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Age, extent, and carbon storage of the central Congo Basin peatland complex

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Abstract/ First paragraph

Peatlands are carbon-rich ecosystems that cover just 3% of Earth's land surface[1], but store one-third of soil carbon[2]. Peat soils are formed by the build-up of partially decomposed organic matter (OM) under waterlogged anoxic conditions. Most peat is found in cool climatic regions where unimpeded decomposition is slower, but deposits

are also found under some tropical swamp forests[2,3]. Here we present field measurements from one of the world's most extensive regions of swamp forest, the Cuvette Centrale depression in the central Congo Basin[4]. We find extensive peat deposits (OM ≥65%, ≥0.3 m deep) beneath the swamp forest vegetation. Radiocarbon dates indicate that peat began accumulating from 10,600 cal yr BP (Before Present, AD 1950), coincident with more humid conditions at the beginning of the Holocene in Central Africa[5]. The peatlands occupy large interfluvial basins, and appear to be a largely rain-fed, ombrotrophic-like system. Although the peat layer is relatively shallow (maximum depth 5.9 m; median 2.0 m), combining in situ and remotely sensed data, we estimate the area of peat to be 145,500 km^2 (95% CI: 131,900–156,400 km^2), making this the most extensive peatland complex in the tropics. This area is greater than five times the 'maximum possible' area reported for the Congo Basin in a recent synthesis of pantropical peat extent[2]. We estimate these peatlands store 30.6 Pg C below-ground (95% CI: 6.3–46.8), which is similar to the aboveground carbon stocks of the tropical forests of the entire ~3.7 million km^2 Congo Basin[6]. Our Cuvette Centrale result increases the best estimate of global tropical peatland carbon stocks by 36%, to 104.7 Pg C (minimum estimate: 69.6 Pg C; maximum estimate: 129.8 Pg C, sensu Ref. 2). This stored carbon is vulnerable to land-use change and any future reduction in precipitation[7,8].

Main text

The Congo Basin drains ~3.7 million km^2, within which lies a central shallow depression overlain by swamp forest, known as the Cuvette Centrale, French for 'Central Basin'[9]. Over this region the Congo River drops just 115 m over 1,740 km, with year-round waterlogging[9], thus we hypothesised that the second largest wetland in the tropics may contain extensive peat deposits. A few little-known grey literature sources since the 1950s briefly mention peat occurring in central Congo, but geolocations or other details were not reported[10-13]. Recently published estimates of tropical peatland area and carbon storage still rely on this scant unverifiable information[2,14]. Thus, here we assess whether the Cuvette Centrale contains significant peat deposits, and if so, estimate its extent and total carbon storage.

We combined a digital elevation model (DEM, from the Shuttle Radar Topography Mission, SRTM) to exclude high ground and steep slopes, radar backscatter (from the Advanced Land Observation Satellite Phased Array type L-band Synthetic Aperture Radar, ALOS PALSAR) to detect standing surface water under forest, and optical data (from Landsat Enhanced Thematic Mapper, ETM+) to categorise likely swamp vegetation, to identify areas to prospect for peat (Extended Data Table 1). We identified nine transects (2.5 to 20 km long) within a ~40,000 km^2 area of northern Republic of Congo (RoC), each traversing more than one vegetation type within waterlogged regions, and collectively spanning the range of non-waterlogged vegetation types (Fig. 1). We confirmed the presence of peat (definition: ≥0.3 m depth; OM content ≥65%) in all eight expected areas (four perpendicular to a low-nutrient black-water river, pH 3.8, three perpendicular to a more nutrient-rich white-water river, pH 7.4, which has high banks and likely does not contribute water to the swamp, and one transect at the midpoint of the two rivers), and no peat in the abandoned meanders of the white-water river where higher nutrient levels likely increase dry-season decomposition, thereby preventing peat formation.

Peat thickness, measured at least every 250 m along each transect, increased with increasing distance from peatland edges, to a maximum depth of 5.9 m near the mid-point between the two rivers (mean depth, 2.4 m, 95% CI 2.2–2.6; n=211; Fig. 2). Such peat thicknesses are shallower than in many other parts of the tropics (Table 1). Radiocarbon dating of basal peat samples returned ages ranging from 10,554 to 7,137 cal yrs BP (calibrated ^{14}C years Before Present [1950], at 2 σ; Extended Data Table 2). These dates are consistent with peat initiation and carbon accumulation being linked to a well-documented increase in humidity across the Congo Basin during the early Holocene, between ~11,000 and ~8,000 cal yr BP, the onset of the African Humid Period[5] (Extended Data Table 3). Additional radiocarbon dates show 0.57–0.80 m of peat accumulation over the past 1,464 to 2,623 cal yrs BP (Extended Data Table 2), indicating that peat has continued to accumulate since the end of the African Humid Period at ~3,000 cal yr BP at the low latitude of the Cuvette Centrale swamps[15].

The waterlogging that inhibits OM decay may be due to poor drainage plus high rainfall (~1,700 mm yr^{-1}) and/or overbank flooding by rivers. One year of continuous peatland water table measurements across four of the transects (Fig. 1) showed no evidence of flood-waves (Extended Data Fig. 1; cf. a flood-wave recorded using a similar sensor in a Peruvian peatland[16]). Recorded water table increases were largely consistent with the Tropical Rainfall Monitoring Mission rainfall record (product 3B42, Extended Data Fig. 1). Furthermore, the calcium concentration within surface peats is low, at 0.3 g kg^{-1}, as is pH, at 3.2, similar to other ombrotrophic rainwater-fed tropical peatlands (typically [Ca]<0.4 g kg^{-1} [Refs 17,18]), cf. minerotrophic river-fed: typically [Ca], 1-10 g kg^{-1} [Refs 16,17]). We also observed peatland inundation whilst river levels were still well below their banks. While supra-annual river flooding cannot be excluded[19], the peatlands of the Cuvette Central can be considered ombrotrophic-like peatlands due to their low-nutrient status and heavily rainwater dependent water tables. This is consistent with past satellite-only studies suggesting that these wetlands are largely hydrologically independent from regional rivers[20,21], and with our radiocarbon dates suggesting that peat accumulation began with an increase in regional precipitation.

Our transect sampling shows that peat is consistently found under two common vegetation types, hardwood swamp forest (with Uapaca paludosa, Carapa procera and Xylopia rubescens often common) and a palm-dominated (Raphia laurentii) swamp forest. Peat was also usually found under another much rarer palm-dominated (Raphia hookeri) swamp forest occupying abandoned black-water river channels. Peat was not found beneath terra firme forest, seasonally flooded forest or savanna (Extended Data Table 4). We then used these peat-vegetation associations to estimate peatland extent within the Cuvette Centrale, via remotely sensed mapping of hardwood and palm-dominated swamp forest extent. Field ground truth points of land cover classes, including hardwood swamp ~300 km from our main study region (total 516), were used to train a maximum likelihood classification derived from eight layers (two polarisations and their ratio from ALOS PALSAR; slope and elevation from the SRTM DEM; Landsat ETM+ bands 3, 4 and 5; Extended Data Fig 2; Extended Data Table 5). Running the classification 1,000 times, each time using a random two-thirds sample of ground truth points as training data, generated a peatland probability map with a median area of 145,500 km^2 (Fig. 1; mean 145,200 km^2; 95% CI 131,900–156,400 km^2; median overall classification accuracy against independent test data 88%: Extended Data Table 6). This is greater than five times the ‘maximum possible’ area reported for this region in a recent synthesis of pantropical peat storage[2]. Comparing our estimated area of swamp vegetation that overlies peat with other remotely sensed estimates of the total regional wetland extent, including seasons wetlands[22], suggests that peatlands account for ~40% of the total regional wetland extent.

While further measurements will be required to improve our first estimate of the area of peat within the Cuvette Centrale, it is very likely the largest peatland complex in the tropics. Peatlands on the tropical Asian islands of New Guinea, Borneo, and Sumatra cover 101,000 km^2, 73,000 km^2, and 69,000 km^2 respectively, but today ~30%, ~40% and ~50% of the area has undergone land-use change and drainage[23]. Each of these estimates is below our lower confidence interval of peat extent within the Cuvette Centrale.

Combining the peatland area estimates with our measurements of peat depth, bulk density, and carbon concentration values, using a resampling approach, we find that the median total peat carbon storage within the Cuvette Centrale is 30.6 Pg C (mean, 29.8 Pg C; 95% CI 6.3–46.8 Pg C; Extended Data Figs 3 and 4). Uncertainty, while absolutely large, is proportionately smaller than initial estimates of other extensive peatlands[3]. Additional peat depth measurements, guided by our map, should reduce the uncertainty on our first estimate. Peat C stocks dwarf those stored in living vegetation overlying the peatland, based on in situ sample plots (median, 1.4 Pg C; 95% CI 0.6–2.5 Pg C; n=60). Total below-ground carbon storage is likely to be greater than peat-only estimates suggest, as beneath the true peat a layer of OM- and carbon-rich material occurs, but is outside our definition of peat (OM ≥65%; Extended Data Fig. 3).

The most recent synthesis of tropical peat carbon storage[2] suggested that total peat carbon storage across the African continent is 7 Pg C, which rises to 34.4 Pg C after taking into account our new Cuvette Centrale estimate. Total tropical peat carbon stocks were also estimated, at 89 Pg, which after accounting for losses from extensive ongoing land-use change and peat fires in Asia in the ~23 years since the data was collected[2], at ~0.5 Pg C yr^{-1} [Ref. 24], and combining with our new Cuvette Centrale data, yields a total contemporary tropical peat carbon stock of 104.7 Pg C, 29% within the Cuvette Centrale (with a minimum estimate of 69.6 Pg C and a maximum of 129.8 Pg C, see Ref. 2). In terms of both peat area and peat carbon stocks DRC (90,800 km^2 peat; 19.1 Pg C) and RoC (54,700 km^2 peat; 11.5 Pg C) become the second and third most important countries in the tropics for peat areas and C stocks[2]. Globally they are the fifth and ninth most important for peat area and the fifth and sixth most important in terms of C stocks[25], and together account for ~5% of the estimated global peat C stock[2]. Translating the long-term C sink in peat into contemporary CO_2 fluxes is challenging, likely requiring an integrated multi-sensor monitoring programme. Combining contemporary CO_2 flux estimates with CH_4 emissions (large, but poorly constrained[26]), would then improve our understanding of the role of the wetland within the global carbon cycle and climate system.

The world's three major regions of lowland tropical peat, in the Cuvette Centrale, tropical Asia islands, and Western Amazonia, appear to strongly differ (Table 1). Surface topography assessments, using either SRTM or ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer), did not reveal clear domes, where the peat surface increases from the edge to interior of the peatland, as expected from a poorly draining rain-fed system ('raised bogs')[27], unlike those seen in many, but not all, Western Amazonian[17], and tropical Asian[18,28] peatlands (Fig. 2). However, our surface topography detection limits are likely 2–3 m, and independent satellite altimetry data suggests that water levels in the interfluvial wetlands are always 0.5–3m higher than adjacent rivers[26], consistent with very small domes. Overall, our results imply that within the Cuvette Centrale large-scale shallow interfluvial basins have filled with peat, which gradually increases in thickness away from the river margins (Fig. 2), having accumulated, on average, slowly over the Holocene (Table 1). By contrast, in a typical tropical Asian system, high precipitation and the persistence of climatic conditions suitable for peat accumulation since the early Holocene, and often before the Last Glacial Maximum, has allowed peat to accumulate to greater thickness, and form clear domes[29,30]. Lowland Western Amazonia differs again: high precipitation levels during the Holocene have permitted relatively rapid peat accumulation since at least 8,900 cal yrs BP in places, and domes to form, but their location on dynamic river floodplains means that peatlands rarely survive long enough to accumulate to great thickness[31]. Such differences extend to peat properties, with Cuvette Centrale peats having much higher bulk density, and slightly higher C concentration, likely reflecting enhanced decomposition than is typical in other lowland tropical peatlands, thereby increasing C storage per unit volume of peat (Table 1).

The Cuvette Centrale peatlands are relatively undisturbed at present, due to difficult access and distance from markets. However, they face two threats: changes in land-use, particularly drainage for agricultural use, as is occurring extensively across tropical Asia; and a regional reduction in precipitation via a changing climate, which may already be occurring[32]. While modelled projections of Central African rainfall are not consistent, some suggest declining annual precipitation[7] and more intense dry seasons[8]. The existence of large carbon stocks in peat – potentially equivalent to 20 years of current fossil fuel emissions from the United States of America – increases the importance of improving climate model projections for Central Africa, a long neglected region.

The Cuvette Centrale swamps are refuges for remaining megafauna populations, including lowland gorillas and forest elephants. Our findings suggest that they are also the world's most extensive tropical peatland complex and amongst the most carbon-dense ecosystems on Earth, on average storing 2,186 Mg C ha^{-1}. The existence of such large and previously unquantified components of the national carbon stocks of both RoC and DRC provides an additional imperative for governments, alongside conservation, development and scientific communities, to work with the people of the Cuvette Centrale to pursue development pathways that radically improve local livelihoods without compromising the integrity of this globally significant region of Earth.

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Author Contributions

S.L.L. conceived the study. G.C.D., S.L.L., I.T.L., S.A.I and S.E.P. developed the study. G.C.D. collected most of the data, assisted by B.E.Y., S.L.L., and I.T.L. Laboratory analyses were by G.C.D. G.C.D. and E.T.A.M. analysed the remotely sensed data. G.C.D., S.L.L., I.T.L., E.T.A.M. and S.E.P. interpreted the data. G.C.D. and S.L.L. wrote the paper, with input from all co-authors.

In text tables:

Table 1. Cuvette Centrale, Southeast Asian and South American peatland properties.

Region and references	Peatland Area (km^2)	Basal Peat Age (cal k yrs BP)	Peat Depth (m)	Peat Bulk Density (g cm^{-3})	Carbon (%)	Carbon Density (g C cm^{-3})	Peat Accumulation Rate (mm yr^{-1})	LORCA (g C m^{-2} yr^{-1})
	Best Estimate (95% CI)	**Mean±1 S.D. (Oldest)**	**Mean±1 S.D. (Max)**	**Mean±1 S.D. (Min; Max)**	**Mean±1 S.D. (Min; Max)**	**Mean±1 S.D. (Min; Max)**	**Mean±1 S.D. (Min; Max)**	**Mean±1 S.D. (Min; Max)**
Central Congo Basin, this study	145,500 (131,900-156,400)	8.9±1.2 (10.6[*])	2.4±1.6[†] (5.9)	0.19±0.06[§] (0.1; 0.32)	59±3[#] (53; 63)	0.11±0.028[††] (0.06; 0.15)	0.21±0.05 (0.16; 0.29)	23.9±5.8 (18.3; 33.1)
Central Kalimantan, Borneo[28-30,33]	30,100 (NR)	14.1±7.0 (~26.0)	4.7±0.9 (9.4[‡])	0.11±0.03[‖] (NR)	57±2[‖] (NR)	0.061±0.015 (0.046; 0.075)	0.54 (NR)	31.3 (16.6; 73.2)
Pastaza-Marañon Basin, Western Amazonia[3,16,31]	35,600 (33,500-37,700)	3.5±2.8 (8.9)	2.5±0.7 (7.5[‡])	0.11±0.06[¶] (0.05; 0.24)	46±8[**] (30; 54)	0.033±0.011 (0.021; 0.050)	1.74±0.72 (0.72; 2.56)	52±22 (36; 85)

Table title and footnotes:

Table 1. Cuvette Centrale, Southeast Asian and South American peatland properties.

NR, Not Reported; LORCA, Long-term rate of carbon accumulation; [†]Median: 2.0 m, n=211; [§]Median: 0.19 g cm^{-3}, n=44 cores, total 372 samples; [#] Median: 59%, n=12 cores, total 181 samples; [††]Median: 0.10 g C cm^{-3}, 12 cores, 181 samples; [‖]n=20 cores, total 173 samples; [¶]n=9 cores, total 134 samples; [**]n=9 cores, total 101 samples; [*]Last ~0.25 m of peat of deepest and oldest basal sample could not be recovered from the ground, thus applying an average peat accumulation rate for this core indicates that peat initiation may be ~980 years earlier than stated, at ~11,500 cal yrs BP (Extended Data Tables 2 and 3); [‡]Deeper values have been reported from other regions within South East Asia and Amazonia[2].

Figure legends:

Figure 1. Location of the Cuvette Centrale wetlands (a), study sites (b), and the peatland probability map (c). (a) Africa, country outlines, and Cuvette Centrale wetland shaded green; (b) ALOS PALSAR radar imagery showing transect locations numbered, 1. Bondoki, 2. Bondzale, 3. Center, 4. Ekolongouma, 5. Ekondzo, 6. Itanga, 7. Makodi, 8. Mbala, 9. Moungouma (yellow), basal peat samples (red) and water table measurements (blue); meandering black-water Likouala-aux-Herbes River on the left, straighter white-water Ubangi River on the right; Green is related to vegetation density, i.e. dark areas are savannas/water and bright areas have tree and palm-dominated vegetation (cross-polarised HV data); Magenta shows palm-dominated swamp, due to the strong double bounce from

stems and wet soil (single-polarised HH data); (c) Probability map of vegetation types derived from 1,000 runs of a maximum likelihood classification using eight remote sensing products (three ALOS PALSAR; two SRTM-derived variables; three Landsat ETM+ bands) and jackknifed selections of training data; black box shows area in (b). Field observations show that peat underlies both hardwood and palm-dominated swamp forest.

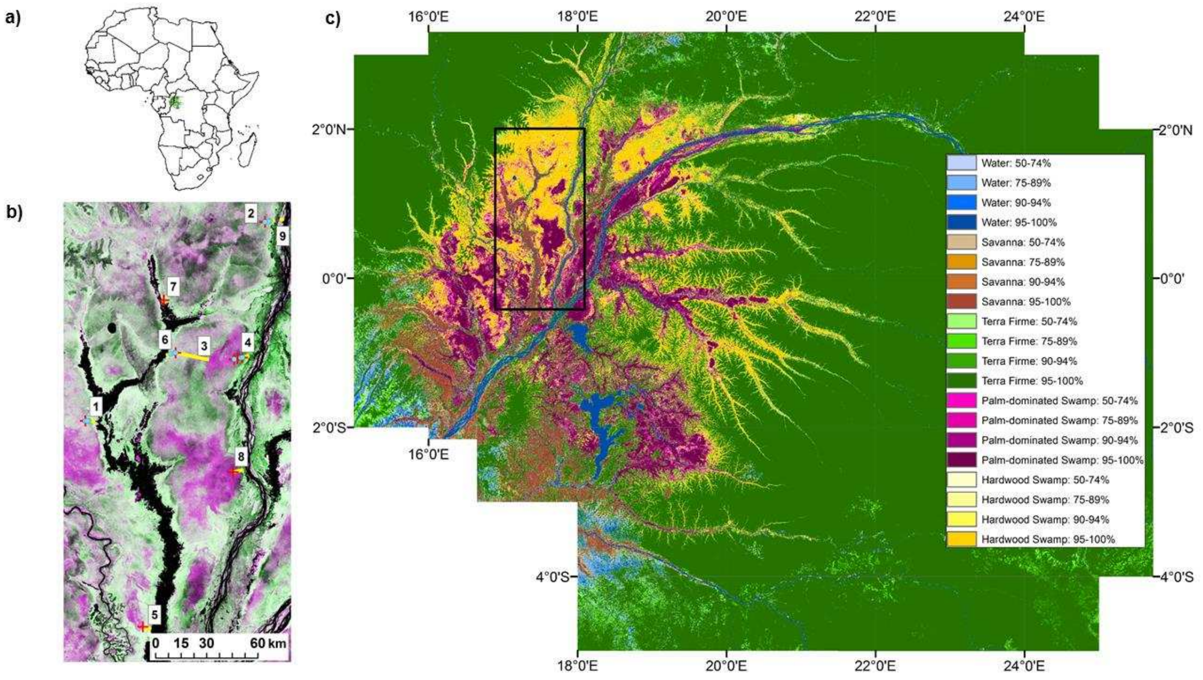

Figure 2. Tree height (a), estimated peatland surface derived from two satellite products (b, c), and peat depth (d) along 24 km of transects extending from the peatland edge to the interfluvial centre. (a) Maximum (light green) and mean (dark green) tree height measured in situ. (b) ASTER-derived estimated peatland surface (grey; ASTER DEM minus maximum tree height), plus linear trend line (grey dashed line; slope, 0.04 m km^{-1}, 95% CI 0–0.08 m km^{-1}, not significant) and a running mean of the estimated peatland surface using 20 data points before and 20 points following the focal data point (red). (c) SRTM-derived estimated peatland surface (light blue; SRTM DEM minus mean tree height), plus linear trend line (blue dashed line; slope, -0.12 m km^{-1}, 95% CI -0.14 – -0.11 m km^{-1}, p<0.001) and

running mean (red). (d) Peat depth, measures in situ, every 250m (brown). The two transects, Itanga (perpendicular to the Likouala-aux-herbes river; No.6 in Fig 1b) and Center (running from the end of the Itanga transect to the mid-point of the interfluvial region between the Likouala-aux-herbes and Ubangui rivers; No.3 in Fig 1b), are contiguous, but follow different bearings (077° and 102° respectively).