The Congo basin is home to the second-largest tropical forest in the world. Therefore, it plays a crucial role in the regional water cycle, the global carbon cycle and the continental greenhouse gas balance. Yet very few field-based data on related processes exist. In the wake of global change, there is a need for a better understanding of the current and future response of the forest biome in this region. A new long-term effort has been set up to measure the exchange of greenhouse gases between a humid lowland tropical forest in the Congo basin and the atmosphere via an eddy-covariance (EC) tower. Eddy-covariance research stations have been used for decades already in natural and man-made ecosystems around the globe, but the natural ecosystems of Central Africa remained a blind spot. The so-called “CongoFlux” research site has been installed right in the heart of the Congo Basin, at the Yangambi research center in DR Congo. This introductory paper presents an elaborated description of this new greenhouse gas research infrastructure; the first of its kind in the second-largest tropical forest on Earth.

Keywords: eddy covariance, flux tower, greenhouse gases, carbon dioxide, nitrous oxide, methane, Congo basin, tropical forest

1 INTRODUCTION

With almost 200 Mha of humid forest, the Congo basin is home to the largest tropical rainforest in the world, second to the Amazon basin (550 Mha). Besides being recognized as a biodiversity hotspot (1), and an important resource pool for the livelihood (e.g. food, wood, medicine) of local communities (2), this region plays a crucial role in the regional circulation of water (3, 4), the global carbon cycle (5, 6) and the continental greenhouse gas (GHG) balance (7). The Congo basin strongly regulates regional precipitation patterns and dominates global tropical rainfall distribution during transition seasons, tightly influencing regional and global climate (3, 8). It sequesters approximately 0.59 Mg C ha⁻¹ yr⁻¹ making it the tropical region with the largest carbon uptake per unit of area (6, 9). Moreover, the net full GHG sink in forests of the Congo basin is approximated at
0.61 Gt CO₂-equivalent yr⁻¹, which is six times stronger than the Amazon basin, although its surface is smaller in extent (7).

Despite its global and regional importance, the Congo basin has among the least environmental observations worldwide (10). The under-representation of the studies conducted in the Congo basin limits our understanding of the contribution of this part of the world to water, carbon and GHG cycles (8, 11–13). A better understanding of this ecosystem and the processes that drive the exchange of water, carbon and GHG fluxes is essential if we want to quantify its role in global change and its response to a changing environment (14). Moreover, such data are also needed to quantify national carbon inventories from deforestation and forest degradation (15, 16). With both the IPCC reports (17, 18) and Paris Agreement (19) recognizing that climate change mitigation goals cannot be achieved without a substantial contribution from forests, it is clear that the above-described data, on the world’s second-largest forest extent, is essential to support the implementation of climate mitigation policies (7).

Baldocchi (20) advocated how a global network of long-term eddy-covariance (EC) flux measurements can help towards a better understanding of terrestrial ecosystems and the processes that drive GHG and energy exchange rates. Over the last decades, the EC technique (21) has been increasingly used to measure land-atmosphere exchanges of GHGs and energy at sites around the world (22, 23). This non-destructive measurement technique, based on high frequency (10–20 Hz) measurements of vertical wind velocity and a scalar (e.g. gas concentrations, temperature, etc.) allows quantification of GHG and energy fluxes at a high temporal resolution at ecosystem scale, making it a unique tool presenting a number of advantages over other techniques (24). Consequently, by analyzing long-term EC-measurements, one can study the spatio-temporal variability of ecosystems’ metabolism (20). Furthermore, this technique can be used to study the response of ecosystems’ metabolism to varying biophysical factors such as climate, phenology, plant functional and structural properties (25–29). As fluxes need to be measured within the boundary layer above the ecosystem of interest, it is essential that the required equipment is installed on a physical structure reaching the correct measurement height (e.g., in a forest stand), so-called “flux towers”.

In 2019, a total of 1421 known active EC sites existed (22). Fluxnet’s FLUXNET2015 dataset provides ecosystem-scale EC data from 212 of these sites (23). Despite these high numbers and the need for a pan-African network of EC flux towers (12, 30), only a total of 11 active EC stations are recording flux data across the entire African continent (13), with no single data reported for the second-largest tropical rainforest extend in the world.

Here we present a new EC research site, situated in Yangambi in the Democratic Republic of the Congo (DR Congo). Yangambi is situated in the heart of the Congo basin and was independently identified as an ideal region to prioritize long-term tropical forest monitoring (31) and the installation of a GHG monitoring station in Africa (32). The specific scientific objectives of this EC station are to 1) measure inter- and intra-annual CO₂ and H₂O exchange allowing to quantify the net ecosystem exchange (NEE) and water use efficiency (WUE), 2) measure N₂O and CH₄ fluxes for full GHG balance quantification and 3) determine the impact of atmospheric pollution including N deposition, tropospheric ozone (O₃) and black carbon (BC) on the NEE.

2 MATERIALS AND EQUIPMENT

2.1 Site Description

2.1.1 Yangambi – a Rich History as Research Site

The CongoFlux research site is situated at the “Institut National pour l’Étude et la Recherche Agronomique” (INERA), Research Centre of Yangambi (“Centre de Recherche de Yangambi” - CRY) in the very heart of the Congo basin. The site is located on the right bank of the Congo river, ca. 100 km northwest of Kisangani, the major city of the Tshopo Province (33) (Figure 1A). The Research Centre has played a historical leading role as a centre of expertise for tropical forestry and agricultural research (soil survey and fertility, phytopathology, plant breeding and botany of perennial and annual crops, etc) in the DR Congo.

The CRY was founded in the 1930s as part of the “Institut National pour l’Étude Agronomique du Congo Belge” (INEAC) with the aim of promoting scientific development of the region, and it has a long and well-documented history (34, 35). In the 1950s, INEAC had up to 32 substations (research stations,
incubation/acceleration of local small- and medium-scale activities (2), while promoting business innovation and socio-economic development of its neighboring communities. The region thus offers an opportunity to develop and test a landscape approach by fostering research, training, educational activities (2), while promoting business innovation and incubation/acceleration of local small- and medium-scale enterprises to support local livelihoods.

2.1.2 The CongoFlux Research Site

The CongoFlux EC tower has been installed in a lowland mixed-species forest, east of the Yangambi research center (0°48’52.0”N 24°30’08.9”E, Figure 1A). According to a recent study (40), this region is part of a floristic group identified as semi-deciduous-evergreen transition being representative for over ca. 1,800 ha (i.e., 16%) of the African rainforests. Canopy height model (CHM) data derived from an unmanned aerial vehicle-digital aerial photogrammetry survey (UAV-DAP survey) performed within the research site (41) indicate the presence of a heterogeneous canopy with an average tree height of 29.3 m and 95% of the identified treetops ranging between 21.2 m and 38.8 m (Supplementary Figure S1). The EC instrumentation is installed at a height of 56.25 m. To be able to install the equipment at this proper height, a tower structure (Figure 1B and Figure 3), having 11 secured platforms and its highest platform situated at 55 m, was constructed. The tower is supplied with electricity from a solar park (26.4 kWp) constructed 2.4 km west from the tower on an existing open spot (Figure 1B). All equipment is protected from lightning. The site is labelled as an associated station of the Integrated carbon observation network (ICOS) and FLUXNET [Station ID: CD-Ygb].

To avoid encroachment and to ensure data security and quality, two restricted areas were defined around the tower (Figure 1B). Within a 300 m radius from the tower, a core site has been established and activities are strictly limited. In a larger area surrounding the CongoFlux research site (Figure 1B), non-destructive experiments are allowed and even encouraged. Within this area, four 1-ha permanent sampling plots have been installed on the most dominant soil type (Haplic Ferralsols; Figure 2) to assess above-ground biomass, soil carbon and other biological variables such as tree mortality and fine root production according to the RAINFOR-GEM (Global Ecosystem Monitoring) field protocol (44). Lateral C exports will also be followed up by the use of flumes (installation planned in 2022).

2.1.3 Climate

The region has a tropical rainforest climate, Af-type according to the Köppen climate classification (45) (Supplementary Figure 2). It experiences a warm and humid climate characterized by a bimodal rain regime. From 1931 to 2017, it experienced a mean annual rainfall sum of 1811.7 ± 214.8 mm, 172 ± 22 rainy days (RDN), a relative air humidity (RH) of 87.2 ± 7.0%, a potential evapotranspiration (PET) of 1132.2 ± 54.4 mm and 2040 ± 98 hours of yearly sunshine (46). For the same period, the annual average temperature was 24.9 ± 0.3°C with annual average maximum and minimum temperatures of 29.8 ± 0.4°C and 19.8 ± 0.3°C, respectively (46).
2.1.4 Topography and Soils
The topography of the research area is characterized by the presence of two successive slightly undulating and deeply dissected plateaus, respectively at 50-70 m and 115-125 m above the Congo river (around 375 m a.s.l.) and its alluvial floodplains (47). The EC tower is located on the higher plateau at an altitude of 466 m a.s.l.

Soils and vegetation were mapped at a scale of 1:50,000 in the early 1950s (43, 48–50). Soil distribution (Figure 2) was hereby assessed by a large number of soil profiles and augering in the different landscape positions and by physicochemical analysis at the soil laboratory of the Yangambi research station. Additional soil data has been made available over the last decades (51–55). The parent material of the colluvial soils is composed of Pleistocene (fluvo-)jaelolan sandy deposits. All soils developed on these deposits (in situ or reworked) are strongly weathered, i.e. Haplic or Xanthic Ferralsols (Y1 and Y2, Figure 2), and Xanthic Ferralsols and/or Sideralic Arenosols (Y3, Figure 2) on colluvial sediments bordering alluvial plains (AT, Figure 2) consisting mostly of very sandy poorly drained soils (42). From the plateaus downwards to the alluvial plains, a clear toposequence is observed. The clay content of the soils is generally decreasing towards the valley floor, from 30-40% in Y1, over 20-30% in Y2 to < 20% in Y3. All soils are kaolinitic, acidic (pH-water <4.5) and poor in organic carbon (<1.5% in topsoil) and exchangeable cations Ca, Mg and K (sum <1 cmol(+)/kg soil in drained soils (42). From the plateaus downwards to the alluvial plains (47). The EC tower is located on the higher plateau at an altitude of 466 m a.s.l.

The topography of the research area is characterized by the presence of two successive slightly undulating and deeply dissected plateaus, respectively at 50-70 m and 115-125 m above the Congo river (around 375 m a.s.l.) and its alluvial floodplains (47). The EC tower is located on the higher plateau at an altitude of 466 m a.s.l.

Soils and vegetation were mapped at a scale of 1:50,000 in the early 1950s (43, 48–50). Soil distribution (Figure 2) was hereby assessed by a large number of soil profiles and augering in the different landscape positions and by physicochemical analysis at the soil laboratory of the Yangambi research station. Additional soil data has been made available over the last decades (51–55). The parent material of the colluvial soils is composed of Pleistocene (fluvo-)jaelolan sandy deposits. All soils developed on these deposits (in situ or reworked) are strongly weathered, i.e. Haplic or Xanthic Ferralsols (Y1 and Y2, Figure 2), and Xanthic Ferralsols and/or Sideralic Arenosols (Y3, Figure 2) on colluvial sediments bordering alluvial plains (AT, Figure 2) consisting mostly of very sandy poorly drained soils (42). From the plateaus downwards to the alluvial plains, a clear toposequence is observed. The clay content of the soils is generally decreasing towards the valley floor, from 30-40% in Y1, over 20-30% in Y2 to < 20% in Y3. All soils are kaolinitic, acidic (pH-water <4.5) and poor in organic carbon (<1.5% in topsoil) and exchangeable cations Ca, Mg and K (sum <1 cmol(+)/kg soil in drained soils (42). From the plateaus downwards to the alluvial plains (47). The EC tower is located on the higher plateau at an altitude of 466 m a.s.l.

Soils and vegetation were mapped at a scale of 1:50,000 in the early 1950s (43, 48–50). Soil distribution (Figure 2) was hereby assessed by a large number of soil profiles and augering in the different landscape positions and by physicochemical analysis at the soil laboratory of the Yangambi research station. Additional soil data has been made available over the last decades (51–55). The parent material of the colluvial soils is composed of Pleistocene (fluvo-)jaelolan sandy deposits. All soils developed on these deposits (in situ or reworked) are strongly weathered, i.e. Haplic or Xanthic Ferralsols (Y1 and Y2, Figure 2), and Xanthic Ferralsols and/or Sideralic Arenosols (Y3, Figure 2) on colluvial sediments bordering alluvial plains (AT, Figure 2) consisting mostly of very sandy poorly drained soils (42). From the plateaus downwards to the alluvial plains, a clear toposequence is observed. The clay content of the soils is generally decreasing towards the valley floor, from 30-40% in Y1, over 20-30% in Y2 to < 20% in Y3. All soils are kaolinitic, acidic (pH-water <4.5) and poor in organic carbon (<1.5% in topsoil) and exchangeable cations Ca, Mg and K (sum <1 cmol(+)/kg soil in drained soils (42). From the plateaus downwards to the alluvial plains (47). The EC tower is located on the higher plateau at an altitude of 466 m a.s.l.

The topography of the research area is characterized by the presence of two successive slightly undulating and deeply dissected plateaus, respectively at 50-70 m and 115-125 m above the Congo river (around 375 m a.s.l.) and its alluvial floodplains (47). The EC tower is located on the higher plateau at an altitude of 466 m a.s.l.
the ecosystem to heat and emit long wave radiation (LW\text{OUT}). Most of the emitted longwave radiation warms the lower atmosphere, which in turn warms the surface. These processes are observable by the lag effect of SWIN on LW\text{OUT}, sensible heat fluxes (H) and air temperature (T\text{air}) (\text{Figure 4}). Obviously, SWIN also triggers vegetation activity as it is a crucial condition for photosynthesis. During the day, in sufficient presence of SWIN, the ecosystem shows a net uptake of CO\text{2} (i.e., a negative NEE) and emits water vapor via evaporation. However, when SWIN levels are insufficient, as is the case during night, photosynthetic activity stops causing the ecosystem to emit CO\text{2} (i.e., a positive NEE) due to respiration. The evaporative flux stops as well. Even though the shown data are only preliminary and should not be further interpreted in their actual state, they already make it possible to observe all of the above described processes (\text{Figure 4}). Further measurement and processing of the data will also enable the partitioning of NEE into gross primary production (GPP) and the total CO\text{2} release due to respiration processes (Reco) of the ecosystem.

In the wake of global change, there is a need for a better understanding of the current and future response of natural ecosystems. Further and continuous measurement of the
ecosystem’s exchange by the above-described climate infrastructure should contribute to a better understanding of the second-largest tropical forest on Earth: The tropical forests of the Congo Basin.

4 SCIENTIFIC COLLABORATION

The CongoFlux research site is open to scientific collaboration. Complementary research contributing to better top-down/bottom-up comprehension of carbon, water and GHG fluxes in the tropical forests of the Congo Basin are specially welcomed.

DATA AVAILABILITY STATEMENT

The data included in Figure 4 are preliminary data and are only presented as a demonstration of what the tower will be measuring in the years to come. The authors thus do not recommend to use these data for any further use. Nevertheless, the tower is part of the ICOS network. All data collected by the flux tower will thus be put online once it has been processed and passed all quality checks. Requests to access the datasets should be directed to thomas.sibret@ugent.be.

AUTHOR CONTRIBUTIONS

TS wrote the paper, with significant contributions from MB and PB and active participation of LL, EB, HV, PC, BM, ML, and JM; TS performed the analyses and the figures with help of MB, PB, and LL; JM collected and shared all meteorological data shown in 2.1.3; LL and EB contributed to the full technical description of the flux towers equipment; PB and HV initiated and designed the CongoFlux-project. All authors actively helped in the realization of the described project. All authors contributed to the article and approved the submitted version.

FUNDING

The authors thank the Directorate General for Development Cooperation and Humanitarian Aid Belgium (DGD Belgium) and the European Commission for the financial support of DGD Belgium through the 10th European Development Fund which allowed the installation of this research infrastructure [B/15226/01]. The authors also do thank the Fonds wetenschappelijk onderzoek (FWO) and the Bijzonder Onderzoeksfonds (BOF) for their financial support via the FWO-IRI [FWO.IRI.2021.0005.01] and Methusalem [BOF.MET.2021.0004.01], respectively, which both ensure the maintenance and daily operationalization of the site. Moreover, we would like to thank the institutions who made the installation of this project possible including UGent, R&SD, CIFOR, ERAIFT, INERA and Enabel.

ACKNOWLEDGMENTS

Moreover, the authors thank Prof. Geert Baert of the Department of Environment, Ghent University for his valuable help in sharing literature on the topography and soils of Yangambi as well as his soil profile description (Figure 2). Finally, the authors thank Dr. He Zhang and Dr. Kristof Van Oost of the Earth and Life Institute, Université Catholique de Louvain for the sharing of canopy height data.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsoil.2022.883236/full#supplementary-material
REFERENCES

1. Harrison JJ, Brummett R, Stassney ML. (2016) The Congo River Basin. In: C.M. Finlayson, G.R. Milton, R.C. Prentice and N.C. Davidson (eds) The Wetland Book. (Dordrecht:Springer). 1-18. doi: 10.1007/978-94-007-6173-5_92-2

2. Beeckman H. The Luki and Yangambi Biosphere Reserves: Laboratories for Climate Change Research and Sustainable Development. IOP Conf Ser Earth Environ Sci (2019) 298:10. doi:10.1088/1755-1315/298/1/012009

3. Malhi Y, Wright J. Spatial Patterns and Recent Trends in the Climate of Tropical Rainforest Regions. Philos Trans R Soc B Biol Sci (2004) 359:311–29. doi:10.1098/rstb.2003.1433

4. Spracklen DV, Arnold SR, Taylor CM. Observations of Increased Tropical Rainfall Preceded by Air Passage Over Forests. Nature (2012) 489:282–5. doi:10.1038/nature11390

5. Lewis SL, Sonke B, Sunderland T, Begne SK, Lopez-Gonzalez G, van der Heijden GMF, et al. Above-Ground Biomass and Structure of 260 African Tropical Forests. Philos Trans R Soc B Biol Sci (2013) 368:20120295. doi:10.1098/rstb.2012.0295

6. Hubau W, Simon L, Oliver L P, Affum-Baffoe K. Asynchronous Carbon Sink Saturation in African and Amazonian Tropical Forests. Nature (2020) 597:607–7. doi:10.1038/s41586-020-0305-0

7. Harris NL, Gibbs DA, Baccini A, Birdsey RA, de Bruin S, Farina M, et al. Global Maps of Twenty-First Century Forest Carbon Fluxes. Nat Climb Change (2021) 11:234–40. doi:10.1038/s41558-020-00976-6

8. Washington R, James R, Pearce H, Pokam WM, Moufouma-Okaia W. Congo Basin Rainfall Climatology: Can We Believe the Climate Models? Philos Trans R Soc B Biol Sci (2013) 368(1625):20120296. doi:10.1098/rstb.2012.0296

9. Palmer PI, Feng L, Baker D, Chevallier F, Bösch H, Somkuti P. Net Carbon Emissions From African Biosphere Dominate Pan-Tropical Atmospheric CO2 Signal. Nat Commun (2019) 10:1–9. doi:10.1038/s41467-019-1107-w

10. Malhi Y, Adu-Bredu S, Asare RA, Lewis SL, Mayaux P. African Rainforests: Past, Present and Future. Philos Trans R Soc B Biol Sci (2013) 368(1625):20120312. doi:10.1098/rstb.2012.0312

11. Williams CA, Hanan NP, Neff JC, Hanan NP, Neff JC, Scholes RJ, Berry JA, Denning AS, et al. Africa and the Global Carbon Cycle. Carbon Balance of Africa: Synthesis of Recent Research Studies. doi: 10.1038/s41558-020-00976-6

12. Williams CA, Hanan NP, Neff JC, Scholes RJ, Berry JA, Denning AS, et al. Africa and the Global Carbon Cycle. Carbon Balance of Africa: Synthesis of Recent Research Studies. doi: 10.1038/s41558-020-00976-6

13. Chave J, Davies SJ, Phillips OL, Lewis SL, Sist P, Schepaschenko D, et al. Ground Data are Essential for Biomass Remote Sensing Missions. Surv Chem Phys Meteorol (2002) 13:085003. doi: 10.1088/1748-9326/13/8/003

14. Reichstein M, Bahn M, Mahecha MD, Kattge J, Baldocchi DD. Linking Plant and Ecosystem Functional Biogeography. Proc Natl Acad Sci U. S. A. (2014) 111:13697–702. doi:10.1073/pnas.1216051111

15. Kim D-G, Bond-Lamberty B, Ryu Y, Seo B, Papale D. Reviews and Syntheses: Enhancing Research and Monitoring of Land-to-Atmosphere Greenhouse Gas Exchange in Developing Countries. Biogeosci Discuss (2021), 1–30. doi:10.5194/bg-2021-85

16. Reichstein M, Bahn M, Mahecha MD, Kattge J, Baldocchi DD. Linking Plant and Ecosystem Functional Biogeography. Proc Natl Acad Sci U. S. A. (2014) 111:13697–702. doi:10.1073/pnas.1216051111

17. Kumar A, Bhatia A, Fagodiya RK, Malyan SK, Meena BL. Eddy Covariance Flux Tower: A Promising Technique for Greenhouse Gases Measurement. Adv Plants Agric Res (2017) 7(4):337–40. doi:10.14504/apar.2017.07.00263

18. Law BE, Falge E, Gu L, Baldocchi DD, Bakwin P, Berbigier P, et al. Environmental Controls Over Carbon Dioxide and Water Vapor Exchange of Terrestrial Vegetation. Agr For Meteorol (2002) 113:97–120. doi:10.1016/S0168-1923(02)00104-1

19. van Dijk AJM, Dolman AJ, Schulze ED. Radiation, Temperature, and Leaf Area Explain Ecosystem Carbon Fluxes in Boreal and Temperate European Forests. Global Biogeochem Cycles (2005) 19:1–15. doi: 10.1029/2004GB002147

20. Keenan TF, Hollinger DY, Bohrer G, Dragoni D, Munger JW, Schmid HP, et al. Increase in Forest Water-Use Efficiency as Atmospheric Carbon Dioxide Concentrations Rise. Nature (2013) 499:324–7. doi:10.1038/nature12291

21. Keenan TF, Gray J, Friedli MA, Toomey M, Bohrer G, Hollinger DY, et al. Net Carbon Uptake has Increased Through Warming-Induced Changes in Temperate Forest Phenology. Nat Climb Change (2014) 4:598–604. doi:10.1038/nclimate2253

22. Reichstein M, Bahn M, Mahecha MD, Kattge J, Baldocchi DD. Linking Plant and Ecosystem Functional Biogeography. Proc Natl Acad Sci U. S. A. (2014) 111:13697–702. doi:10.1073/pnas.1216051111

23. Reichstein M, Bahn M, Mahecha MD, Kattge J, Baldocchi DD. Linking Plant and Ecosystem Functional Biogeography. Proc Natl Acad Sci U. S. A. (2014) 111:13697–702. doi:10.1073/pnas.1216051111

24. Kumar A, Bhatia A, Fagodiya RK, Malyan SK, Meena BL. Eddy Covariance Flux Tower: A Promising Technique for Greenhouse Gases Measurement. Adv Plants Agric Res (2017) 7(4):337–40. doi:10.14504/apar.2017.07.00263

25. Law BE, Falge E, Gu L, Baldocchi DD, Bakwin P, Berbigier P, et al. Environmental Controls Over Carbon Dioxide and Water Vapor Exchange of Terrestrial Vegetation. Agr For Meteorol (2002) 113:97–120. doi:10.1016/S0168-1923(02)00104-1

26. van Dijk AJM, Dolman AJ, Schulze ED. Radiation, Temperature, and Leaf Area Explain Ecosystem Carbon Fluxes in Boreal and Temperate European Forests. Global Biogeochem Cycles (2005) 19:1–15. doi: 10.1029/2004GB002147

27. Nickless A, Scholes RJ, Vermeulen A, Beck J, Lopes-Ballesteros A, Ardö J, et al. Greenhouse Gas Observation Network Design for Africa. Tellus Ser B Chem Phys Meteorol (2020) 72:3–30. doi:10.1080/16000889.2020.1824486

28. Leonard J, Aperçu Préaliminaire Des Groupements Végétaux Pionniers Dans La Region De Yangambi (Congo Belge). Vegetatio (1952) 3:279–97. doi:10.1007/BF00359822

29. Bauters M, Ampoorter E, Huygens D, Kearsley E, De Hauleville T, Sellan G, et al. Functional Identity Explains Carbon Sequestration in a 77-Year-Old Experimental Tropical Plantation. Ecosphere (2015) 6:11–11. doi:10.1890/ES15-00342.1

30. Bernholdt W, Meyer J, Laudelout H. Mineral Nutrient Immobilization Under Forest and Grass Fallow in the Yangambi (Belgian Congo) Region. Pbl L Institut Natl Pour L’Etude Agron du Conge Belge Ser (1953) 57:1–27.

31. Kearsley E, De Hauleville T, Huken S, Kimidou A, Toirambe B, Baert G, et al. Conventional Tree Height-Diameter Relationships Significantly Overestimate Aboveground Carbon Stocks in the Central Congo Basin. Nat Commun (2013) 4:2269. doi:10.1038/ncomms3269

32. UNESCO Man and the Biosphere (MAB) Programme . Available at: https://en.unesco.org/mab (Accessed March 29, 2021).

33. Kyale Koy J, Wardell DA, Mikwa J-F, Kabuanga JM, Monga Ngonga AM, Osvald J, et al. Dynamiche De La Déforestation Dans La Réserve De Biosphére De Yangambi (République Démocratique Du Congo) : Variabilité Spatiale Et Temporelle Au Cours Des 30 Dernières Années. Bois Forest Des Trop (2019) 341:15. doi:10.19182/2019.341.a31752
Ngongo M, Van Ranst E, Baert G, Kasongo E, Verdoodt A, Mujinya BB, et al. Guide Des Solus En R.D. Congo. Tome I: Description Et Données Physico-Chimiques De Profils Types. Lubumbashi: Imprimerie Salama-Don Bosco (2009).

Ngongo M, Kasongo E, Muzinga B, Baert G, Van Ranst E. "Soil Resources in the Congo Basin: Their Properties and Constraints for Food Production. Proceedings International Conference ‘Nutrition and Food Production in the Congo Basin’,” In: Royal Academies for Science and Arts of Belgium, Brussels, vol. 35–54. (2014).

Alongo LS. Etude Microclimatique Et Pédologique De L’effet De Lisiere En Cuvette Centrale Congolaise: Impact Écologique De La Fragmentation Des Écossymès, Cas Des Séries Yangambi Et Yakonde À La Région De Yangambi (R.D. Congo). (2013).

Yang H, Detto M, Liu S, Yuan W, Hsieh CL, Wang X, et al. Effects of Canopy Gaps on N2O Fluxes in a Tropical Montane Rainforest in Hainan of China. Ecol Eng (2017) 105:325–34. doi: 10.1016/j.ecoleng.2017.04.042

Germain R, Evrard C. Etude Écologique Et Phytosociologique De La Forêt De Brachystegia Laurentii. Bruxelles: Institut National d’Étude Agronomique du Congo belge: Des Presses des Ets Vromant, s.a (1956).

Foken T., Gockede M., Mauder M., Mahrt L., Amiro B. D., Munger J. W. Micrometeorology: A Guide for Surface Flux Measurements, Dordrecht: Kluwer Academic, 81-108.

Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher’s Note: All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

Copyright © 2022 Sibret, Bauters, Balanza, Leferve, Cerutti, Lokonda, Mbiro, Michel, Verbeek and Boeckx. This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY). The use, distribution or reproduction in other forums is permitted, provided the original author(s) and the copyright owner(s) are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.