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Seasonal variability of CO₂ fluxes at different interfaces and vertical CO₂ concentration profiles within a *Rhizophora* mangrove forest (Can Gio, Viet Nam)

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Abstract

Despite being organic-rich, mangrove soils are usually characterized by low rates of CO₂ emissions due to waterlogged conditions, mangroves being thus considered as valuable blue carbon sinks. However, these emissions are highly variable, notably depending on climatic parameters. Can Gio mangrove is a tropical one, being the largest in Vietnam, having being replanted after the war in the late 70's. The main objectives of this study were to quantify the seasonal variability of CO₂ emissions at different interfaces (soil-air, water-air, and trunk-air) within a mature *Rhizophora* stand, and to assess the influence of these emissions on the vertical CO₂ concentration profiles in the canopy. CO₂ emissions from the soil in the dark were the highest of the different interfaces studied, and were among the highest measured for a mangrove soil, with a mean yearly value reaching more than 270 mmol CO₂ m⁻² d⁻¹. We suggest that the very high temperatures characterizing Southern Vietnam all year round were responsible for these elevated CO₂ emissions. In addition to temperature, the first rainfall pulse of the monsoon resulted in the highest CO₂ fluxes both from the soil, reaching up to 500 mmol CO₂ m⁻² d⁻¹, and from the trunks, reaching almost 230 mmol CO₂ m⁻² d⁻¹. Because rainfall pulses are usually followed by a period of increasing rates of ecosystem photosynthesis, and a decrease of ecosystem respiration, we measured lower CO₂ fluxes during the middle of the wet season. Additionally, it is possible that, during the rainy season, part of the CO₂ produced within the soil was exported through pore-water seepage, which was enhanced because of the higher level of the river. Concerning CO₂ emissions at high tide within the *Rhizophora* stand, the seasonal trend followed the one of precipitation. During the rainy season, estuarine waters are enriched in organic matter and CO₂ due to increased runoff in watersheds, and consequently CO₂ fluxes from the water column were the highest. However, these emissions were much lower than those from the soil

at low tide or from the trunks. Eventually, CO₂ concentrations profiles in the canopy varied with the season, the tide, and the night-day alternation. Elevated CO₂ concentrations at the root level may imply that prop roots can produce high amount of CO₂ but also that they may trap gas emitted from the soil or the water column, possibly acting as physical barriers to air movement. Further studies using eddy-covariance technique should be developed to confirm the hypothesis suggested in this preliminary study.

Keywords: Mangrove forest; Carbon dioxide; Blue carbon; Monsoon; Vietnam

1 Introduction

Despite simple structure, low biodiversity, and limited extent, less than 150 000 km² (Giri et al., 2011; Polidoro et al., 2010), mangrove forests have potentially high impact on the global carbon budget. On the one hand, because of their high productivity ($218 \pm 72 \text{ Tg C y}^{-1}$, Bouillon et al. (2008) and because of high carbon burial rates in waterlogged soils, they are a sink for atmospheric CO₂ (Donato et al., 2011). On the other hand, because of tidal flushing and pore-water seepage, they can be an important source of organic and inorganic carbon for coastal waters (Dittmar et al., 2001; Maher et al., 2013). Despite organic-rich soils, mangroves are usually characterized by lower rates of CO₂ emission than terrestrial forests developing both under temperate or tropical climate (Leopold et al., 2015). Several authors worked on the quantification and on the drivers of CO₂ fluxes at the soil-air interface in mangroves (Chen et al., 2012; 2014; Leopold et al., 2015; 2013; Lovelock, 2008; 2014). They notably demonstrated the importance of carbon stock, soil water content, temperature, microphytobenthos, and conduits like crab burrows or pneumatophores. Elevated temperature

may result in an increase of mangrove forests productivity but also an increase in microbial transformation rates, resulting in higher greenhouse gas production and emission (Alongi, 2018). However, Lehette et al. (2016) showed that in the tropics, seasonal or monsoonal effects on metabolic rates may be limited due to the low range of temperatures, from 26 to 32°C. Jacotot et al. (2018) were interested in greenhouse gas emissions from the water column at high tide within a *Rhizophora* mangrove forest, demonstrating that CO₂ fluxes were maximum at low tide, and decreased with the flow. Nevertheless, when CO₂ is emitted from mangrove soils or from the water column within the mangrove, it may not reach the atmosphere but being used by the mangrove trees during photosynthesis. In fact, Alongi (2009) highlighted that the largest component of gas exchange between mangroves and the atmosphere was the canopy respiration/photosynthesis. Net ecosystem exchanges in mangroves were recently studied using eddy-covariance technique, notably showing strong seasonal variability of CO₂ fixation (Barr et al., 2012; Leopold et al., 2016). Recently, Troxler et al. (2015) demonstrated a more significant contribution of below-canopy respiration to ecosystem respiration (ER) than previously considered. They suggested that an understanding of below-canopy CO₂ component fluxes and their contributions to ER would help to refine C cycling in mangrove forests. In addition to CO₂ emissions from the soil and the water column, mangrove trunks may also emit considerable amount of CO₂ through respiration processes. Consequently, quantifying the seasonal variability of CO₂ emissions at the different interfaces in mangrove forests would be highly relevant.

In Vietnam, more than 80% of the total mangrove forest area develops in the south of the country (Hawkins et al., 2010). Can Gio mangrove is the largest contiguous mangrove in Vietnam, covering approximately 32,125 ha. It is situated at the edge between a densely populated megacity, Ho Chi Minh City, and the East Sea (Vietnamese name's Bien Dong).

Most of the Can Gio area was replanted, after the war, using *Rhizophora apiculata* Blume in the late 70's and early 80's.

The main objectives of the present study were to determine the seasonal variability of CO₂ fluxes at different interfaces: soil-air, water-air and trunk-air, and to characterize CO₂ concentrations profiles in the canopy. Our hypothesis were that CO₂ fluxes will be higher during the hot season, temperature increasing respiration rates, and that CO₂ emissions will be higher at low tide than at high tide, the incoming water being poorer in CO₂ than mangrove soils (Jacotot et al., 2018, 2019). Our dataset is composed of data collected during eight sampling campaigns performed between July 2016 and September 2017 in a mature *Rhizophora* stand of 37 years old.

2 Materials and methods

2.1 Study Area

The present study was conducted in the Can Gio Estuary (Fig. 1), which is located approximately 25 km southeast of Ho Chi Minh City center, between 10° 22' – 10° 40' N; 106° 46' – 107° 00' E (Vietnam). The Can Gio Estuary is a deltaic confluence of the Sai Gon, Dong Nai and Vam Co Rivers, which drain into the East Sea. In 2000, Can Gio mangrove forest was recognized by UNESCO as the first Mangrove Biosphere Reserve in Vietnam. In this region, replanted mangrove forests are dominated by *Rhizophora apiculata* Blume, they cover 23,508 ha over a total mangrove area of 49,180 ha (Vinh, 2018). This region is affected by irregular semi-diurnal tides, and the tidal amplitude ranges from 2 m at mean tide to 4 m during spring tides (Tri et al., 2000). The climate conditions of this region are typically monsoonal, with a dry season lasting from December to April and a rainy season from May to November. Total annual rainfall is 1816 mm yr⁻¹ with most of the rain concentrated in the

rainy season (1599 mm yr^{-1}) and a total of 154 rainy days during the year. The average annual temperature in Can Gio is 27.4°C , with the highest (37.6°C) in October and lowest (21.7°C) in February. The mean annual humidity is 86%, ranging from 80.8 to 91.4

Figure 1: Map showing the study location in Can Gio mangrove (Southern Vietnam).

2.2 Data collection

The study was carried out every 2 months from July 2016 to September 2017, for a total of 8 fieldtrips in a 37 years old *Rhizophora* stand. The characteristics of this stand are presented in table 1.

Table 1. Stand characteristic of the *R. apiculata* stand studied in Can Gio

Age year	Tree density n ha ⁻¹	Mean DBH cm	Mean height m	Basal Area m ² ha ⁻¹	Soil TOC %
37	1127	18.6	19.4	28.4	3.3

2.2.1 Trunk-air CO₂ fluxes measurement

CO₂ fluxes were measured on stems at 1.30 m height or just above the highest prop roots on *Rhizophora apiculata* trees. Closed dynamic custom-built chambers (58.9 cm³; 98.2 cm²) were installed on 3 different trees in locations where there were no visible mosses or algae on stems. These chambers were connected to a non-dispersive Infra Red Gaz Analyzer (IRGA) (Li-820), which was calibrated every day during fieldstrips with pure nitrogen (0 ppm of CO₂) and two CO₂ spans of 545 and 2867 ppm (prepared by Air Liquide). A pump and a flow-meter were used to allow the circulation (1 L min⁻¹) of the air trapped in the chamber through the system. These measurements were made only during the day with a clear chamber, so the CO₂ fluxes measurements represent the sum of trunk respiration and possible photosynthesis by microorganisms developing at its surface. However, during the first two fieldtrips, we performed measurements in the dark and at light, and we did not observe any significant differences. So in order to reduce the length of the experiment and to be sure not to have a modification of the tidal level during it, we chose to perform them only

at light. On each tree, we performed three replicates at high tide and three replicates at low tide. The incubation time for each measurement was 5 minutes. Stem temperature was measured with a handheld infrared thermometer DT8280, before each CO₂ flux measurement.

2.2.2 Soil-air and water-air CO₂ fluxes measurements

Concerning CO₂ fluxes at the soil-air and water-air interfaces, we used different closed dynamic custom-built chambers of the same size (471 cm³; 314 cm²). For the soils, we used one clear and one dark chamber in order to assess the possible influence of photosynthetic organisms developing at soil surface. At high tide, we performed the measurements with a floating chamber. Chambers were connected to an IRGA (Li-820), which was calibrated every day during fieldtrips with pure nitrogen gas (0 ppm of CO₂, Air Liquid Inc.) and two CO₂ spans (545 and 2,867 ppm of CO₂, Air Liquid Inc.). The instrument measurement range is 0 to 20,000 ppm, and the accuracy is less than 3 % of reading (Licor 820). Five replicates were performed, with an incubation time of 5 min for each measurement. At the water-air interface, measurements started 30 mins before the high tide and finished 30 mins after. At the soil-air interface, measurements started one hour before the high tide and finished one hour after (because we performed measurements both at light and in dark from the soil, but just in the dark from the water column). For the 8 fieldtrips, we chose high and low tides that occurred at the same moment of the day. Furthermore, the air temperature, soil temperature and wind speed were measured with a handheld thermometer and anemometer, before each CO₂ flux measurements.

2.2.3 CO₂ fluxes calculation

For the 3 different interfaces, CO₂ fluxes (F) were calculated according to the following equation:

$$F = (\delta pCO_2 / \delta t) * V/R.T.S$$

Where F is the CO_2 flux from soils ($\mu\text{mol m}^{-2} \text{ s}^{-1}$); $\delta pCO_2 / \delta t$ is the variation of pCO_2 as a function of time (ppm s^{-1}); V is the total volume of system (m^3); R is the ideal gas constant of $8.20528 \cdot 10^{-05}$ ($\text{atm m}^3 \text{ K}^{-1} \text{ mol}^{-1}$); T is the absolute air temperature (K); and S is the substrate surface of the incubation chamber (m^2).

2.2.4 Vertical CO_2 concentrations profiles in the canopy

One small tower was installed in the *Rhizophora* stand to measure CO_2 concentrations distribution in the canopy (Etzold et al., 2010; Paul-Limoges et al., 2017). CO_2 concentrations were measured at six different heights, with air inlets at: 0.5, 1, 2, 4, 8, and 12 m above the ground. The intake hoses were connected to an automated CO_2 flux system Li-8100A (LI-COR), calibrated before each survey. The measurement range is from 0 to 20,000 ppm and accuracy less than 1.5 % of reading (Licor 8100). Measurements were performed 4 times during 72 hours between July 2016 and July 2017. For each air inlet, we measured the concentrations every seconds during 5 mins, and we calculated the mean value. We allow a purge time of 10 seconds between each air inlet measurement. Switching between the canopy heights was performed by a control port module and a series of solenoid valves (flow rate of 1 L min^{-1}). We then split the values in 4 categories: high tide during the day, low tide during the day, high tide at night and low tide at night, and we then combined the values collected during the rainy season, and those collected during the dry season.

2.2.5 Soil characteristics

Triplicate soil cores in the *Rhizophora* stand were collected thanks to a gouge auger (1 m long, 3 cm wide) attached to a cross handle. Cores were collected during the dry season 2016 and the wet season 2017 from the surface to a depth of 100 cm. Pore-water salinity was

measured thanks to a hand-held refractometer. Redox potential and pH were measured using respectively a combined Pt-Ag/Ag-Cl electrode and a glass electrode, both connected to a pH/mV/T meter (Marchand et al., 2004). The pH electrode was calibrated prior sampling using three standards solutions of pH 4, 7 and 10 at 25°C (National Institute of Standards and Technology, USA) and the redox electrode was checked prior utilization with a 0.43V standard solution and demineralized water (Marchand et al., 2004). Total organic carbon (TOC) contents were determined using a Total Organic Carbon Analyzer coupled to a SSM-5000A Solid Sample Module (TOC-LCPH-SSM500A, Shimadzu Corporation, Japan). The analytical precision was checked using glucose standard (Sigma Aldrich) and was less than 1%.

2.3 Data analysis

All statistical analyses were conducted on the data using the XLSTAT software version 2017.4 for MacOS version 10.13.4. A parametric two-way analysis of variance (ANOVA) was used to test the significant effects ($p < 0.05$) of seasons on water-air, trunk-air and soil-air interface CO₂ fluxes. Two-way ANOVA was also applied to assess the significant differences ($p < 0.05$). Student's t-test was used to test the significant differences ($p < 0.05$) on water-air, trunk-air and soil-air interface CO₂ flux and CO₂ concentrations at: 0.5, 1, 2, 4, 8, and 12 m above the ground.

3 Results and Discussions

3.1 Temperature and precipitation controls on CO₂ emissions from mangrove soils and trunks

In the Can Gio *Rhizophora* stand studied, mean soil CO₂ emissions during the year was 266.4 ± 124.8 mmol CO₂ m⁻² d⁻¹, being higher in the dark than at light (Fig. 2). This

mean value is much higher than in other mangroves, with for instance values of 80.5 ± 37.0 mmol CO₂ m⁻² d⁻¹ in New Caledonia (Leopold et al., 2013), 168.5 ± 45.8 in New Zealand (Lovelock et al., 2014), 88.6 in Kenya (Lang'at et al., 2014), and 65.5 ± 25.6 in Northern Vietnam (Grellier et al., 2017). However, some of these mangroves contained as much soil organic carbon content as in Can Gio (3.3%, Table 1) suggesting that soil organic carbon content may not be the main driver of soil CO₂ emissions in mangroves.

Figure 2: Mean CO₂ emissions during the year from different compartments in the mangrove (water, soil in the dark, soil at light, and trunk). Solid vertical black lines represent the standard deviation (SD).

Climate and temperature play a key role on CO₂ emissions from mangrove soils (Leopold et al., 2015), biogeochemical processes, including soil organic matter decomposition, are highly sensitive to temperature, increasing with it (Conant et al., 2011; Fang and Moncrieff, 2001). In addition, roots respiration present higher sensitivity to temperature than that of bulk soil (Boone et al., 1998). Consequently the higher CO₂ fluxes

measured during the hot season may result from both enhanced OM decomposition rates but also elevated roots respiration. Lovelock (2008) showed that soil respiration declined when the soil temperature was above 26 °C. However in Vietnam, temperatures were always higher than 26°C, but we observed higher CO₂ emissions when the temperature increased during the hot season, which may imply that temperature threshold may be site specific (possibly depending on mangrove species and climate). Pongpurn et al. (2009) showed that soil temperature affected significantly rates of soil respiration in mangrove forest in eastern Thailand at temperature higher than 26°C, with soil respiration increasing from 39.4 to 75.71 mmol CO₂ m⁻² d⁻¹ when the temperature increased from 27.7 to 30.1 °C. Moreover in Southeast Asian mangroves developing at approximately the same latitude that the one studied here, Kosugi et al. (2007) showed that CO₂ emissions from mangrove soils increased from 216 to 561.6 mmol CO₂ m⁻² d⁻¹ when the temperature increased. Consequently, we suggest that the very high temperatures characterizing Southern Vietnam all year round were responsible for the high CO₂ emissions measured. Thus, even if the carbon stocks are elevated, the high CO₂ emissions related to the high temperature may reduce tropical mangrove value as carbon sink.

Table 2: F values of two-way ANOVA tests showing the effect of sampling site and month on the different types of CO₂ fluxes and environmental parameters. *, **, and *** indicate statistically significant effects for p-Values < 0.05, < 0.01 and < 0.001, respectively .ns means no statistically significant difference (p > 0.05). Types mean measurements performed in the dark or at light (only from the soil).

Parameters	n	Source of variations		
		Types	Seasons	Interaction
Soil-air	256	22.80***	9.73***	6.59***
Trunk-air	279	Tidal	Month	Interaction
		30.25***	10.32***	7.49***
Water-air	135	-	113.32***	-

Soil CO₂ fluxes were significantly different when measured in the dark or at light (P < 0.001) (Table 2), with mean CO₂ emissions of 289.6 and 243.1 mmol CO₂ m⁻² d⁻¹, in the dark and at light, respectively (Fig. 2). Microphytobenthos (MPB) development at soil surface may strongly influence greenhouse gas emissions from mangrove soils (Leopold et al., 2013). At light, MPB can perform photosynthesis processes, and use the CO₂ produced within the soil, either from OM decomposition or roots respiration. These processes induce thus lower emissions to the atmosphere, and can explain that CO₂ fluxes measured at light were 16% lower than those measured in the dark. Eventually, CO₂ fluxes values significantly varied with seasons (P < 0.001) (Table 2).

Figure 3: Mean CO₂ fluxes (mmol CO₂ m⁻² d⁻¹) (vertical bars represent the standard deviation) at (a) Soil-air interface; (b) Trunk-air interface; (c) Water-air interface in the dark (brown) and at light (green) in the *Rhizophora* stand; (d) Monthly average temperature and rainfall.

The highest CO₂ fluxes at the soil-air interface, reaching more than 520 mmol CO₂ m⁻² d⁻¹, were measured in May during the transition between the dry and the rainy season, when the mean monthly temperature was the highest, reaching almost 30°C (Fig. 3 d). In addition, the first rainfall of the season may stimulate the decomposition of OM by microorganisms, thereby decreasing the porewater salinity (Fig. 4 a) and increasing soil CO₂ emissions (Yuan et al., 2007). Conversely, when the temperature decreased, during the dry and cool season, CO₂ emissions from mangrove soils also decreased, reaching down to 127.7 mmol CO₂ m⁻² d⁻¹ (Fig. 3 a).

Figure 4: Soil vertical profiles of salinity, redox and pH. Blue lines are the results for the rainy season, and the orange lines for the dry season. Horizontal bars represent the SD.

The relationship between the dark CO₂ fluxes, light CO₂ fluxes and air temperature, from 25 °C to 35 °C, allowed us to estimate Q₁₀ ratios, which represent the sensitivity of a reaction to temperature (for an increase of 10 °C) and are commonly used in soil CO₂ emissions studies (Fang and Moncrieff, 2001; Janssens and Pilegaard, 2003; Xu and Qi, 2001) (Fig. 5 a, b). In Can Gio, Q₁₀ were 3.47 and 12.09 for CO₂ emissions at light and in the dark, respectively (Fig. 5). These values are much higher than those determined in other forests (Lewis et al., 2014; Lovelock, 2008; Raich and Schlesinger, 1992), and may be specific to tropical mangroves, but they confirm the importance of temperature on OM mineralization and organisms' respiration at these latitudes.

Figure 5: Relationships between CO₂ emissions and temperature at two interfaces (soil-air and trunk-air).

Precipitation may also influence CO₂ fluxes in another way. In fact the lowest CO₂ emissions were measured in the middle of the rainy season despite high temperatures (Fig. 3). During the monsoon, the water level of the river was higher and thus mangrove soils were

more waterlogged, which may have induced anoxic conditions in the soils and limited OM decay processes. Redox values were lower in the upper 10 cm during the rainy than during the dry season (Fig. 4). In addition, it is possible that, during the rainy season, part of the CO₂ produced within the soil was exported through pore-water seepage (Maher et al., 2013), while during the dry season, CO₂ accumulated in mangrove soils because the stand was less frequently flooded, and was further emitted towards the atmosphere. Taillardat et al. (2018) showed that pCO₂ in the water column of an adjacent tidal creek were higher during the rainy season notably because of enhanced exchanges between mangrove soils and the creek, which can confirm our hypothesis. Surprisingly, CO₂ emissions from the trunks of *R. apiculata* trees presented the same trend during the year that the one of CO₂ emissions from the soil, with values ranging from 107.4 to 221.9 mmol CO₂ m⁻² d⁻¹ (Fig. 3b), and with a Q₁₀ value (between 25 and 35°C) of 5.8 (Fig. 5 c). This observation may suggest a dominant role of climatic parameters (temperature and precipitation) on ecosystem respiration, on CO₂ emissions from the soil but also from the trees. The highest fluxes were measured when the temperatures were maximum just at the beginning of the rainy season. This period corresponds to the lowest productivity of the ecosystem most probably because the lack of water during the dry season induced a stress on mangrove trees (Vinh, 2018). We suggest that the very high temperature and the first rains at the beginning of the rainy season increased ecosystem respiration. Yepez et al. (2007) showed that CO₂ release from respiration during the first summer rains can be more than 45% of the carbon fixed by plants during the growing season. Conversely the lower fluxes, either from the soil or from the trunk, were measured during the middle of the rainy season, which corresponds to the fruiting period and the highest litterfall (Vinh, 2018). Huxman et al. (2004) suggested that following a rainfall pulse, a period of net ecosystem accumulation of CO₂ should occur, because of increasing rates of ecosystem photosynthesis through plant acclimation and/or leaf growth, concomitantly to a decrease of ecosystem respiration. When upscaling CO₂ emissions from mangrove trunks,

considering trunk area and tree density, we obtained a total of 20.74 Mg CO₂ ha⁻¹ yr⁻¹, which is considerable and must be definitely taken into account in mangrove carbon budget.

3.2 CO₂ emissions from the water column within a mangrove stand depend on the estuarine water inputs.

CO₂ emissions from the water column at high tide in the *Rhizophora* stand, with a mean value during the year close to 78 ± 58.6 mmol CO₂ m⁻² d⁻¹, were much lower than from the soil at low tide (Fig. 2). Jacotot et al. (2018) evidenced that the water column above a mangrove forest floor was a mix between soil pore-waters, enriched in gaseous compounds originated from OM decomposition and root respiration, and incoming lagoon water, poor in CO₂ and characterized by enriched $\delta^{13}\text{C}$ values, resulting in lower fluxes when the water column thickness increased, and thus confirming our results. In addition, when mangrove soils are waterlogged, OM decay processes are slower and thus greenhouse gas production is reduced (Kristensen et al., 2017). Eventually, gas diffusion is faster in air than in water, which also play a role in the differences of fluxes observed between low tide and high tide. Like for the soils, the CO₂ emissions we measured from the water column were higher than in other mangroves in New Caledonia (Jacotot et al., 2018) or in Florida (Troxler et al., 2015), most probably because of the high temperatures, as explained for CO₂ emissions from the soil at these latitudes. However, CO₂ emissions from the water column presented a different seasonal trend than those from the soil or from the trunks. These emissions seem to follow the seasonal trend of precipitations, decreasing from 146.1 in November (rainy season) to 39.6 mmol CO₂ m⁻² d⁻¹ in March (dry season), and then increasing till September (rainy season), reaching more than 91.4 mmol CO₂ m⁻² d⁻¹ (Fig. 3 c). During the rainy season, the freshwater flow is enhanced, as a consequence salinity drops in the estuary (down to 0 at the mangrove limit), the water column is enriched in organic carbon (from 2 to 4%), and characterized by low DO concentrations (down to 2 mgO₂ l⁻¹) (Thanh-Nho et al., 2017). As observed in New

Caledonia at high tide, the main contributor of CO₂ emissions at the water-air interface is the incoming estuarine waters (Jacotot et al., 2018). David et al. (2018) measured partial pressure of CO₂ (pCO₂) in the Can Gio estuary, and they clearly demonstrated the influence of the monsoon season on it. During the dry season, pCO₂ ranged from 660 to 3,000 µatm, while during the wet season, values ranged from 740 to 5,000 µatm, and as a consequence they measured CO₂ fluxes up to 876 mmol CO₂ m⁻² d⁻¹. They concluded that these high CO₂ emissions might be due to both the high water temperature and to the high organic load, being increased during the monsoon due to enhanced runoff in watersheds. Additionally, Borges et al. (2018) also showed that creeks in Ca Mau (Southern Vietnam) were enriched in CO₂ during the rainy season compare to the dry season. These measurements fit well with our observations within the mangrove, and we can thus suggest that at high tide, CO₂ emissions are probably controlled by the incoming estuarine waters. During the rainy season, Can Gio estuarine waters were enriched in OM and CO₂ (David et al., 2018; Thanh-Nho et al., 2018), which may have induced the higher CO₂ emissions at the water-air interface within the *Rhizophora* stand.

3.3. Vertical profiles of CO₂ concentrations in the canopy

Concerning vertical profiles of CO₂ concentrations in the canopy (Fig. 6), values were significantly different between seasons ($p < 0.001$), between night and day ($p < 0.001$), but also between high tide and low tide ($p < 0.001$). At night, profiles were relatively stable without significant differences between heights. Conversely during the day, CO₂ concentrations varied with heights but differently during the dry and the rainy season. During the rainy season, maximum CO₂ concentrations were measured within the prop roots, possibly because of roots respiration, possibly varying like for the trunks with season, and we suggest that it is also possible that the prop roots may act as a physical barrier for the CO₂

emitted from mangrove soils, limiting air movement. Then CO₂ concentrations decreased with height, most probably because it was used by the *Rhizophora* trees for their photosynthesis.

Figure 6: Vertical profiles of CO₂ concentrations (ppm) in the canopy at different month, (a) November 2016, (b) January 2017, (c) March 2017, (d) May 2017. LT means low tide, HT means high tide, DT means daytime, NT means nighttime, t°_{NT} means average temperature during the night, t°_{DT} means average temperature during the day.

The beginning of the rainy season is a period with higher primary productivity and net ecosystem accumulation of CO₂ (Vinh, 2018). Consequently, we suggest that the CO₂ produced during mangrove-derived OM decomposition, and further emitted at the soil surface may be recycled by the trees and not being exported towards the atmosphere. However during the dry season in January and March, CO₂ concentrations increased from the forest

floor to the canopy, which may suggest that photosynthesis was limited during the dry and cool season. Eventually, we measured higher CO₂ concentrations along height profiles at low tides than at tides, which corresponds to our previous results of higher CO₂ emissions from mangrove soils than from the water column. The highest CO₂ concentrations in the profiles, reaching almost 480 ppm, were measured at night in May (Fig. 6 d), which corresponds to the period of highest CO₂ emissions from soils and trunks due to the high temperature and the first rainfall of the rainy season. Further research using eddy-covariance technique and using ¹³C-CO₂ should be developed to have a more accurate understanding on the recycling of CO₂ emitted from mangrove soils during photosynthetic processes. Our hypothesis is that CO₂ emitted under the canopy may be recycled during photosynthesis processes

4. Conclusions

CO₂ emissions from mangrove soils, water column and trunks varied with seasons and influenced CO₂ concentrations vertical profiles in the canopy. CO₂ emissions from the soils at low tide were among the highest reported for a mangrove ecosystem, and are suggested to be related to the very high temperature all year round in Southern Vietnam. Differences between CO₂ fluxes measured in the dark and at light confirm the key role of microphytobenthos developing at soil surface. The latter can use the CO₂ produced within the soil for photosynthesis processes, limiting its evasion to the atmosphere. Seasonal variations of temperature and precipitation also strongly influenced CO₂ emissions, both from the soil and from the trunks. The highest CO₂ fluxes were measured during the transition between the dry and the rainy season, when the mean monthly temperature was the highest, and the first rainfall occurred. Temperature and precipitation both increased OM decomposition and organisms' respiration. However, we suggest that during the middle of the rainy season, enhanced exchanges between mangrove soils and adjacent tidal creeks due to higher level of

the river, resulted in an export of the CO₂ through pore-water seepage that limited its emission from mangrove soils. Within the mangrove at high tide, CO₂ emissions were lower than from the soil at low tide, and were mainly controlled by the incoming estuarine waters. During the rainy season, higher CO₂ emissions at the water-air interface are suggested to be related to the higher level of the river, which is known to be enriched in OM and CO₂ due to increased runoff in watershed. As a result of the difference of CO₂ emissions between low tide and high tide, CO₂ concentrations in the vertical profiles in the canopy were higher at low tide. In addition, *Rhizophora* prop roots seemed to be able to trap the CO₂ emitted from mangrove substrate, with peaks of concentrations at the prop roots level. Eventually, CO₂ concentrations increased or decreased towards the upper canopy depending on season. We suggest that temperature and precipitation influences the ratio photosynthesis/respiration, which was responsible for this variability. A CO₂ eddy-covariance (EC) study should be develop to confirm this hypothesis. EC flux towers are used to measure the net ecosystem exchange and allow for integration, at a very high temporal resolution, of the components (temperature, precipitation, solar radiation, etc) that control the ability of an ecosystem to act as a CO₂ sink or source. In addition, it will allow to determine the exact contribution of below-canopy respiration to ecosystem respiration.

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