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Methane fluxes from tropical wetlands of the Orinoco River Basin and their regional implications

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Abstract. The Llanos del Orinoco, a vast tropical savanna floodplain in northern South America, plays a significant yet understudied role in the global methane (CH_4) budget. This study synthesizes existing data to evaluate CH_4 emissions from the region, highlighting the interplay between natural processes and anthropogenic influences. Top-down and bottom-up estimates for 2018 reveal annual CH_4 emissions ranging from 3.27 ± 0.71 to 5.31 ± 2.50, with wetlands contributing 41–70% of total fluxes. Seasonal variability follows precipitation patterns, with greater emissions occurring during the rainy season (April–October). However, discrepancies between global biogeochemical models and sparse field measurements underscore significant uncertainties, exacerbated by inconsistencies in inundation mapping and outdated local data. Anthropogenic activities, including oil extraction, livestock farming, and expanding rice cultivation, further modulate CH_4 fluxes, though their impacts remain poorly quantified. Historical trends show declining precipitation and increasing temperatures, with models predicting more extreme weather events, potentially reducing wetland extent but favouring CH_4 release during remaining inundated periods. Critical research gaps, including the need for updated field measurements, improved inundation mapping, and a better understanding of neglected habitats like peatlands and seasonal wetlands, are discussed. Addressing these gaps is essential for refining global and regional CH_4 budgets and developing mitigation strategies. This work calls for integrated monitoring efforts to reconcile model disparities, assess land-use impacts, and predict responses to climate change, ensuring accurate representation of the Llanos del Orinoco in regional and global carbon cycle models.

1 Introduction

Understanding Earth's greenhouse gas dynamics requires a comprehensive view of both anthropogenic emissions and the natural processes that regulate atmospheric composition. Methane (CH_4) is the second most important greenhouse gas. While CH_4's atmospheric lifetime (11.2 years; Prather et al., 2012) is shorter than that of Carbon Dioxide (CO_2), it has a much higher radiative forcing efficiency (Myhre et al., 2014). As such, atmospheric CH_4 plays an important role in medium-term global warming, especially considering potential overshoot scenarios. Globally-averaged atmospheric CH_4 mole fractions were 1941 ppb in November 2024 (Lan et al., 2025), corresponding to nearly 2.5 times higher levels than pre-industrial concentrations of approximately 800 ppb (Heilig, 1994; Saunois et al., 2024). Though CH_4 levels were thought to be stabilizing from 1999 to 2006 (Dlugokencky et al., 2003;Turner et al., 2019), concentrations have been increasing since approx 2008 (Turner et al., 2019; Lan et al., 2025). While increments throughout the 20th century are attributed largely to industrial and agricultural emission sources, the post-2008 increase has been attributed to several processes, including changes in the lifetime of CH_4 However, recent studies increasingly point to a rise in tropical wetland emissions as a key factor (Basu et al., 2022; Drinkwater et al., 2023; Michel et al., 2024; Poulter et al., 2017).

Recent estimates of CH_4 emissions, both natural and anthropogenic, obtained from atmospheric inversion-based emissions indicate the dominant (65%) contribution from tropical and southern hemisphere emissions (<30°N) to the global budget: 575 Tg CH_4 yr^{-1}, range 553-586, corresponding to the minimum and maximum estimates of the model ensemble (Saunois et al., 2024). Tropical wetlands are highly productive ecosystems with rich organic matter, high temperatures, and are seasonally or permanently inundated. The combination of such characteristics often generates conditions favorable for CH_4 production. Global wetlands currently contribute about 159 Tg CH_4 yr^{-1}, accounting for roughly 25% of total CH_4 emissions from natural and anthropogenic sources (Saunois et al., 2024). However, large uncertainties in the global CH_4 budget are associated with sparse measurements in wetlands, especially in the tropics (Kirschke et al., 2013; Saunois et al., 2016, 2024), partly because estimates of wetland extent area and temporal variations in CH_4 fluxes used in bottom-up estimates remain limited for tropical wetlands (Delwiche et al., 2021; Saunois et al., 2024). In addition, representative site-level CH_4 flux measurements at required spatial and seasonal scales are scarce (Melack et al., 2022).

Some of the largest tropical wetlands are located in South America, with approximately 20% of its territory covered (Junk, 2013). The largest wetland systems of the sub-continent are in the tropical latitudes, including the floodplains of the lowland Amazon basin with 800,000 km^2 of total area (Melack & Hess, 2010); the Pantanal in Brazil, with small portions of its area also located in Bolivia and Paraguay, with 109,590 km^2 (Hamilton et al., 2002); the Llanos del Orinoco in Colombia and Venezuela with 105,450 $km^{2.}$ (Hamilton et al., 2004); the Llanos de Moxos in Bolivia with 92,000 km^2. However, large uncertainties in wetland area estimates exist (Fleischmann et al., 2022; Junk, 2013; Melack and Hess, 2010). Furthermore, the limited availability of ground-based data on CH_4 production, oxidation, consumption, and anthropogenic fluxes in tropical landscapes, which inform bottom-up models, hampers efforts to constrain global budgets and detect emerging trends.

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While a large effort has been dedicated to improving CH_4 emission estimates across the Amazon basin, little is known about these other large wetlands. Here, we focus on the floodplains of the Llanos del Orinoco, which are a mosaic of rivers, lakes, lagoons, floodplain channels, and large areas of alluvial soils with seasonally-inundated savannas. These systems and their carbon cycling are understudied compared to other South American wetlands (Malhi et al., 2021; Melack et al., 2022). The floodable savannas in the Llanos del Orinoco have a marked dry-wet season strongly influenced by local rainfall and runoff. Hence, its inundation is spatially heterogeneous, with lower amplitude and different frequency when compared to the Amazon (Hamilton et al., 2002, 2004; Fleischmann et al., 2022). Another marked difference between the two systems is the dominant woody vegetation in the Amazon compared to the dominant savanna vegetation in the Llanos del Orinoco (Rondón et al., 2006; Smith et al., 2000).

In this study, we review the current understanding of the CH_4 budget and identify the research efforts needed to improve knowledge of the carbon cycle in tropical inundated savannas across the Llanos del Orinoco region of Colombia and Venezuela. We aim to answer the following questions: (I) What is known about sources, sinks, and underlying processes that drive the CH_4 cycle in the Llanos del Orinoco in Colombia and Venezuela? (II) What is the CH_4 budget uncertainty for the region, based on freely/open-access global models? Based on our analysis, we discuss: (III) What are the research priorities and the current challenges to advance our knowledge of the CH_4 cycle in this important tropical wetland? and (IV) What are the main threats that can alter the CH_4 cycle in the Llanos del Orinoco of Colombia and Venezuela under ongoing global change?

2 Methods

2.1 Study area

The floodplains of the Llanos del Orinoco are located in northern South America within the Orinoco River watershed. The floodplains are bounded to the south by the Amazon forest–savanna transition (approximately 2°N to 3°N), to the west by the Andean piedmont (about 3°N to 7°N), to the north by the transition toward the Caribbean uplands (around 8°N to 9°N), and to the east by the Orinoco River delta and Atlantic coastal lowlands (roughly 8°N to 9°N; 60°W to 62°W) (Fig.1). The llanos are dominated by sedimentary deposits from the upper Tertiary and Quaternary, but an undulated relief from the Pliocene and Pleistocene is present on their southernmost border. The central and eastern regions are geologically elevated, favouring erosion and the occurrence of tertiary deposits near the surface (Randon et al., 2006). The rainy season starts in April and extends until October. During this period, local rains accumulate in clay-rich soils and water levels of large tributaries increase considerably, flooding the adjacent alluvial floodplain.

The Llanos del Orinoco are savanna ecosystems intersected by gallery forest, with four subregions: alluvial overflow plains, aeolian plains, elevated or high plateaus, and rolling hillsides. These are the dominant types of savannas in the Llanos, conforming a mosaic of rivers, lakes, lagoons, floodplain channels, and large areas of alluvial soils with temporally inundated savannas. Habitats include low-terrain portions susceptible to accumulating water for longer periods with submerged macroalgae. These are locally named "esteros". "Banquetas" are characterized by a mixture of grass and sedges, shrubs and forests on terrain that is slightly more elevated and thus less inundated than the lower savannas called "bajos", which are inundated for a longer period and dominated by C4 grasses (Lasso et al., 1999). These terrestrial-aquatic ecosystems have variable duration and extent of inundation according to their connectivity with other aquatic habitats, soil, and vegetation characteristics, which is determined by the seasonal rainy patterns and small variations in elevation (Rondon, 2000). Geomorphic and hydrologic factors on the floodplain modulate biogeochemical processes in rivers and associated floodplains, population dynamics and species distribution, community structure, food webs and energy flow, all of which influences CH_4 production and emissions (Botero Pito et al., 2024; Lewis et al., 2000; Morales-Rincon et al., 2021; Rondón et al., 2006).

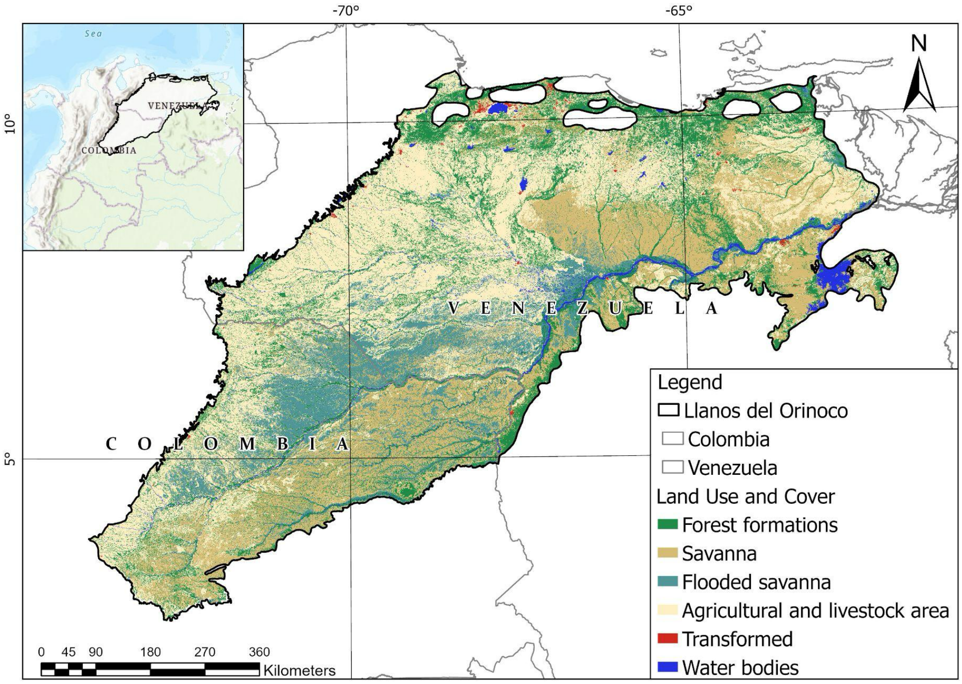

Figure 1: Land use and cover class for the Llanos del Orinoco in Colombia and Venezuela. The map was generated by the authors based on data from MapBiomas Colombia (Collection 3.0) (MapBiomas, 2023, https://drive.google.com/drive/folders/1J6FcSFzAAJLAIbFXWDA-Rq1GXCXM_M0F?usp=sharing), and Terrestrial Ecoregions of the World from WWF http://www.worldwildlife.org/ecoregions (Olson et al., 2001). Shape includes llanos, Apure-Villavicencio dry forests and La Costa xeric shrublands from the database.

2.2 Datasets used

We used a wide range of existing global and regional datasets that represent the wetland area extent, CH_4 surface emissions, climate, land use and land management, as well as peat areas in the Llanos del Orinoco. Only datasets that cover the entire Llanos del Orinoco region, and bilinearly interpolated to 1 km resolution were included: (1) Global Lakes and Wetland Database (GLWD) (Lehner & Döll, 2004), (2) Tropical and Subtropical Wetland Distribution Database v7.1 (TSWD) (Gumbricht et al., 2017a), (3) Wetland Cover map from the Globcover Project (Arino et al., 2007; Bicheron et al., 2006), (4) The global surface water extent (Pekel et al., 2016), (5) The Global Inundation Extent from Multi-Satellites (GIEMS) (Fluet-Chouinard et al., 2015), (6) The PEATMAP dataset (Xu et al., 2018) and The Tropical and Subtropical Peat Distribution v2.1 (TSPD) (Gumbricht et al., 2017b). Databases associated with lakes and wetlands were analyzed at 1 km resolution. We focused our analysis on 2018 as all the datasets overlap this year. Also, it is important to highlight that our main goal with the analysis is to contextualize the llanos into a regional CH_4 budget, sorting out the contribution of the different sources, instead of exploring interannual variability of the fluxes computed.

We used several approaches and available products to estimate CH_4 emissions and CH_4 concentrations for the Llanos del Orinoco. The process-based model, Wetland CH_4 Emission Ensemble (WetCHARTs, Bloom et al., 2017), and the data-driven (surface and GOSAT satellite observations using TM5-MP 4D-Var) CAMS CH_4 Inversion (Bergamaschi et al., 2013) -Copernicus Atmosphere Monitoring Service (2020): CAMS global inversion-optimised greenhouse gas fluxes and concentrations, version v22r2. Copernicus Atmosphere Monitoring Service (CAMS) Atmosphere Data Store, DOI: 10.24381/ed2851d2 (Accessed on 12-09-2024) was used to derive bottom-up (WetCHARTs) and top-down (CAMS-Inversion) estimates for CH_4 emissions. WetCHARTs provides an ensemble of models based on a global scaling factor, temperature dependence of CH_4 emissions (Q10), and wetland extent parameterization. For our analysis, we selected the six ensemble members of the middle global scaling factor (#2) and averaged each (n=2) wetland extent over the three possible Q10 (1, 2, 3). Therefore, we ended up with two ensemble members that represent the mean effect of varying Q10: WetchartsX3 based on the Global Lakes and Water Database (Lehner & Döll, 2004) and with WetchartsX4 based on the GLOBCOVER (Bontemps et al., 2012). Additional bottom-up information from the Global CH_4 Budget Project (GCP-CH4, Saunois et al., 2024) was downloaded (https://www.icos-cp.eu/GCP-CH4-2024) and compared to the other estimates. The top-down and bottom-up budget were calculated as follows:

$$F_{total\ top\ down} = F_{wet} + F_{rice} + F_{bb} + F_{other\ (livestock,termites,waste,soilsink)} \tag{1}$$

$$F_{total\ bottom\ up} = F_{wet} + F_{livestock} + F_{oil\ gas} + F_{rice} + F_{other\ (\ termites,waste,freshwater)} - F_{soil} \tag{2}$$

Climate projections were obtained from 30 CMIP6 global climate models (Appendix B, Table B1) and statistically downscaled to a 0.25° × 0.25° spatial resolution using the NASA Earth Exchange Global Daily Downscaled Projections dataset (NEX-GDDP-CMIP6), available at https://www.nccs.nasa.gov/services/data-collections/land-based-products/nex-gddp-cmip6.

A bibliography search and compilation were done in November 2023 to gather the available information from field studies that have measured CH_4 fluxes in the Llanos del Orinoco. We used keywords in English and Spanish such as "carbon stocks”, “Llanos flooding”, “emissions”, “greenhouse gases”, “climate change”, “methane“, “carbon accumulation in the Llanos”, and “Flood pulse theory”. We searched across Web of Science, Scopus, Google Scholar, and PubMed and included

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theses and dissertations from repositories in Colombian universities. Criteria for inclusion were CH_4 field data that included tables and figures, and a geographical focus on the Llanos del Orinoco. Exclusion criteria included missing data and indirect estimates based on IPCC emission factors or similar approaches.

3 Results

3.1 Top-down and bottom-up estimates for 2018

The total CH_4 budget for the Orinoco region ranges (mean and annual standard deviation) from 3.27 ± 0.71 (GCP-CH4) to 5.31 ± 2.50 (CAMS-Inversion prior) and 4.97 ± 2.33 Tg CH_4 yr^{-1} (CAMS-Inversion posterior) (Fig. 2). Wetlands are the main source of CH_4 emissions in the Llanos del Orinoco, contributing between 41% (GCP-CH4, bottom-up) and 70% (CAMS, top-down) of the total estimated fluxes. The small change from prior to posterior in the CAMS-Inversion suggests that the region is not well constrained by the assimilated data. Bottom-up estimates for wetland fluxes are variable and associated with differences in model inputs and parametrization. The GCP-CH4 estimate (1.34 ± 0.74 Tg CH_4 yr^{-1}), is of the same magnitude (Wetchartsx4, 1.1± 0.7 Tg CH_4 yr^{-1}) or lower (Wetchartsx3, 3.2 ± 2.1 Tg CH_4 yr^{-1}) than wetland estimates from Wetcharts (Fig. 2). The anthropogenic share of the total fluxes is dominated by livestock (24%) and the oil and gas industry (23%) (Fig. 2). Soil fluxes are the only negative biospheric flux compiled in our study (Fig. 2). Rice (0.3%-CAMS, 0.4%- GCP-CH4) and biomass burning (1.6%-CAMS, 1.9%-GCP-CH_4) represent only a small fraction of the total CH_4 flux for both top-down and bottom-up approaches.

The seasonality of CH_4 fluxes mirrors regional precipitation patterns, with higher monthly fluxes during the rainy season (April–October). These peak fluxes are larger in the top-down CAMS posterior estimates (3.9–7.66 Tg CH_4 yr^{-1}) than in the bottom-up GCP-CH_4 estimates (2.78–4.55 Tg CH_4 yr^{-1}) (Fig. 3).

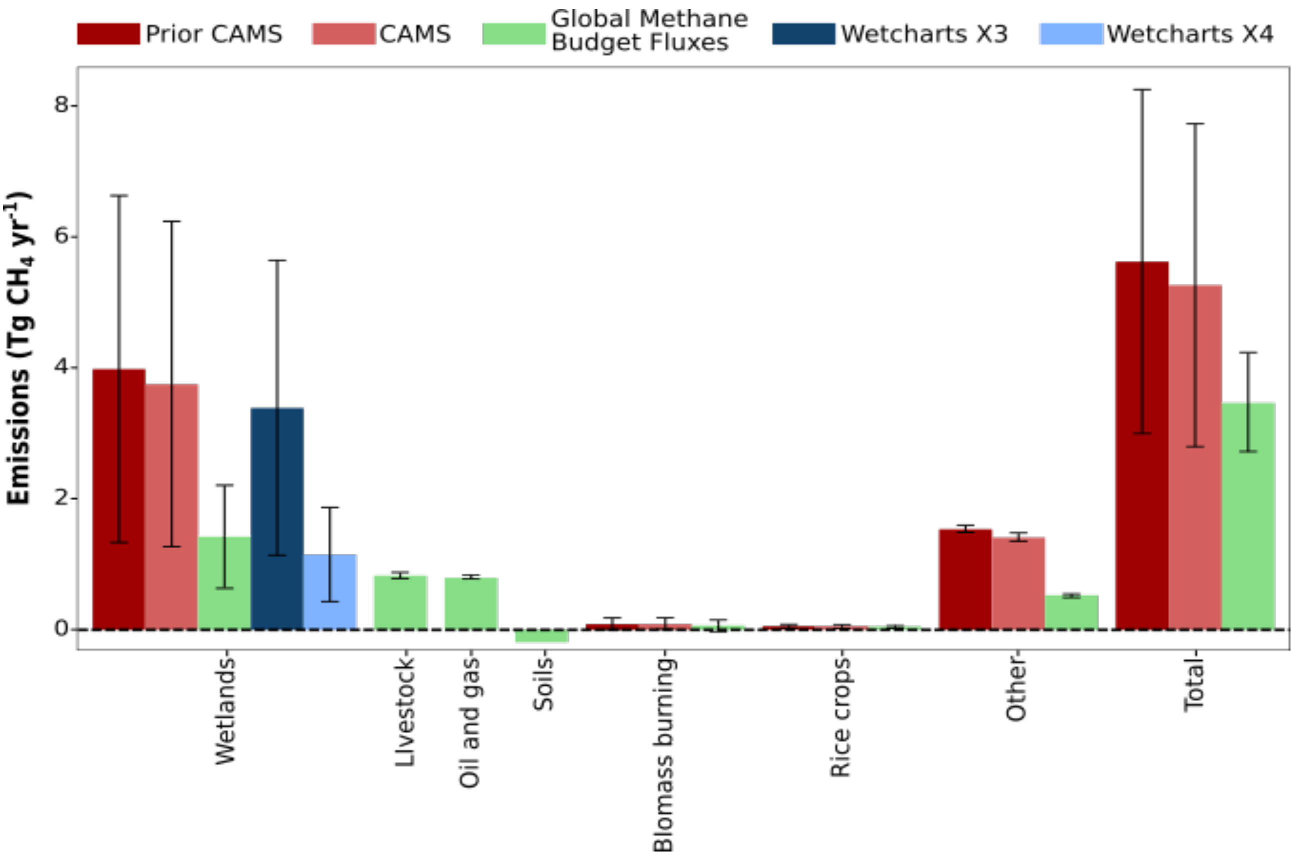
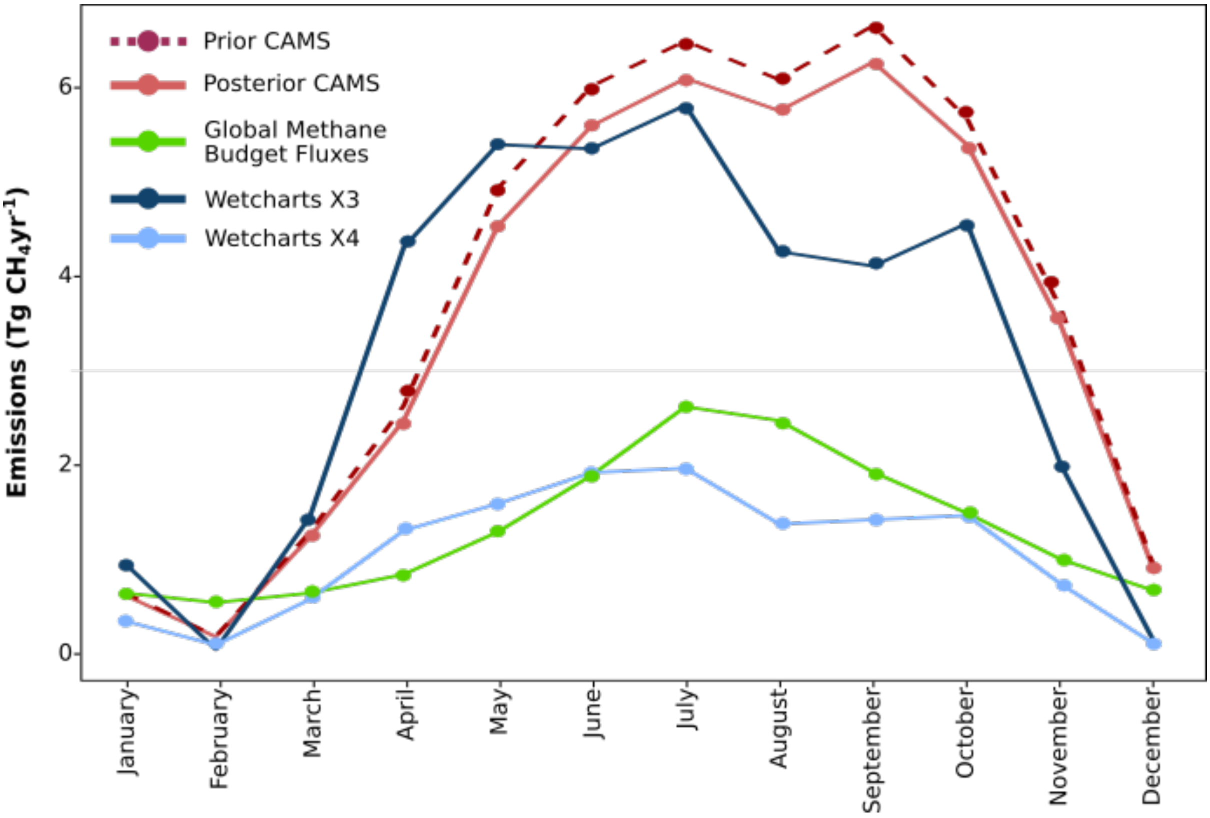


Figure 2: Annual mean CH_4 emissions for 2018 in the Llanos del Orinoco region as reported by different data sources: (1) Prior and posterior CH_4 emissions provided by the Copernicus Atmosphere Monitoring Service (dark red and light red; CAMS, 2024). (2) CH_4 emissions from the Global CH_4 Budget (GCP-CH_4, green bars; Saunois et al., 2024). (3) Methane fluxes based on the WetCHARTs v1.3.1 model. The set of WetCHARTs ensemble members shows average values from different temperature dependence factors for the CH_4 respiration fraction (Q10) and two different wetland extents: Global Lakes and Water Database - X3 dark blue bar (Lehner and Döll 2004), and GLOBCOVER - X4 light blue bar (Bontemps et al., 2012). The bars display the standard deviation due to seasonal variability from the monthly means for each emission source and are given in the text as (±) to indicate the variability within the year; sources without error bars indicate no seasonal variability or a single value available for the monthly time-series. The category other for GCP-CH4 (green bar) includes waste, freshwaters and termite fluxes; for CAMS, it represents all sources except wetlands, fire, and rice emissions.



185 **Figure 3:** Seasonal cycle of wetland CH_4 fluxes based on the WetCHARTs v1.3.1 model, top-down inversions for CAMS (prior and posterior), as well as data from the Global CH_4 budget (GCP-CH_4) for 2018. The set of WetCHARTs ensemble members shows average values from different temperature dependence factors for the CH_4 respiration fraction (Q10) and two different wetland extents: Global Lakes and Water Database - X3 dark blue line (Lehner and Döll 2004), and GLOBCOVER - X4 light blue line (Bontemps et al., 2012).

190

The difference in peak emissions during the wet period between top-down and bottom-up approaches does not appear to be structural (Fig. 3). The bottom-up estimate from Wetcharts X3 is of a similar magnitude as the top-down estimates, and the discrepancy between prior and posterior top-down estimates is minimal (Fig. 3). This suggests that the differences between the two approaches are primarily driven by uncertainties in input data and parameterization in the bottom-up method, as well as in the priors used for the top-down inversion. 195

The seasonality in both Wetcharts (X3 and X4) ensemble members has a similar shape to the other products, suggesting that they capture well the variability in CH_4 emissions associated with seasonal factors. However, large differences are observed in the magnitude of the estimated emissions, and mainly during the rainy season (April-October) (Fig. 3). Such differences can be explained primarily by the structural differences in inundation map areas, rather than differences due to different parameterizations of Q10. Wetcharts X3 (Global Lakes and Water Database) uses a product with a greater inundation map area (5 times greater) compared to Wetcharts X4 (GLOBCOVER) (Fig. 4).

3.2 **Current field estimates of CH_4 evasion**

Only a limited number of studies have examined CH_4 fluxes from seasonally or permanently inundated ecosystems in the Llanos del Orinoco floodplain. Our literature search identified only 7 relevant manuscripts that report field measurements for CH_4 emissions (Table 1), although others (Etter et al., 2010; Rondón et al., 2006; San José & Montes, 2001) use the information to discuss the regional role of the Llanos de la Orinoquia in the carbon cycle. The field studies suggest that the Llanos del Orinoco floodplain is a small source of CH_4 to the atmosphere compared to other wetlands in South America. Annual estimates of CH_4 flux from the Llanos del Orinoco floodplain and upper delta (total area, 14.5 × 10^3 km^2) in Venezuela are 0.17 Tg CH_4 yr^{-1} or 113.6 mg CH_4 m^2 d^{-1} as reported by Smith et al. (2000), which is restricted to aquatic or inundated habitats. Castaldi et al. (2004) report that the Llanos del Orinoco in Colombia and Venezuela, for a total area of 357 × 10^3 km^2 (including woodland, herbaceous savannas, open tree savannas, and cultivated pastures), act as a source of CH_4, contributing 0.13 Tg CH_4 yr^{-1}. A study at the Colombian portion of the Llanos del Orinoco calculated, for Colombia and Venezuela, annual CH_4 emissions of 0.16 Tg CH_4 yr^{-1}, including estimates for the savanna ecosystem (soils under crops, pasture, gallery forests, and natural savannas, termites) together with burning and cattle (Rondon 2000).

Table 1: Methane fluxes from the Llanos del Orinoco. Data is extracted from the literature, and includes direct measurements of CH_4 fluxes in the field. Measurements span a variety of aquatic and savanna habitats and are given as mean values (mg CH_4 $m^{-2}d^{-1}$).

Reference	Country/ Season/n.º measurements	Habitat/ Land use	Mean CH_4 mg $m^{-2}d^{-1}$	Annual Fluxes. Tg yr^{-1}	Area Used ($X10^3km^2$)
*Castaldi et al 2004	Venezuela	Cultivated Grassland	- 0.06 / -0.05		
	Dry/Wet	Herbaceous Savanna	0.27 / 0.19		
	40	Open Tree Savanna	- 0.29 / 0 .66		
		Woodland Savanna	- 0.14 / - 0.02		

*Sanhueza et al 1994	Venezuela	Savanna	0.92		
	Wet	Ploughed savanna	1.35		
	51	Ploughed and fertilized savanna	1.14		
*Scharffe et al 1990	Venezuela	Savanna	0.8		
	Wet	Forest	- 1.14		
	153				
Smith et al 2000	Venezuela	All data (Diffusive + Ebullition)	114	0.17	14
	Dry and Wet				
	Floodplain and upper delta	Flooded forest (Diffusive)	40.3		
	412	Open Water (Diffusive)	15.7		
		Macrophytes (Diffusive)	12		
Rondon 2000	Colombia	Burned savannas	0.05		
	Dry and Wet	Umburned savanna	0.07		

		Soil	-0.15		
	N.A.	effect of burning on soil	0.02		
		burning products	1.86		
		Cattle	6.78		
		Termite	0.002		
		All data	8.64	0.17	120
Sanhueza and Donoso 2006	Venezuela Wet 64	Cleared soil	-0.41		
		Undisturbed soil (Trachypogon sp)	0.52		
Hao et al 1988	Venezuela Dry 43	Woodland	0.98 (all)		
		Natural grassland			

* Extracted from (Castaldi et al., 2006). N.A = Not Available.

The compiled studies have different approaches and research focus, and are more than 20 years old. Some focus on aquatic sites (lakes, rivers, and fringing floodplains), while others focus on soil fluxes from native vegetation and croplands. The calculated annual CH_4 flux estimates (Table 1) are in general, one order of magnitude lower than our top-down and bottom-up estimates (previous section). However, the seasonal patterns in CH_4 fluxes are consistent. Therefore, such a large difference in magnitude between site-level extrapolations and the top-down and bottom-up models highlights the lack of local data, as well as the challenges in obtaining accurate maps of wetland extent for flux upscaling.

https://doi.org/10.5194/egusphere-2026-2080
Preprint. Discussion started: 29 April 2026

4 Discussion

4.1 The Llanos del Orinoco CH_4 fluxes in context

Our total CH_4 budget for the Orinoco region ranges from 3.27 (+- 0.71, GCP-CH_4) to 5.31 (+- 2.50, CAMS-Inversion prior), indicating that the region is a significant but not dominant CH_4 source, compared to other important wetlands in South America (Table 2). On an annual basis, our estimate is at a similar magnitude as other seasonal savannas in the continent (Pantanal, Llanos de Moxos), but an order of magnitude smaller than the Amazon Basin (Table 2). Compared to other relevant known CH_4 sources, our estimate, represents one- seventh of CH_4 fluxes from boreal arctic wetlands and lakes (Table 2), one-fifth of global CH_4 fluxes reported from reservoirs (25, range 13–65 Tg CH_4 yr^{-1}), one-sixth from rivers and streams (29 ±17 (±CI95 %) Tg CH_4 yr^{-1}), one-tenth of global emissions (53, range 19–86 Tg CH_4 yr^{-1}) from large lakes (>0.1 ha), small lakes and ponds (>0.1 ha), reported by the recent Global CH_4 Budget (bottom-up approaches, 2010-2019) (Saunois et al., 2024). However, areal CH_4 flux rates are similar, or within the range, reported for mean areal fluxes for important natural sources like the Amazon, other savanna ecosystems, or for global medians for northern wetlands (Table 2).

Livestock and oil and gas industry are the dominant CH_4 fluxes from anthropogenic sources in our study. This result is in agreement with a study evaluating CH_4 emissions, estimated by inversions from satellite information, from Latin American countries, where livestock is the main source. However, the oil and gas industry is particularly important for countries like Colombia and Venezuela, which are among the top five anthropogenic emitting countries in South America (Hancock et al., 2025).

Wetlands were the dominant flux from our regional budget, but uncertainties were the largest for this component (Fig. 2). Wetlands are known to be hotspots of CH_4 production (Kirschke et al., 2013) as they are commonly associated with high primary productivity (Piedade et al., 1991; Bodmer et al., 2024). Enricheded with organic matter, in combination with inundated conditions, produce low oxygen environments, which favor CH_4 production (Barlett and Harris 1993;Barbosa et al 2020). Wetland area was the dominant uncertainty term for CH_4 fluxes in a recent regional estimate for Boreal-Arctic wetlands and lakes (Kuhn et al 2025). Likewise, the differences in our wetland CH_4 fluxes estimates from wetcharts are largely explained by the wetland area used at each estimate (Fig. 3). It is challenging to delimitate the areas where CH_4 is produced or consumed within the wetland domain, although segmenting fluxes by aquatic habitats (Amaral et al., 2020) or ecosystem types can reduce emissions uncertainties avoiding double counting of CH_4 fluxes (Kuhn et al 2025).

Water temperature, vegetation structure/composition, and water table depth are common drivers of CH_4 dynamics (Pangala et al 2017; Rosentreter et al 2021; Calabrese et al., 2021; Li et al., 2025), whereas variations on these parameters could affect the magnitude and direction of CH_4 exchange with the atmosphere (Zhao et al., 2026), as they change the oxygen environment that controls methanogenic vs methanotrophic microbial activity (Hanson and Hanson 1996; Conrad et al., 2014).

https://doi.org/10.5194/egusphere-2026-2080
Preprint. Discussion started: 29 April 2026

Table 2: Summary of CH_4 fluxes from the Llanos del Orinoco, other wetlands in South America, wetlands at northern latitudes, and other savannas. Data is extracted from a few references to provide a comparative context with similar estimates for South America and other regions of the globe. Information on methods associated with the different estimates is given at column " Key methods & data sources".

Region	Annual Emission ($Tg\ CH_4\ yr^{-1}$)	Areal Flux Rates ($mg\ CH_4\ m^{-2}\ d^{-1}$)	Key Methods & Data Sources	Reference
South America				
Llanos del Orinoco	3.3 ± 0.7 to 5.31 ± 2.5	Range 17.5 – 28.4	Bottom-up (process-based models) and Top-down (inverse modeling).	This study
Llanos del Orinoco		Range -1.14 to 114	Chamber measurements	References at Table 1
Llanos de Moxos, Bolivia	3.6	140.9*	Airborne vertical profiles, ground measurements, box-model, inverse modeling, Bayesian methods.	France et al., 2022
Pantanal	~3 (range 2.0 – 3.3)	50	1Flux chambers + spatial integration. 2Aircraft + boundary layer mass balance vs. 3-D atmospheric inversion.	[1]Marani & Alvalá, 2007 [2]Gloor et al, 2021
Amazon Basin	46.2 ± 10.3	17.4 ± 3.9	Airborne vertical profiles over 8 years, atmospheric column-based technique.	Basso et al., 2021
		Global Context (field measurements)		
71 Northern Wetlands (Subtropical, Temperate and High latitude)		Range (Median) -0.3 to 68.4 Range (Mean) 4.4 ± 0.9 to 112.2 ± 6.2	Primarily flux chamber measurements.	Turetsky et al., 2014
Boreal-Arctic wetlands and lakes	34 ± 25-43	Boreal wetlands (20.7), Large glacial lakes (0.9), mid size glacial lakes (2.4)	BAWLD-CH4. Primarily site-level chamber measurements together with eddy covariance data	Kuhn et al., 2025
Global Savannas		Range (Mean) -- 22.8 to 3.15	Flux chamber compilation from multiple countries.	Castaldi et al., 2006

*Calculated from annual estimate for a total area of 70.000 km^2

4.2 Research needs and challenges for understanding CH_4 dynamics in the Llanos del Orinoco

4.2.1 Inundation mapping and seasonal dynamics.

We identified three key research areas that require further attention to improve CH_4 emission estimates and dynamics. The first one is ***Inundation mapping and seasonal dynamics***. Inundation mapping is a central need for reducing uncertainties. A clear need for this is exemplified by the marked seasonal pattern of CH_4 fluxes, driven by local precipitation, and consistently captured by both, top-down and bottom-up estimates as well as field studies. Inconsistencies in mapped inundated areas currently represent the primary source of uncertainty in bottom-up CH_4 emission estimates (Fig. 2).

There are large inconsistencies in the inundation extent between products and a lack of coincidence between them (Fig. 4), highlighting the need for improved inundation mapping for the Llanos del Orinoco region. Savannas and interfluvial wetlands have less predictable inundation dynamics, as it is largely governed by local rainfall and runoff (Fleischmann et al 2022). Furthermore, there are fundamental differences in sensor technology, coarse resolution among different products, the temporal representation and the definition criteria for delimitating inundation areas among products that explaining such contrast in inundation mapping area (*see* Fleischmann et al., 2022). GLWD-3 and TSWD provide inundation areas greater than 100,000 km^2, but when the inundated mapped areas are compared between these two products, they only coincide in ~49,000 km^2. Other available products (GlobCover and GSWE) for inundation mapping in the Llanos del Orinoco have a much lower inundation area, with ~20,000 km^2. Comparisons between GlobCover and GSWE inundated mapped area coincide by only ~11,000 km^2 (Fig. 4). As shown in Fig. 2, uncertainty in the extent of flooded areas directly translates into uncertainty in CH_4 emissions, with inundation extent currently being the dominant factor limiting the accuracy of bottom-up CH_4 emission estimates. Accurate maps of the extension of inundation, including duration and interannual variability, are an urgent call for action.

Global models provide a broad overview of CH_4 emissions; however, they often lack the detail necessary to accurately represent regional variations to CH_4 emissions. None of the studies compiled from the literature have evaluated the impact of variations in inundation extent on CH_4 fluxes. Mapping the frequency and duration of inundation for the different aquatic habitats and wetlands in the Llanos del Orinoco is crucial for properly upscaling CH_4 emissions. These habitats represent the major CH_4 flux in our budget, and seasonally inundated areas can act as a source or a sink depending on inundation and soil water saturation conditions (Smith et al., 2000; Rondon 2000).

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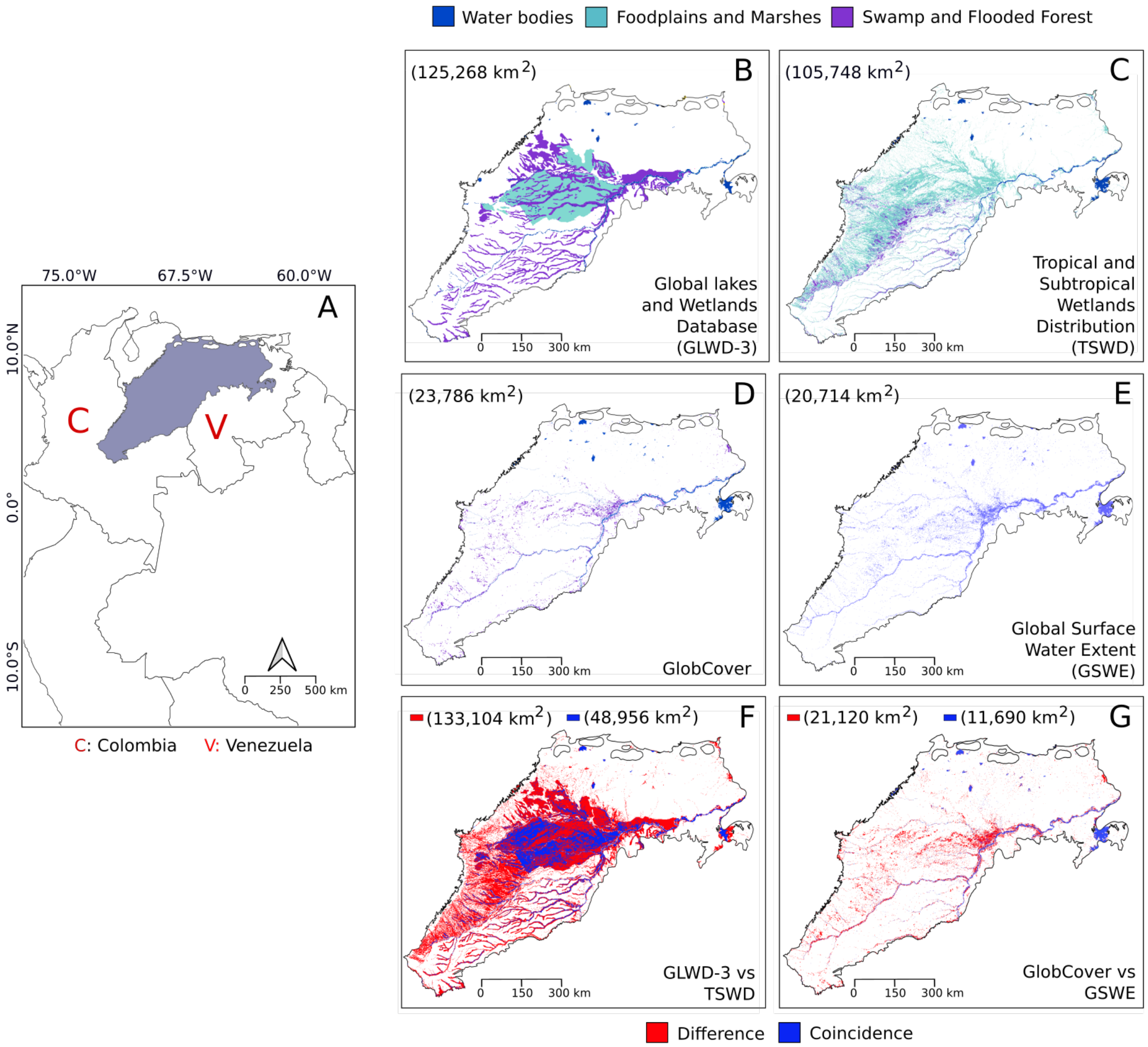

Figure 4: Comparative analysis of wetland area in the Llanos del Orinoco Ecoregion based on four products. A. Geographical location of the Llanos del Orinoco ecoregion, spanning areas across Colombia and Venezuela. B. Global Lakes and Wetland Database-Level3 (GLWD-3) C. Tropical and subtropical wetland distribution (TSWD) from The Sustainable Wetlands Adaptation and Mitigation Program (SWAMP). D. Wetland cover map from the Globcover project. E. Global Surface Water Extent (GSWE). Difference and coincidence maps comparing wetland areas between F. GLWD-3 and TSWD, and G. Globcover and GSWE. Land cover classifications for each product were merged to have the same wetland classification: Water bodies, Floodplains and Marshes, and Swamp and inundated Forest.

Wetlands and Morichales and Peatlands

Peatlands were recently identified as a frequent wetland type in parts of the Colombian Llanos del Orinoco (Winton et al. 2025), a somewhat counterintuitive finding given that the region is characterized by intense hydrologic seasonality and that peat soils require persistent saturation to form in the tropics (Takada et al., 2016). Maps of peatlands based on these new field observations indicate that morichales (palm swamps) and floodplain forests are the most extensive peatland type in this region (92% of peatland extent, Uhde et al. 2025). Floodplain forests may support peat soils in the region, though such observations are scarce (Flores Llampazo et al., 2022). However, open herbaceous swamps are also documented (7%). To date, no CH_4 emissions data have been recorded from peatlands of the Llanos del Orinoco, though data from Amazonian peatlands suggest that they could be potent emitters (Winton et al. 2017, Teh et al. 2017, Soosar et al. 2022).

Peatlands that are dependent on rainwater (bogs) are typically poor producers and emitters of CH_4 because the provision of fresh carbon inputs by plants is limited by their nutrient-poor setting. Peatlands of the Llanos del Orinoco, however, are likely to be of higher productivity and minerotrophic since they are often subject to pulses of surface water during wet season floods and sustained by groundwater inputs during dry seasons. Although they may represent a small fraction of total wetland area, they may contribute disproportionately to regional CH_4 budgets because of their potential for high perennial primary productivity and persistent soil saturation. However, field-based measurements are needed to ascertain their contribution to CH_4 relative to other wetland types.

Notably, peatlands of Colombia are often forested, so care must be taken to measure both direct soil flux as well as emissions facilitated by tree transport, as the latter pathway has been shown to represent up to half of forested wetland CH_4 flux in neotropical wetlands (Pangala et al. 2017).

4.2.2 **Agricultural expansion and infrastructure**

A second research priority is to understand the effects, if any, of ***agricultural expansion*** on CH_4 flux dynamics**.** Agricultural expansion is mainly due to the conversion of natural savannas to exotic pastures for cattle activities, palm for oil production, and rice crop expansion. These changes may be driven by increased direct emission from plant-mediated fluxes in rice crops, as well as rising CH_4 emissions from expanding cattle herds in the region, where enteric fermentation releases CH_4 primarily through eructation (cow burp). Changes in CH_4 dynamics can also be indirect, through modifications of hydrological connectivity between natural habitats following land preparation (e.g., clearing, burning, leveling) for crops or cattle. These alterations affect inundation patterns and soil biogeochemistry, influencing CH_4 production and consumption.

Rice crops

Rice cultivation and biomass burning represent only a small fraction of the total CH_4 fluxes (0.3-1.7%) according to bottom-up and top-down estimates (Fig. 2). However, rice crops have expanded in the region over the last decade (Appendix A, Fig.A1), replacing land that was previously designated for cattle activities (Botero Pito et al., 2024). Earlier projections suggested that CH_4 emissions from rice would increase fourfold between 1970-2020 (Etter et al., 2010). Rice crops often need a persistent condition of inundation, which favors methanogenesis (Jiang et al., 2019). Also, CH_4 is emitted actively by plant mediated transport (Hamilton et al 1995; Boadner et al 2024), but has variable fluxes associated with different plant-specific traits such as aerenchyma structure, root oxidase activity, and root exudation (Bhattacharyya et al., 2019). CH_4 studies in rice crops are needed to evaluate the impact of converting natural savannas to this agricultural practice, and to elucidate plant mediated fluxes associated with the species cultivated in the Llanos del Orinoco. Finally, this poses the question of whether estimates from the global CH_4 budget (Saunois et al., 2024) and CAMS are capturing the CH_4 fluxes associated with rice crop increments that we noticed for the Llanos del Orinoco in the last decade (Appendix A, Fig. A1). Similarly to the inundation extent (Fig. 4), structural uncertainties in input data of bottom up and prior estimates of top-down estimates are currently limiting our understanding of the CH_4 budget and temporal dynamics across the region.

Livestock

CH_4 fluxes from livestock are comparable in magnitude to emissions from the oil and gas sector, the largest anthropogenic contributors in our dataset (Fig. 2). Cattle numbers in Colombia have increased by about 25% since 2016, largely linked to deforestation and expanding demand from international markets (e.g., China, Russia, Algeria). This growth is particularly evident in the Llanos del Orinoco, where cattle ranching has long been a dominant economic activity and cattle herd numbers have expanded steadily over the last decade (see https://www.fedegan.org.co/estadisticas/general). Such land-use change and/or increases in grazing intensity can also influence CH_4 dynamics indirectly by altering hydrological connectivity through clearing, burning, or leveling, which affects inundation patterns and soil biogeochemistry. These livestock-related CH_4 emissions remain insufficiently quantified and likely represent overlooked or underestimated sources in both top-down and bottom-up approaches. Targeted experimental studies are needed to evaluate how ongoing land transformation, especially the expansion of grazing areas and rice cultivat ion, affects CH_4 production and consumption in these ecosystems.

Oil and Gas

The anthropogenic share of the total fluxes compiled in our study is dominated by the oil and gas industry, which together contribute 0.75 Tg CH_4 yr^{-1} (Fig. 2). The oil and gas industry in the Llanos del Orinoco is concentrated close to the Andean foothills, as well as in the southern-eastern portion of the Llanos del Orinoco (Fig. 1). A recent work in Venezuela (Nathan et al., 2024) reveals that CH_4 emissions from Venezuela's oil production, particularly around Lake Maracaibo, remain alarmingly high despite a sharp decline in oil exploitation, suggesting leaks from abandoned or deteriorating infrastructure rather than active production. The region around Lake Maracaibo contributes 1.2 Tg CH_4 yr^{-1}, with approximately half of it being attributed to oil production, which is about the same magnitude of the oil and gas evasions reported in our study (Fig. 2). Using analytical inversions with 2018-2020 TROPOMI satellite CH_4 data, Nathan et al. (2024) estimate national emissions for Venezuela of 7.5 Tg CH_4 yr^{-1} in 2019, which is higher than our regional estimate for the entire Llanos del Orinoco. These findings highlight the urgent need for better monitoring of CH_4 fluxes and leaks in oil-producing regions to mitigate climate impacts. The authors also highlight limitations of using TROPOMI to obtain CH_4 flux estimates due to the region's complex topography, persistent cloud cover, and low albedo, making satellite observations difficult. TROPOMI's high resolution and daily coverage provide unprecedented data. Still, uncertainties remain due to limited observational constraints for northern

South America (Nathan et al., 2024), which can be improved with more ground measurements or atmospheric monitoring stations.

4.2.3 **Climate change**

The third key research area, is *Climate change*, that might play a fundamental role in future CH_4 emissions. Our analysis of historical temperature and precipitation extremes from 1981-2023 reveals a warming climate with hotter days and nights, fewer cold nights, and decreasing precipitation over the Orinoquia region (Appendix B, Fig. B1, Table B2). Higher temperatures can enhance CH_4 production (Conrad, 2023), but reduced rainfall is likely to reduce the inundated conditions that are more conducive for CH_4 production (Conrad, 2020). Annual daily maximum (TXx) and minimum (TNn) temperatures have increased by 0.22 °C/decade and 0.15 °C/decade, respectively (Table S1). Hot days (TN90p) increased by 3.1%/decade, and cold nights (TN10p) decreased by 2.0%/decade. Precipitation indices showed mostly negative trends, with total annual precipitation (PRCPTOT) and RX1day (maximum 1-day precipitation) experiencing the most significant declines of -40.1 mm/decade and -1.2 mm/decade, respectively (Appendix B, Table B2, Fig. B1). Lower precipitation could also limit conditions that favor methanogenesis.

Several environmental factors are known to influence CH_4 fluxes and concentrations in inland aquatic ecosystems, which are related to precipitation and temperature. Water temperature (Yvon-Durocher et al., 2014), hydrodynamics (MacIntyre et al., 2021), aquatic metabolism (Amaral et al., 2018; Barbosa et al., 2018), organic matter quality (Mayorga et al., 2005; Ward et al., 2013), water currents (Alin et al., 2011; MacIntyre et al., 2019) and connectivity between different aquatic ecosystems (Abril et al., 2014; Abril & Borges, 2019; Amaral et al., 2022; Melack et al., 2009) and even grazing of macrophytes by aquatic herbivores (Winton et al. 2017) can be important factors impacting CH_4 dynamics. All of these are likely to be affected by climate change and land use forces acting in the Llanos del Orinoco. The above-mentioned environmental factors that influence CH_4 dynamics have seldom been examined in the Llanos del Orinoco region. Also, studies exploring how they have been affected, and will be affected, by changes in precipitation and temperature, are yet to be explored. Doing so is crucial to improve our mechanistic understanding of carbon fluxes from these environments, as well as to improve modelling attempts to evaluate how tropical floodplains will respond to changes in climate and land use.

Future projections for the Llanos del Orinoco reveal two counteracting climate trends with critical implications for CH_4 emissions. On the one hand, the region will become hotter and drier overall, with annual rainfall decreasing by 5% and warm spells extending up to 177 days longer by 2100 under high-emission scenarios—conditions that reduce wetland extent and inundation persistence, that could lead to decreases in CH_4 production. On the other hand, climate models paradoxically predict more intense extreme rainfall events (up to 15.5% increase in single-day downpours), which combined with low-permeability alluvial soils could trigger hot spots and hot moments of elevated CH_4 emissions after temporary flooding. Rising temperatures (up to 3.06°C for extreme heat days) may further amplify these emissions during wet phases, as warmer waters might accelerate microbial CH_4 production (Conrad, 2023). The interaction between prolonged aridification and intermittent extreme rainfall events is projected to destabilize the region's hydrological regime. This could represent a decrease in inundation extent and less water infiltration in savannas soils, as inundation in the Llanos del Orinoco is more governed by local precipitation (Fleischmann et al., 2022, 2023; Hamilton et al., 2002, 2004), likely shifting CH_4 emission patterns from stable fluxes to episodic pulses.

5 Conclusions

The Llanos del Orinoco represent a key yet underestimated component of the global CH_4 budget. Current estimates suggest that the Llanos del Orinoco emit between 3.27 (± 0.71, GCP-CH4) to 5.31 (± 2.50, CAMS-Inversion prior) Tg CH_4 yr^{-1}, with wetlands contributing significantly (41–70% of total emissions). However, major uncertainties remain due to the lack of updated local measurements and discrepancies in available inundation maps. Top-down and bottom-up approaches show notable differences in CH_4 emissions, underscoring the need for more empirical data to reduce uncertainty. Anthropogenic activities, such as the oil industry and livestock farming, contribute significantly to CH_4 emissions, while rice cultivation, though expanding, remains a minor source.

Ground-based studies in Llanos del Orinoco show complex CH_4 dynamics shaped by seasonal hydrology and land use. Key findings indicate that water-saturated soils and inundated vegetation act as CH_4 sources, while dry soils do not emit (Rondon, 2000; Castaldi et al., 2004; Smith et al., 2000). Human conversion to agriculture, especially pastures (Botero Pito et al., 2024), tends to increase emissions (Castaldi et al., 2004). Collectively, these studies estimate the region is a modest CH_4 source (0.13–0.17 Tg CH_4 yr^{-1}). However, the available information is old and limited to a few measurements in time and space (Table 1). Establishing new ground-based monitoring programs to measure CH_4 emissions from representative habitats in the Llanos del Orinoco is needed. In addition, atmospheric measurements of CH_4 concentrations will be crucial to validate satellite and model results further.

Advancing our understanding of this ecosystem is crucial for predicting and mitigating the impacts of climate change and human activities on its carbon dynamics. Our call for action is divided into four principal directions: (1) high-resolution monitoring of flood extent and duration, (2) Local Measurements: continuous CH_4 flux measurements spanning hydrological transitions and continuous monitoring of atmospheric mole fractions that combined with inverse modeling can provide refined flux estimates, (3) Climate Change Impacts: manipulative experiments replicating projected climate extremes and their impact on CH_4 sources and sinks and (4) Better understanding of the role of ecosystems like peatlands and inundated savannas in the CH_4 cycle.

Appendix A

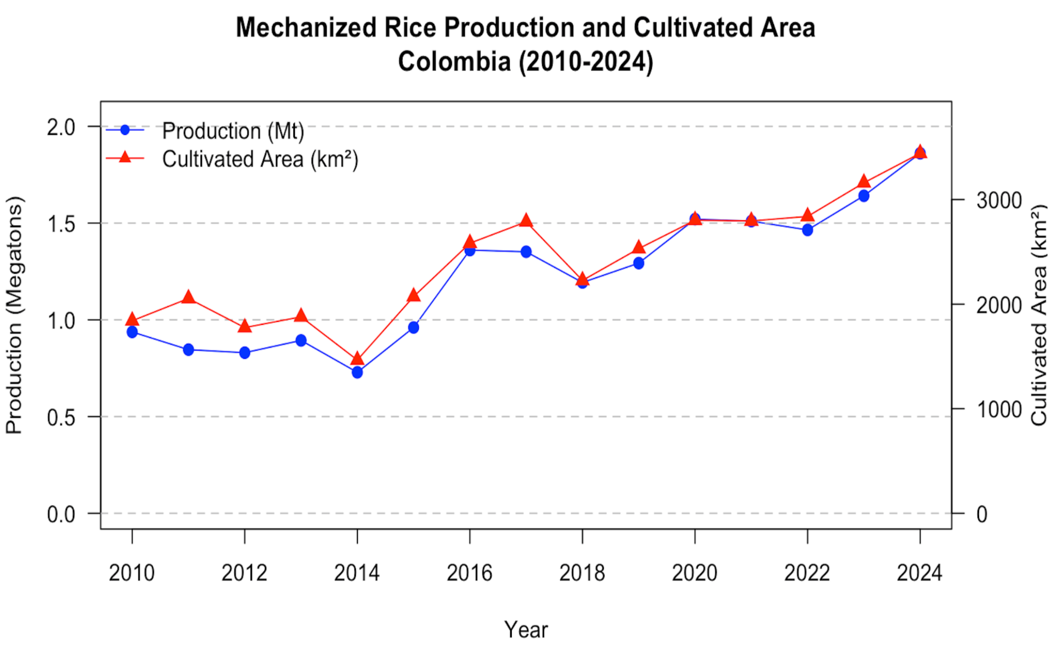

Figure A1: Annual mechanized rice production in megatons (Mt) and total cultivated rice area in kilometers per square (km^2) for the Llanos del Orinoco region in Colombia, for the period between 2010 and 2024. Data source DANE - Fedearroz - FNA downloaded from: https://fedearroz.com.co/es/fondo-nacional-del-arroz/investigaciones -economicas/estadisticas-arroceras/area-produccion-y-rendimiento/

Appendix B

Table B1: CMIP6 models include downscaled from NEX-GDDP-CMIP6

ID	Model	ID	Model	ID	Model
1	ACCESS-CM2	11	GFDL-CM4_gr1	21	MIROC6
2	ACCESS-ESM1-5	12	GFDL-CM4_gr2	22	MIROC-ES2L
3	BCC-CSM2-MR	13	GFDL-ESM4	23	MPI-ESM1-2-HR
4	CanESM5	14	GISS-E2-1-G	24	MPI-ESM1-2-LR

5	CMCC-ESM2	15	HadGEM3-GC31-LL	25	MRI-ESM2-0
6	CNRM-CM6-1	16	INM-CM4-8	26	NESM3
7	CNRM-ESM2-1	17	INM-CM5-0	27	NorESM2-LM
8	EC-Earth3-Veg-LR	18	IPSL-CM6A-LR	28	NorESM2-MM
9	EC-Earth3	19	KACE-1-0-G	29	TaiESM1
10	FGOALS-g3	20	KIOST-ESM	30	UKESM1-0-LL

Table B2: Decadal trends during 1981-2023 for the Llanos del Orinoco. Values in bold indicate significant values at a confidence level of 0.1.

Index	**Trend**
PRCPTOT (mm/decade)	-40.1
Total Annual Precipitation (mm/decade)	-39.6
RX1day (mm/decade)	**-1.2**
RX5day (mm/decade)	**-2.1**
R95p (mm/decade)	**-23.2**
R1mm (days/decade)	-0.2
R10mm (days/decade)	-1.4
R20mm (days/decade)	**-1.0**
CWD (days/decade)	0.1
CDD (days/decade)	**0.5**

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TXx (°C/decade)	**0.2**
TNn (°C/decade)	**0.2**
Tasmean (°C/decade)	**0.2**
TX90p (% of days/decade)	**3.1**
TX10p (% of days/decade)	**-2.0**
WSDI (days/decade)	**1.5**

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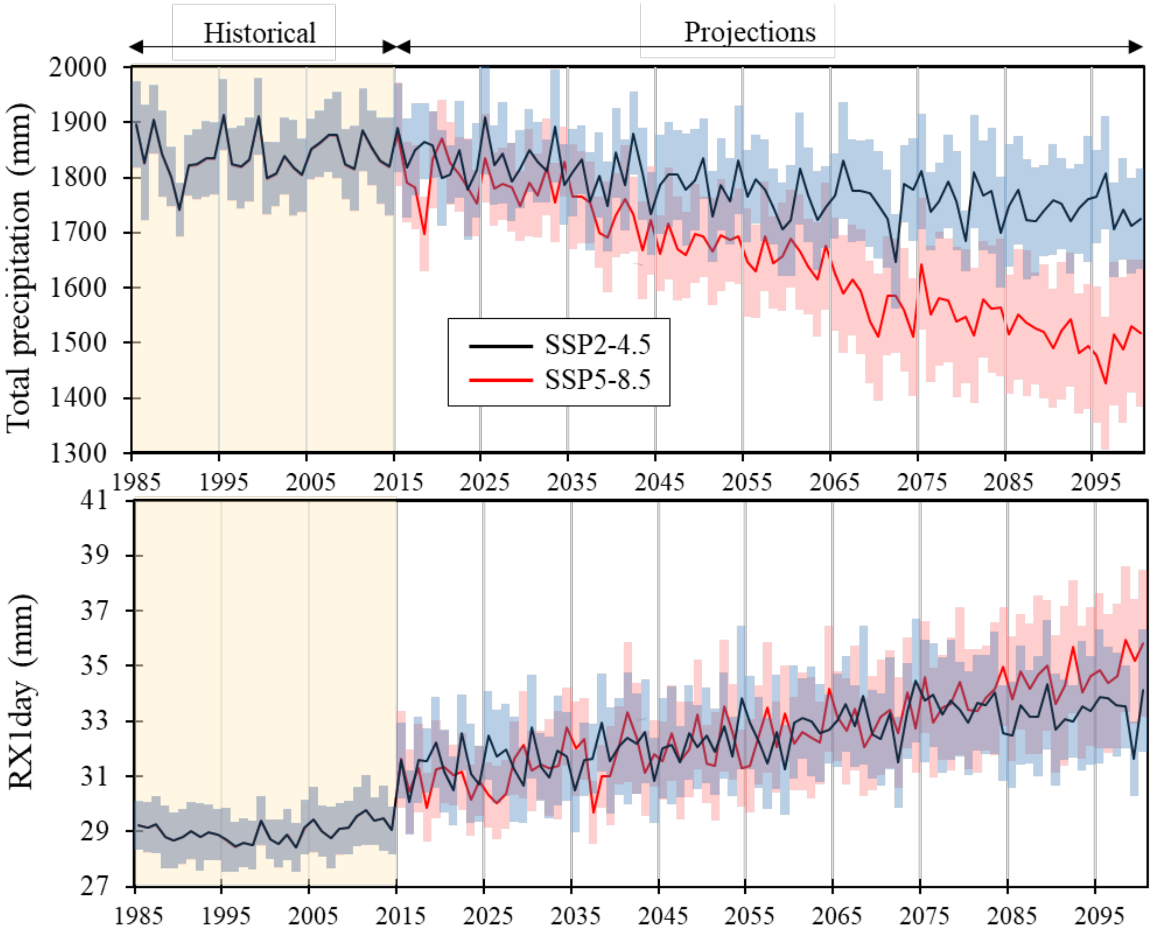

455 **Figure B1:** Time series of total annual precipitation and RX1day under SSP2-4.5 (black line) and SSP5-8.5 (red line) from the Multi-Model Ensemble (MME) during 1985 to 2100. Shaded bands show the 95% confidence interval for each scenario of the MME using 30 downscaled CMIP6 models (NEX-GDPP-CMIP6).

Code and data availability: The data supporting this study will be available at https://research-data.urosario.edu.co/dataverseuser.xhtml?selectTab=accountInfo after the conclusion of the review process

Author contributions: JHFA, SH, SB – Conceptualization. JHFA, SH, SB PTQ,DH, performed inversions and formal analysis AAD BQ, climate simulations, JHFA, SH, SB wrote the manuscript, with contributions from PTQ, ASGR,DH,AS,AAD, AU,BQ, JCB, RSW, CAS, MANR, DDPB .All co-authors reviewed and edited it.

*Competing interests***:** The contact author has declared that none of the authors has any competing interests.

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