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CongoFlux – The First Eddy Covariance Flux Tower in the Congo Basin

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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 gasses 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 CO_2equivalent 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 extend, 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 CO_2 and H_2O exchange allowing to quantify the net ecosystem exchange (NEE) and water use efficiency (WUE), 2) measure N_2O and CH_4 fluxes for full GHG balance quantification and 3) determine the impact of atmospheric pollution including N deposition, tropospheric ozone (O_3) 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'Etude 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,

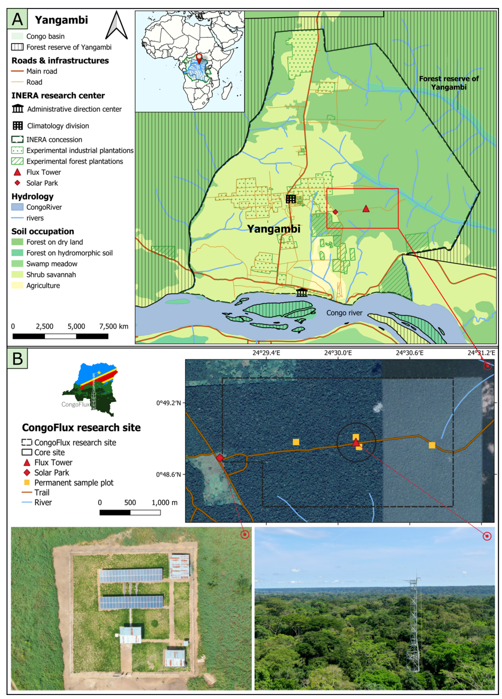


FIGURE 1 | Map of the research center of Yangambi in the Democratic Republic of the Congo (Panel **(A)** and detailed map of the CongoFlux research site (Panel **(B)** with illustrations of the solar park (Panel **(B)** bottom left) and the 55m-tall eddy covariance flux tower (Panel **(B)** bottom right). Source: Shape-files of Yangambi downloaded at https://maps.elie.ucl.ac.be/geoportail/.

experimental stations and plantations) spread all over different agro-ecological zones of the then Belgian Congo. As main station, CRY covered about 25,000 ha, bordering a forest area of over 200,000 ha, which allowed scientists to carry out tropical forestry and agronomic research (e.g. 33, 36). To support its scientific development objectives, CRY employed more than one hundred researchers working in twenty-one divisions, leaving behind a rich set of historical data and information still very useful today. For example, long-term records of meteorological data (since the 1930s), large scale forest plots where various silvicultural treatments were tested (34, 37), and one of the richest herbariums still well maintained in Sub-Saharan Africa.

The political and socio-economic turmoil affecting the DR Congo in recent decades did not spare the country's research stations, including the CRY, with many research, collaboration and training activities coming to a halt over the years. Yet during the last decade, many efforts have been made by the Government in collaboration with financial and technical partners to revamp research activities – also following the ongoing LMD (*Licence, Master, Doctorat*) reforms – and the CRY is currently being re-established as an international center of research with the enormous potential to once again become a global benchmark for the study of tropical forests, agriculture, and agroforestry. In addition, due to its status as Man and Biosphere (MAB) Reserve (38), obtained in 1977 (39), the Yangambi Biosphere Reserve, including the CRY and the Forest reserve of Yangambi surrounding the CRY (**Figure 1A**), also has to sustain the 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 21.2m 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 Ferrasols; **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).

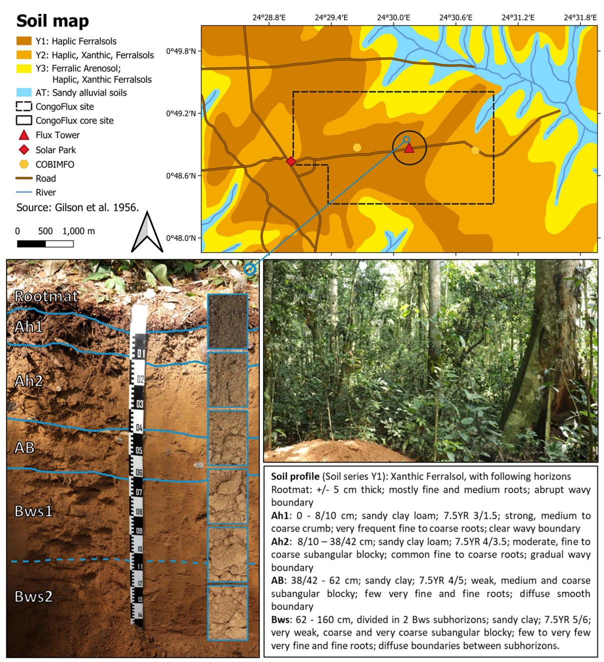


FIGURE 2 | Soil map (top) of the CongoFlux research site and soil profile (bottom) of a Haplic Ferrasol (Y1) near the eddy covariance flux tower [0°48'52.0"N 24°30'08.9"E] in Yangambi, Democratic Republic of the Congo. The understory present on the described soil profile is also shown (middle-right). Source soil description: personal communication; Prof. Geert Baert. Soil classification reference: IUSS Working Group WRB (42). Source for soil map: (43).

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 (fluvio-)aeolian 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 gradually 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^{-1} soil in ferralic B-horizon). The CongoFlux research site is dominated by Haplic Ferrasols (Y1, **Figure 2**).

2.1.5 Vegetation

CongoFlux is installed in a mixed semi-deciduous moist forest. Vegetation belongs to the Oxystigmo-Scorodophloeion alliance (48) and is dominated by *Scorodophloeus zenkeri*, *Panda oleosa*, *Anonidium mannii*, *Petersianthus macrocarpus*, *Stautia kamerunensis* and *Erythrophleum suaveolens* species (37). According to Kearsley etal. (37), living trees (>10 cm diameter at breast height) of the forest stand have a mean stem density of 467 ± 99 trees ha^{-1}, a mean basal area of 31.5 ± 3.3 m^2 ha^{-1} and an average above-ground carbon stocks (AGC) of 160.5 ± 23.8 Mg C ha^{-1} whilst the soil organic carbon (SOC) is estimated at 95 ± 11 Mg C ha^{-1}. Human activities, such as logging, are very rare and forest succession is thus mainly triggered by tree fall. This affects carbon and energy fluxes, and subsequently other nutrient cycles (36, 56).

Phenological traits, referring to periodic phenomena like flowering, leaf shedding and cambial activity (2), have a strong influence on ecosystems' metabolism. In the tropical forests of Yangambi, a particularly wide variety of phenological patterns exist (2). Leaf shedding, for example, periodically occurs on both deciduous and evergreen species (36, 57). This trait influences material and energy exchange between the forest and the atmosphere (2).

2.2 Equipment

2.2.1 Installed Equipment

The first measurements of the "CongoFlux" research site have been launched on the 5th of October 2020, but were interrupted between the 29th of April 2021 and the 25th of October 2021 due to power issues. Currently this includes measurements of CO_2, water vapor (H_2O), latent heat (LE) and sensible heat (H) exchanges between the mixed semi-deciduous forest of the Yangambi Biosphere Reserve and the atmosphere. The CO_2 and H_2O concentrations are measured *via* an enclosed infrared gas analyzer (LICOR Biosciences, LI-7200RS, Lincoln, USA) coupled to a non-orthogonal 3-axis ultrasonic anemometer (Gill Instruments, HS-50, Lymington, UK), following the ICOS guidelines. These devices are logging 56.25 m above ground level with a frequency of 10 Hz (**Figure 3**). Furthermore, CO_2, temperature and relative humidity (RH) profiles are measured at 8 heights along the tower (**Figure 3**). These measurements should allow to quantify inter- and intra-annual CO_2, H_2O and energy exchange and to derive net ecosystem exchange (NEE) and water use efficiency (WUE).

Moreover, an ensemble of meteorological and hydrological data is recorded, including incoming and outgoing short and longwave radiation, photosynthetic active radiation (PAR), incoming diffuse light, air pressure, temperature, precipitation and wind-direction and –speed (**Figure 3**). Such data should enable to analyze the climatic factors that control the seasonal patterns of NEE and WUE.

Soil microclimate is measured at three different soil pits around the tower. Each pit contains five soil temperature sensors (at 0.02, 0.05, 0.10, 0.50, 1.00 m depth) and three soil water content sensors (at 0.10, 0.50, 1.00 m depth) (**Figure 3**).

With the intention to study the impact of tropospheric ozone (O_3) on the NEE, an O_3 analyzer was mounted with an inlet at 56.25 m in February 2021.

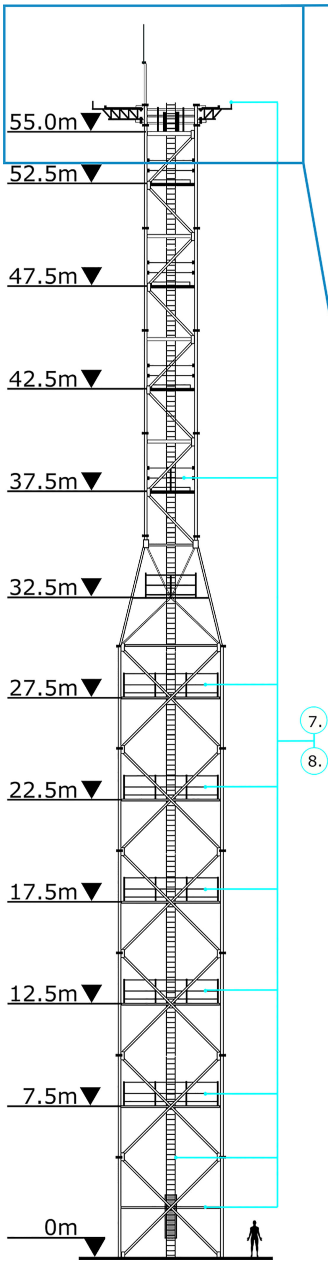
2.2.2 Planned Equipment Installation

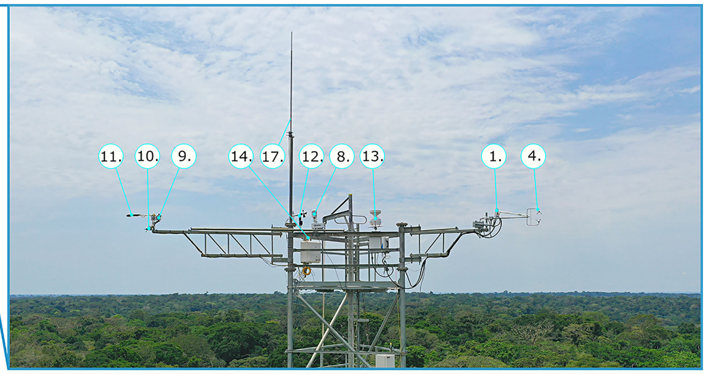
To achieve full GHG balance quantification, the site will also be equipped with a high-frequency N_2O and CH_4 analyzer (installation planned for 2022). Furthermore, during the same period, a system with nine automated soil chambers is to be installed to measure the CH_4, N_2O and CO_2 fluxes between the soil and the atmosphere. In order to study the impact of black carbon (BC) on the NEE, a BC analyzer will be installed in 2022 at the same inlet height as the O3 analyzer (e.i. 56.25 m). Moreover, to further study atmospheric pollution's impact on the NEE, an NO_x analyzer will be installed (installation planned for 2023).

3 DEMONSTRATION

As a demonstration of what the tower will be measuring in the years to come, we present selected data of an average day for a 30-days wet period (23/10/2020 – 21/11/2020, P_{tot} = 283 mm) and an average day for a 30-days dry period (01/01/2021 – 30/01/2021, P_{tot} = 88 mm) (**Figure 4**). Although these data still need gap filling, storage correction and obviously longer monitoring periods are needed to conclude on the forest's C and H_2O balance, the data already show clear diurnal patterns.

The driver of these diurnal patterns is incoming shortwave radiation (SW_{IN}) from the sun. As SW_{IN} reaches the ecosystem, it gets partially reflected (SW_{OUT}) and partially absorbed causing





ID	Variables	Measurment height (m)	Frequency	Sensors	Company	(Planned) installation date
1.	CO_2 / H_2O concentration & flux	56.25	10 Hz	LI 7200 RS	LI-COR Inc., Lincoln, Nebraska, USA	October 2020
2.	N_2O concentration	56.25	10 Hz	Los Gatos research analyser	Los Gatos Research, 3055 Orchard Dr, USA	*October 2022*
3.	CH_4 concentration	56.25	10 Hz	Los Gatos research analyser	Los Gatos Research, 3055 Orchard Dr, USA	*October 2022*
4.	3D wind speed & direction	56.25	10 Hz	HS 50	Gill Ltd., Lymington, Hampshire, UK	October 2020
5.	Ozone concentration	56.25	0.2 min^{-1}	Ozone monitor	B2B instrument	February 2021
6.	Black Carbon	56.25	0.2 min^{-1}	Aethalometer	Paul Scherrer Institut, Forschungsstrasse 111, Switzerland	February 2021
7.	CO_2 profil storage	2.00 | 5.00 | 7.50 12.50 | 17.50 | 22.50 27.50 | 37.50 | 56.2	5 min^{-1}	AP 200	Campbell Scientific Inc., Hathern Road, UK	October 2020
8.	Air temperature & relative humidity	2.00 | 5.00 | 7.50 12.50 | 17.50 | 22.50 27.50 | 37.50 | 56.2	2 min^{-1}	HC2S3 L	Campbell Scientific Inc., Hathern Road, UK	October 2020
9.	PAR (Photosynthetic active radiation) IN & OUT	56.25	3 min^{-1}	LI190R	LI-COR Inc., Lincoln, Nebraska, USA	October 2020
10.	Global and diffuse radiation	56.25	3 min^{-1}	SPN 1	Delta-T Devices Ltd, Cambridge CB25 0EJ, UK	October 2020
11.	Short and longwave radiation balance	56.25	3 min^{-1}	CRN 4	Kip & Zonen, Delth, the Netherlands	October 2020
12.	2D Wind speed & direction	56.25	2 min^{-1}	5103	RM Young, Traverse City, Michigan 49686, USA	October 2020
13.	Precipitation	56.25	2 min^{-1}	ARG 100	Campbell Scientific Inc., Hathern Road, UK	October 2020
14.	Air pressure	56.25	2 min^{-1}	PTB 210B	Vaisala, Glasgow, UK	October 2020
15.	Soil water content	-0.02 | -0.50 | -1.00	1 min^{-1}	CS 616	Campbell Scientific Inc., Hathern Road, UK	October 2020
16.	Soil temperature	-0.02 | -0.05 | -0.10 | -0.50 | -1.00	1 min^{-1}	T 107	Campbell Scientific Inc., Hathern Road, UK	October 2020
17.	Lightning rod	58.00	-	-		October 2020

FIGURE 3 | The CongoFlux eddy covariance flux tower structure and its equipment, Yangambi (DR Congo) [Top-right picture was taken on October 2020].

the ecosystem to heat and emit long wave radiation (LW_{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_{OUT}, sensible heat fluxes (H) and air temperature (T_{air}) (**Figure 4**). Obviously, SW_{IN} also triggers vegetation activity as it is a crucial condition for photosynthesis. During the day, in sufficient presence of SW_{IN}, the ecosystem shows a net uptake of CO_2 (i.e., a negative NEE) and emits water vapor *via* evaporation. However, when SW_{IN} levels are insufficient, as is the case during night, photosynthetic activity stops causing the ecosystem to emit CO_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 (**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_2 release due to respiration processes (R_{eco}) 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

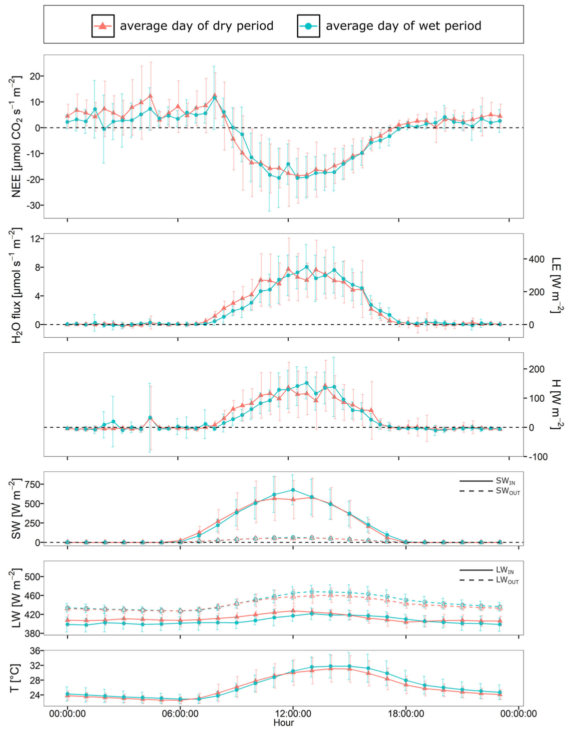


FIGURE 4 | Sample data of the CongoFlux eddy covariance flux tower, Yangambi (DR Congo). Net ecosystem exchange (NEE), water flux (H_20 flux), latent (LE) and sensible (H) heat flux, short wave incoming radiation (SW_{IN}) and short wave outgoing radiation (SW_{OUT}), long wave incoming radiation (LW_{IN}) and long wave outgoing radiation (LW_{OUT}), and air temperature (T) for an average day within a dry period (red, 01/01/2021 – 30/01/2021, P_{tot} = 88 mm) and wet period (blue, 23/10/2020 – 21/11/2020, P_{tot} = 283 mm). The above flux-data (NEE, H_20, LE and H fluxes) were processed by using LICOR EddyPro 7 software (Version 7.0.6). Because of the nature and purpose of data presented, no post-processing (e.g. gap-filling, storage correction) has been applied. The flux data (NEE, H_20, LE and H fluxes) were all quality checked using the steady-state test (58). Using this method fluxes are divided in best quality (0), suitable for analysis (1) and bad fluxes (2). Only fluxes flagged as 0 and 1 were included.

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.

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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

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