fine roots, and we used a closed chamber corer to reduce the risk of contamination with younger material during core extraction. The inclusion of older carbon (e.g. from underlying mineral soils, or from fluvial transportation and deposition) is also a possibility. Many of our oldest dates are from sites which, at least in the early stages of peatland development, were likely flooded by nearby rivers, so it is possible that these locations have received reworked older organic carbon from elsewhere in the catchment. However, the central Congo Basin is generally of low relief and not considered a particularly geomorphologically dynamic landscape [27], which should limit the degree to which material is reworked across the landscape. Furthermore, the oldest basal ages are distributed across multiple transects, and in several cases clear spatial patterns emerge along the transects, giving confidence that these dates are reliable.

The sieved samples were sent to the NERC Radiocarbon Facility, East Kilbride. Samples were pretreated by digesting in 1 M HCl at 80 °C for 8 h and then washed free from mineral acid with deionised water before being digested in 0.5 M KOH at 80 °C for 2 h. The digestion was repeated using deionised water until no further humic acids were extracted. The residue was rinsed free of alkali and digested in 1 M HCl at 80 °C for 2 h before being rinsed free of acid, then dried and homogenised. The total carbon in a known mass of the pre-treated sample was recovered as CO_2 by heating with CuO in a sealed quartz tube. The gas was then converted to graphite by Fe/Zn reduction, which was dated by AMS using a 5 MV and 250 kV National Electrostatic Corporation AMS system [28–30].

2.4. Radiocarbon date calibration and summed probability distribution

Radiocarbon dates were calibrated using the Oxcal version 4.4 [31] radiocarbon calibration software using a 50:50 mixed northern (IntCal20) [32] and southern (SHCal20) [33] hemisphere curve, to take account of the influence of both northern and southern air masses on this equatorial region. The 'Sum' function of Oxcal was used to create a summed probability distribution of the 52 basal dates, using a bin size of 100 yr, to visualise the time series of peat initiation (figure 2). For each 100 yr bin, the summed probability of peat initiation is the sum of the individual probability distributions of each calibrated radiocarbon date in that bin [34] (SI figure 1).

2.5. Lateral expansion rate calculations

For transects where we had multiple basal dates, and these basal dates were spatially ordered, we calculated apparent lateral expansion rates between adjacent cores. Lateral expansion rates between pairs of adjacent cores were calculated as the difference in calibrated median basal age between the cores, divided by the distance between them [35].

2.6. Marine core GeoB6518-1 foraminifera δ^{18}O record

We extend a qualitative proxy palaeo-discharge record for the Congo River, from 20 000 to 42 000 yr BP, to cover the time period encompassing the peat basal ages, by presenting previously unpublished planktic foraminifera δ^{18}O data from the offshore core GeoB6518-1 (−5.555 00°, 11.221 67°, 962 m water depth) [18]. The ratio of ^{18}O to ^{16}O in the shells of planktic foraminifera reflects the isotopic composition of the water at the time of shell formation. As fresh water is depleted in ^{18}O, owing to the preferential evaporation of ^{16}O, we interpret higher levels of ^{18}O depletion in the planktic foraminifera shells to represent increased freshwater input from the Congo River, i.e. discharge. We assume higher river discharges represent wetter conditions in the central Congo Basin, and vice versa. Published radiocarbon ages of GeoB6518-1 were recalibrated using Calib 8.2 and the Marine20 calibration curve [36]. Sample ages were determined by linear interpolation between tie-points.

For oxygen isotope analyses, about 30 specimens of *Globigerinoides ruber* (white) (>150 μm) were measured using a Finnigan MAT 251 mass spectrometer equipped with an automatic carbonate preparation device. Internal precision, based on replicates of a laboratory standard, was better than ±0.07‰ (VPDB). The $\delta^{18}O$ carbonate values have been corrected for the effects of calcification temperatures [37] using alkenone-derived sea-surface temperatures and for continental ice mass using modelled $\delta^{18}O$ seawater compositions [38] interpolated to sample ages. The residual $\delta^{18}O$ values reflect isotopic changes in the surface waters of the Congo plume, determined by the variable ^{18}O-depleted freshwater discharge of the Congo River. However, this proxy record of changes in river discharge is qualitative, as it depends on the actual isotopic composition of the freshwater and the relative position of the core site to the river mouth which changes with sea level.

3. Results

The oldest basal date we found was c. 42 300 (2σ range: 41 200–43 800) and the youngest was c. 400 (320–490) cal yr^{-1} BP (table 1). The oldest date is in the Late Pleistocene and pre-dates the Last Glacial Maximum (LGM; 19 000–26 000 yr BP [39]). It increases the estimated maximum age of peat establishment in the central Congo Basin by c. 23 000 yr, more than twice as old as the previous oldest sample from the region, which dated to 19 250 cal yr^{-1} BP [17]. The age-depth profile of this core (SI figure 2) suggests continuous peat accumulation at this site, giving us confidence that the basal age represents a genuine date of peat initiation at this location, rather than an artifact of contamination or reworked ancient carbon.

The temporal distribution of the 52 dates across the 42 000 yr time span is highly uneven (figure 2). Overall, there are two clear time periods when we have numerous basal dates, indicating widespread peat initiation and/or lateral expansion: between the LGM and the Younger Dryas (YD; 19 000–12 900 yr BP); and during the Early to Middle Holocene (11 700–7,100 yr BP). Two shorter time periods noticeably contain almost no basal dates, suggesting pauses in the increase in peat area: during the YD (12 900–11 700 yr BP [39]); and during the Middle to Late Holocene (7 100–3 320 yr BP).

Only ten out of 52 basal dates indicate peat formation during the LGM (19 000–26 000 yr BP [39]) or prior to it (42 300–26 000 yr BP). This equates to one basal date per 2330 yr over the time period 42 300–19 000 yr BP. Between the end of the LGM (19 000 yr BP) and the beginning of the YD (12 900 yr BP), there are ten basal dates, which equates to one basal date per 610 yr over this time. Next, there is a notable lack of basal dates from the YD itself (12 900–11 700 yr BP [39]). There are 14 basal dates from the Early Holocene (11 700–8 200 cal yr^{-1} BP), which equates to one basal date per 250 yr during this time. Eight further basal dates are from the Middle Holocene (8200–4200 yr BP), i.e. one basal date per 500 yr, and ten date to the Late Holocene (4200 yr BP to present day), i.e. one basal date per 427 yr. However, for approximately 4000 yr between 7100 and 3320 yr BP, towards the end of the Middle Holocene and the very beginning of the Late Holocene, we find only one basal date, which equates to the lowest rate of peat formation in our dataset, at one basal date per 3780 yr.

Across the regional landscape, peatlands are found, broadly, in two distinct geomorphological settings: either on the wide interfluves between rivers (e.g. figure 1, insets 1 and 2), or on river floodplains. The river floodplain peatlands are mostly along the left-bank tributaries of the Congo River, which form a dendritic drainage network incised into terra firme uplands (figure 1). There appears to be a pattern in the basal dates corresponding to these different geomorphological settings. Basal dates from the Late Pleistocene, particularly those from the LGM or before, are mostly from floodplain peatlands. The interfluvial peatlands, however, tend to have post-LGM basal dates (e.g. figure 1, inset 1). An exception is a peatland in the southwest of the region, where there are two LGM basal dates (figure 1, inset 7). Although this is an interfluvial peatland, it presents unusual characteristics—flark-like patterns are visible in satellite imagery at this site, and in the field we encountered a higher number of channels than typical within the forest. This suggests that hydrological processes at this site, both past and present, may be different to the other interfluvial peatlands.

Where we have multiple basal dates along transects, the dates appear typically to be spatially ordered for some transects. For example, the peat occupying the large interfluve shown in figure 1, inset 1, which we sampled along three transects, is oldest in the centre of the interfluve and becomes progressively younger towards the margins. Similarly, at sites located on the floodplains of left-bank tributaries of the Congo River, the peat is progressively younger towards the river, for example in figure 1, inset 3, and inset 4 north of the river. For other transects there appears to be no spatial ordering to the dates, for example, figure 1, inset 2, or the dates appear to be

Table 1. Radiocarbon results for the 52 basal dates discussed in this study.

Transect	Sample publication code	Core code	Sample depth (cm)	Latitude	Longitude	Conventional radiocarbon age (years BP ± 1 σ)	Pre-treated sample carbon content (%)	$\delta^{13}C_{VPDB}$‰ (±0.1)	Calibrated age (cal yr BP) median	Calibrated age (cal yr BP) range (95% CI)	Original publication
Boboka	SUERC-106 852	BOB_6.00P1	58–59	1.495 05	18.864 59	1330 ± 35	39.1	−30.6	1230	1180–1290	This study
Boboka	SUERC-106 853	BOB_9.00P1	221–222	1.516 16	18.847 51	11 483 ± 46	29.1	−27.3	13 350	13 250–13 450	This study
Boboka	SUERC-107 784	BOB_11.00P1	129–130	1.529 85	18.835 88	7151 ± 39	46.5	−30.1	7960	7870–8020	This study
Boboka	SUERC-106 854	BOB_LAC	228–229	1.540 22	18.826 67	9629 ± 41	25.4	−30.0	10 950	10 750–11 150	This study
Bobuéta	SUERC-108 659	BBT_5.00P	238–239	−0.428 73	16.495 08	26 692 ± 223	30.5	−30.0	30 900	30 400–31 200	This study
Bobuéta	SUERC-107 788	BBT_8.00P	320–330	−0.437 93	16.469 71	24 060 ± 163	30.0	−29.2	28 200	27 800–28 600	This study
Bolengo	SUERC-106 846	BNG1_1.00P1	216–217	−0.293 75	19.809 46	12 066 ± 47	NA	−30.0	13 900	13 800–14 050	This study
Bolengo	SUERC-106 847	BNG1_3.00P1	335–336	−0.310 24	19.802 56	12 319 ± 49	40.7	−29.8	14 250	14 100–14 800	This study
Bolengo	SUERC-99 642	BNG1_4.00P	405–406	−0.318 71	19.799 35	22 886 ± 140	38.1	−30.0	27 200	26 900–27 500	This study
Bolengo	SUERC-106 851	BNG1_6.00P1	399–400	−0.335 19	19.792 23	17 546 ± 80	33.4	−30.4	21 200	20 900–21 400	This study
Bondamba	SUERC-94 354	BDM1_1.00P	166–167	−0.226 50	19.686 98	7022 ± 39	31.4	−30.3	7840	7730–7940	This study
Bondamba	SUERC-94 355	BDM1_3.00P	558–559	−0.208 78	19.689 68	9492 ± 42	28.2	−29.4	10 700	10 600–11 050	This study
Bondamba	SUERC-94 359	BDM1_5.00P	569–570	−0.191 18	19.693 22	14 610 ± 57	44.9	−30.4	17 900	17 550–18 100	This study
Bondamba	SUERC-94 362	BDM1_7.00P	569–570	−0.173 44	19.695 99	15 980 ± 65	49.4	−30.2	19 250	19 100–19 450	Garcin *et al* [17]
Bondoki	SUERC-56 866	BDK_6.0	140–150	0.855 50	17.010 50	7352 ± 38	55.0	−30.0	8110	8020–8280	Dargie *et al* [1]
Bondzale	SUERC-57 586	BZB_6.0	160–170	1.904 06	17.959 54	6817 ± 39	35.0	−25.1	7640	7580–7690	Dargie *et al* [1]
Centre	SUERC-99 658	CEN_4.00	290–300	1.207 52	17.522 07	11277 ± 44	32.8	−25.5	13 150	13 100–13 250	This study
Centre	SUERC-99 659	CEN_8.00	370–380	1.200 11	17.557 50	11259 ± 45	24.9	−24.7	13 150	13 100–13 250	This study
Centre	SUERC-99 660	CEN_12.00	460–470	1.194 04	17.592 63	12299 ± 47	35.9	−22.2	14 200	14 050–14 800	This study
Centre	AWI-1824.1.2	CEN_17.4	625.2	1.183 46	17.639 91	14050 ± 55	NA	NA	17 050	16 950–17 300	Garcin *et al* [17]
Centre	SUERC-99 661	CEN_20.00	510–520	1.178 76	17.662 97	15216 ± 59	38.7	−24.7	18 450	18 300–18 650	This study
Ekolongouma	SUERC-49 350	SPT_0.0	270–273	1.180 77	17.796 32	9340 ± 41	54.7	−29.6	10 550	10 400–10 650	Dargie *et al* [1]
Ekolongouma	SUERC-49 355	SPT_2.0	237–240	1.184 60	17.813 85	9091 ± 39	49.2	−21.8	10 250	10 200–10 300	Dargie *et al* [1]
Ekolongouma	SUERC-49 358	SPT_5.0	147–150	1.189 99	17.840 23	8484 ± 41	40.0	−29.6	9490	9430–9540	Dargie *et al* [1]
Ekolongouma	SUERC-99 652	EKG02	102–103	1.192 06	17.847 02	6333 ± 39	17.6	−29.4	7230	7160–7320	This study
Ekolongouma	SUERC-99 653	EKG03	156–157	1.215 88	17.929 52	8802 ± 40	31.7	−29.4	9800	9560–10 100	Garcin *et al* [17]
Ekolongouma	SUERC-99 657	KM7	251–252	1.182 58	17.805 11	9704 ± 42	31.0	−25.1	11 100	10 800–11 200	Garcin *et al* [17]
Ekondzo	SUERC-106 855	EKZ_2.0	70–80	−0.236 28	17.340 56	1865 ± 37	NA	−29.9	1770	1640–1870	This study
Ekondzo	SUERC-106 856	EKZ_3.0	100–110	−0.234 23	17.331 87	1747 ± 37	22.3	−30.4	1630	1540–1700	This study
Ekondzo	SUERC-106 857	EKZ_4.0	90–100	−0.232 03	17.323 21	1110 ± 37	37.3	−30.2	995	930–1060	This study

(Continued.)

Table 1. (Continued.)

									Calibrated age (cal yr BP)		
Transect	Sample publication code	Core code	Sample depth (cm)	Latitude	Longitude	Conventional radiocarbon age (years BP $\pm$ 1 σ)	Pre-treated sample carbon content (%)	$\delta^{13}C_{VPDB}$‰ ($\pm$0.1)	median	range (95% CI)	Original publication
Ekondzo	SUERC-56 868	EKZ_5.0	210–220	−0.229 97	17.314 44	2147 ± 35	33.0	−30.0	2090	2000–2300	Dargie *et al* [1]
Ikelemba	SUERC-99 688	IKE1_1.0	110–120	0.309 46	18.802 87	8124 ± 39	19.0	−30.9	9050	8810–9260	This study
Ikelemba	SUERC-99 689	IKE1_3.0	190–200	0.296 58	18.815 28	18597 ± 85	35.4	−30.0	22 500	22 300–22 800	This study
Ikelemba	SUERC-99 693	IKE1_5.0	380–390	0.283 48	18.827 55	38050 ± 917	32.2	−28.9	42 300	41 200–43 800	This study
Ipombo	SUERC-107 774	IPB_6.00P2	274–275	0.336 05	18.196 39	2244 ± 35	11.6	−30.3	2230	2140–2340	This study
Itanga	SUERC-107 775	ITG_0.0	20–30	1.202 48	17.434 49	370 ± 35	28.3	−20.2	400	320–490	This study
Itanga	SUERC-107 776	ITG_2.0	40–50	1.206 08	17.452 14	1415 ± 35	33.4	−30.4	1300	1190–1360	This study
Itanga	SUERC-107 778	ITG_3.0	110–120	1.208 51	17.469 53	4458 ± 36	51.5	−30.0	5050	4880–5280	This study
Itanga	SUERC-107 782	ITG_4.0	140–150	1.210 68	17.469 53	6691 ± 38	20.4	−27.6	7540	7430–7610	This study
Itanga	SUERC-107 785	ITG_5.0	160–170	1.212 86	17.478 24	7453 ± 39	23.8	−23.1	8260	8180–8350	This study
Itanga	SUERC-56 869	ITG_6.0	190–200	1.215 08	17.487 01	8575 ± 46	58.0	−26.6	9530	9470–9660	Dargie *et al* [1]
Lobaka	SUERC-107 783	LBK_6.00P1	117–118	0.985 22	18.561 08	3128 ± 35	26.7	−30.0	3320	3220–3390	This study
Lokolama	SUERC-99 679	LOK5_1.0	400–410	−0.303 20	18.200 69	9497 ± 39	25.2	−30.2	10 700	10 600–11 050	This study
Lokolama	SUERC-99 680	LOK5_3.0	280–290	−0.314 95	18.187 10	8429 ± 40	47.0	−30.3	9450	9310–9530	This study
Lokolama	SUERC-99 687	LOK5_5.0	590–600	−0.326 84	18.173 44	9285 ± 42	48.6	−31.0	10 450	10 300–10 550	Garcin *et al* [17]
Makodi	SUERC-56 870	TTO_22	117–120	1.492 50	17.424 49	6239 ± 39	42.0	−30.3	7100	7000–7250	Dargie *et al* [1]
Mbala	SUERC-56 873	MBL_6.0	240–250	0.58610	17.791 55	7765 ± 38	36.0	−30.2	8520	8430–8590	Dargie *et al* [1]
Mpama	SUERC-99 662	BEL1_3.00	230–240	−0.441 99	18.551 93	18625 ± 85	42.3	−29.3	22 500	22 400–22 800	This study
Mpeka	SUERC-99 663	PEK1_10.00P1	530–540	−0.134 82	18.923 14	31806 ± 422	47.2	−30.9	36 100	35 300–37 000	This study
Ossango	SUERC-107 787	OSG_01_SP1	130–140	−0.499 42	16.082 51	13515 ± 52	40.7	−29.7	16 250	16 100–16 450	This study
Otsendo	SUERC-108 658	OTS_1.30P	474–475	−0.497 86	15.990 86	18696 ± 86	34.0	−20.6	22 600	22 400–22 900	This study
Tumba	SUERC-99 667	TUM1_1.00	140–150	−0.100 73	18.351 98	2571 ± 37	25.1	−30.5	2630	2490–2760	This study

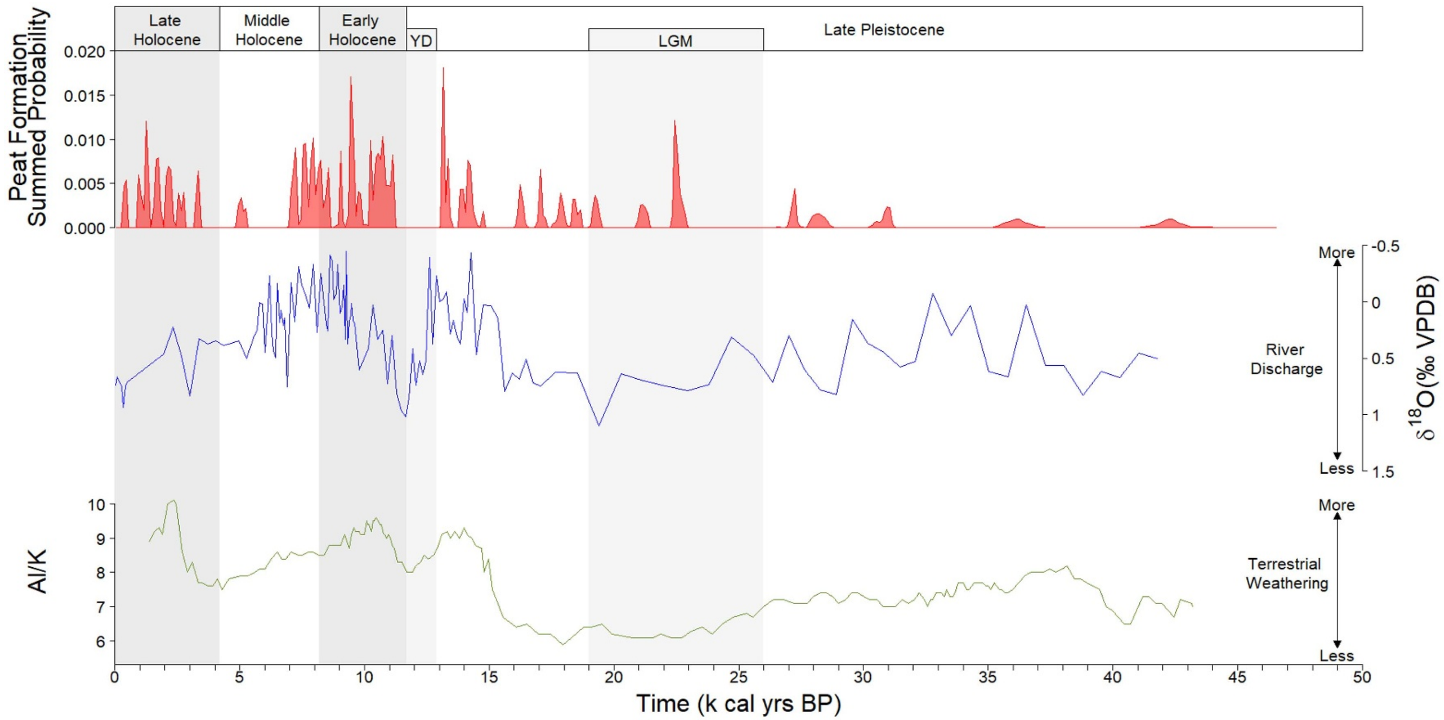

Figure 2. Top panel: summed probability distribution of peat formation in the central Congo Basin from this study (see methods for details). Middle panel: foraminifera $\delta^{18}O$ record from marine core GeoB6518-1 recovered from the Congo River plume, providing a proxy record of freshwater discharge from the Congo River [18] (see methods for details). Bottom panel: Al/K ratios from marine sediment core KZAI-01 from the Congo River plume, presented in Bayon *et al* [40], a proxy record of chemical weathering for the Congo Basin (higher ratios represent higher weathering rates and assumed wetter climates). Official geochronological stages are shown as a white and dark grey backdrop: Late Pleistocene (126 000–11 700 yr BP [39]), Early-(11 700–8200 yr BP [39]), Middle- (8200–4200 yr BP [39]) and Late Holocene (4200 yr BP to present [39]). Widely used but unofficial stadial periods are shown as a light grey backdrop: Last Glacial Maximum (LGM; 19 000–26 000 cal yr^{-1} BP [39]) and the Younger Dryas (YD; 12 900–11 700 yr BP [39]). *R* version 4.0.0 [41] and the *R* packages shape [42] and tidyverse [43] was used to create the figure.

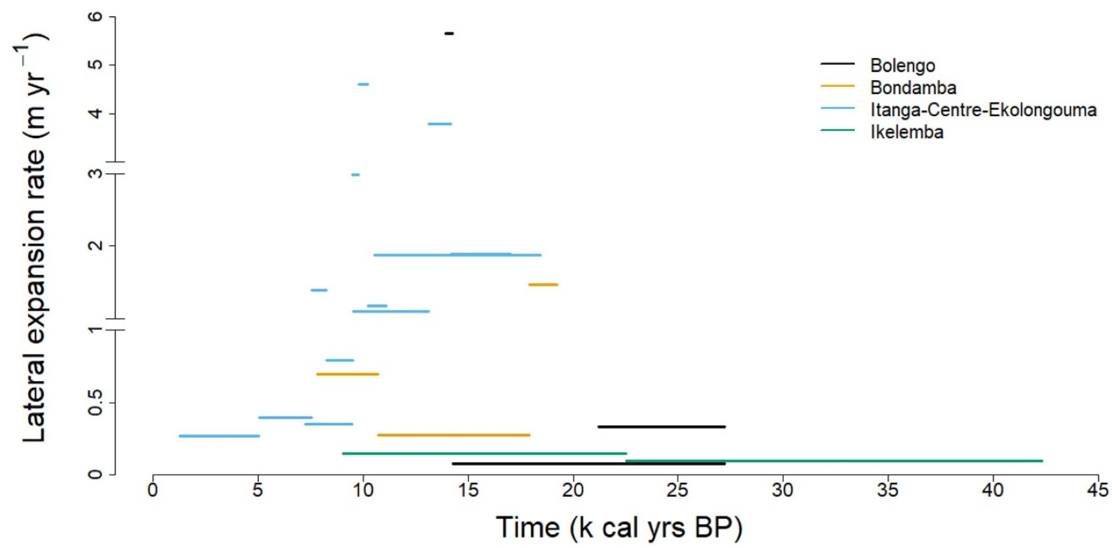

Figure 3. Lateral expansion rates calculated for transects where basal dates were spatially ordered. The horizontal lines represent the apparent lateral expansion rates between each pair of adjacent peat cores along each transect. There are two breaks in the *y*-axis, to allow better visualisation of the data. The Bolengo (shown in figure 1, inset 4, south of the river), Bondamba (shown in figure 1, inset 4, north of the river), and Ikelemba (shown in figure 1, inset 3) transects are located in floodplain peatlands. The combined transects of Itanga, Centre, and Ekolongouma (shown in figure 1, inset 1) are located in an interfluvial peatland.

very similar in age across the transect, for example figure 1, inset 5.

For the transects where dates show a clear spatial order, we calculated apparent lateral expansion rates. For the interfluvial peatland (represented by the combined Itanga, Centre, and Ekolongouma transects in figure 3) apparent lateral expansion rates range from 0.27–4.61 m $yr^{-1,}$ with a median of 1.39 m $yr^{-1,}$ and are higher in the post-LGM—Early Holocene period, than in the Mid- to Late Holocene period. For the floodplain peatlands (represented by the Bolengo, Bondamba, and Ikelemba transects, figure 3) apparent lateral expansion rates are generally lower. Apparent lateral expansion rates along the Bolengo transect range from 0.08–5.65 m yr^{-1}, with a median of 0.33 m yr^{-1}. Along the Bondamba transect apparent lateral expansion rates range from 0.28–1.47 m yr^{-1}, with a median of 0.69 m yr^{-1}, and along the Ikelemba transect they range from 0.10–0.15 m yr^{-1}, with a median of 0.15 m yr^{-1}.

4. Discussion

4.1. Re-evaluating the timing of central Congo peat formation

Our new basal dates show that peat is, in places, more than twice as old as previously reported in the central Congo Basin [17]. Furthermore, our data reveal that peat has persisted throughout—and in some cases appears to have even formed new peat areas during—the LGM, a time which palaeoclimate records indicate was considerably drier than the Holocene in central Africa [18, 44]. Our oldest basal date is one of the oldest reported from lowland peatlands anywhere in the tropics, and is only ∼4500 yr younger than the oldest extant tropical peatland, a lowland inland site in Southeast Asia, which initiated at ∼47 800 cal yr^{-1} BP [45].

The temporal distribution of our calibrated dates suggests that relatively few areas of the peat in the basin today began to form prior to or during the LGM. More peat began to form between the end of the LGM and the beginning of the YD, but most of the peat appears to have begun to accumulate during the Holocene.

4.2. Late Pleistocene peat initiation and the role of hydrogeomorphic setting

The concentration of relatively old (Late Pleistocene) peat basal dates along the left-bank tributaries of the Congo River may be attributable to hydrogeomorphic factors. A combination of river inundation from seasonal flooding, surface run-off, and/or subsurface recharge from the adjoining terra firme may have helped to generate and maintain sufficiently waterlogged conditions for peatlands in these areas to initiate or persist through the relatively dry LGM. This contrasts with the interfluvial peatlands, which are, present day at least, situated further away from the rivers, in receipt of little, if any, water from river flooding events [46], and are surrounded by low topographical relief (figure SI 3).

The fact that the oldest peatlands in the central Congo Basin are mostly situated on river floodplains suggests remarkably little channel migration over tens of millennia. This finding is in striking contrast to other peatlands in riverine landscapes. For example, in the Pastaza–Marañón Foreland Basin (PMFB) in Peruvian Amazonia, most basal dates are from the Late Holocene [47, 48], and the oldest peat basal date

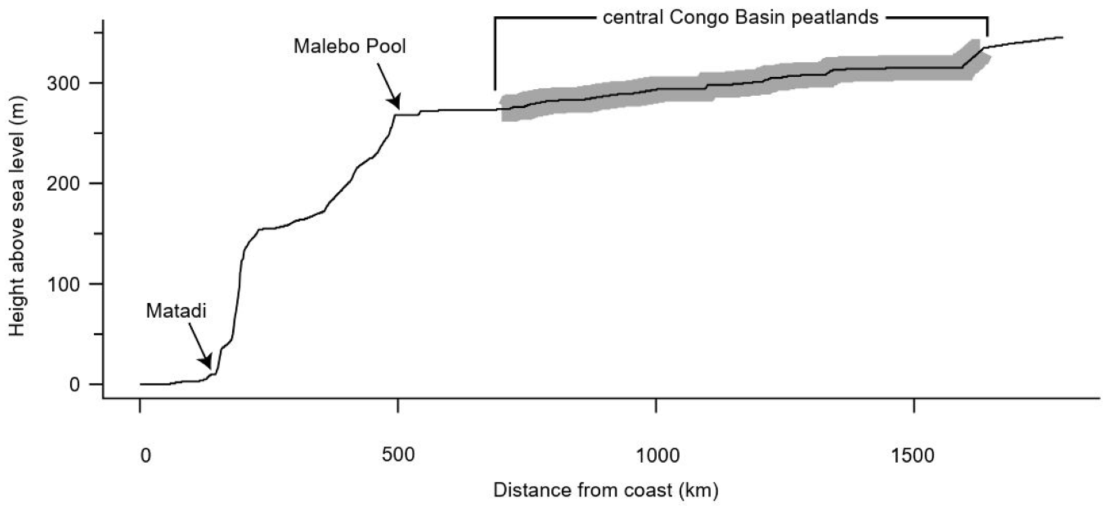

Figure 4. The long profile of the Congo River from its river mouth to just upstream of the central Congo Basin peatlands, showing the elevation step after the Malebo Pool to the city of Matadi, and the location of the central Congo Basin peatlands (shown in dark grey) along the Congo River course. The long profile was created using elevation data from the Forest And Buildings removed Copernicus Digital Elevation Model (FABDEM) [57] and the free and open source software QGIS [25].

is just 8900 cal yr^{-1} BP [49]. The interpretation is that the highly dynamic river systems in the PMFB, many of which are fed by sediments from the Andes and hence undergo regular channel migration, have repeatedly reworked most of their floodplains during the Holocene [50], limiting the maximum age of floodplain peatlands [47].

The implied limited channel migration in the Congo River left-bank tributaries indicated by the great ages of floodplain peatlands may be a result of channel migration being constrained by basin-scale tectonic structures, such as fault lines or horst/graben structures, as has been postulated for some tributaries of the Congo River [51–53]. Larger-scale geomorphological structures may also play an important role in peatland stability. Specifically, there is an abrupt 267 m step in elevation in the lower course of the Congo River, ca. 300 km downstream of the central Congo Basin peatlands, over the rapids between Malebo Pool and Matadi [54] (figure 4). This step likely isolates the middle course of the Congo River—the portion that passes through the central Congo Basin peatland region—from the extremes of orbitally-driven sea-level fluctuations (i.e. changes in base level), between glacial and interglacial phases. For many rivers elsewhere in the world such fluctuations have caused repeated channel reorganisation, including changes to river planform, during the Quaternary [55]. This contrasts with peatlands in Southeast Asia, where post-LGM sea level change has played an important role in patterns of peatland expansion [56]. There, inland peatlands expanded in response to a rise in base level, as sea levels rose following deglaciation [56]. Conversely, late Holocene lowering of sea levels permitted peat development along the coastal regions, as new areas of land became exposed [56].

Alternatively, or in combination with the factors outlined above, river planform stability in these locations may be a consequence of low sediment load and the presence of the peat itself [58–60]. It has been suggested, perhaps counterintuitively, that peat can be cohesive enough to resist erosion by rivers with a low channel sediment load [61, 62]. Therefore, rather than a channel impacting on a peatland through erosion, the relationship can, in some cases, be inverted, with the peatland itself having influence over channel evolution [61, 62]. Characteristic signs of this inverted relationship include sharp angular bends and/or unusually straight segments in the river planform [58, 61–63], both of which are visible along the Ruki River (figure 5), a left-bank tributary of the Congo River, where we find a continuous presence of peat from the Late Pleistocene to the present day. The sharp angular bends are thought to result from relatively erosion-resistant peatlands slowing migration of river channels, forcing a sharp change in channel direction further downstream [61, 62]. The prevention of lateral migration by the peatland can lead to straight channel segments, and as the peatland expands laterally, it can force the channel to flow along the valley margins [58, 61].

4.3. The role of climate change in Holocene peat formation

Of the peat present in the landscape today, by far the most intensive period of peat initiation and/or lateral expansion is from the Early to Middle Holocene (figure 2), with 22 of our basal dates from this 4000 yr

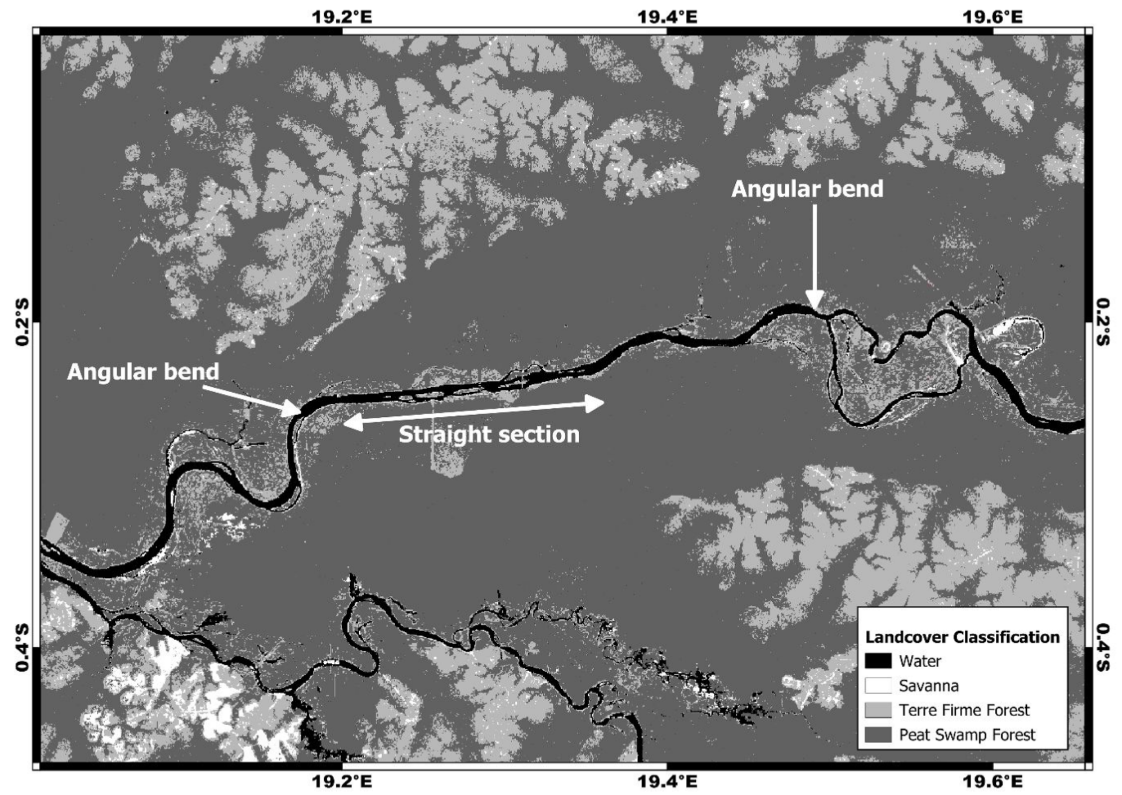

Figure 5. Examples of a straight section and angular bends along the Ruki River, visible in a landcover classification of the region [2]. The figure was created using the Free and Open Source Software QGIS [25].

period, compared to only 20 basal dates from the preceding 30 000 yr period. This clear finding is unlikely to be due to sampling error, given the wide spatial distribution of the dates. Independent palaeoenvironmental evidence from marine sequences, including our palaeo-discharge record (figure 2), indicates that this Early to Middle Holocene peak in basal dates coincides with an increase in river discharge and terrestrial weathering across the basin, indicating wetter conditions [18]. This finding supports previous inferences that climatic wetting may explain this phase of widespread peat formation across the central Congo Basin [1, 17].

By contrast, a period of climatic drying between 5000–2000 yr BP is recorded in hydrogen isotopes of plant waxes, and has been linked with widespread decomposition and wasting of peat across the central Congo Basin, previously referred to as the 'Ghost Interval' [17]. The decomposition signal of this climatic event in places affects peat dating back to at least 7500 yr BP, as water tables descended into older peat, exposing them to aeration and wasting [17]. The temporal distribution of our basal ages supports the hypothesis of climatic drying around this time. The occurrence of only one basal date during the ~4000 yr period between 7100 and 3320 yr BP is a strong indication that this drying event limited new peatland areas from forming, and may have also eradicated areas of peatland that had formed between 7100 and 3320 yr BP. Four of our basal dates fall between 2000 and 3320 cal yr^{-1} BP, towards the end of the proposed drying event [17]. This apparent inconsistency may reflect (i) the limited sampling resolution of some of the cores studied, which make the exact timing of the climatic drying unclear, (ii) variation in the timing of the climatic drying event across the region, and/or (iii) site-specific factors (e.g. topographic situation) which meant that some sites were able to begin accumulating peat before the drying event had fully ceased.

4.4. Possible processes of peat lateral expansion

The 167 600 km^2 of peatland within the central Congo Basin [2] is found in large, continuous blocks of peatland, rather than many small discrete peatlands. Our basal dates suggest that peat expanded across these large areas through a mix of processes. Sites where we see basal ages becoming progressively younger from the peatland centre to the margins, would suggest that peat initiated at a central nucleus and then spread out over a large area through lateral expansion [12]. At sites where there is a wide range of basal ages with no clear spatial pattern, the coalescence of several smaller peatlands through lateral expansion could be the model of peat formation [12]. Sites with a small temporal range of basal dates across a large area could be the result of simultaneous peat initiation across a large area [12].

The apparent lateral expansion rates for the interfluvial site (0.27–4.61 m yr^{-1}) are at the higher end of lateral expansion rates reported for high latitude peatlands (0.02–7.92 m yr^{-1}) [35, 64, 65]. Low topographic relief, as found at the interfluvial site, can help facilitate higher rates of peat lateral expansion [64]. Conversely, the lower apparent rates of lateral expansion within the floodplain peatlands (0.08–1.47 m yr^{-1}, with an outlier of 5.65 m yr^{-1}) could reflect a lack of space into which the peatland can laterally expand, being bordered by a river on one side and relatively high topography on the other (SI figure 3). This may also explain the low lateral expansion rates at the margins of the interfluvial site, or it could be owing to the climatic drying event between 5000–2000 yr BP eradicating thin marginal peats [17].

4.5. Peatlands as biodiversity refugia?

The persistence of peat since before the LGM, apparently the most climatically dry period during the last 42 000 yr in this region (figure 2), implies that some sites remained sufficiently waterlogged to maintain at least part of the peat stock throughout the whole period. This evidence for persistent retention of water in a drier climate means that these areas may have played an important biogeographical role as refugia for forest taxa during glacial-interglacial cycles. During the Pleistocene, central Africa's forests are thought to have contracted to isolated refugia during cooler, drier glacial phases, and re-expanded and coalesced during warmer, wetter interglacials [66]. Maley [67] and Hardy *et al* [66], among others, have proposed that the central Congo Basin was one of several regions that hosted forest refugia. Our basal dates show that parts of this region were not only wet enough for closed canopy tropical forest, but also wet enough for peatland persistence throughout the last 42 000 yr.

In support of this conclusion, at least two swamp-forest endemic animals are known from the central Congo Basin—a dwarf crocodile, *Osteolaemus osborni*, and Allen's monkey, *Allenopithecus nigroviridis*—providing additional evidence that Congo Basin swamp forest habitats may have been maintained through evolutionary timescales [68, 69]. On the other hand, no endemic plant species have yet been reported from the central Congo Basin peatlands, although sampling has so far been extremely limited, particularly for smaller plant species with shorter generation times. Future phylogenetic and palaeoecological studies could test the significance of peatlands to the palaeo-biogeography of central Africa and help to assess whether or not they were an ephemeral habitat that disappeared entirely during earlier Quaternary dry phases.

5. Further research

The new basal dates and their interpretation suggest priorities for further research. Firstly, we need to understand the processes resulting in the channel stability of the left-bank Congo River tributaries. Testing whether channel stability is linked to low sediment loads and/or the isolation of these tributaries from the influence of sea-level change (base level stability) would help to identify potential impacts of human activities. For example, dam construction, deforestation or mining [27] could increase sediment loads and decrease base level stability, impacting the carbon stocks and biodiversity of the peatlands.

Secondly, our data raise questions about the role of hydrogeomorphic settings in determining the resistance of the peatlands to climate change this century. Some of the central Congo Basin peatlands have persisted since before the LGM, mostly floodplain peatlands of left-bank tributaries of the Congo River, suggesting substantial resistance to past climate change. Does this therefore imply less resistance to a drying climate in other hydrogeomorphic settings? Understanding the factors governing the stability of peatland ecosystems is particularly urgent given the possibility of longer or more severe dry seasons in the central Congo Basin [16]. Further palaeoecological, ecological and hydrological data are needed to understand the behaviour of peatlands in different hydrogeological settings, to better understand the dynamics and stability of the central Congo Basin peat carbon stock and predict their response to future climate change.

Data availability statement

Al/K ratios presented in figure 2 are available from Bayon *et al* [40]. All other data are included in the manuscript or are available in an open GitHub repository, along with any code, at https://github.com/CongoPeat/Congo_Basin_Peat_Intitation.

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Author contributions

S L L, I T L, G C D, S E P, and E T A M conceived the study; G C D S L L, I T L, P G, A B, C E, E T A M, P J M, S A I, S E P and S S developed the study; G C D, B C, S L L, B E Y, J K, O E, P B, C E, B M, D R V B, G J K, J P M M, L L, N T G, D H, G B and I T L, organised and conducted the fieldwork; P G organised and conducted the laboratory work; E S,Y G and R R S contributed data; G C D interpreted the data; G C D wrote the paper with significant inputs from I T L, S L L, P J M, and E S All authors reviewed and commented on the paper.

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