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Greenhouse gas emissions and their relationship with hydropower generation in a tropical reservoir in Colombia

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ABSTRACT

Studies of emissions of greenhouse gas (GHG) such as CO_2 and CH_4 in hydroelectric reservoirs are very important in the debate on whether hydropower can be classified as a 'clean energy' source. In this study, GHG emissions in the Topocoro reservoir in Colombia during the first five years after filling were evaluated and related with hydropower generation. The floating static chamber and inverted funnel methodology were used for the collection of GHG and the gas chromatography with flame ionization detector (FID) – methanizer and electron capture detector (ECD) methodology for its detection in the laboratory. The results showed emission values between 256,613 and 654,643 tCO_2eq/year. The intensity of gases was also determined in a range between 81 and 148 gCO_2eq/kWh, depending on the evolution of the filling and the power generation in the reservoir. The results suggested that as the filling percentage of the surface of the reservoir increases, there will be more GHG emissions, due to the biotic and abiotic decomposition of organic matter. At the same time, higher energy production will be generated.

Key words: Colombia, GHG intensity, Greenhouse gases, Hydroelectricity, Power density, Reservoir

HIGHLIGHTS

- A tropical reservoir in Colombia was monitored for five years during the post-filling phase.
- The floating static chamber and inverted funnel methodology were used.
- It analyzed the relationships of the GHG with energy production and power density in the reservoir.
- This is the first investigation carried out in Colombia to determine the net emissions in a reservoir.

1. INTRODUCTION

Hydropower has been recognized as an alternative energy source and a means to mitigate greenhouse gas (GHG) emissions (Li *et al.*, 2017; Zhao *et al.*, 2019). Environmental, economic and energy policies seek to increase the development of renewable sources to replace carbon and fossil fuels (Lu *et al.*, 2020; Giannakis & Zittis, 2021). In hydroelectric reservoirs and in certain natural environments, the GHG emissions depend on the geological background, the hydrology, climatic conditions (Valipour *et al.*, 2021), the characteristics of the reservoir, carbon reserves, water quality, physical conditions (Barros *et al.*, 2011; Wang *et al.*, 2015; Grinham *et al.*, 2018; Kumar *et al.*, 2019a, 2019b), sedimentation, bottom shear stress (Joyce & Jewell, 2003; Sobek *et al.*, 2012; Deemer *et al.*, 2016; DelSontro *et al.*, 2016), geological, soil characteristics (Grinham *et al.*, 2018), biological and vegetative conditions and related hydroelectric operations activities (Teodoru *et al*., 2012; Wang *et al*., 2015; dos Santos *et al*., 2017; Yang *et al*., 2017; Kumar *et al*., 2019a).

According to Tremblay *et al*. (2005) and the IPCC (2006), autochthonous organic matter influences emission rates in aquatic systems (natural or artificial), specifically, after 10 years, where GHG emissions are related to organic carbon and flooded and decomposing organic matter. In this regard, approximately 84% of GHG is emitted from shallow lakes (depth less than 5 m) (Li *et al*., 2020), and new reservoirs in tropical and equatorial regions create the best conditions for CH_4 emissions (Demarty & Bastien, 2011), due to temperatures that favor the kinetics of degradation of organic matter.

Measurements of fluxes of GHG such as CO_2 and CH_4 are considered an important source of data of environmental interest. These provide information on sinks and sources of GHG including both fossil fuel energy (such as coal), and renewable energies, of which 26% are made up of wind, biodiesel, ethanol, thermoelectric, solar-photovoltaic, biomass, wind turbines, biogas (Pokharel, 2007), and 19% of hydroelectric power (Tang, 2020). Globally, reservoirs comprise an area of 3.4×10^5 km^2, of which 20% corresponds to hydroelectric reservoirs (Barros *et al*., 2011; Kemenes *et al*., 2011; Li *et al*., 2017). Barros *et al*. (2011) estimate global CO_2 and CH_4 emissions from reservoirs to be 48 and 3 Tg C, respectively, representing 4% of global carbon emissions from inland waters, while Ometto *et al*. (2013) state that tropical hydroelectric reservoirs represent 76% of these emissions. Meanwhile, large hydroelectric dams emit 104 Tg of CH_4 annually, making up 20% of total emissions (Kumar *et al*., 2019a).

Studies of GHG emissions in hydroelectric reservoirs have been made in different climatic conditions and latitudes, such as in Canada (Quebec), French Guiana, Finland, Sweden, South Korea, China, the United States, Brazil and Laos (Zhao *et al*., 2019). One of the first hydroelectric reservoirs where diffusive flow GHG emissions (in summer) were measured, was Eastmain in Québec, Canada, where measurements were made after filling from 2003 to 2009, and degassing emissions measured from 2007 to 2009 (Bastien *et al*., 2011). In Eastmain, the highest diffusive emissions of CO_2 and CH_4 (daily summer) were observed in the first year after filling, while three years after filling of the reservoir, they decreased to a level below that of natural lakes (Bastien *et al*., 2011). In South America, the country with the highest number of reported studies of greenhouse effect emissions in hydroelectric reservoirs is Brazil (Ometto *et al*., 2013), with a particularly high concentration of studies in the Amazon region of this country. The World Bank (2017) states that only a few reservoirs in the world have records that go back more than a few years. Examples of studies with extensive measurements are Petit-Saut (French Guiana); Nam Theun (Laos); Eastmain (Bastien *et al*., 2011) and La Grande (both in Canada); and Tucuruí and Samuel (both in Brazil).

This study, is one of the first steps in developing knowledge of this topic in the Colombian context and contribute to a better understanding of the conditions of GHG emissions compared to the generation of hydroelectric power in a new reservoir, being a pioneering study in Colombia and related to tropical reservoirs that, under certain climatic characteristics, tend to be called the largest GHG generators (Barros *et al*., 2011; Fearnside, 2015), but that a broad analysis also depends on analyzing other factors such as power density to have more critical indicators in the discussion. In Colombia, the energy matrix corresponds to 70% hydroelectricity, corresponding to 11,726 MW and an electrical generation of 54,915 MW (IHA, 2018), therefore, the importance of this study lies in knowing the GHG emissions associated with hydroelectricity and in this way be able to define policies that allow mitigating the derived environmental impacts and reducing the effects of climate change from GHG emissions in the country.

Gross emissions of CO_2 and CH_4 from a new reservoir in Colombia were determined over a period of five years and the relationship of GHG intensity emissions with regard to the evolution of annual energy production as a specific power density. Different power densities were compared with the object to analyze these indicators in hydroelectric reservoirs, configuring a study that show how the tropical location is not a specific condition to consider more influence in the GHG emissions related with the energy production. This study is unique in Colombia, since it shows the evolution of the GHG intensity results after the first five years of filling and in Latin America there is little information about the behavior of tropical reservoirs.

2. MATERIALS AND METHODS

2.1. Study area

Topocoro hydroelectric reservoir is located in the department of Santander, Colombia (7 °6′3.68″N73 °24′20.58″W), between 140 and 330 m above sea level, in the canyon where the Sogamoso River crosses the Serranía de La Paz, 75 km upstream from the Magdalena River and 62 km downstream from the confluence of the Suárez and Chicamocha rivers (Figure 1). The dam and reservoir have territorial influence in the municipalities of Girón, Betulia, Zapatoca, Los Santos, Lebrija and San Vicente de Chucurí (Rodriguez & Peñuela, 2022). Effluents flow through the Chicamocha, Suarez and Sogamoso canyons, where the landscape is mountainous, the relief is abrupt and complex, and the variation of the slopes ranges from moderately steep to very steep, differing in degrees of inclination, length and shape (Ruiz *et al.*, 2019). In the Suarez and Chucuri Rivers as well as in the Agua Blanca stream, the predominant land use is extensive cattle raising and agriculture with rotating crops. Sogamoso and Chicamocha are notable for the exploitation of quarries and industrial dumping. The high and medium parts of all the effluents present torrential regimes during the rainy season, which have strong hydraulic action that causes sediment to travel along the course of the river (Lopera *et al.*, 2016).

2.2. GHG monitoring

Diffusive gases were taken on the surface with an air pump adapted to a floating acrylic chamber (0.4 m$\times$0.4 m$\times$0.5 m) at the air–water interface (Figure 2(a)), and four samples every 7 min (28 min in total). In the case of bubbling gases, these were monitored using an inverted funnel (diameter 1 m and h=0.5 m), in the water column, 4 m below the surface for 4 h (Figure 2(b)). Both methodologies followed the protocols established by the IHA (2010). The gas samples were collected with 500 mL Tedlar bags and taken to the laboratory for gas analysis.

Four sampling campaigns were carried out per year, in different climatic conditions. Field samples were carried out in eight stations located spatially around the reservoir, in order to have a representative analysis (reservoir, turbines, rivers or downstream). The average flow per year was estimated as the average of all the results of the sampling campaigns.

2.3. Laboratory analysis

The CO_2 and CH_4 samples collected in Tedlar bags were transported by land under ambient temperature conditions to the GDCON group laboratory, by land, avoiding abrupt changes in pressure (Miranda *et al.*, 2020). The analyzes of the gas samples were carried out in the laboratory of the GDCON group, accredited for water analysis by the IDEAM under the NTC-ISO/IEC 17025 standard, Resolution 1665 of July 12, 2011, following the analytical criteria of Standard Methods (APHA, 2017), using a 7890To gas chromatograph (GC) with a 5975C mass spectrometer and a conductivity detector (Hoyos *et al.*, 2021).

To calibrate and verify the GC analysis procedure, standard gas samples of 996 and 1010 ppm, obtained from certified standards (Linde Brand), were injected for CO_2 and CH_4, respectively, and read after every 10 samples. After the laboratory analysis process, the GHG fluxes were calculated from the slope of the linear regression of the gas concentration in the chamber vs. time. The flow correlation coefficients (R^2) of the linear regression were greater than 0.85, and the flows were multiplied by the average area (filling of the reservoir) of each sampling campaign, in order to report the results in tons of CO_2 or tons of CH_4 per year, or according to the requirements of equivalent units, such as CO_2eq.

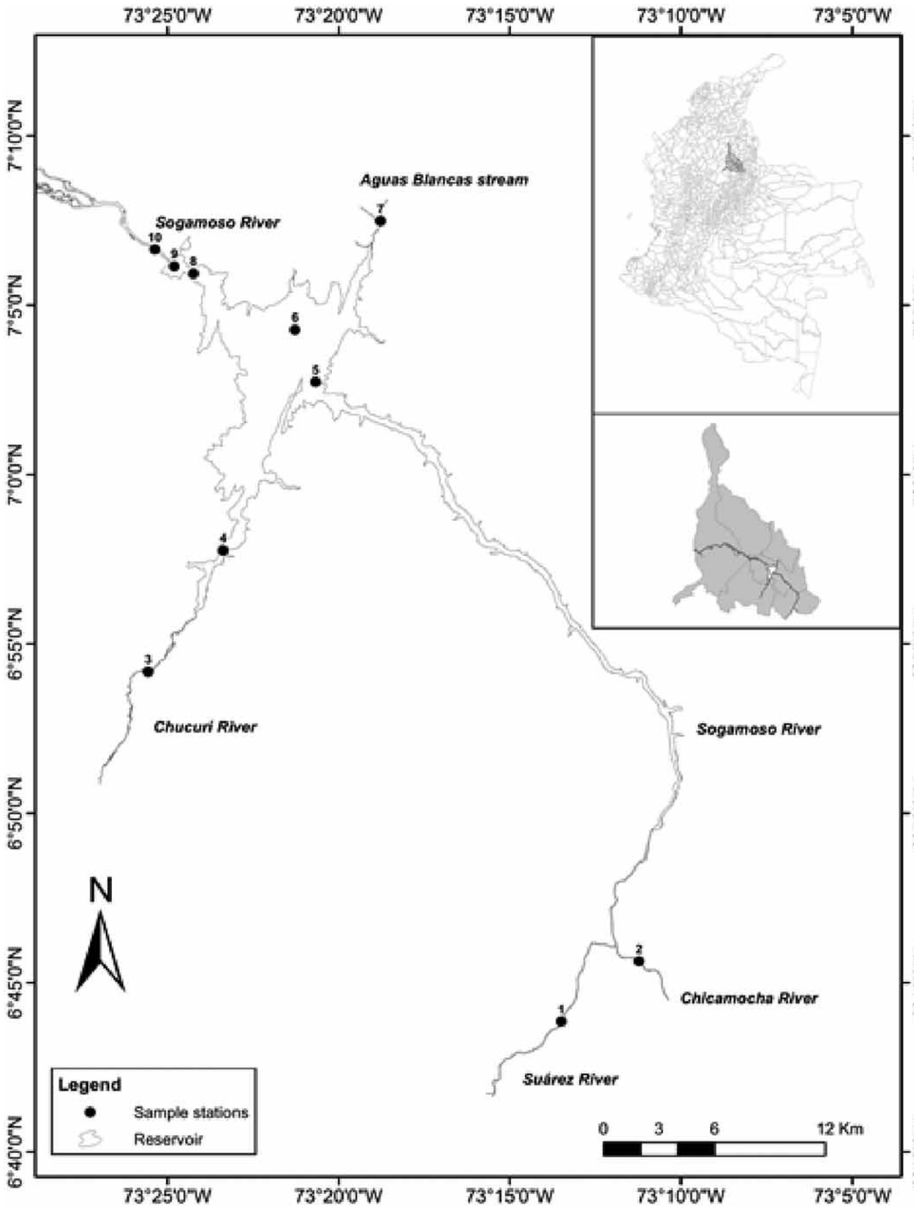

Fig. 1 | Topocoro reservoir, tributaries and sampling points established. Suarez River (No. 1), Chicamocha River (No. 2), Chucuri River (No. 3), Chucuri reservoir (No. 4), Tablazo (No. 5), Trigueros (No. 6), Agua Blanca Stream (No. 7), Dam (No. 8), Discharge (No. 9) and Esgamo (No. 10).

2.4. GHG intensity and power density

Emission intensity (gCO_2eq/kWh) was calculated as GHG emissions (gCO_2eq) per unit of electricity generated (kWh), for each year, using Equation (1):

$$\text{GHG intensity}\left(\frac{gCO_2eq}{kWh}\right) = \frac{\text{Annual reservoir emissions } (gCO_2eq/\text{year})}{\text{Power annual generation } (kWh/\text{year})} \quad (1)$$

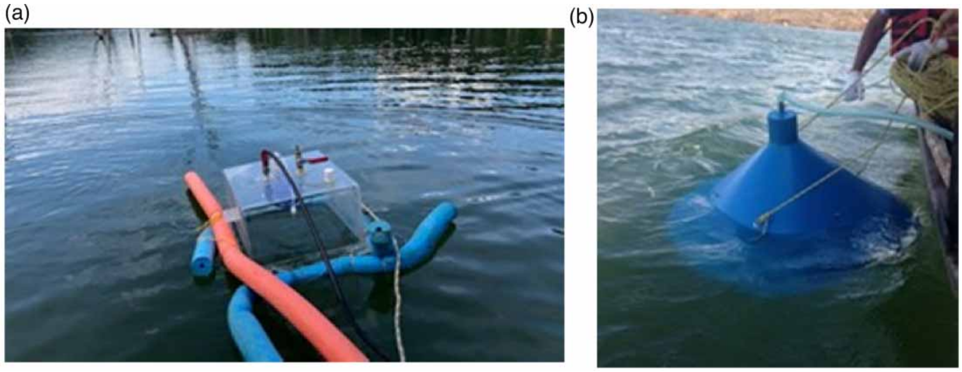

Fig. 2 | GHG monitoring: (a) floating static chamber scheme for monitoring diffusive flows and (b) inverted funnel for bubbling gases.

Power density was estimated as the relationship between installed power capacity and reservoir area, Equation (2):

$$\text{Power density}\left(\frac{\text{W}}{\text{m}^2}\right) = \frac{\text{Installed power capacity (W)}}{\text{Reservoir area (m}^2\text{)}} \quad (2)$$

The relationship between GHG intensity and power density was also calculated for other tropical reservoirs, using the information from Demarty & Bastien (2011), in order to compare and analyze these indicators at specific ages for reservoirs aged between one and five years, and older. The Topocoro results were compared with other reservoirs under tropical conditions in different parts of the world.

3. RESULTS AND DISCUSSION

3.1. Gross annual emissions in the reservoir

Figure 3 establishes the GHG emissions in the reservoir in the first year post-filling, expressed as tCO_2eq/year, as well as the mutual influence of the diffusive fluxes of CO_2 and CH_4 and the bubbling of CH_4.

GHG emissions were 256,613 tCO_2eq in 2015 and 654,643 tCO_2eq in 2019 (Rodriguez & Peñuela, 2022). This represents an increase in emissions in four years. The largest increase of 534,863 tCO_2eq/year occurred in 2017, and the magnitude of this was double that of the emission that took place in 2015. Due to the increase in the filling area, diffusive CO_2 fluxes increased more than CH_4 bubbling. The latter did not have a major impact on total emissions, although methane has a warming potential 25 times greater than that of CO_2 (UNESCO/IHA, 2010).

The large increase in emissions in 2017 was due to the increase in biodegradable organic matter in the reservoir, resulting from the hydrolysis or decomposition of high molecular weight organic compounds present in flooded vegetation. Due to the high molecular weight compounds of the different submerged plant species, organic matter decomposition begins with an enzymatic hydrolysis, and then continues with the formation of low molecular weight organic intermediate metabolites, which degrade much more easily, producing CO_2–CH_4 (anaerobic processes) or CO_2 (aerobic processes). Climatic and hydrological conditions are important factors in GHG emissions, as are the evolution of the reservoir over time, the variation in reservoir filling, and the degradability and amount of the organic matter both present in the water and those settled. The highest levels of

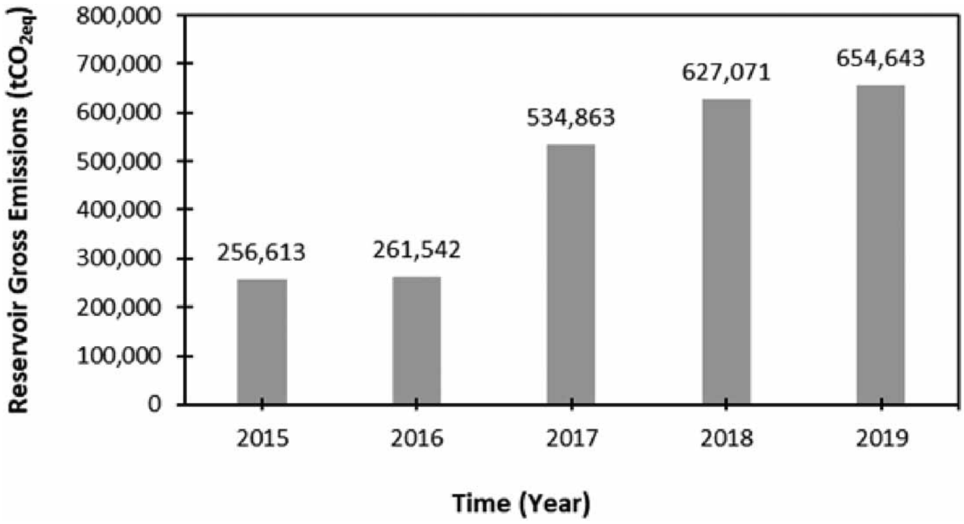

Fig. 3 | Annual gross emissions in the reservoir.

gas emissions are reached during the first 5–15 years of flooding (World Bank, 2017), and they then decrease exponentially until reaching stable behavior when carbon availability is limited.

This study makes an important contribution to knowledge of hydroelectric reservoir emissions in tropical conditions in Colombia. Li & Zhang (2014a) state that tropical reservoirs are chiefly responsible for CO_2 emissions, while boreal and temperate reservoirs contribute a lower percentage of emissions. However, studies of the emissions of GHGs from hydroelectric reservoirs must also take into account the relationship between these emissions and the power density provided by the hydroelectric station. In the Topocoro reservoir, a part of the plant biomass to be flooded was eliminated, as was the case for a reservoir studied in China (Li *et al.*, 2018). This was done to prevent and reduce the formation of GHG emissions, by having less material that could dissolve in water from the reservoir and thereby generate GHGs or even eutrophication problems. A greater depth will cause more pressure and bubbling flows to manifest, considering that CO_2 has a higher solubility than CH_4, although bubbling will occur in low proportions even in shallow water. The extension of the water in the littoral zone allows for more flooded surface, forming areas prone to greater sedimentation (World Bank, 2017).

3.2. Relationship between GHG intensity and power generation

Figure 4 shows the relationship between the intensity of GHGs and power generation during the first five years post-filling of the Topocoro reservoir. Although the intensity of gases has an implicit direct relationship with the energy produced, it is shown in the differential form that the increase in energy production does not necessarily have an influence on the increase in GHG emissions, as can be seen in the year 2017.

Power generation in the first two years remains relatively stable, between 3177 and 3134 GWh, and then increases to 5439 GWh in 2017, before decreasing to 4490 GWh in 2018 and to 4421 GWh in 2019. The results from 2017 shows that there is no direct relationship since the increase in energy produced was much greater than that in GHG emission. In this regard, the intensity of gases increases from 80.77 gCO_2eq/kWh in 2015 to 148.07 gCO_2eq/kWh in 2019, while during the years 2015 and 2016, and 2018 and 2019, respectively, its behavior is stable compared to power generation. However, in 2017, the highest power generation was presented in the evaluation period of five years after filling, with an intensity of 98.35 gCO_2eq/kWh. These results show that, at

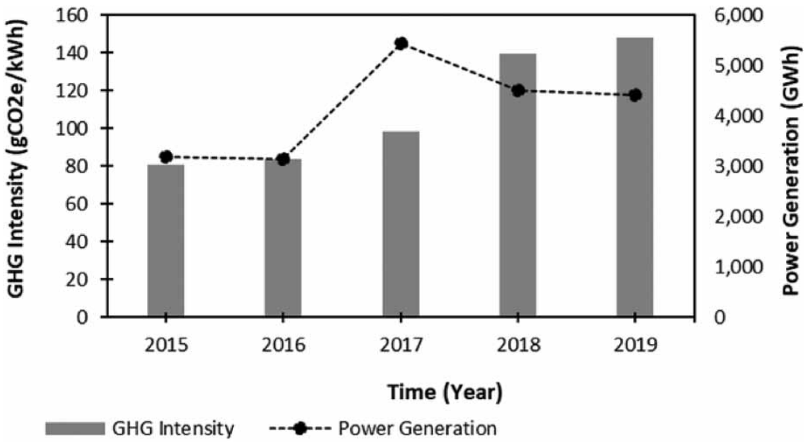

Fig. 4 | The relationship between GHG intensity and power generation.

times, the generation of energy and the intensity of gases are independent of one another, energy generation depending instead on the control and operation activities of the generation plant and not on the filling of the reservoir or the emissions of GHGs. Flow control operations, turbine operation, energy storage capacity, availability and capacity of electrical distribution networks, water storage capacity and permitted concession flow (Maran *et al.*, 2014), conditions and hydrometeorological seasons (dry or rainy), water cycle, and priority uses for reservoirs (electricity production, water supply, recreation, irrigation); attending to market and energy demand fluctuations according to the operation of the plant (Amor *et al.*, 2011), the type of plants and dams (Song *et al.*, 2018) are factors that condition the production of energy in the system of a reservoir-hydroelectric plant. In addition, economic factors in the country or export and import of energy (Morcillo *et al.*, 2018). Regarding the above, with the intensity of GHG emissions from the reservoir, the emissions evolve in this case in an aquatic system that is in the process of filling over the first five years and the CO_2 and CH_4 flows vary according to the physicochemical reactions and biological (aerobic and anaerobic) to oxidize and reduce carbon; conditioned to temperature, reservoir age, shape, water storage capacity, flooded area, for example. Emissions are in the process of evolution in the reservoir, while electricity production can be controlled technically.

In Topocoro, high CO_2 and CH_4 emissions were still being generated in the first five years of post-filling and power generation. However, in 2018 and 2019 the rate of increase of CO_2 and CH_4 emissions decreased, indicating that emissions were stabilizing. Emissions can vary according to the age of the reservoir, but also depending on other factors. A study by Khan *et al.* (2018) in New Zealand identified that the intensity of gases can vary both on a daily and monthly basis due to the spatiotemporal and climatic conditions of the time, in association with the energy demands for each period.

The conditions responsible for the intensity of emissions from a source of energy such as hydroelectric reservoirs depend not only on the demand for energy, but also on the rate of decomposition of organic matter, climatic conditions and the percentage of filling of the reservoir. Khan *et al.* (2018) evaluated the correlation between coal intensities (GHG) (gCO_2eq/kWh) and energy demand in New Zealand in 2015, performing an analysis of marginal generation proportions, which reveal the relationship between changes in generation of energy from a particular source within the total generation. They found that there was no direct correlation for diesel, wind and biomass. Meanwhile, significant correlations were found for hydraulic sources (R^2=0.926), and gas (R^2=0.466), as well as a low correlation for geothermal (R^2=0.004) and a very low correlation for coal (R^2=0.162).

3.3. Comparison between tropical reservoirs and Topocoro

Figure 5, adjusted with data from Topocoro, was modified from a study carried out by Demarty & Bastien (2011), in order to include Topocoro within a group of tropical and world-relevant reservoirs and thus carry out a complementary analysis within a representative group of reservoirs with different climatic conditions, such as boreal, temperate, subtropical and, in this case, tropical (Barros *et al.*, 2011).

The Topocoro reservoir is specifically compared with reservoirs of the same age in Brazil (10) and in French Guyana (Petit-Saut). The intensity of emissions from Topocoro at one year of age was 15 gCO_2eq/kWh lower than that of the Miranda reservoir. At the same age, it was 172 gCO_2eq/kWh lower than that of Serra da Mesa. At an age of four years, emissions intensity from Topocoro surpassed that of Xingó by 132 gCO_2eq/kWh. Meanwhile, emissions intensity from Segredo reservoir at an age of six years was lower than that of Topocoro by 132 gCO_2eq/kWh, although Topocoro was five years old at the time of this study. Finally, the Tucuruí reservoir has two reference intensities. The first of these is at five years, with a value of 1220 gCO_2eq/kWh, higher than that of Topocoro. The second, at age 14, is still greater than that of Topocoro, with a magnitude of 473 gCO_2eq/kWh.

In another approach, intensity of emissions from reservoirs that were not of the same or similar age to Topocoro were not directly compared. According to Demarty & Bastien (2011), intensities in reservoirs older than five years, such as Barra Bonita, Samuel, Tres Marías and Balbina, were much greater than that of Topocoro. From this point of view, Topocoro had emissions intensity greater than Xingó and Xegredo, but less than Miranda, Serra de Mesa and Tucuruí at five and 14 years and specifically in the last of these and at an age of five years. The intensity of gases in Tucuruí decreased from 1368 gCO_2eq/kWh at five years old to 473 gCO_2eq/kWh at 14 years old, approximately three times its magnitude. This implies that under constant power generation of 21,000 GWh/year, gas emissions decreased from 28,730 to 9940 $tCO_2eq \times 10^3$, according to data from Demarty & Bastien (2011). This means that, on the basis that emissions decrease considerably in 5–15 years (World

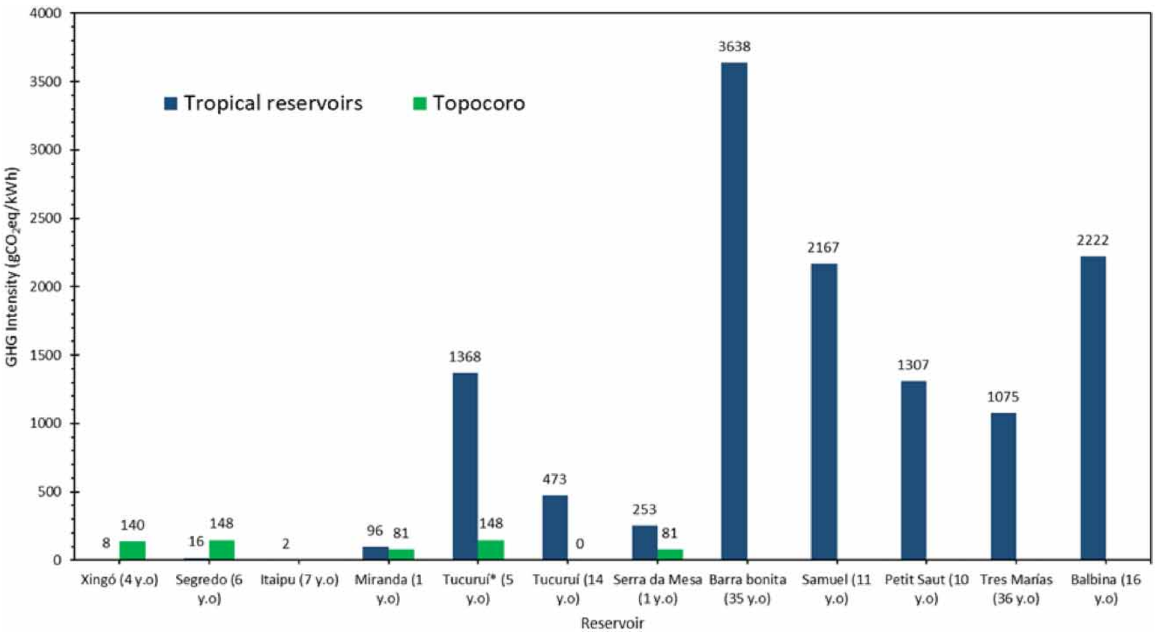

Fig. 5 | Comparison between the intensity of greenhouse gas emissions from tropical reservoirs and Topocoro. Adjusted and modified from Demarty & Bastien (2011).

Bank, 2017), it is expected that in the case of Topocoro they will decrease and therefore there will be lower emission intensities than in 2019.

It is observed in Figure 5 that the intensities of the reservoirs studied by Demarty & Bastien (2011) are between 2 and 4100 gCO_2eq/kWh, values higher than those found in Topocoro. Brazil, Canada (World Bank, 2017) and China (Li *et al.*, 2017, 2018; Wen *et al.*, 2017) are the countries that have most developed gas emission studies in the world and therefore, in terms of tropical, subtropical and temperate reservoirs, it is interesting to analyze and compare emissions from reservoirs similar to Topocoro in countries such as Brazil.

3.4. Relationship between GHG emissions and power density in tropical hydroelectric reservoirs

Figure 6 shows the comparison between power density and GHG intensity in the tropical reservoirs with Topocoro, using the information recorded by Demarty & Bastien (2011). This enables analysis within a group approach of reservoirs located in South America with similar climatic conditions.

It is observed that the reservoir that has the highest power density in relation to intensity of gases is Xingó, while Barra Bonita has the lowest. Topocoro has the third highest power density (11.9 W/m^2) and one of the lowest intensities of gases within the group analyzed. Reservoirs such as Barra Bonita (0.4 W/m^2), Balbina (0.1 W/m^2), Samuel (0.4 W/m^2), Petit-Saut (0.4 W/m^2) and Tres Marías (0.3 W/m^2) (in descending order) had higher GHG intensities compared to power density than other reservoirs, including Topocoro. Based on the above, hydroelectric reservoirs with higher power densities have lower GHG emissions intensities, while the intensity also depends on the evolution of emissions over time. This is the case in Tucuruí at 14 and five years, and in Topocoro during the five years of monitoring.

This is one of the first studies available on GHG emissions in a young hydroelectric reservoir in tropical conditions in Colombia. It compared Topocoro with reservoirs with tropical characteristics in Brazil and French Guiana, considering gas intensity and power density. This study is an important contribution to knowledge on renewable sources in the Colombian energy sector, especially those of hydraulic nature. In addition, it contributes to information available for future carbon inventories, with a view to finding alternative energy sources with

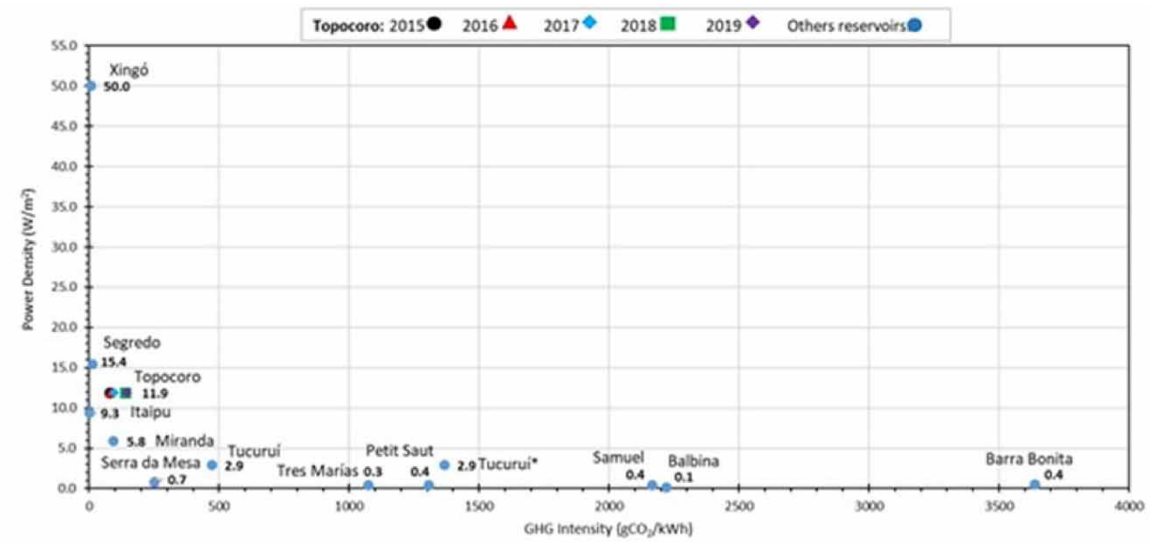

Fig. 6 | The relationship between greenhouse gas emissions intensity and power density in the tropical hydroelectric reservoir.

lower GHG emissions than fossil sources. As stated by Li & Zhang (2014b), future studies and monitoring will allow a broader understanding of the evolution of emissions and the intensity of GHGs in Topocoro, optimizing energy generation in inverse proportion to emissions.

The results of the emissions, intensities and power densities of the reservoirs could be compared with other cases in similar or different climatic conditions, through a greater bibliographic consultation that allows to include, in addition, semitropical, temperate and boreal conditions, with reference studies or databases carried out by scientific researchers (Barros *et al*., 2011) or entities such as the IHA (in a life cycle) (Prairie *et al*., 2017a, 2017b, 2017c) or the IPCC (CDM, 2006; UNESCO/IHA, 2010), for example, comparative, general and specific analyzes for each characteristic could be given to qualify how GHG emissions work in relation to electricity generation and define qualification levels and classification of emissions in reservoirs.

4. CONCLUSIONS AND RECOMMENDATIONS

GHG emissions in Topocoro are favored by the increase in the filling surface of the reservoir, with the presence of diffusive fluxes of CO_2 and bubbling of CH_4 from the first year, and the increase in diffusive fluxes of CH_4 from the third year. During the three years where both methane fluxes occur, the highest contribution corresponds to diffusive fluxes (72.6%) and indicates the presence of physicochemical and biological processes in the water column that favor the dissolution of CH_4 over its release by bubbling. As a new reservoir, the intensity of gases from Topocoro increased according to its filling. This was favored by a greater amount of submerged organic matter and by the process of degradation through oxidation (CO_2) and reduction (CH_4). With a power density of 11.9 W/m^2, Topocoro is one of the tropical reservoirs with the lowest GHG intensities in the first five years post-filling, taking into account its energy production (81–148 gCO_2eq/kWh), with respect to reference reservoirs of homologous ages in South America. Therefore, it can be established that this reservoir provides favorable conditions for the generation of hydroelectric energy in Colombia while contributing to the reduction of GHG within the energy matrix in Colombia.

Within this type of study possible sources of error are contemplated, which must be considered and try to mitigate in future investigations, some of them are as follows: the collection of GHG samples in the field related to interferences due to waves and wind that estimate the movement of the boat from which the samples are taken. For this, measurements of samples (diffusive) were made in duplicate in the field, to verify the measurements, prior to the validation of the technique in the field and in the laboratory. It is also possible to contemplate considerations of sealing and transporting the samples under controlled conditions, which must be considered to reduce the effects of changes in temperature and pressure and especially when there is no online measurement equipment, and the transport of the samples is required. The standardization of the analysis methods in gas chromatography and the calibration of the equipment at the moment of the measurement of the samples, of the respective calculations and correction of the measurements for pressure and temperature. As a verification measure of a good reading, quality control measures and certified gas standards were carried out. Possible errors in the power generation records could occur due to the sensitivity of the sensors or equipment for recording this data. The consolidation of an operating system and software that allows data to be collected as accurately as possible helps in these aspects, if they exist. Finally, calculations related to all the processes as base information for the figures in this study may consider errors in data processing. A technical and structured approach to calculations can reduce errors, both conceptual and numerical.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST STATEMENT

The authors declare there is no conflict.

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