Tropical peat deposits undergoing land-use change: the case of Buhandanda and Lushala peatlands (Democratic Republic of Congo)

Patrick M. Senga[1], Julie Talbot[2], Steeve Bonneville[3]

[1] Department of Environmental Sciences, University of Kinshasa, Kinshasa, Democratic Republic of Congo
[2] Department of Geography, University of Montreal, Montreal, Canada
[3] Département de Géosciences, Environnement et Société, Université Libre de Bruxelles, Belgium

SUMMARY

Discovery of the world's largest known peat deposit in the Central African Basin creates a need for the Democratic Republic of Congo (DRC) to undertake a realistic national assessment of peat carbon. In the study described here we determined physicochemical properties of the Buhandanda and Lushala peat deposits, located in Sud-Kivu Province, to gain insights about their structure and functioning and provide a first estimate of C stocks. A change of land use (to seasonal subsistence agriculture) operating in the last few decades has dramatically modified the vegetation, which was originally dominated by mesophilic forest species. Several peat properties (pH, organic matter content, porosity, dry matter, ash and fibre contents) increased with depth in the peat profile, although some (nitrogen, nitrate, phosphate content and air-filled porosity) decreased and others (bulk density, solids density, C/N) showed no trend. The C densities of peat at the two sites were 68.60 and 60.64 kg m^{-3}, our estimates of mean (± SD) peat thickness were 324 ± 139 and 212 ± 109 cm, and total C storage was 0.136 and 0.023 Mt, for Buhandanda and Lushala, respectively. The range of calibrated radiocarbon dates for a 200 cm deep core collected from Lushala was 648–2005 cal. AD, with a high modern carbon fraction ($F^{14}C$) near the surface (at depths of 15 cm and 80 cm). Overall, our results indicated that carbon accumulation has declined at these two sites owing to the reduction in litter flux associated with land use change. Using the average C densities and peat thicknesses measured at Buhandanda and Lushala, we estimated that the total C storage in Sud-Kivu peatlands is approximately 1.23 Mt.

KEY WORDS: carbon stocks, greenhouse gas, mountain peatland, peat soil, subsistence agriculture

INTRODUCTION

In the topical context of climate change, governments, non-governmental organisations (NGOs) and other actors have focused on protecting carbon (C) stocks and reducing greenhouse gas (GHG) emissions. Peatlands accumulate organic carbon (OC) when primary production exceeds organic matter (OM) decomposition, allowing the build-up of partially decomposed plant material or "peat". Peatlands are major C sinks that are important in the terrestrial storage of OC globally (Chimner & Ewel 2004, Navarro-Pedreño *et al.* 2021) and are estimated to cover 30 million ha or around 6 % of the total land area in tropical regions (Inubushi *et al.* 2003, Ali *et al.* 2006). However, there are important gaps in knowledge about the extent and location of tropical peatland. Estimates of the total peatland area in Africa range from 4,856,500 ha to 11,000,000 ha, which is less than 1 % of the land area of the continent (Grundling & Grootjans 2016). The African country Democratic Republic of Congo (DRC) has ratified international conventions and initiated several programmes aiming to assess all C stocks and identify all sources of GHG emissions, so the discovery of a large peatland (estimated to contain 30.6 Pg of carbon) in the African Cuvette Centrale (Dargie *et al.* 2017) has prompted efforts to produce a realistic national estimate of peatland C stocks and GHG emissions. Whereas the Cuvette Centrale peatland is mostly undisturbed (Dargie *et al* 2017), many fragmented areas of peatland and organic soils remain unaccounted for and are currently being deforested, burned or exploited for subsistence agriculture (Kabony 2012), which may change their carbon sink functions (Chimner & Ewel 2004).

In their natural wet state, peatlands provide indispensable nature-based solutions for adapting to and mitigating effects of climate change including the regulation of water flows, minimising the risk of flooding and drought, and preventing seawater intrusion (in the case of coastal peatlands), but especially favouring the sequestration of C (Nõges *et al.* 2010). When factors such as land use change, global warming and fire disrupt the peatlands' functioning the effects may manifest themselves in hydrology, temperature (directly and indirectly), peat erosion, altered evapotranspiration, biogeochemistry, amounts of suspended sediment loading in runoff, and increased oxidation of organic material (Harenda *et al.* 2018). Physicochemical characteristics of the peat such as pH, porosity and content of phosphorus, potassium, calcium and magnesium may increase. At the same time, the peatland's hydrological functioning is impaired, with effects characterised by water table drawdown and increased bulk density along with reduced water content and hydraulic conductivity (Salim *et al.* 2021). In addition to changes resulting directly from human activities, continued global warming may shift the status of tropical peatlands from sinks to sources of C (Ali *et al.* 2006, Wang *et al.* 2018).

Data on the extent, volume and C stocks of DRC peatland are largely lacking. Our goal is to assess the physicochemical characteristics of two mountain peatlands (Buhandanda and Lushala) which are currently utilised as agricultural land, and to calculate their carbon stocks. We hypothesise that the varying intensity of disturbance in these peatlands leads to variations in physicochemical characteristics of the peat with implications for their C stocks.

METHODS

Study sites

The study was carried out on two of the peatlands located in Kabare territory, Sud-Kivu Province, DRC (Figure 1).

The geology of the region has an Archaean (Eozoic) basement formed by thick sedimentary rock overlain by formations of gneiss, quartzite, quartzophyllades and schists. Cenozoic rocks are mainly volcanic rocks (basalts and trachytes), alterites and recent alluvium. Several types of soils developed from basaltic flows are observed in the region, such as argillaceous ferrisols (in USDA soil taxonomy) which are ochre to red in colour with a well-developed A1 horizon and large OM content. At altitudes between 1,500 and 2,000 m a.s.l., organic-rich hydromorphic soils (or Histosols in USDA soil taxonomy) have developed in valleys (Kabony 2012).

The study area has a tropical climate (Aw) with a dry season of up to three months (June, July and August) (Kottek *et al* 2006). For the period 2017–2020 (when this study was undertaken), average annual temperature was 18.5 °C and mean annual precipitation was 1554 mm.

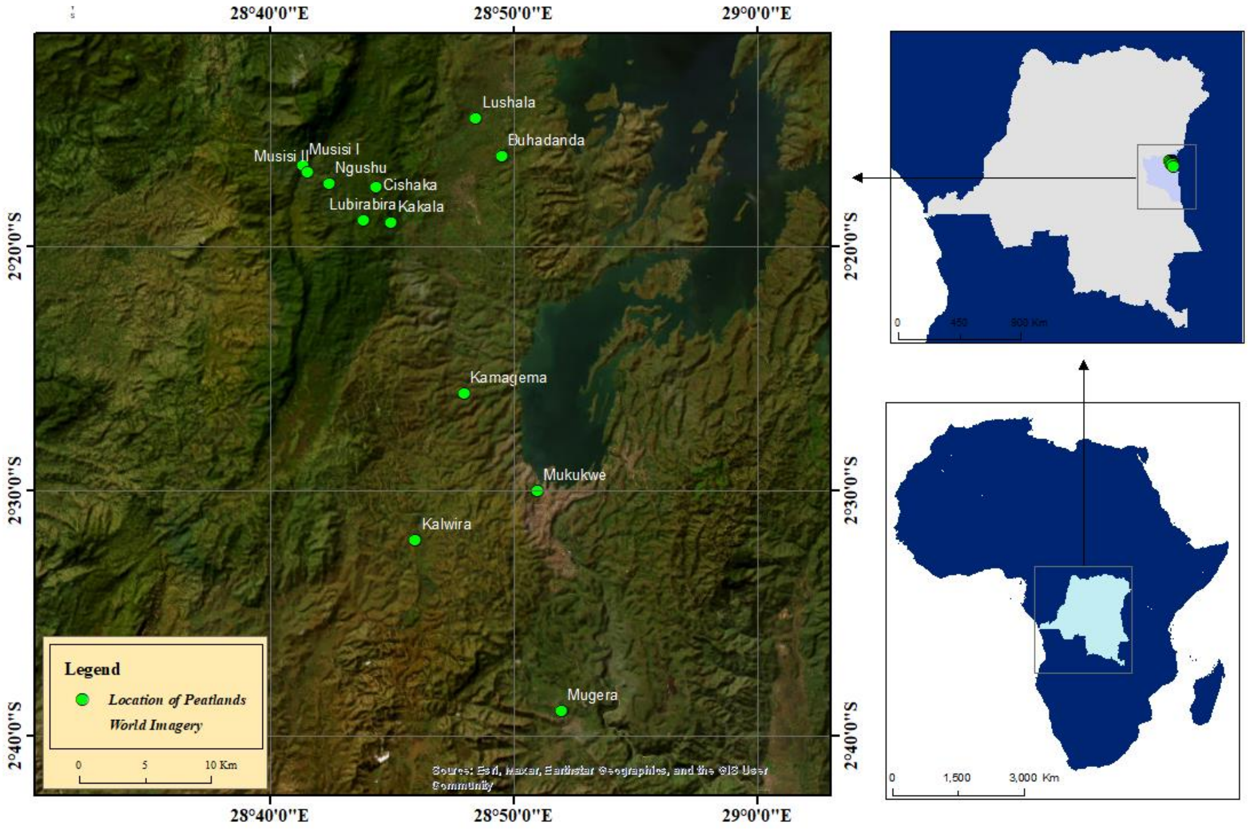

Figure 1. Locations of the main peatlands in Sud-Kivu Province, DRC. The insets show the locations of the DRC within Africa (below) and of Sid-Kivu Province and its peatlands within the DRC (above).

The Buhandanda (02° 16' 17.3" S, 28° 49' 32.1" E; 1607 m a.s.l.) and Lushala (02° 14' 44.9" S, 28° 48' 28.6" E; 1609 m a.s.l.) peatlands cover areas of 613,000 and 179,000 m^2, respectively (Figure 2). The peatlands are not permanently flooded. Three (Tshongoloka, Kalehe and Kanamukongo) and two (Kalengo and Loterie) rivers, each feeding a network of irrigation canals, flow through the Buhandanda and Lushala peatlands, respectively. Two sources of water (precipitation and surrounding environment) feed the rivers and irrigation canals, and excess water is discharged through the same channels after rainfall events.

The mesophilic forest vegetation that formerly occupied the zone between 1,500 and 1,700 m a.s.l. has completely disappeared owing to various anthropic pressures, mainly subsistence agriculture. The most extensively cultivated species are sweet potato (*Ipomoea batatas*), purple yam (*Dioscorea alata*), cassava (*Manihot esculenta*), soybean (*Glycine max*), common bean (*Phaseolus vulgaris*), sugar cane (*Saccharum officinarum*), great millet (*Sorghum bicolor*), maize (*Zea mays*), American black nightshade (*Solanum americanum*), aubergine (*Solanum melongena*) and cherry tomato (*Lycopersicon esculentum*). For this reason, plant species growing on the whole peatland area were exhaustively identified during periods of non-cultivation. This survey determined that the majority of woody species (e.g. *Eucalyptus globulus*) had been introduced to mark out agricultural field boundaries and the only vestige of the original marshy forest was seven specimens of *Syzigium rolandii* (Myrtaceae) in Lushala.

At both peatlands the original morphology of the peat layer has become almost impossible to discern because of land use change. The soil is continually being reworked, as growing beds are commonly laid out before each growing season. Some results of this study may be used to classify the current peat soils.

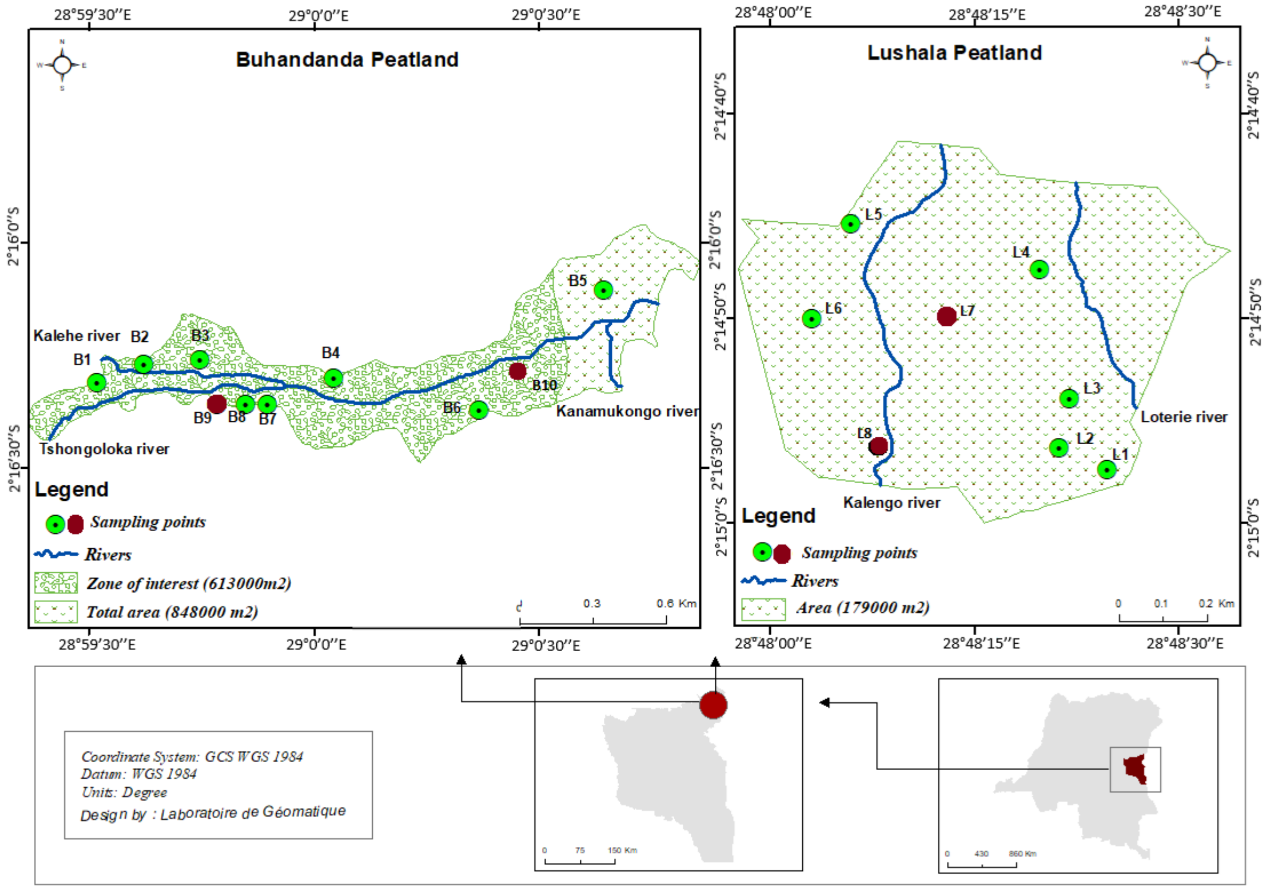

Figure 2. Locations of sampling points in the Buhandanda and Lushala peatlands. Short (70 cm) peat cores were collected at B1–4, B6–8 and L1–6 during the first (2017) field campaign (green dots), while long (200 cm) cores were collected at B9, B10, L7 and L8 in 2018 (red dots). Water table depth, pH (of peat) and peat thickness were measured at Locations B1–4, B6–9 and L1–8. No samples or data were collected at B5 because it did not have a peat layer. Insets show the location of Sud-Kivu Province within the DRC (right) and the location of the study area within Sud-Kivu Province (left).

Peat sampling and field measurements

Peat cores were collected in two field campaigns conducted during the rainy seasons of 2017 (12 Aug to 20 Sep) and 2018 (17 Feb to 15 Apr) using a Russian peat sampler (50 cm × 5 cm × 2.25 cm), following the method described by Kabony (2012). In 2017, seven and six cores of length ~70 cm were collected from Buhandanda and Lushala, respectively; and in 2018 two 200 cm long cores were collected from each site. Factors that influenced the selection of core locations were accessibility, access permissions from smallholders, and distance from an irrigation canal. The geographical locations of these sampling points (Figure 2) were recorded using a hand-held GPS (Garmin GPSMAP 78, precision < 10 m (33 pi)). The cores were stored in a cooler box at 4 °C until analysis.

In February 2018, eight perforated PVC tubes (diameter 5 cm) were installed on each site, at locations where peat had previously been collected (see Figure 2). The tubes were used to measure water table (WT) depth according to Melling *et al.* (2005), at weekly intervals from February to April 2018. The first measurement was taken two hours after installation of the tubes. To measure peat thickness, the collection process (Kabony 2012) was repeated continuously at each location until a harder horizon (signaling a change of properties and material) was reached. Because of accessibility and weight considerations, the maximum length of probe and available extensions was 500 cm. Where peat thickness exceeded this limit (at Buhandanda) it was recorded as ≥ 500 cm, meaning that only minimum estimates of mean peat thickness could be calculated.

Physicochemical properties of peat and pore water

Subsamples 1 cm thick were extracted from three short peat cores per site, at 2 cm intervals for the uppermost 15 cm and at 5 cm intervals for the remainder of each core (70 cm maximum), giving 16, 17 and 15 subsamples for Buhandanda and 15, 15 and 18 subsamples for Lushala. Subsamples of the same thickness were extracted at 10 cm intervals along the 200 cm cores, providing 20 subsamples for analysis. Mineral-free bulk density, water and dry matter content was determined for each subsample according to Chambers et *al*. (2011) (drying temperature 105 °C). To determine loss on ignition and ash content, the subsamples were then burned at 550 °C according to Könönen *et al.* (2015). The inclusion of only a subset of the cores is justified on the basis that, given the lack of previous studies on these sites, it was necessary to initially confirm the peaty nature of their soils before committing to more substantial expenditure on these analyses.

Fibre content (mass of dry fibres as a fraction of total dry mass) was measured according to Sneddon *et al.* (1970), and on this basis the studied peats were classified as sapric (fibre content < 10 %), mesic (fibre content 10–40 %) or fibric (fibre content > 40 %) (ASTM D 1997–13).

pH was measured potentiometrically at ambient temperature, in 1 : 5 peat : H_2O and peat : KCl suspensions (Mulaji 2011). For this, 10 g of peat (from five depths: 10–20, 20–40, 50–60, 70–80 and 90–100 cm) was oven dried for seven hours at 105 °C, sieved, placed in an Erlenmeyer flask with 50 mL of 1M KCl solution, agitated on an orbital shaker for two hours and allowed to equilibrate for 30 minutes. The pH of the supernatant was then measured using a FiveEasy F20-Standard-Kit benchtop pH Meter (Mettler-Toledo GmbH, Giessen, Germany).

Total nitrogen (TN) and organic carbon (OC) were determined using a Shimadzu TOC-VCSH Total Organic Carbon Analyzer (Belyea & Warner 1996).

Pore water was obtained by centrifugation of two 1 cm thick peat slices for ten minutes at 3,500 rpm in a Teflon filter system (pore size 0.2 µm). The nitrate (NO_3^-) concentration in the extracted pore water was measured by colorimetry (Treguer & Le Core 1975). A similar procedure was used to obtain pore water samples for the determination of phosphate (PO_4^{3-}) concentration according to Grasshoff (1983).

Radiocarbon dating of four Lushala peat samples using mass spectrometry according to Crann *et al.* (2017) was provided by the AMS Radiocarbon Laboratory at the University of Ottowa. The samples were from depths of 15, 80, 150 and 200 cm. The ^{14}C age was adjusted to calendar years using either the Shcal20 calibration curve or the post-bomb atmospheric curve, depending on whether the modern carbon fraction (F^{14}C) was less than or greater than unity (Bronk Ramsey 2009).

Calculations

We calculated density of solids (D_s), porosity (φ; % v/v) and air-filled porosity (ε; % v/v) as:

$$\frac{1}{D_s} = \left[\frac{\left(OM_{550°\mathrm{C}}/D_p\right)+\left(C_e/D_a\right)}{100}\right] \qquad [1]$$

where $OM_{550°\mathrm{C}}$ is the percentage of OM determined by weight after combustion at 550 °C, C_e is ash percentage, D_p is peat solid density (1.43 g cm^{-3} for tropical peat) and D_a is ash solid density (2.56 g cm^{-3}) (Könönen *et al*. 2015, Chapman et *al*. 2017);

$$\varphi = \left(\frac{D_s - BD}{D_s}\right) \times 100 \qquad [2]$$

where D_s is density of solids (g cm^{-3}) and BD is (dry) bulk density (g cm^{-3}); and

$$\varepsilon = \varphi - P_H \qquad [3]$$

where P_H is humidity percentage (% v/v). Peat volume (V_p; m^3) was calculated as:

$$V_p = A_p \times T_p \qquad [4]$$

where A_p is peatland surface area (m^2) and T_p is the mean peat thickness (m) (Verwer & van der Mee 2010). Then carbon stock (C_p; Mt) was determined using the following equation:

$$C_p = \frac{V_p \times BD_{be} \times C_c}{10^6} \qquad [5]$$

where BD_{be} is a best estimate of mean dry BD (g cm^{-3}) and C_c is the dry carbon concentration in peat (g g^{-1}).

Statistica (version 12.0) was used for basic statistical analyses such as the calculation of mean values, standard deviation (SD), skewness and coefficient of variation (CV). OriginLab 2021b was used for the graphs. The Kolmogorov–Smirnov (K-S) test was used to determine whether the samples were normally distributed. Comparison of means was carried out at the 5 % level (Furukawa *et al* 2005).

RESULTS

Peat thickness and water table depth

Average peat thickness was > 324 cm (SD > 139 cm) (n = 8) at Buhandanda and 212 ± 109 cm (n = 8) at Lushala (Table A1 in the Appendix). Water table depth varied from -7.7 to -48 cm in Buhandanda and from -22 to -44 cm in Lushala. The water table was closest to the ground surface near rivers and irrigation canals (at B3, L1, L4 and L8 in Figure 2) and WT depth increased moving away from irrigation/drainage channels. The average values were -35.3 ± 1.3 cm (n = 24) for Buhandanda and -26.5 ± 1.5 cm (n = 24 for Lushala.

Fibre content, pH, organic matter and ash

The range of fibre content was 9–49 % at Buhandanda and 8–47 % at Lushala. Fibre content showed a clear decreasing trend with depth (Figure 3), which can be associated with the changes in particle structure and size that accompany increasing OM degradation (Boelter 1968). pH was generally low and tended to decline with depth in both peatlands. At the surface, $\mathrm{pH_{KCl}}$ was 3.4 (Buhandanda) and 5.04 (Lushula) ($\mathrm{pH/_{H2O}}$ 3.5 and 5.25), declining to 3.06/3.1 ($\mathrm{pH_{KCl}}$) and 3.11/3.17 ($\mathrm{pH/_{H2O}}$) at depth (Figure 4). Average OM content at Buhandanda was 83.6 ± 10 % (n = 77) based on the cores collected in 2017 and 72.9 ± 10 % (n = 20) based on the 2018 cores. The equivalent results for Lushala, were 70.3 ± 7.4 % (n = 71) in 2017 and 74.4 ± 6.15 % (n = 20) in 2018 (Figures 5 and 6). Ash content ranged from 10.05 % to 26.35 % at Buhandanda and from 22.02 % to 36.71 % at Lushala, with the highest values recorded near the surface (Figure 5).

Bulk density and porosity

The range of BD was 0.12–0.32 g cm^{-3} for Buhandanda and 0.13–0.27 g cm^{-3} for Lushala. The density of peat solids (D_s) did not vary much along the profile at either Buhandanda (1.42–1.61 g cm^{-3}) or Lushala.(1.49–1.74 g cm^{-3}) (Figure 5). From the surface to 7–9 cm depth, total porosity (φ) increased with depth, from 82–88 % to 90–93 % at Buhandanda and from and 85–88 % to 90–92 % at Lushala, then stabilised at ~ 90 %. Below > 20 cm depth, porosity in Lushala started to drop again and this trend continued down to 60–70 cm depth, reflecting a similar trend in BD. Air-filled porosity (ε) usually tends to decrease with depth but did not show this trend at our sites; it varied between 5–7 % and 10–11 % at Buhandanda and between 7–8 % and 9–13 % at Lushala (Figure 5).

Carbon, nitrogen and C/N quotient

Average organic C percentages were 43.1 ± 6.3 % (2017 campaign) and 37.0 ± 2.8 % (2018 campaign) for Buhandanda, and 34.6 ± 9.5 % (2017) and

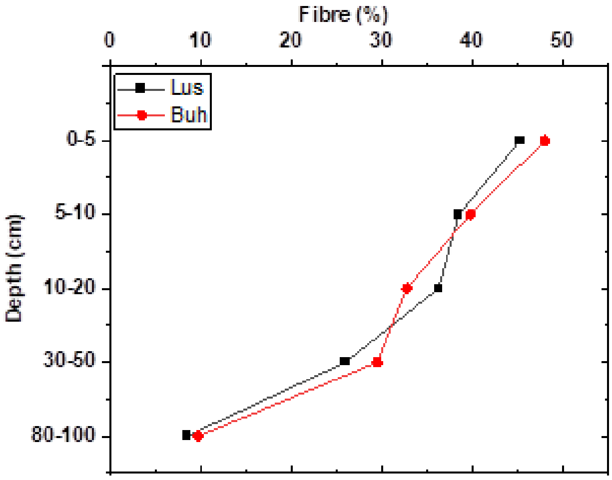

Figure 3. Fibre content determined on peat collected from depths of 0–5, 5–10, 10–20, 30–50 and 80–100 cm at Buhandanda (Buh) and Lushala (Lus).

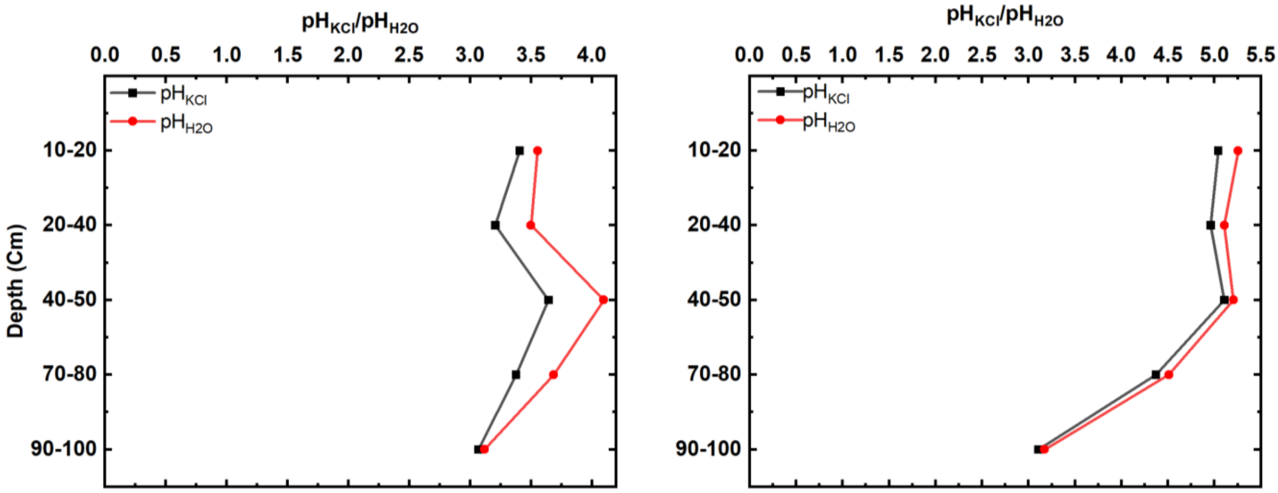

Figure 4. pH_{KCl} and pH_{H2O} profiles constructed from measurements on peat collected from depths of 10–20, 20–40, 50–60, 70–80, and 90–100 cm at Buhandanda (A) and Lushala (B).

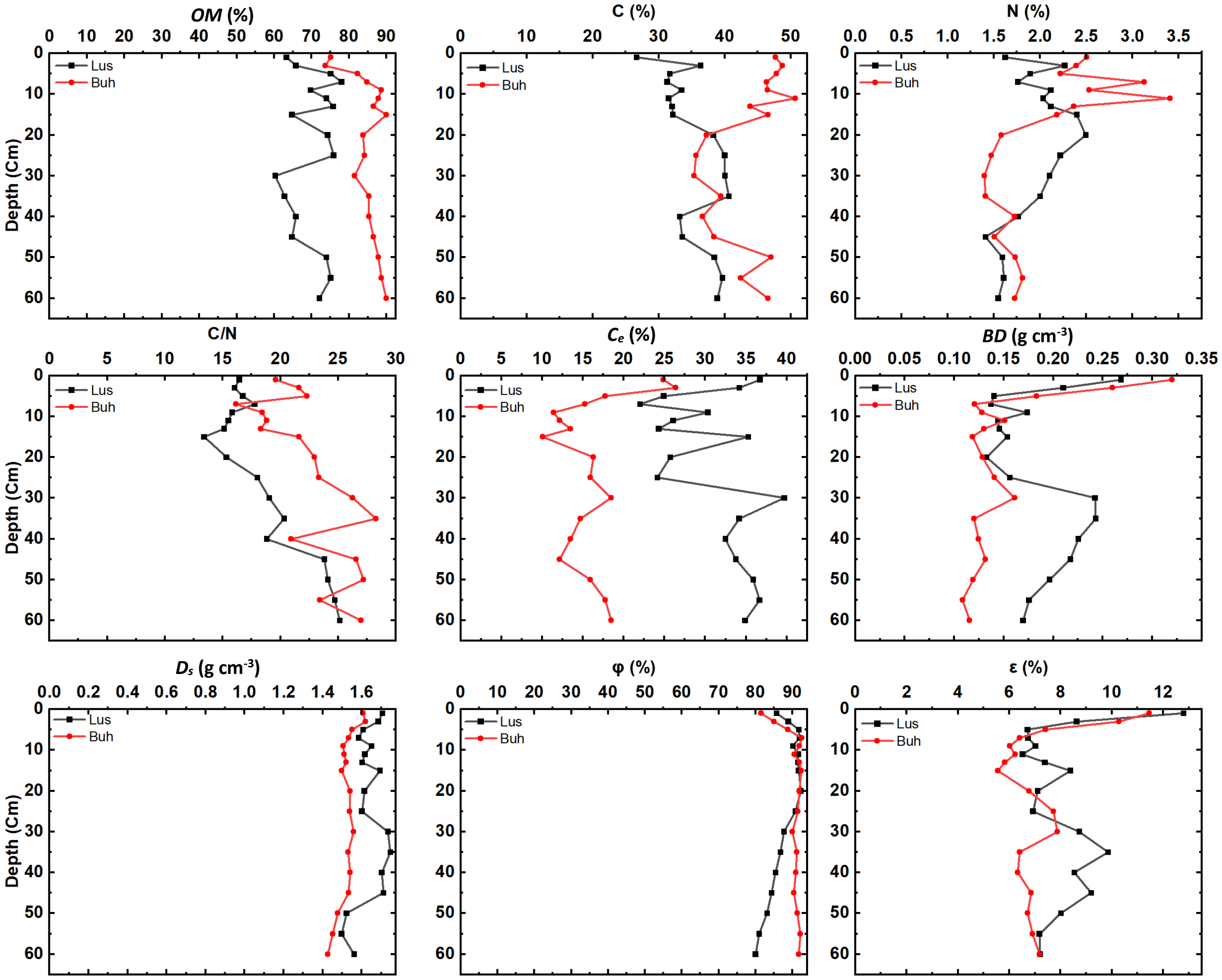

Figure 5. Physicochemical characteristics of peat cores from the first (2017) field campaign at Buhandanda (Buh) and Lushala (Lus). The profiles show, from left to right: organic matter (*OM*), carbon (C), nitrogen (N) (top row); C/N, ash content (C_e), bulk density (*BD*) (middle row); density of solids (D_s), total porosity (φ) and air-filled porosity (ε) (bottom row).

36.4 ± 3.9 % (2018) for Lushula, and did not differ significantly between the two sites (Figures 5 and 6). The highest C content (62.84 %) was found at L2 (2 cm) while the largest N content (5.62 %) was recorded at B4. Average N contents reached 2.1 ± 0.2 % and 1.9 ± 0.4 % (2017 campaign) and 2.1 ± 0.4 % and 1.7 ± 0.3 % (2018 campaign) for Buhandanda and Lushala, respectively. N content showed decreasing trends with depth in the long cores collected at both sites. C content in Buhandanda varied between 32 % and 43 % from the surface to 140 cm depth, then fell beyond this depth. In Lushala, the C content was relatively low (30–35 %) in the topmost 40 cm, then increased to 43 % at 50 cm before decreasing gradually to ~ 35 % at ~ 1 m, then eventually increased again at 160 cm. Overall, C content remained within the range 30–45 % throughout the profile whereas N content tended to decline with depth. This observation is consistent with the results of Chimner & Karberg (2008) and Könönen *et al*. (2015).

In general, the C/N quotients in Lushala and Buhandanda show an increasing trend with depth. The C/N values for the 70 cm cores (Figure 5) show a wide range of variation, particularly in Buhandanda. In Lushala, the variations are less marked and show an increasing trend at depths > 20 cm. Average C/N values were 22.4 ± 4.7 at Buhandanda and 18.9 ± 0.18 at Lushala during the first (2017) campaign and did not change significantly during the second (2018) campaign (21.7 ± 3.51 at Buhandanda and 18.3 ± 4.05 at Lushala).

Nitrate and phosphate concentrations in pore water

NO_3^- concentrations are below 2 mg L^{-1} in the Lushala and Buhandanda peat profiles, except at 20 cm and 30 cm depth in Lushala where nitrate levels reach ~ 30 and ~ 90 mg L^{-1}, respectively. PO_4^{3-} concentrations are also low (~ 0.001 mg L^{-1}) throughout the profile with single higher values of ~ 0.028 mg L^{-1} at 150 cm in Buhandanda and ~ 0.066 mg L^{-1} at 15 cm in Lushala (Figure 7).

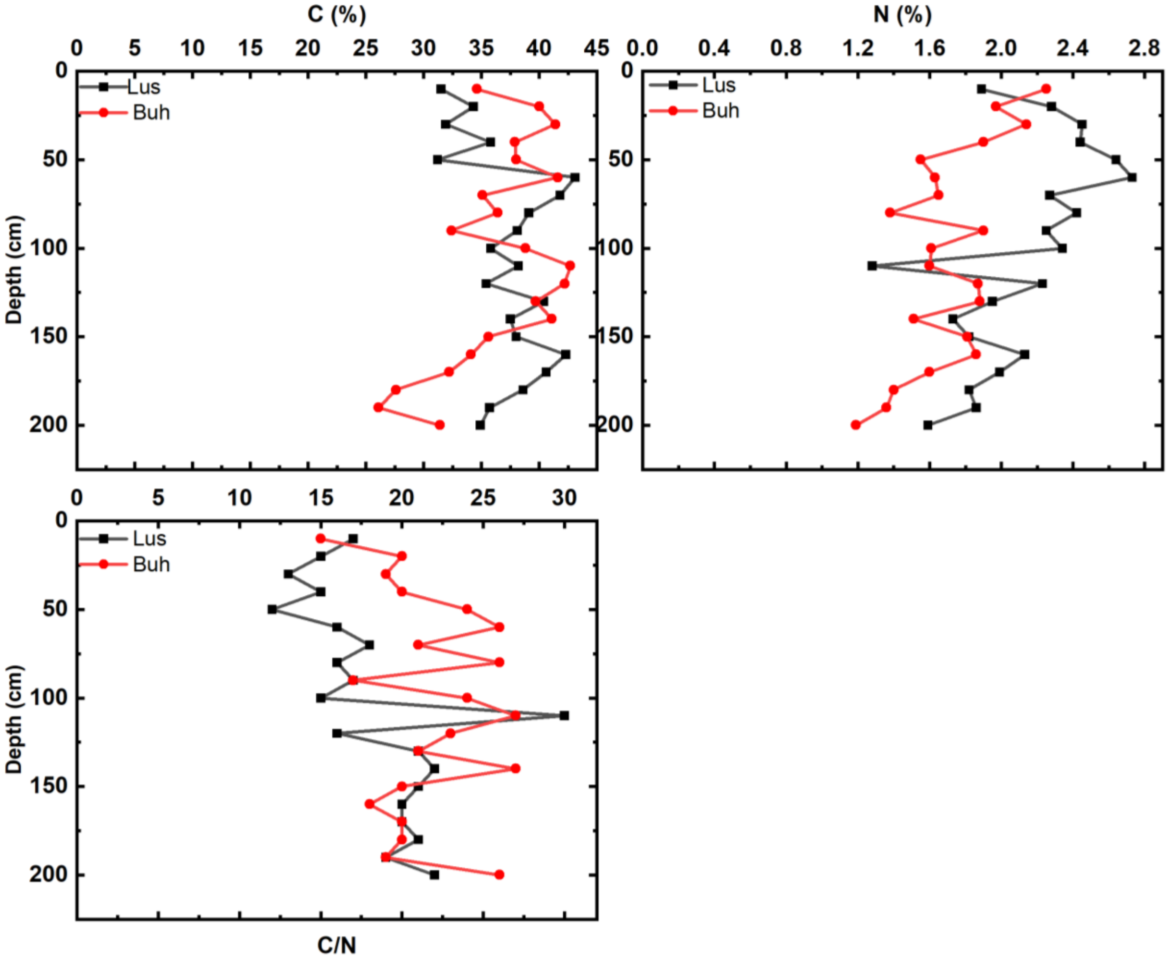

Figure 6. Profiles of C, N and C/N for peat cores from the second (2018) field campaign at Buhandanda (Buh) and Lushala (Lus).

Carbon stocks and radiocarbon dates

The C density per unit volume was 68.6 kg m^{-3} for Buhandanda peat and 60.6 kg m^{-3} for Lushala peat (Table 1), and thus consistent with literature values for the average carbon density of tropical peats (64.2 ± 20.9 kg m^{-3} and 71 kg m^{-3}; Warren *et al.* 2012, Rudiyanto *et al.* 2016). The C stocks were > 0.136 Mt for Buhandanda and 0.023 Mt for Lushala. The range of radiocarbon dates for Lushala peat was 648–2005 cal. AD (464 to 1,332 ^{14}C yr BP), see Table 2.

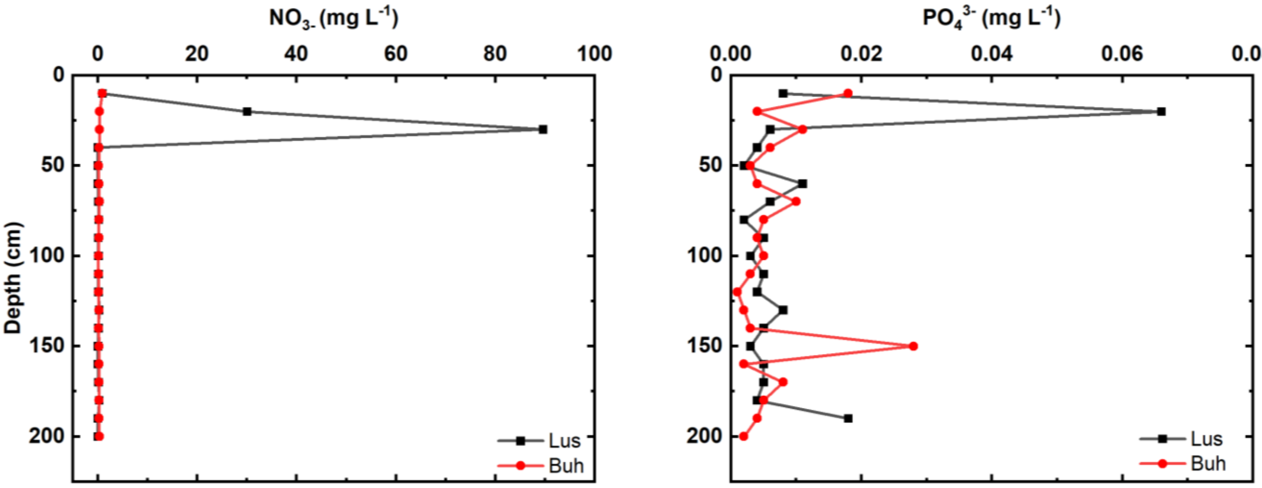

Figure 7. Profiles of nitrate (NO_3^-) and phosphate (PO_4^{3-}) for peat cores from the second (2018) campaign at Buhandanda (Buh) and Lushala (Lus).

Table 1. Carbon stock data for the Buhandanda and Lushala peatlands. A_p = surface area, T_p = peat depth, V_p = peat volume, BD = bulk density, C_c = C concentration in peat, C_p = C stock, C_d = C density.

site	A_p (m^2)	T_p (m)	V_p (m^3)	BD (g cm^{-3})	C_c (g g^{-1})	C_p (Mt)	C_d (kg.m^{-3})
Buhandanda	613,000	> 3.24	> 1,986,120	0.159	0.4315	> 0.136	68.60
Lushala	179,000	2.12	379,480	0.175	0.3461	0.023	60.64

Table 2. Radiocarbon results (errors are 1σ) for Lushala peat. Calibration was performed using the IntCal20 (Reimer *et al.* 2020) and Bomb13 SH3 (Hua *et al.* 2013) calibration curves. Material codes are described in Crann *et al*. (2017). Note that the (% values) are probability densities. SD = standard deviation.

Depth (cm)	^{14}C yr BP	SD	F^{14}C	SD	cal AD (year)
15	464	26	0.9439	0.0031	1412–1460 (95.4 %)
80	modern	-	1.0819	0.0040	1957–1958 (7.7 %) 2001–2005 (87.8 %)*
150	1235	29	0.8575	0.0031	680–745 (33.2 %) 759–883 (62.2 %)
200	1332	30	0.8472	0.0031	648–708 (59.6 %) 735–775 (35.8 %)

* The ShCal20 and Bomb13 SH3 calibration curves were selected for calibration based on sample location slightly south of the Equator. Depending on the exact location and location/mix of Southern Hemisphere and Northern Hemisphere air masses, the Bomb13 SH3 curve is more suitable for calibration.

DISCUSSION

Water table depth

WT depth is controlled by site-specific factors such as vegetation, pedo-geological nature of the soils and bedrock, hydrological catchment, precipitation and topography (Hooijer *et al.* 2010). Other authors evoke altitude (Furukawa *et al.* 2005) and peatland age (Ausec et *al.* 2009) as controls of WT depth. In this study, the rather shallow WT (despite the presence of drainage ditches) could be explained by clearing of the original vegetation, clay formations under the peat, and/or frequent rainfall events during the periods of measurement. Although WT depth may vary rapidly in response to seasonal hydroclimatic events (Hooijer *et al.* 2010), it can decline during dry intervals because of a combination of evapotranspiration and the divergence of groundwater flow (Cobb et *al*. 2017), especially when there is a change in land use (Barral et *al*. 2022). Indeed, land use change causes peatland degradation and reduces the water retention capacity of peat. Topography can also influence the WT behaviour at different locations according to the uniformity (or otherwise) of hydraulic properties of the environment (Cobb et *al*. 2017). In our study the WT was initially low (-59 cm on Lushala) at the end of the 2018 dry season whereas it was high (-28 cm) and more or less stable during November and December 2019. No significant difference (based on t-test) was observed in average WT depth between the two measurement periods on Buhandanda, perhaps because of the shape of its basin (valley) and its many rivers. Ali *et al.* (2006) observed that the WT was shallow in exploited forests, medium in recently cleared or burnt forests and deeper in agricultural areas, highlighting the considerable role of vegetation in determining WT depth. Yet, it seems that land use change did not have a significant effect on WT depth at our sites. To fully verify this assertion and better understand the WT behaviour, however, data should be collected during dry seasons.

Organic matter, ash and fibre content

OM content appears to increase with depth in the long cores. This could be related to degree of humification, which is generally dependent on water table depth (Duchaufour & Souchier 1983). The high OM contents ≥ 65 % coupled with a peat thickness largely exceeding 30 cm, as observed here, confirm the peatland nature of the Lushala and Buhandanda sites (Andriesse 1988).

Ash content in Lushula was almost double that in Buhandanda. This could arise from a difference in distance and direction to the emission source leading to different volcanic ash inputs at the two sites, or from the deposition process of alluvial material. Lushala (1679 m a.s.l.) is indeed closer (~ 5 km) than Buhandanda (1607 m a.s.l., ~ 7 km) to the Kahuzi and Biega volcanos. Lithology could also play a role as several volcanic formations (basalt flows) rest unconformably on the Archean basement. High ash content could also result from altered atmospheric dust deposition, climate-related changes (vegetation, water table fluctuations, decomposition, mineralisation processes), or even from fire (Zaccone *et al.* 2014). Ash content may also vary depending on the geological environment and the type of land use change. Thus, Buteau (1988) found ash contents similar to those at our sites for Canadian peatlands, whereas Inubushi *et al.* (2003) reported 35.5–48.6 % for abandoned mountain crop fields and 2.4–8.2 % for secondary forest in the tropics.

Because of the spatial variability of litter, temperature and humidity, the peat fibre composition varies greatly from site to site (Huat *et al.* 2011). For instance, large values (70–76 %) were reported for peat soils from the Banyuasin Regency in Indonesia (Sutejo *et al.* 2017), medium values (~ 60 %) from the Palangkaraya peat bog in Indonesia (Yulianto *et al.* 2019), and low values (11.51 %) from the reconstituted Parit Nipah Darat peat bog in Malaysia (Johari *et al.* 2016). Our results from Buhandanda and Lushala show that the uppermost 20 cm of the profiles consist of moderately decomposed peat belonging to the hemic class (33–67 % fibre) (Johari *et al.* 2016). Below 20 cm, fibre content drops below 33 % so this peat falls into the sapric type. Several authors (Johari *et al.* 2016, Ramu *et al.* 2017, Sutejo *et al.* 2017) have stated that a peat classification based on fibre content alone is often incomplete, and this attribute should preferably be combined with others such as ash content, pH, or even water retention capacity. Our study showed that Buhandanda peat is acidic (pH 3.9) with medium to high ash content (6–10 %), while Lushula peat has a circumneutral pH (6.1) and high ash content (22–39 %). With pH two units higher and ash content twice as high, Lushala peat differs dramatically from Buhandanda peat, yet these peats cannot be distinguished from each other on the basis of fibre content. Based on pH and nutrient contents, our sites could be regarded as primarily ombrotrophic peatlands that receive some water by surface inflow. Indeed, the nutrient content (nitrate and phosphate) is low on these two sites and the annual average precipitation over the four last years was rather large at 1,554 mm.

Porosity and bulk density

Rezanezhad *et al.* (2016) report two porosity zones in peat profiles, reflecting distinctive porous structures with high active porosity at the surface and reduced active porosity at depth. This physical structuring of porosity is linked to the extent of OM decomposition. Poorly decomposed peat has generally large pores while extensively degraded peat has limited porosity. Similarly, Gosch *et al* (2019) found high porosity (90 %) in poorly decomposed peat and significantly lower porosity (78 %) in heavily degraded peat. In our view the porosity profiles in both of our sites show signs of disturbance, with the topmost 7–9 cm being possibly made of degraded OM and exhibiting lower porosity than deeper sections. This might be the result of frequent surface ploughing (with rudimentary equipment) combined with the quasi-absence of litter input to mitigate the accelerated decomposition. The decrease in porosity observed below 50 cm depth in Lushala could be explained by the fact that the peat would have been disturbed by stump removal after tree cutting, which possibly deposited surface peat at depth. Surface (10–15 cm) peat from an undrained forest would have higher bulk density and lower porosity than deeper peat, while the opposite occurs at the same depth in a degraded site (Könönen *et al.* 2015).

BD values decreased with depth, contrary to the observations by Chimner & Karberg (2008) on a site in Ecuador where peat had similarly developed over volcanic lithology. According to these authors, BD values were higher (0.48–0.76 g cm^{-3}) at depths of 35–130 cm and dropped in deeper parts of the profile. Our results do not corroborate the BD values of 0.35–0.45 g cm^{-3} reported by Ali *et al.* (2006) for degraded peatlands or peaty agricultural sites. Rather, our data are consistent with those from sites investigated by Dargie *et al.* (2017) (0.19 ± 0.06 g cm^{-3}) where the highest BD values were in the upper layers. This feature of the BD profiles is probably related to tillage and/or the drainage system (Könönen *et al.* 2015) which, in case of dysfunction, could cause periodic flooding. The relatively high BD values reflect the high ash contents. The latter are larger than would be expected for wood-derived peat and suggest the input of mineral material during the periodic flooding, which brings in sediment from the surrounding hills, as well as inputs of wind-borne dust and volcanic ash. Indeed, drainage causes the groundwater level to fall which accelerates peat decomposition, while tillage facilitates oxygen diffusion to depth and thus increases the thickness of the layer of peat undergoing degradation. Gosch *et al.* (2019) also observed a decreasing trend of BD with depth but related it to the degradation process of peat. Indeed, as peat decomposes, the remaining solids tend to increase the mass of dry material per unit volume of peat and, thus, its BD (Rezanezhad *et al.* 2016). Nevertheless, a BD of 0.17 g cm^{-3} was reported for peat collected at 10 cm depth in the study by Gosch *et al.* (2019).

Nitrate and phosphate concentrations in pore water

In Lushala, NO_3^- concentration shows high values in the topmost 30 cm of the peat profile, and concentrations are very low below that layer (Figure 7). In Buhandanda, NO_3^- concentration is uniformly low. The high NO_3^- concentrations near the ground surface in Lushala could be explained by contamination with sewage wastewater or fertilisation by green manures, for both of which one of the breakdown products is NO_3^-. These concentrations were higher than those reported by Bougon *et al.* (2011) (11–17 mg L^{-1}) and by Mališauskas & Kutra (2008) (36 mg L^{-1} for water). Van Dijk *et al.* (2019) considered that high NO_3^- content in a similar part of the profile resulted from the inflow of contaminated groundwater. In our OM status evaluation, high NO_3^- content could also indicate a localised zone of very high OM degradation (Koretsky *et al.* 2007). The spectacular drop in NO_3^- concentration in the subsurface part of the profile could be explained by efficient advection or consumption by microbial processes. Microbial NO_3^- reduction involves three processes, namely dissimilatory reduction, autotrophic denitrification and heterotrophic denitrification (Bougon *et al.* 2011). Alternatively, microbes can absorb NO_3^- for the biosynthesis of amino acids through an assimilation process (Camargo & Urquiaga 2015). It is also necessary to mention that, in the deeper section of the profile, the prevailing conditions (anaerobic, low pH) slow down mineralisation and causes a relative 'immobilisation' of nutrients and soluble mineral compounds (Joosten & Clarke 2002).

The PO_4^{3-} concentrations in the two sites corroborate the assertion that PO_4^{3-} contents in terrestrial ecosystems are usually low (Gosch *et al.* 2019). However, moderately high PO_4^{3-} concentrations of 50 µM (Koretsky *et al.* 2007) and 59 µmol L^{-1} (Loeb *et al.* 2007) have sometimes been observed. To alleviate P deficiency, direct application of P-rich fertiliser in organic or mineral form is often carried out, and a fraction of this is regularly immobilised by micro-organisms. Contrary to the findings of Lee *et al.* (2008), no increasing trends of PO_4^{3-} concentration with depth were observed despite the reducing conditions in the rainy season. At different times of year, PO_4^{3-} fractions might be released due to sulphide production and the subsequent reduction of Fe(III) phases to form FeSx minerals (Beltman *et al.* 2000, Gosch *et al.* 2019), that may release previously adsorbed/coprecipitated PO_4^{3-} into the pore water. However, in the context of peatland, PO_4^{3-} is significantly influenced by complexation with humic substances and metal ions (Tuukkanen *et al.* 2017). Land use change can disturb the P biogeochemical cycle by interrupting the formerly regular supply of litter and the absorption of nutrients, of which P is one, by macrophytes (Koretsky *et al.* 2007).

Carbon, nitrogen and C/N quotient

Concomitant yet opposite trends in C and N concentrations can be explained by the fact that N-rich compounds (amino acids in proteins) are prime targets for microorganisms involved in OM mineralisation. Thus, as decomposition proceeds, N becomes progressively depleted with increasing depth, while the remaining OM is increasingly 'refractory' in nature with longer residence time (Wijesinghe *et al.* 2020). High N percentages in the topmost layers would result from periodic applications of chemical and/or organic fertilisers before seasonal cultivation or from biological fixation of atmospheric N by plant-microorganism associations (Camargo & Urquiaga 2015). Compared with the average C levels (45–48 %) reported for peat soils (FAO-UNESCO 1974), our results reveal relatively low C levels while the N contents are consistent with other values reported for peat (1.8–2.0 %; Melling 2016). Melling *et al.* (2005) obtained similar N contents (1.77–1.99 %) in three peat ecosystems (forest, sago and palm grove) in Malaysia. For Congolese peatlands, C content can reach higher values (59 ± 3 %) in forested peaty swamps with little human footprint (Dargie *et al.* 2017). However, our sites are geomorphologically different and subject to perpetual reworking of the topmost 20–30 cm along with periodic fertiliser inputs. These circumstances favour microorganisms that can degrade peat (Lal 2015) to supply energy and increase their biomass. Without natural vegetation, the supply of litter is not large enough to allow OM accumulation and peat formation, which leads to low C content. Also, in transformed peatlands, decomposition exceeds production, which presents an obstacle to peat accumulation. However, the difference in volumetric C content between the Buhanhanda and Lushala peats could result from differences in mineral content, specifically the higher ash content at Lushala. In addition, the peat profile is peppered in places (e.g., 20–35 cm in the core from B6, 0–10 cm at L3) with thin argillaceous layers, which reduces the C content. C losses due to leaching tend to increase with peat degradation resulting from agricultural practices (Błońska & Lasota 2017). However, changes in total soil organic carbon (SOC) in response to land use can be difficult to detect due to natural soil variability (Silveira 2005). On the other hand, if nothing is done to restore these two peatlands, there is a risk that their millennia-old C stocks will gradually crumble with time due to unsuitable agricultural activities.

Some of the C/N values indicated the presence of humus formed from improving litter consisting of poorly lignified N-rich leaves (C/N < 25). In other cases, the humus resulted from indifferent litters, i.e., from plants intermediate between improving and acidifying litters (C/N = 30–50) (Duchaufour & Souchier 1983). It should be noted that a C/N > 30 is characteristic of an undisturbed acid peat (Duchaufour & Souchier 1983), as documented for 25 (33), 30 (44), 35 (43), 45 (39) and 60 (35) cm depths in core B4 on Buhandanda (Figure 6). The large disparity observed in our C/N values can be explained by local-scale characteristics related to vegetation, geomorphology, water supply, temperature, etc. (Camargo & Urquiaga 2015). Again, soils with C/N < 12 are considered biologically active (Mutonkole 2013) and to involve strong OM decomposition processes. High C/N indicates an accumulation of fresh, undecomposed OM (Tan 2014). This seems to be the case in the core from B3 which was collected in a vegetated plot covered with a 10–15 cm thick layer of litter. The tendency for values of C/N to increase with depth in the peat profile is essentially due to a lower N percentage at depth while C contents remain roughly constant or increase slightly with depth (apart from abrupt changes in some short cores. The cultivation of peat soils is often justified by their fertility but the latter is associated with the degree of humidity, i.e., when peat soil is more humid, it displays a lower C/N value, indicating the importance of the mobile N reserve (Sim *et al.* 2017).

C stocks and radiocarbon dates

Our carbon density values are lower than the results of Dargie *et al.* (2017) for Congo peatland (~ 110 kg m^{-3}) and of Rudiyanto *et al.* (2018) for Bengkalis Island in Indonesia (85 ± 26 kg m^{-3}). C density may differ between regions and ecosystems due to contrasting rainfall patterns, peat hydraulic conductivity, peatland productivity and decomposition rates (Cobb *et al.* 2020).

Kabony (2012) reconstructed 35,000 years of environmental history for the region by carrying out a basal palynological analysis in the Kahuzi-Biega National Park (DRC). This revealed a climatic instability around 3000–2000 yr BP at the origin of the alternations of ombrophilous and mesophilous influences. Despite this, peat continued to accumulate, as indicated by the dates assigned to the upper layers (L-15 cm, L-80 cm in Table 2). The date inversion at the top of the profile could be attributed to reworking of the peat due to tillage. The date when peat accumulation started was not obtained because the base of the deposit could not be reached. Nevertheless, a coherence remains between dates measured here and those obtained by Kabony (2012) and Dargie *et al.* (2017) (8.9 ± 1.2 cal kyr BP). The peat accumulation rate, obtained from the peat slice containing 100 % modern layer and the sampling date, is evaluated to 1.74 mm y^{-1} and is higher than that obtained (0.21 ± 0.05 mm y^{-1} with 0.16 and 0.29 as minimum and maximum, respectively) in the Dargie *et al.* (2017) study.

Implications

The map of Sud-Kivu mountain peatlands (Figure 1) and probing data from Kabony (2012) were used to determine the total peat volume and overall C stock for the region. In the absence of bulk density and C content data for any other sites, an average C density of 65 kg m^{-3}, derived from the data for Buhandanda and Lushala, was applied throughout. In other words, it was assumed that peat characteristics do not differ greatly across the region. The calculations showed that 0.0066 % of the total area of Sud-Kivu Province is occupied by peatlands with a total C stock of 1.23 Mt (Table A2 in the Appendix).

Two threats weigh on these peatlands, namely climate change and human activity. Higher temperatures would favour the loss of peatlands to the detriment of natural species (Harenda *et al.* 2018). Physical disturbance of the peat soil consequent on their conversion to market gardening would disturb the exchange of gases with the atmosphere, and this would lead in turn to subsidence of the peat layer and further carbon loss (Talbot *et al.* 2010).

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Author for correspondence:
MSc Patrick Mutonkole Senga, Department of Environmental Sciences, Faculty of Sciences, Université de Kinshasa, B.P. 190 Kinshasa XI. Tel: +243817558435; Email: patrick.mutonkole@unikin.ac.cd

Appendix

Table A1. Some physicochemical attributes measured at the sampling locations on the Buhandanda (Buh) and Lushula (Lus) peatlands. All measurements except peat thickness were repeated twice between February and April 2018 (n = 3) and the data shown are means ± SD. Temperature and conductivity were measured using a coupled probe inserted directly into the peat soil or into the water contained in the pre-installed PVC tubes in which WT depth was measured.

Locations (Figure 2)	Peat thickness (cm)		WT depth (cm)		Temperature (°C)				Soil water conductivity (μS cm^{-1})	
					soil water		soil at depth 5 cm			
	Buh	Lus	Buh	Lus	Buh	Lus	Buh	Lus	Buh	Lus
B1, L1	120	185	38.7 ± 1.4	7.75 ± 0.35	21.0 ± 0.85	22.9 ± 0.70	25.40 ± 2.68	30.05 ± 0.21	586.0 ± 11.3	1,086.5 ± 590.4
B2, L2	340	300	35.8 ± 0.9	26.5 ± 2.12	18.5 ± 0.0	21.7 ± 0.28	-	24.75 ± 0.49	269.5 ± 18.8	563.5 ± 4.94
B3, L3	> 500	315	22.8 ± 2.8	17.5 ± 3.53	21.9 ± 0.30	22.0 ± 0.28	26.15 ± 1.90	26.30 ± 2.54	554.0 ± 231.2	654.5 ± 77.0
B4, L4	180	350	43.7 ± 0.7	-	22.1 ± 0.64	-	27.00 ± 6.78	-	573.0 ± 104.6	-
B9, L5	> 500	30	35.3 ± 0.0	24.5 ± 3.53	20.9 ± 0.95	20.6 ± 0.14	28.05 ± 9.12	29.40 ± 0.0	296.5 ± 134.3	538.0 ± 53.7
B6, L6	345	150	24.7 ± 1.4	-	22.0 ± 0.75	-	24.30 ± 1.83	-	643.0 ± 71.4	-
B7, L7	235	125	44.7 ± 0.7	35.0 ± 1.41	20.8 ± 0.92	21.8 ± 0.56	24.00 ± 0.70	25.00 ± 5.37	359.0 ± 25.4	985.0 ± 52.9
B8, L8	370	240	37.1 ± 1.9	48.0 ± 0.00	21.8 ± 0.80	22.0 ± 0.00	23.45 ± 3.04	28.55 ± 2.12	-	827.0 ± 74.9
mean ± SD	> 324 ± 139	212 ± 109.2	35.3 ± 1.2	26.54 ± 1.52	21.1 ± 0.74	21.8 ± 0.23	25.48 ± 3.72	27.30 ± 0.0	468.71 ± 96.5	775.75 ± 221

Table A2. Estimates of carbon stocks for the 12 main peatlands in Sud-Kivu Province (see Figure 1). A_p = area of peatland; T_p = mean peat thickness from Kabony (2012) except for Buhandanda and Lushala (this study); V_p = volume of peat (Equation 4); C_p = carbon stock (Equation 5). Missing data are indicated by '-'. Carbon density ($C_d = BD \times C_c$) is known for Buhandanda and Lushula only. In all cases of missing data, the calculations were performed using mean values calculated from available data (T_p = 4.22 m; BD = 0.167 g cm^{-3}; C_c = 0.3888 g g^{-1} (38.88 %)).

Site name	A_p (m^2)	T_p (m)	V_p (m^3)	C_p (Mt)	C_d (kg m^{-3})
Buhandanda	613,000	> 3.24	> 1,986,120	> 0.13626	68.60
Lushala	179,000	2.12	379,480	0.02301	60.64
Cishaka	947,838	6	5,687,028	0.36926	-
Lubirabira	159,961	3	479,883	0.03116	-
Ngushu	112,911	8	903,288	0.05865	-
Musisi I	180,626	4.8	867,005	0.05629	-
Musisi II	168,665	2.4	404,796	0.02628	-
Kakala	156,095	-	658,721	0.04277	-
Kalwira	180,968	-	763,685	0.04959	-
Kamagema	78,173	-	329,890	0.02142	-
Mukukwe	793,942	-	3,350,435	0.21754	-
Mugera	724,636	-	3,057,964	0.19855	-
Mean	-	4.22	-	-	64.62
Total	4,295,815	-	18,868,295	1.23078	-