Émissions de gaz à effet de serre dans les estuaires tropicaux : Cas du delta du Mékong et de la rivière Saigon (Vietnam)

Greenhouse Gas Emissions and Drivers in Tropical Estuaries: Insights from the Mekong Delta and Saigon River (Vietnam)

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RÉSUMÉ

Les estuaires tropicaux sont de plus en plus reconnus comme des contributeurs significatifs aux émissions mondiales de gaz à effet de serre (GES), mais ils restent sous-représentés dans les bilans carbone mondiaux. Nous avons étudié comment l'utilisation des terres et le débit des rivières contrôlent la dynamique des GES dans le delta du Mékong et le système fluvial de Saigon (Vietnam) en combinant des mesures de CO_2, CH_4 et N_2O avec des paramètres biogéochimiques complets. Nos résultats révèlent des zones distinctes de traitement des GES façonnées par l'interaction entre l'utilisation des terres et l'hydrologie. La rivière Saigon urbanisée présentait des concentrations extrêmes de GES (pCO_2 : 6 913–11 802 ppm) coïncidant avec un appauvrissement sévère en oxygène (4–40 %) et des nutriments élevés, indiquant une décomposition intense de la matière organique. Les zones agricoles montraient des niveaux modérés de GES (pCO_2 : 2 040–4 388 ppm), avec un débit élevé assurant une dilution efficace malgré des activités agricoles intensives. Des pics de méthane ont été observés dans les zones agricoles et aquacoles, mettant en évidence une méthanogenèse sédimentaire localisée. Les zones dominées par les mangroves ont montré des dynamiques variables, avec une diminution des GES le long du gradient de salinité mais des rejets occasionnels de CO_2, potentiellement dus au pompage tidal et à la respiration des sédiments. Ces résultats fournissent des contraintes observationnelles essentielles pour améliorer les estimations des émissions de GES dans les estuaires tropicaux et seront intégrés dans un cadre de modélisation visant à simuler les émissions de GES historiques, actuelles et futures dans des conditions environnementales en évolution, en particulier dans les régions tropicales en urbanisation rapide.

ABSTRACT

Tropical estuaries are increasingly recognized as significant contributors to global greenhouse gas (GHG) emissions, yet they remain underrepresented in global carbon budgets. We investigated how land use and river discharge control GHG dynamics across the Mekong Delta and Saigon River (Vietnam) by combining measurements of CO_2, CH_4, and N_2O with comprehensive biogeochemical parameters. Our findings reveal distinct GHG processing zones shaped by the interaction between land use and hydrology. The urbanized Saigon River exhibited extreme GHG concentrations (pCO_2: 6913-11802 ppm) coinciding with severe oxygen depletion (4-40%) and elevated nutrients, indicating intense organic matter decomposition. Agricultural zones showed moderate GHG levels (pCO_2: 2040–4388 ppm), with high discharge providing effective dilution despite extensive farming activities. Methane hotspots were observed in both agricultural and aquaculture zones, highlighting localized sedimentary methanogenesis. Mangrove-dominated areas demonstrated variable dynamics, with a decrease in GHGs along the salinity gradient but occasional CO_2 release, potential due to tidal pumping and sediment respiration. These findings provide observational constraints for improving GHG emission estimates from tropical estuaries and will be integrated into a modelling framework to simulate historical, present, and future GHG emissions under changing environmental conditions, particularly in rapidly urbanizing tropical regions.

MOTS CLÉS

gaz à effet de serre, estuaire tropical, processus biogéochimiques, débit fluvial, urbanisation

greenhouse gases, tropical estuary, biogeochemical processing, river discharge, urbanization

1 INTRODUCTION

Tropical estuaries are increasingly recognized as critical components of the global carbon cycle, acting as both carbon sinks and significant sources of greenhouse gas (GHG) emissions, including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) (Lauerwald et al., 2023). These regions serve as biogeochemical hotspots, where terrestrial organic and inorganic carbon inputs are processed, transformed, and often emitted into the atmosphere. Despite their importance, tropical estuaries remain underrepresented in global GHG inventories, which predominantly rely on data from temperate systems. This knowledge gap is particularly concerning given the rapid environmental changes occurring in tropical regions, such as urbanization, agricultural intensification, and mangrove deforestation (Borges et al., 2018; Nguyen et al., 2022).

The Mekong Delta, one of the world's largest and most productive deltas, faces pressures from human activities. The Saigon River, which flows through Ho Chi Minh Megacity, is heavily impacted by urban wastewater discharge and industrial activities. Understanding these agricultural, urban impacts become crucial as similar development patterns in other developing countries in tropical regions. The main objective of this study is to quantify and compare GHG emissions across different land-use categories in the Mekong Delta and Saigon River. The specific objectives are (1) to quantify concentrations of CO_2, CH_4, and N_2O across diverse land-use types, including urban areas, agricultural zones, mangroves, and aquaculture systems; (2) to identify key drivers of GHG emissions, focusing on hydrodynamic controls, biogeochemical processes, and land-use impacts.

2 METHODOLOGY

2.1 Study Area

The Mekong Delta and Saigon River system in southern Vietnam provide an exemplary case for examining the interplay between hydrology, land use, and greenhouse gas (GHG) dynamics. The Mekong Delta is characterized by its complex network of distributaries, carrying over 15000 m^3/s of discharge during the rainy season, and encompasses a range of land-use types, including rice paddies, woody crops, aquaculture zones. The Mekong Delta is characterized by a complex network of distributaries with varying discharge rates: the Tien River (12,500 m^3/s, 83% of total flow) including 3 sub-branches (Co Chien, Ham Luong, Mekong), and a smaller branch - the Hau River (2500 m^3/s, 17%) (Fig. 1). In contrast, the Saigon River (100 m^3/s), flowing through Ho Chi Minh City (population >9 million, 2021), represents an urbanized system heavily impacted by wastewater inputs.

To capture the spatial variability of GHG emissions, sampling sites were selected to represent urban areas (e.g., Saigon River near Ho Chi Minh Megacity with 10M inhabitants in 2023), agricultural zones (e.g., Tien and Hau Rivers in the Mekong Delta), mangrove-dominated areas (e.g., Can Gio Biosphere Reserve). These sites allowed for a comparative analysis of GHG dynamics across diverse land-use categories and hydrology.

2.2 Sampling and measurement

During the rainy season June-July 2024, we conducted extensive field surveys in the Mekong Delta and Saigon River, covering Saigon River, Dong Nai River, Hau River and Ham Luong River (Fig. 1). The sampling strategy combined high-resolution continuous measurements with discrete water sampling.

Real-time measurements of partial pressure of CO_2 (pCO_2) were conducted along river transects using a high-accuracy infrared gas analyzer (Li-Cor 830). pCO_2 was recorded every 30 seconds. Geospatial data from GPS systems was used to map pCO_2 distributions. At selected stations, water samples were collected to analyze the following parameters. GHGs: Dissolved CO_2, CH_4, and N_2O concentrations were measured using headspace equilibration and gas chromatography techniques. Biogeochemical Parameters: Dissolved oxygen (O_2), pH, total alkalinity (TA), dissolved organic carbon (DOC), chlorophyll-a (Chl-a), nitrate (NO_3^-), and phosphate (PO_4^{3-}) were analyzed.

3 RESULTS AND DISCUSSION

3.1 Land use and discharge controls on GHG Dynamics

The spatial patterns of GHG emissions across the Mekong Delta and Saigon River reflect distinct land-use and hydrodynamic influences (Fig. 1). The agricultural zones of the Mekong Delta, primarily consisting of rice paddies and aquaculture, exhibited moderate but persistent GHG levels. In the Ham Luong and Hau Rivers, pCO_2 ranged from 2 040 to 4 388 ppm under well-oxygenated conditions (65–87% saturation), while CH_4 (0.08–0.15 µmol/L) and N_2O (0.03–0.05 µmol/L) remained relatively low (Fig. 2). These areas demonstrated a gradual increase in

pCO_2 concentrations moving inland from the coast, correlating with decreasing salinity.

In contrast, the urbanized Saigon River, with lower discharge (100 m^3/s), exhibited extreme pCO_2 concentrations (6913–11802 ppm) near Ho Chi Minh City. These high values coincided with elevated CH_4 (0.3–0.5 µmol/L) and N_2O (0.6–0.8 µmol/L) in the low-salinity zone (0–1), along oxygen depletion (4–40% saturation) (Fig. 2). The nutrient-rich wastewater inputs from urban areas led Saigon River to be a hotspot of GHG emissions. Compared to other Asian megacities, such as the Pearl River Delta (2000–4000 ppm) (Guo et al., 2009), the Saigon River illustrated significantly higher pCO_2, reflecting the compounded effects of urbanization and low hydrodynamic flushing. Downstream of this urban zone, the Dong Nai River—contributing higher discharge from the Tri An Reservoir—observed lower but still elevated pCO_2 levels (2111–6016 ppm), likely due to a mix of urban and agricultural inputs but reduced by stronger hydrodynamic flushing and dilution.

Further downstream, the Saigon River splits into two main branches: the mainstream and the mangrove-influenced branch (Fig. 1). Along the salinity gradient, the mainstream, characterized by higher discharge and lower salinity, showed relatively lower pCO_2 concentrations (Fig. 2). In contrast, the mangrove-influenced branch showed higher pCO_2 despite increasing salinity, suggesting localized carbon release from sediment decomposition, root respiration, and tidal pumping. This highlights the dual role of mangroves, which can both sequester and release CO_2 depending on local biogeochemical and hydrodynamic conditions (Koné et al., 2008; Rosentreter et al., 2018).

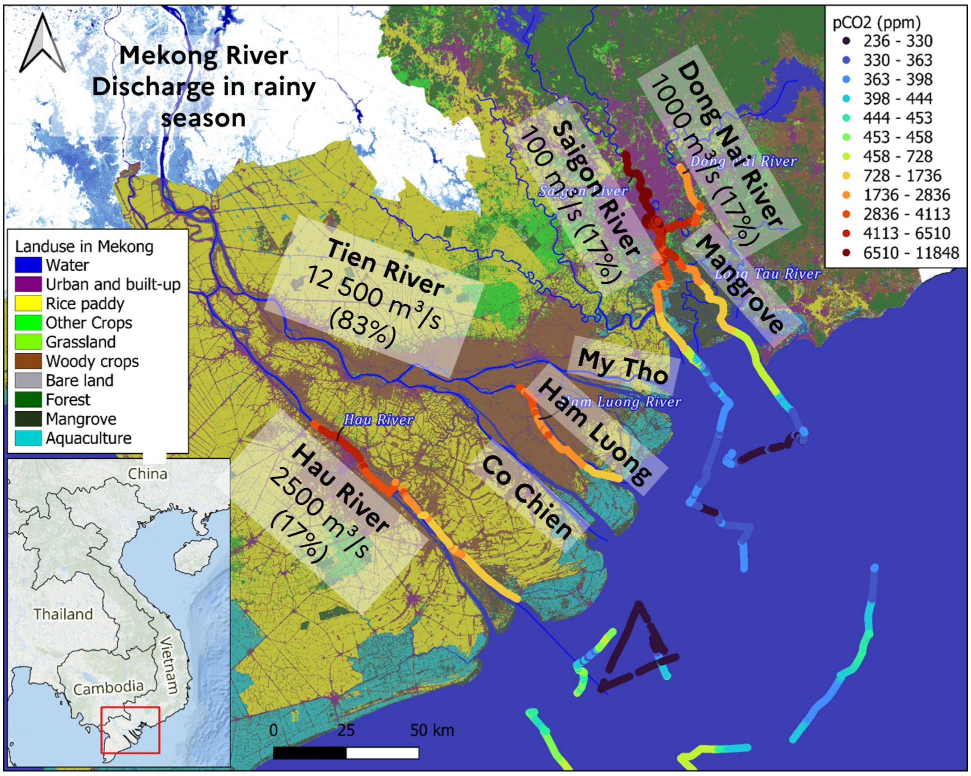

Figure 1. Spatial distribution of pCO_2 (ppm) overlaid on land use map of the Mekong Delta and Saigon River Estuary. Discharge are average values in the rainy season.

3.2 Biogeochemical Controls on GHG Dynamics

The spatial variations in GHG concentrations were closely coupled with biogeochemical parameters across the salinity gradient. The urban Saigon River showed a strong inverse relationship between pCO_2 and oxygen saturation and nutrient-rich water (Fig. 2). These conditions were accompanied by elevated Chl-a concentrations (35-60 µg/L), however, the dominance of heterotrophic respiration driven by the decomposition of organic matter led to a net release of CO_2. The combination of low discharge, prolonged water residence times, and high nutrient input amplify GHG emissions in this urbanized tropical estuary.

In the agricultural Mekong Delta branches, moderate oxygen levels (56-87%) corresponded with intermediate pCO_2 concentrations (2040-4388 ppm). These areas showed lower Chl-a (1-20 µg/L) and DOC (2-3 mg/L) compared to urban zones, reflecting different organic matter sources and processing rates compared to Saigon River. However, localized CH_4 peaks were observed near aquaculture areas (Hau River) and woody crops (Ham

Luong), likely driven by anaerobic conditions and methanogenesis in nutrient-rich sediments. This highlights the interplay between land use and biogeochemical conditions, with agricultural zones acting as potential hotspots for methane production despite the overall influence of high discharge in agricultural branches.

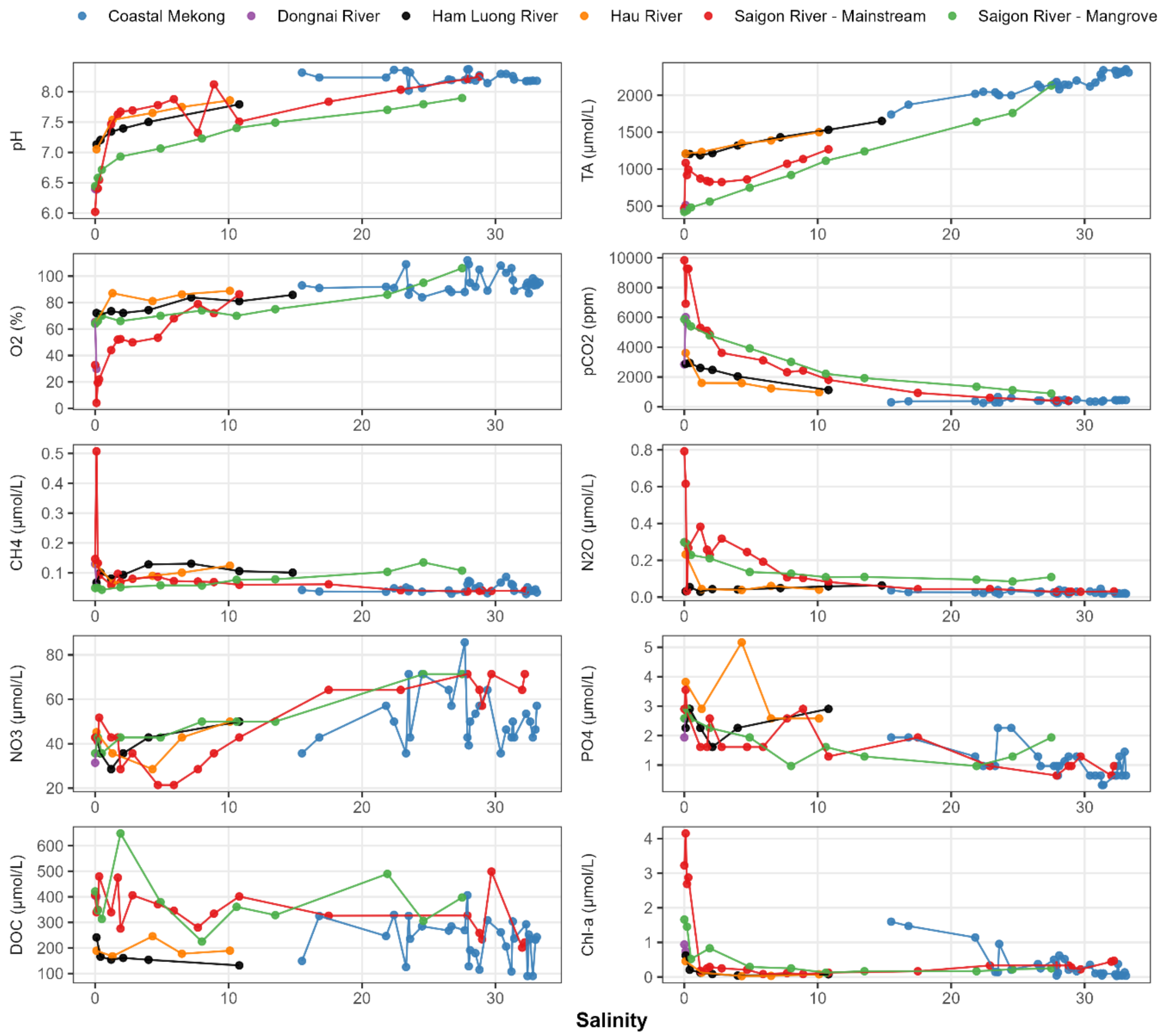

Figure 2. Biogeochemical parameters along the salinity gradient for different river branches.

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