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Current knowledge on the Cuvette Centrale peatland complex and future research directions

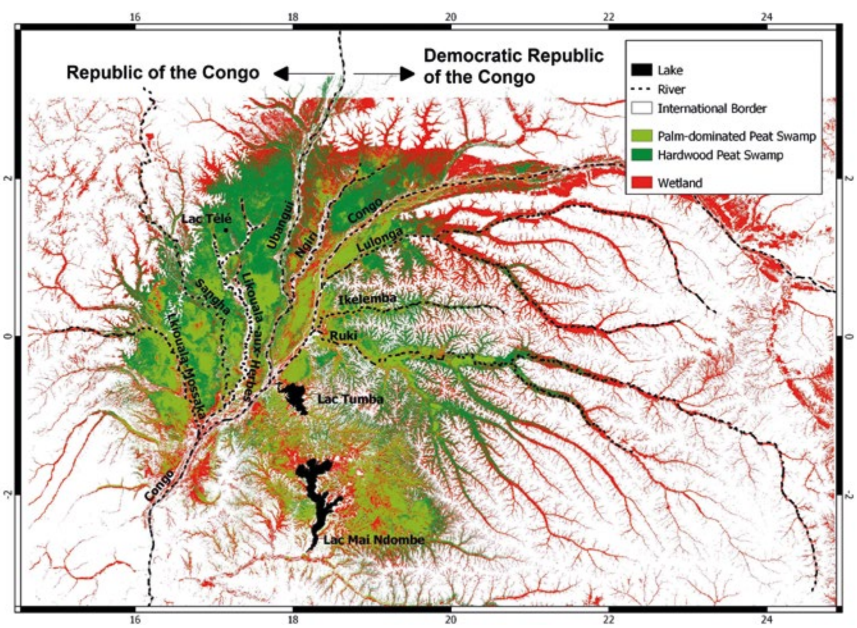

Figure 1.
Map of the Cuvette Centrale showing the spatial distribution of hardwood peat swamp forest (dark green fill) and palm-dominated peat swamp forest (light green fill) sourced from Dargie *et al.* (2017) and the much wider distribution of wetland ecosystems (red fill) sourced from Bwangoy *et al.* (2010), the major lakes (black fill) and rivers (black dashed line) and international borders (grey line).

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RÉSUMÉ

Connaissances actuelles sur le complexe de tourbières de la Cuvette centrale et orientations futures pour la recherche

La Cuvette centrale est le plus vaste complexe de tourbières tropicales au monde, qui s'étend sur environ 145 000 km^2 en République du Congo et en République démocratique du Congo. Ce complexe stocke environ 30,6 Pg C, soit l'équivalent de trois années d'émissions mondiales de dioxyde de carbone, et représente désormais le premier site Ramsar transnational. Malgré sa taille et son importance mondiale en tant que puits de carbone, les aspects clés de son écologie et de son histoire, notamment sa formation, l'ampleur des flux de gaz à effet de serre, sa biodiversité et l'histoire de l'activité humaine, demeurent relativement peu connus. Nous synthétisons ici les connaissances disponibles sur la Cuvette centrale, en identifiant des domaines clés pour la poursuite des recherches. Enfin, nous examinons le potentiel des modèles mathématiques pour évaluer les trajectoires futures des tourbières en termes d'impacts prévisibles de l'exploitation de ressources et du changement climatique.

Mots-clés : tourbière tropicale, stockage du carbone, émissions de gaz à effet de serre, paléoécologie, biodiversité, Anthropocène, République démocratique du Congo.

ABSTRACT

Current knowledge on the Cuvette Centrale peatland complex and future research directions

The Cuvette Centrale is the largest tropical peatland complex in the world, covering approximately 145,000 km^2 across the Republic of Congo and the Democratic Republic of Congo. It stores ca. 30.6 Pg C, the equivalent of three years of global carbon dioxide emissions and is now the first trans-national Ramsar site. Despite its size and importance as a global carbon store, relatively little is known about key aspects of its ecology and history, including its formation, the scale of greenhouse gas flows, its biodiversity and its history of human activity. Here, we synthesise available knowledge on the Cuvette Centrale, identifying key areas for further research. Finally, we review the potential of mathematical models to assess future trajectories for the peatlands in terms of the potential impacts of resource extraction or climate change.

Keywords: tropical peatland, carbon storage, greenhouse gas emissions, palaeoecology, biodiversity, Anthropocene, Democratic Republic of Congo.

RESUMEN

Conocimientos actuales sobre el complejo de turberas de la Cuvette Centrale y futuras direcciones de investigación

La Cuvette Centrale es el mayor complejo de turberas tropicales del mundo, con una extensión aproximada de 145 000 km^2 entre la República del Congo y la República Democrática del Congo. Almacena unas 30,6 Pg C, el equivalente a tres años de emisiones mundiales de dióxido de carbono, y es la primera zona Ramsar transnacional. A pesar de su tamaño e importancia como almacén mundial de carbono, se sabe relativamente poco sobre aspectos clave de su ecología e historia, como su formación, el balance de los flujos de gases de efecto invernadero, la biodiversidad y la historia de la actividad humana. En este artículo sintetizamos los conocimientos disponibles sobre la Cuvette Centrale, identificando las áreas clave para la investigación futura. Por último, revisamos el potencial de los modelos matemáticos para evaluar las trayectorias futuras de las turberas en términos de impacto potencial de la explotación de recursos o del cambio climático.

Palabras clave: turbera tropical, almacenamiento de carbono, emisiones de gases de efecto invernadero, paleoecología, biodiversidad, Antropoceno, República Democrática del Congo.

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Introduction

Relatively recently it became apparent that the Cuvette Centrale, a vast region of wetlands in the centre of the Congo Basin, shared between the Republic of the Congo (ROC) and Democratic Republic of the Congo (DRC), is home to the largest tropical peatland complex in the world. Peatlands are a type of wetland, but are distinguishable from other wetland ecosystems by the considerable amounts of organic matter, and therefore, carbon they have accumulated. As a result, peatlands are widely recognised as playing an important role in the global carbon cycle, storing an estimated 600 peta-grams of carbon (Pg C; Yu *et al.*, 2010), accounting for over a third of the global soil carbon stock (Page *et al.*, 2011). Peatland ecosystems can also play a valuable role in regulating regional hydrology and provide habitat for endangered or unique flora and fauna (Parish *et al.*, 2008). In some regions of the world peatlands are important for the provision of food, construction materials, as well as medicines (Parish *et al.*, 2008) and worldwide often form an important part of peoples' culture and heritage (Schulz *et al.*, 2019).

Across the world, peatlands are coming under threat from land use conversion and climate change. In Southeast Asia, the scale and rapidity of peatland degradation, primarily from conversion to oil palm and pulpwood plantations, has been alarming (Miettinen *et al.*, 2016). Following extensive peatland fires, which started during the dry and hot conditions of an El Niño year, in areas of peatlands made vulnerable to fire by drainage (Miettinen *et al.*, 2017), Indonesia was the fourth largest emitter of greenhouse gases in 2015 (Climate Watch, 2019). The disruption to trade, transport and education from these fires cost Indonesia the equivalent of 2% of its GDP (World Bank, 2016). It is estimated that across the region the air pollution from these fires resulted in 100,000 excess deaths (Koplitz *et al.*, 2016). The irony is that the long term productivity and future of many of these peatland plantations is at risk owing to peatland subsidence from drainage, which in turn increases the risk of plantations becoming completely inundated as the peatland surface is lowered below the wet season high water table (Sumarga *et al.*, 2016) and to the exposure of potential acid sulphate soils consisting of underlying pyrite-rich marine clays in coastal and sub-coastal peatlands (Haraguchi, 2016). Furthermore, the naturally nutrient poor status of domed tropical peatlands, means that fertilisers are often required when these peatlands are converted to agricultural land, which leads to increased nitrous oxide emissions (Cooper *et al.*, 2020).

The Southeast Asian experience highlights the perils of implementing policies that seek short-term economic gains at the expense of an ecosystem function. The Cuvette Centrale peatlands were first mapped in 2017 (Dargie *et al.*, 2017), and whilst the peatlands are at present largely intact, a number of potential threats have been identified including climate change, hydrocarbon exploration, industrial logging and infrastructure development with negative impacts on carbon stocks, biodiversity and water quality expected if these threats were to materialise (Dargie *et al.*, 2019). Research into the Cuvette Centrale peatlands is very much in its infancy. Building up knowledge of these ecosystems is essential for their preservation. Here we summarise the current state of knowledge of the Cuvette Centrale peatlands, whilst highlighting the many unknowns which remain.

Peatland extent

The only field-based study to date to map the peatlands of the Cuvette Centrale, estimate that they cover an area of 145,500 km^2 (Dargie *et al.*, 2017), accounting for circa 77% of all African peatlands (based on a total African peatland extent of 187,061 km^2; Xu *et al.*, 2018). Independently, Gumbricht *et al.* (2017) estimate the size of the Cuvette Centrale peatlands to be 125,440 km^2, based on remotely sensed data alone.

Both Dargie *et al.* (2017) and Gumbricht *et al.* (2017) have strict definitions of what they consider to constitute peat: a layer of partially decomposed vegetation, with a minimum thickness of 30 cm and an organic matter content of at least 65% (Dargie *et al.*, 2017) or 50% (Gumbricht *et al.*, 2017). As a result, the peatland area estimates of both Dargie *et al.* (2017) and Gumbricht *et al.* (2017) are considerably smaller than estimates of the total wetland extent in the Cuvette Centrale (table I, figure 1, photos 1 and 2). For example, Betbeder *et al.* (2014), estimate that the forested wetlands (consisting of forests with a stable water level, forests that experience a seasonal flood pulse and forests experiencing a low-amplitude and short-duration flood pulse) of the Cuvette Centrale cover 230,000 km^2. On the other hand, Bwangoy *et al.* (2010) developed a wetland probability map for the region, again using a multi-sensor remote sensing approach, which encompasses all wetland types. They estimated a total wetland extent (all pixels with a $\geq$ 50% probability) to be 360,000 km^2.

Photo 1.
Photo of hardwood peat swamp
Photo Simon Lewis.

Table I.
Estimates of the extent of the Cuvette Centrale peatlands and the larger wetland area that they are part of.

Study	Wetland area (km^2)	Peatland area (km^2)	Notes
Bwangoy *et al.* (2010)	360,000	-	Supervised classification of optical, radar, and topographic data, using manual photo-interpretation
Betbeder *et al.* (2014)	230,000	-	Unsupervised classification of MODIS-Enhanced Vegetation Index (EVI)
Gumbricht *et al.* (2017)	-	125,440	Rules-based model combining hydrological modelling and optical and topographic data
Dargie *et al.* (2017)	-	145,500	Supervised classification of optical, radar, and topographic data, using field data

Peatland carbon stocks and cycling

While the peatland area estimates of Dargie *et al.* (2017) and Gumbricht *et al.* (2017) are not far apart, Gumbricht *et al.* (2017) calculated the associated total peat volume to be 915 km^3, almost 3 times the size of the 350 km^3 estimate of Dargie *et al.* (2017). This discrepancy is primarily caused by the very large peat depth estimate that was used by Gumbricht *et al.* (2017), which is not in line with recent *in situ* measurements by Dargie *et al.* (2017), who recorded a mean (± SD) and maximum depth of 2.4 ± 1.6 m and 5.9 m respectively. Whilst the use of *in situ* data warrants more confidence in an estimate, Dargie *et al.* (2017) still report a large uncertainty around their peat carbon stock estimate for the Cuvette Centrale (6.3–46.8 Pg C, 95% confidence interval), which is mostly attributable to large variability in recorded peat depths. Dargie *et al.* (2017) report a best estimate of 30.6 Pg C belowground, which is equivalent to approximately 29% of the total tropical peat carbon pool, or 5% of global peat carbon stock. With uncertainty in total carbon stock estimates driven by uncertainties in peatland area and peat depth, as well as peat bulk density and peat carbon concentration, more *in situ* data, which is representative of the basin, will improve belowground peatland carbon stock estimates in the Cuvette Centrale.

A further 0.6–2.5 Pg C is estimated to be stored in the vegetation of the Cuvette Centrale peatlands (Dargie *et al.*, 2017). When compared to adjacent *terra firme* and seasonally flooded forests, Bocko *et al.* (2017) found that the peatland swamp forests of the Cuvette Centrale had considerably lower aboveground carbon stocks (peatlands swamp forest: 147.7 ± 69.7 t/ha; terre firme forest: 295.3 ± 96.3 t/ha, seasonally flooded forest: 292.3 ± 62.8 t/ha). Differences in forest structure were also noted with the contribution of very large individuals (dbh › 70 cm) to the aboveground carbon stock being much more important in *terra firme* and seasonally flooded forests, whilst the peatland swamp forests had far fewer very large trees (Bocko *et al.*, 2017).

In addition to improving estimates of above and belowground carbon stocks, it is also important to understand the carbon dynamics within tropical peatlands. Bocko *et al.* (2017) quantified the deadwood carbon pool in the swamp forests of the Cuvette Centrale. However, at present there are currently no published studies on gross primary productivity and net primary productivity in the Cuvette Centrale peatlands. This is not a problem unique to this region; across the globe, few studies have tried to quantify the full carbon budget of a tropical peatland (Bocko *et al.*, 2017; Dargie *et al.*, 2017; Pangala *et al.*, 2017).

Despite its large spatial extent, relatively little is known about greenhouse gas (GHG) emissions from the Cuvette Centrale. Although pristine tropical peatlands are significant sources of methane (CH_4) emissions (Girkin *et al.*, 2020) they are usually net carbon sinks (i.e. they accumulate more carbon than the amount of carbon released through decomposition). However, when these peat swamp forests are drained and converted to other land uses, they become a significant source of carbon dioxide (CO_2) and nitrous oxide (N_2O) while CH_4 emissions decrease significantly (Cooper *et al.*, 2020 and references therein). GHG fluxes are regulated by environmental factors including water table dynamics, peat temperature, peat properties and pore water chemistry (e.g. pH, availability of terminal electron acceptors and nutrient levels), and vegetation type. Peat surface CO_2 emissions generally increase with increasingly aerobic conditions associated with low water tables, whilst CH_4 emissions increase with increasingly anaerobic conditions under high water tables (Couwenberg *et al.*, 2010). N_2O on the other hand shows a nonlinear relationship with soil moisture content (Couwenberg *et al.*, 2010). Increases in soil temperature, occurring in response to climate warming and increased exposure to solar radiation through deforestation and degradation of tropical peatlands, can drive feedbacks that drastically increase CO_2 and CH_4 emissions, although we hypothesise the tropical peat swamp forest is likely to remain a net carbon sink in the absence of other disturbances (Cooper *et al.*, 2020). Whilst N_2O emissions can increase under increasing soil temperatures (with degraded tropical peatlands being hotspots of N_2O emissions), this response is dependent on other optimal environmental conditions, such as optimal water content and nitrate concentrations, first being met (Pärn *et al.*, 2018). Higher pH, which can be driven by drainage and mineralisation of soil organic matter, has also been linked to higher CO_2 and N_2O emissions, with the effect on CH_4 being less clear (Hatano *et al.*, 2016). Although tropical peatlands in their natural state emit GHGs, this should not be confounded with peatlands being a net source of carbon emissions or having a net warming effect on the climate. Indeed, the opposite is true for healthy peatlands which continue to accumulate organic matter; they are an overall net carbon sink and have a cooling effect on the global climate (Gallego-Sala *et al.*, 2018).

The overlying vegetation also influences peatland GHG emissions: first, by providing substrates for the soil heterotrophic population through litterfall and roots (Girkin *et al.*, 2018). Second through species-specific adaptations found in flood-tolerant plants in tropical peat swamp forest that increase gas exchange under waterlogged conditions, such as enlarged lenticels (stem pores), the presence of aerenchyma (spongy, porous tissue) and pneumatophores (aerial roots specialised for gas exchange; Pangala *et al.*, 2017). These adaptations can affect fluxes by either increasing oxygenation in the rooting zone, potentially increasing CO_2 production or decreasing CH_4 production, or by providing a physical pathway through which CH_4, produced belowground, can travel to the atmosphere (Girkin *et al.*, 2020).

To date, the only published *in situ* gas flux measurements for the Cuvette Centrale show emissions from wetlands soils to be highly variable over short spatial distances (less than a few km; Tathy *et al.*, 1992). When scaled up, the authors estimate that the swamp forests of the Cuvette Centrale emit between 0.0013–0.0043 Tg CH_4/ha/yr. This is broadly comparable to the 0.0019–0.0028 Tg CH_4/ha/yr estimated by Lunt *et al.* (2019), who combined satellite data and modelling to estimate monthly emissions over the region between 2010 and 2016. The sparsity of gas flux data from the Cuvette Centrale peatlands means there is a limited understanding of the magnitude and the relationships between fluxes and environmental variables. Moving forward, *in situ* data from both static chamber (‹ 1 m^2) and flux-towers (‹ 1 km^2) should be integrated with remotely sensed gas flux data (e.g. OCO-2/OCO-3 and Tropomi instruments; scales of › 1 km^2) to better understand the spatio-temporal variations in fluxes from the Cuvette Centrale peatlands. If combined with plant community distributions, peatland and inundation maps and land-surface and atmospheric models can be used to produce accurate estimates of greenhouse gas emissions for the peatlands at a regional scale.

Peatland hydrology: water origin and dynamics

Our understanding of the water dynamics across the central Congo Basin is still in its infancy (Alsdorf *et al.*, 2016). Satellite-based studies suggest that some parts of the Cuvette Centrale peatlands, particularly interfluvial basins in the ROC, are mostly hydrologically distinct from adjacent rivers, with limited water flow from the rivers to the peatlands (Jung *et al.*, 2010; Lee *et al.*, 2011). Water levels at various locations along the Congo main stem appear to be consistently lower than in the adjacent forested wetlands (by 0.5 to 3 m; Lee *et al.*, 2011). Furthermore, seasonal changes in the stage height of the main stem of the Congo River range between 2 and 3 m (Kim *et al.*, 2017; Lee *et al.*, 2011), while changes in water table levels in the forested wetlands appear to be small. This suggests that during the wet season, water flows from the wetland area towards the river (Yuan *et al.*, 2017). Alsdorf *et al.* (2016) hypothesise that the shallow fluctuations in swamp forest water table levels, varying between the dry and wet season by only 0.5–1 m (Lee *et al.*, 2011), could be driven by precipitation alone. Dargie *et al.* (2017) also propose that rainfall is the main water source in the interfluvial basin peatlands of ROC, based on geochemical analysis and *in situ* water level measurements. Furthermore, a recent study which combined *in situ* peat depth measurements and LiDAR topography measurements of the surface of a large interfluvial peatland in the Likouala Department, ROC, showed that the peatland has a shallow domed structure (Davenport *et al.*, 2020). Domed peatlands are a classic indication of ombrotrophic, i.e. rain-fed, conditions.

However, the research cited above focused on the interfluvial basins of the ROC and the conclusion that the peatlands are ombrotrophic systems is unlikely to apply to all areas of the Cuvette Centrale peatlands. Based on multi-sensor remote sensing data, Lee *et al.* (2011) concluded that local upland run-off (from higher-ground *terra firme* forest) is the main water source of the Congo wetlands. In addition, while shallower flood depths (‹ 0.6 m) are found in interfluvial basins, such as between the Congo main stem and the Ubangi or Ngiri River (Lee *et al.*, 2015), narrow bands of riverine wetlands next to the Congo main stem and along some of the Congo's left-bank tributaries in DRC experience large inundations of up to 1-1.5 m in the main wet season (Lee *et al.*, 2015). Rather than precipitation alone, this suggests that river influx or upland runoff could also be a source of water in some parts of the Cuvette Centrale peatlands. The spatial extent of these riverine peatlands across the basin is unclear, as most of the recent remote sensing studies focus on the same 350 x 350 km area in the central part of the region (e.g. Kim *et al.*, 2017; Lee *et al.*, 2011, 2015). Earlier research using maps of low and high-water table levels across the larger Congo Basin suggest floodplains with high water tables can be found: north and east of Lac Mai-Ndombe; further east/up-river on the left-bank tributaries of the Congo; and along the Likouala-Mossaka and Sangha rivers in ROC (figure 1, photos 1 and 2; Jung *et al.*, 2010; Rosenqvist and Birkett, 2002).

Future work should prioritise monitoring of water table levels across the peatlands, both *in situ* and remotely, targeting a wide range of peatland sites within the Cuvette Centrale, in terms of both different hydrologies and vegetation types. Long wavelength radar data are particularly useful for mapping inundation over the Congo Basin, as the radar signal can pass through the forest canopy and detect patterns of spatial flooding at ground level (Alsdorf *et al.*, 2016; Betbeder *et al.*, 2014; Bwangoy *et al.*, 2010; Jung *et al.*, 2010). Radar satellite missions including ESA's BIOMASS (due for launch in 2021) and NASA's NISAR (due for launch in 2022) will provide open source data that will contribute to improved assessment of flood dynamics across the peatlands. In addition to the peatlands themselves, understanding the hydrodynamics of the Congo River and its tributaries is crucial to understanding the relationship between the rivers and adjacent peatlands. Whilst improvements in the spatial and temporal resolution of remotely sensed surface water data are expected with the launch of new satellite missions, such as SWOT (Surface Water and Ocean Topography; NASA, 2020), Carr *et al.* (2019) demonstrate that *in situ* data on river bathymetry, discharge and stage height on the main stem Congo River cannot be fully replaced by remotely sensed data. Furthermore, it would be useful to extend the work by Davenport *et al.* (2020) and measure peatland surface elevation and topography at different sites, including valley-bound riverine peatlands to help distinguish peatland areas that are rain-fed alone from those which receive water from other sources. Little is known about how surface run-off and sub-surface flow may contribute to the water balance across the peatlands. Water run-off from adjacent *terra firme* forests is especially interesting, given how this could be affected by future land use change, e.g. deforestation.

By developing a finer scale understanding of peatland hydrological dynamics, the foundations will be laid for research to move towards a more process-based understanding of the peatland's hydrology through modelling (Baird *et al.,* 2017). An improved understanding of the water balance of the peatland is essential for understanding peatgrowth and determining which regions of the peatland are most at risk from climate change impacts. Comprehensive spatio-temporal mapping of the water balance will also improve understanding of GHG fluxes, either by acting as a data input for modelled fluxes or by allowing *in situ* measurements to be scaled up across the basin.

Peatland formation and development

Radiocarbon dating of basal peats from several sites within the Cuvette Centrale show peat initiation between 10,554 to 7,137 cal yrs BP (calibrated ^{14}C years before the present, where the present is defined as the year 1950; Dargie *et al.*, 2017) during the African Humid Period (14,800–5,500 yrs BP), a period of higher rainfall across Africa. At present, all peatland sites within the Cuvette Centrale for which basal dates are available are located in the Likouala Department, ROC, and are all within interfluvial basins. However, there is potentially large heterogeneity between the hydrologies of the peatlands across the Cuvette Centrale and therefore possibly contrasting processes and timings of peat initiation and development. Obtaining peatland basal dates from a wide range of peatland types across the Cuvette Centrale is crucial for establishing the potential spatial variation associated with the timing of peat initiation. This will also contextualise the peat initiation with coeval climatic and vegetation changes. In addition to dating the base of peat profiles, it is equally important to date several points in the overlying column to determine the rate of vertical peat accumulation. When combined with paleoclimate and paleoenvironmental information, this can improve our understanding of the drivers of peat development through time, by allowing us to investigate the relationships between peat accumulation, and climate and environmental conditions.

Waterlogging, influenced by precipitation is an important factor in peat development, but the impacts of previous climatic changes on the development of the Cuvette Centrale peatlands are still not understood (Dargie *et al.*, 2019). Mean annual rainfall in the Congo Basin (~1,700 mm/yr; Samba and Nganga, 2012) is comparatively lower than other tropical peatlands, however, the bi-annual wet season and low topographical gradients help to maintain a high-water table to support current peat preservation. The role of the Congo River in peatland initiation and development is still unknown however; but it is likely that the patterns of flow, discharge and drainage would affect the peatlands' water table. The rivers of the Congo Basin have an extremely low gradient (c. 3 cm over 1 km^{-1}), and mostly lack the meandering characteristics seen in other tropical regions e.g. in Amazonia. The Congo River also has low water level fluctuations, when compared to the Amazon Basin, which may contribute to water retention within the Cuvette Centrale (Kim *et al.*, 2017 and refe-

Photo 2.
Photo of palm-dominated swamp.
Photo Greta Dargie.

rences therein). In order to explore this variation in terms of peat accumulation and preservation, measurements from different areas of the peatlands and from different peatland morphologies will be important, not only in characterizing the developmental history of the peatlands, but also in understanding the relationships between hydrology, vegetation, peat depth and peat occurrence. Additionally, future studies combining multiple proxies such as testate amoebae, both bulk and compound-specific isotope analysis, and hydrological studies allow for the reconstruction of past water table height, rainfall patterns and insights into the degree of past peat degradation. Combined with current hydrological studies such as present-day flood mapping, the approach can provide an additional understanding of water table fluctuations of the Cuvette Centrale peatlands.

Insights into past vegetation change within the Cuvette Centrale are limited. A few studies have been published from swamp forests examining past vegetation change in the Late Holocene from a maximum age of 3300 cal yrs BP (e.g. Brncic *et al.*, 2007, 2009; Tovar *et al.*, 2015). Whilst these records show periods of increased aridity, the persistence of swamp forest vegetation throughout shows some degree of resilience to changes in rainfall. Outside of the Cuvette Centrale, in the south of the ROC, older paleoecological records exist. The oldest, a peat core taken from Ngamakala Pond (Elenga *et al.*, 1994) on the Plateaux Batéké, dates back to 24,000 cal yrs BP and records several phases of swamp forest retreat and expansion in response to climate. Swamp forests at this site, after experiencing a decline from 24,000 cal yrs BP, began re-expanding during the Early Holocene. However, at 3,000 cal yrs BP there was a marked decline in forest extent. This decline is also recorded in Congolese coastal peatlands (Elenga *et al.*, 2001) and indeed across numerous records in Central Africa (Giresse *et al.*, 2020). Whilst both offshore (Schefuss *et al.*, 2016) and onshore (Bonnefille and Chalie, 2000) records show an increase in aridity across the region at this time, debates continue as to the extent in which climate alone or climate combined with anthropogenic activities caused this forest retreat (Garcin *et al.*, 2018; Giresse *et al.*, 2020). Charcoal remains indicate an increase in fires in the Congo Basin in the Late Holocene, particularly around 1,000 cal yrs BP associated with anthropogenic burning (Hubau *et al.*, 2015). However, throughout the Holocene there have also been several periods of increased fire frequency linked to drier climatic conditions (Hubau *et al.*, 2013). At these times, savannahs expanded and forests became more open, providing flammable fuels and fire prone open patches within the forest (Hubau *et al.*, 2013). Currently there are no detailed multiproxy paleo records for the Cuvette Centrale region. Additional palynological and charcoal records from the Cuvette Centrale will help shed light on the vegetation and fire histories of these peatlands providing insights into their level of resilience to climatic change and anthropogenic activities. Ideally, paleo records from multiple cores from a single site or multiple sites should be studied in order to ascertain the degree of heterogeneity in peatland development within or across sites, an approach that has proven to be of value in other peatland sites (e.g. in Amazonia; Kelly *et al.*, 2020).

Peatland biodiversity: flora and fauna

The sheer extent and inaccessibility of the Cuvette Centrale wetland forests and the lack of systematic survey since the 1960’s means that there remain many unknowns surrounding the biodiversity of the Cuvette Centrale peatland vegetation communities. Within the DRC, some of the most renowned works on vegetation community classifications are Lebrun and Gilbert (1954) and Evrard (1968). Whilst the classification of Lebrun and Gilbert groups together many diverse forests associated with hydromorphic soils, e.g. swamp, flooded, riparian, riverine, vallicole-alluvial forests and mangroves, Evrard (1968) specifically focuses on the ecological classification of different hydromorphic forest types in the Congo Basin, which later Betbeder *et al.* (2014) used to interpret their flood map of the Cuvette Centrale forests. However, there is frequently a confusion and semantic drift between the definitions of forests linked to hydromorphic soils and humid forest areas. Evrard (1968) enumerated 106 tree species grouped into 21 families of vascular plants, which are characteristic of hydromorphic forest ecosystems. Additionally, species such as *Symphonia gobulifera* L. f. (Clusiaceae), species of the genus *Mitragyna* (Rubiaceae) and *Alstonia* (Apocynaceae), as well as other species such as *Oubanguia africana* Baill. (Scytopetalaceae), *Entandrophragma palustre* Staner (Meliaceae), *Daniellia pynaertii* De Wild and *Guibourtia demeusei* (Harms) J. Léonard (Fabaceae), *Raphia laurentii* De Wild., *R. sese* De Wild. and various rattans (Arecaceae) have been listed by several authors as being characteristic of swamp, flooded or periodically flooded forests of the Congo Basin (Hughes and Hughes, 1992; Bocko *et al.*, 2016, and references therein). Specifically related to peatlands, a recent preliminary study has so far documented approximately 100 species of woody and herbaceous plants in one peatland site in the Cuvette Centrale (Befale and Mpama, DRC; Ewango C., personal communication, 2020). Despite this, there is still much work to be done characterising the peatland vegetation communities in terms of their phylogeny and phytomorphology as well as disentangling the factors (biotic and abiotic) which drive species composition. In particular, understanding the relationship between peatland vegetation communities and hydrology, such as flooding depth and duration and water geochemistry is something which remains to be understood and explored in detail. Additionally, variations in the pollen production and dispersal of characteristic vegetation communities has important implications for past palynological studies and the reconstruction of past vegetation change. Elenga *et al.* (2000) compared the pollen signal in modern surface samples with the surrounding vegetation composition in the Congo Basin, and confirm that the modern pollen rain largely reflects the present-day vegetation observed. However, future studies such as this are needed within the Cuvette Centrale to determine the relationship between pollen rain, deposition and the abundance of individual taxa, to improve palynological interpretations and increase our understanding of the pollen production and dispersal of individual swamp forest taxa. For example, Tovar *et al.* (2019) established that in a monodominant *Gilbertiodendron dewevrei* forest, this taxon is largely underrepresented in the pollen signal due to its low pollen production, having major implications for palynological interpretations. The Cuvette Centrale peatland forests are found along river floodplains (of acidic black water rivers) and interfluvial basins, adjacent to rivers with a wide range of different biogeochemistry (Bouillon *et al.*, 2014). Therefore, it is likely that factors such as nutrient status, flooding depth and duration would drive some of the spatial variation in vegetation distribution, whilst biotic factors such as seed dispersal limitations and canopy structure, affecting radiation and surface temperatures, could also be at play. Furthermore, it is important to understand these processes at different spatial scales, from across the basin, down to very localised scales.

Research into the faunal diversity of the Cuvette Centrale has highlighted that the wetland forests in particular have high population densities of ape species such as the lowland gorilla (*Gorilla gorilla gorilla*), chimpanzee (*Pan troglodytes* Blumenbach) and bonobo (*Pan paniscus* Schwartz; Rainey *et al.*, 2010; Inogwabini *et al.*, 2013). Other species noted to be present in the swamps of the Cuvette Centrale include the African forest elephant (*Loxodonta cyclotis* Matschie) and the dwarf crocodile (*Osteolaemus tetraspis* Cope), which has been recorded using the peat to construct its nests (Riley and Huchzremever, 1999). However, research into less emblematic species within the peatlands is limited. In the Equateur province, DRC, Monsembula R. (personal communication, 2020) reported that local hunters could count at least 40 species of mammals, 26 species of reptiles and 17 species of birds present within the peatlands. No information is available for amphibians and macro-invertebrates, but 53 species of fish have been identified (Monsembula R., personal communication, 2020).

Human Use of Peatland Resources

There are few studies on the socio-economic activities of the communities living within or adjacent to the Cuvette Centrale peatlands. Whilst some data exists for community natural resource use within national parks containing peatlands (WCS, 2019a; WCS, 2019b), it is not specified within which ecosystem the natural resources referred to were collected. We, the authors, have personally observed community members sourcing food from the peatlands such as bushmeat, fish, caterpillars, fruits and honey, and fuel for fires. Additionally, certain tree and liana species have medicinal uses and provide construction materials and fibres, and *R. laurentii* fronds are used for roofing material. Although not an internationally commercial species, a demand from local markets for the species *D. pynaertii*, used for construction in urban areas, has also led to high levels of selective logging in the peatland forests of the DRC (personal observations of the authors). It is also clear that many communities have strong spiritual beliefs and practices linked to their forests. However, the true economic and cultural value of the peatlands to local communities is not well understood by the academic world and this is an area that is grossly understudied. Work by Cole *et al.* (2021) in Southeast Asia has revealed a severe lack of communication between local and international communities, leading to large gaps in knowledge and a complete disconnect between the two in terms of how they want the peatlands to be managed. Work in Amazonian Peru, carrying out interviews with local communities and accompanying them to areas of the peatlands used by the community, has not only shown how communities value the peatlands, in terms of resources and cultural and spiritual beliefs, and the diversity in these values between different communities, but has also helped to identified ways in which external actors could assist communities to meet their needs whilst simultaneously managing the peatlands sustainably (Schulz *et al.*, 2019). Similar conversations and consultations need to happen with the communities of the Cuvette Centrale to ensure the direction of peatland management in the region is for the benefit of and is supported by local communities.

At present there are few large-scale economic activities occurring within the Cuvette Centrale peatlands. However, Dargie *et al.* (2019) have highlighted the potential threats from hydrocarbon exploration and logging within the peatlands. The announcement in 2019 that oil had been found beneath a hydrocarbon concession overlying peatland in the ROC (Le Monde/AFP, 2019), is a reminder of how real this threat is. With these activities comes infrastructure development, such as roads and this can inadvertently increase forest access, increasing deforestation, degradation and biodiversity loss, as well as potentially affecting peatland hydrology. Within the DRC, in particular, areas mapped as peatland forests have been subjected to deforestation from slash and burn agriculture along roadsides (Miles *et al.*, 2017).

The future of the Cuvette Centrale peatland complex

The future of the Cuvette Centrale peatlands will depend strongly on socio-economic factors and the political will and capacity at both a national and international level to preserve the peatlands. The Brazzaville Declaration signed by the nations of ROC, DRC and Indonesia, declared there would be a collaborative effort between the three nations to ensure the protection of the Congo Basin peatlands (United Nations Environment Programme, 2018). However, the degree to which this commitment is met will likely depend on the level of international financial support provided and competing economic development pathways.

Climate change will also be crucial in determining the future of the Cuvette Centrale peatlands. Changes in precipitation patterns, temperature and therefore evapotranspiration rates, will impact the hydrological balance of the peatlands and as a result the balance between organic matter accumulation and decay. However, it is far from clear how climate change will play out across the Congo Basin. Temperatures are predicted to rise by 0.5 °C by 2100 even under modest emission scenarios (Niang *et al.*, 2014), which in turn may increase evapotranspiration rates. However, changes in precipitation are a lot less clear. A distinct lack of ground-based observations across the basin poses problems for estimating rainfall across the basin present day, let alone in the future under different emission scenarios (Washington *et al.*, 2013; Nicholson *et al.*, 2019). Whilst some model ensembles show a slight wetting trend in response to global heating across Central Africa, the magnitude of change is small in comparison to the variability between individual models (Creese *et al.*, 2019). Other model ensembles, on the other hand, show an increase in rainfall extremes, with an increase in rainfall intensity, but also the intensity and frequency of dry events (Dosio *et al.*, 2019). Future projections are further complicated by uncertainties in land use change, which in turn impacts the feedbacks between the biosphere and atmosphere (Akkermans *et al.*, 2014). Whilst efforts should be made to establish more ground based long-term meteorological observations, the urgency of the situation means that there have also been calls for intensive field campaigns focused on obtaining meteorological data which in the short term can help refine satellite derived estimates of rainfall across the basin (Washington *et al.*, 2013).

As well as being subject to the effects of climate change, peatlands can also help mitigate against or contribute towards changes in climate, by either taking up carbon from the atmosphere when accumulating organic matter or by releasing carbon to the atmosphere when in a state of decay. For example, peatlands in the northern high latitudes are estimated to have taken up 547 Pg C since the Last Glacial Maximum (Yu *et al.*, 2010). Future simulations project that this northern peatland carbon sink is set to continue until at least the end of the century despite the higher global temperatures, thanks to an increase in the growing season length for the peatland vegetation communities (Qiu *et al.*, 2019, and references therein), although some argue this may be offset by an increase in drought, continued land use change and fire (Loisel *et al.*, 2021). However, in tropical regions, where peatland vegetation communities are already growing under high temperatures, biomass productivity is unlikely to increase with further temperature increases and there are signs that the fertilisation effect of rising CO_2 levels on tropical forests is beginning to plateaux (Hubau *et al.*, 2020). Therefore, a rise in temperatures is more likely to mean an increase in peat decomposition, potentially switching tropical peatlands to a net source of carbon (Gallego-Sala *et al.*, 2018).

Mathematical models can be used to make predictions about the future of the Cuvette Centrale peatlands under different land use change and climate change scenarios at different spatial scales. Peatland development models operate on a site-specific scale and there are several in existence, which could potentially be adapted to a tropical setting (Farmer *et al.*, 2011). However, at present only three models have been applied to tropical peatlands. The first is HPMTrop, a one-dimensional model where the peatland is represented as a single column which can accumulate or lose peat (Kurnianto *et al.*, 2015). The second is Digibog, a three-dimensional model, where the peatland is represented as a grid of peat columns which interact with one another (Baird *et al.*, 2017). And the third from Cobb *et al.* (2017) who have developed a model to simulate peatland topography under different tropical climates, which they have applied to both intact and drained Bornean peatlands (Cobb *et al.*, 2020). However, one major barrier to the implementation of these models is the lack of *in situ* data across the tropics, but particularly in the Congo Basin, for their parameterisation and validation.

On a regional to global scale earth system models (ESM) are models which, as well as representing the global climate systems, try to represent the biogeochemical processes of land and aquatic systems and the interactions between these different components. Traditionally, peatlands have not been included in these ESM and whilst progress has been made to incorporate high latitude peatlands into some of the earth system models (e.g. Bechtold *et al.*, 2019; Qiu *et al.*, 2019), the Cuvette Centrale peatlands are yet to be represented by any ESM. Therefore, any potential feedbacks from the Cuvette Centrale peatlands are currently not considered in climate change scenarios, adding to the uncertainty for the region.

Conclusion

The peatlands of the Cuvette Centrale are undoubtedly a globally significant carbon store. Work is still needed to improve peatland maps and reduce the large uncertainties around the carbon stock estimate, with data acquisition in the region made challenging by the vast extent and relative inaccessibility of these peatland ecosystems. However, it is not just a question of carbon stocks; very little is known about the carbon dynamics of the Cuvette Centrale peatlands and their role in the global carbon cycle. Carbon accumulation and preservation in a peatland ecosystem is strongly dependent on the hydrological regime of the peatland. There is strong evidence to suggest that at least some of the Cuvette Centrale peatlands are rain fed ecosystems, but consideration needs to be given to the likely heterogeneity of peatland hydrology across the region and more work is needed to understand the relationship between the river networks and the adjacent wetlands. Whilst studies started characterising different wetland vegetation communities within the Cuvette Centrale many decades ago, there is still much to learn about the phylogeny and phytomorphology of peatland vegetation communities and their spatial variations. In terms of faunal biodiversity, the Cuvette Centrale peatlands are home to some of the most emblematic species of Central Africa, such as the forest elephant and the western gorilla, but beyond this, very little is known about the role these peatlands play in supporting faunal biodiversity. The need to understand the ecological value of these peatlands, beyond their role in carbon storage, also extends to understanding how peatlands support local livelihoods and cultures. Whilst the Cuvette Centrale peatlands are largely intact, a number of potential threats, including hydrocarbon exploration, logging and plantations, have been identified. The lack of data from the Cuvette Centrale peatlands makes it difficult to assess the full degree to which these activities would negatively impact the peatlands, although any lowering of water table levels is likely to result in increased carbon emissions. Uncertainty also surrounds the impact of climate change. As only a handful of basal dates are available from one region within the Republic of the Congo, the developmental history of the peatlands and how they have responded to past climatic changes is largely unknown. This limits our insight into possible future trajectories. However, perhaps a bigger limitation is the uncertainty around how future climate change will impact precipitation patterns across the region. The lack of *in situ* meteorological data from the Congo Basin to inform earth system models highlights that the urgent need for data acquisition from this region is not just restricted to the peatlands themselves. In the face of such uncertainties, it is clear that a sustained, international effort is crucial to protect this globally important ecosystem.

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