Methane and carbon dioxide emissions from different ecosystems at the end of dry period in South Vietnam

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Abstract

The carbon cycle includes important fluxes of methane (CH₄) and carbon dioxide (CO₂) between the ecosystem and the atmosphere. The fluxes may acquire either positive (release) or negative values (consumption). We calculated these fluxes based on short-campaign in situ chamber measurements from four ecosystems of South Vietnam: intact mountain rain forest, rice field, *Melaleuca* forest and mangroves (different sites with *Avicennia* or *Rhizophora* and a typhoon-disturbed gap). Soil measurements were supplemented by chamber measurements of gas fluxes from the tree stems. Measuring CH₄ and CO₂ together facilitates the assessment of the ratio between these two gases in connection with current conditions and specificity of individual ecosystems. The highest fluxes of CH₄ were recorded in the *Melaleuca* forest, being within the range from 356.7 to 784.2 mg CH₄-C m⁻² day⁻¹ accompanied by higher fluxes of CH₄ release from *Melaleuca* tree stems (8.0–262.1 mg CH₄-C m⁻² day⁻¹). Significant negative soil fluxes of CH₄ were recorded in the mountain rain forest, within the range from –0.3 to –0.8 mg CH₄-C m⁻² day⁻¹. Fluxes of CO₂ indicate prevailing aerobic activity in the soils of the ecosystems investigated. Quite a large variability of CO₂ fluxes was recorded in the soil of the *Avicennia* mangroves. The in situ measurements of different ecosystems are fundamental for follow-up measurements at different levels such as aerial and satellite gas fluxes observations.

Keywords *Avicennia alba* · Mangroves · *Melaleuca cajuputi* · Mountain rain forest · *Rhizophora apiculata* · Rice field

Introduction

Functioning of different ecosystems over the landscapes is connected to different dynamics of gas exchange between the atmosphere as the major temporary exchange sink/source of gases, and the whole ecosystem. In carbon cycle, involving biogenic processes, there are important fluxes of methane

(CH₄) and carbon dioxide (CO₂), which may acquire either positive (release) or negative values (oxidation/uptake). These gases together with nitrous oxide (N₂O) and water vapour (H₂O), belong to greenhouse gases which affect global climate change [World Meteorological Organization (WMO) 2019]. Gradually increasing global concentration of these gases is important in relation to exchange of these gases at ecosystem level. Efflux of CH₄ and CO₂ is closely related to the functioning of individual ecosystems, especially in their soils. Anaerobic reducing conditions facilitate CH₄ production and its subsequent positive fluxes (emissions) from the soils (Mer and Roger 2001; Richardson and Vepraskas 2001). CH₄ is produced by different groups of microorganisms in sequence within the anaerobic food chain (Mer and Roger 2001; Wagner 2017). On the other hand, positive fluxes (release) of CO₂ are related to prevailing aerobic conditions in the soil profile. In general, CO₂ production in soils results from autotrophic respiration of live belowground plant parts (roots and rhizomes) and from heterotrophic respiration, mainly that of microorganisms (Kutsch et al. 2005; Kuzyakov 2006). Fluxes of both gases

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are mostly highly variable both in space and time (Nicolini et al. 2013; Darenova et al. 2016; Acosta et al. 2019). The dynamics of the gas fluxes is connected with highly variable and heterogeneous conditions, which varied from strictly anaerobic to strictly aerobic ones.

Soil heterogeneity can be understood in terms of matter structure, functioning and scale (size), all changing dynamically over time. In tropical ecosystems, potential CH_4 and CO_2 fluxes occur under favourable conditions, almost without any temperature and/or humidity limitation (Chimner 2004). Final rates of CH_4 and CO_2 fluxes are usually related to the highest rates of decomposition of organic matter (Segers 1998), resulting in a rapid turnover of organic matter (Wang et al. 2017), connected with gas fluxes from the soil. In tropical peatlands, the measured soil respiration (release of CO_2) rates can be lower than those measured in temperate and boreal peatlands in summer (Chimner 2004). Tropical peatlands receive a continuous supply of organic carbon throughout the year, which results in more stabilized CO_2 fluxes. Typical of tropical soils is also their usually small diurnal dynamics of gas fluxes due to similar soil temperatures during the light and the dark period of the day when the soil moisture does not change (Kursar 1989; Chimner 2004). Very low soil moisture enables increase of the soil temperatures up to 50°C mainly in subhumid and semiarid tropical regions (Lal and Sánchez 1992). Dynamics and sensitivity of CH_4 and CO_2 emissions to changing soil temperature characterized by the temperature coefficient (Q_{10}) may be less sensitive to the increase of the soil temperature than a decrease of the soil temperature. The temperature sensitivity (Q_{10}) usually was not changed in the tropical soil, if the soil temperature increased but changed if the soil temperature decreased (Bekku et al. 2003). In general, methanogenesis is more temperature sensitive than aerobic respiration (Yvon-Durocher et al. 2014; Chowdhury et al. 2015) and CH_4 fluxes have consistent temperature dependence across scales from cultures of methanogens to ecosystems (Yvon-Durocher et al. 2014).

The knowledge of CH_4 and CO_2 fluxes from various tropical ecosystems is important to determine the response of carbon cycle to climatic changes. In connection with that, is crucial to keep the ecosystems in a state suitable for their long-term mitigation functioning ongoing climate changes. Overall, one-fifth of anthropogenic greenhouse gas emissions can be sequestered by the terrestrial part of the biosphere. This situation represents a high opportunity for applying an important “natural solution” (e.g., the blue carbon initiative) to climate change (Griscom et al. 2017; Banerjee et al. 2020).

We report here the results of a short-term campaign of in situ measurements of CH_4 and CO_2 fluxes from the soils (five sites), stagnant shallow water (one site) and measurements of gas fluxes from the tree stems (tree sites) in

different ecosystems. Merely short-term campaign measurements were carried out in view of the impossibility to realize long-term in situ measurements. The study sites are lacking an infrastructure that would support long-term measurements with complex scientific equipment.

Although during the last decade increased number of studies from the tropical regions, there are still not enough especially in situ measurements from the tropical wetland ecosystems. The motivation of our measurements was to obtain in situ measured data of CH_4 and CO_2 fluxes measured at end of the dry (intermediate/transition) period, using the same methods, employing manual soil and tree-stem emission gas chambers. The results should allow us to make meaningful comparisons of gas fluxes in various ecosystems and also can be used in different approaches using in situ data together with satellite CH_4 observations (Bloom et al. 2010; Fraser et al. 2014; Parker et al. 2018). Measuring both gases together enables us to assess the relation (ratio) between them and relations to current conditions and specificity of individual ecosystems. The ratio of $\text{CO}_2:\text{CH}_4$ itself shows settings of ongoing processes associated with gas fluxes at the soil and ecosystem level (McMillan et al. 2007; Chowdhury et al. 2015).

We try to verify the following hypotheses: (1) high efflux of CH_4 occurs mainly in water-saturated soils (mangrove sites and *Melaleuca* forest) whereas high CO_2 efflux occurs in soils of the mountain rain forest. (2) The ratio of CH_4 to CO_2 emissions will reflect the actual hydrological conditions, especially in the terms of anaerobic versus aerobic conditions. (3) Fluxes of both gases from the tree stems will be related to fluxes from the soil or stagnant water. (4) In forest ecosystems, minor negative fluxes of CH_4 take place, thereby indicating consumption (oxidation) of CH_4 in the soil or tree stems.

Methods

Site description

In situ measurement of gas fluxes was carried out in the Bidoup montane evergreen broadleaved rain forest, Tram Chim National Park, and the Can Gio Mangrove forest, on 29–30 April, 3–4 and 6–7 May 2017, respectively (Fig. 1; Table 1). Soil flux measurements were taken in situations when the water level was close to or below soil surface except situation in rice and mangrove sites where water level was above soil surface.

Mountain rain forest

The mountain rain forest Bidoup is a montane evergreen broadleaf forest in the Bidoup-Nui Ba National Park, Lam

Fig. 1 A map of Southeast Asia and southern part of Vietnam showing the location of sites which host in total 6 studied ecosystems: Da Lat-Bidoup (mountain tropical rain forest), Tram Chim (stagnant shallow water under *Melaleuca* forest canopy, rice field), Can Gio (*Avicennia*, *Rhizophora* and typhoon-disturbed gap). The main and detailed maps were drawn using the R packages (Chambers 2008) “rworldmap” version 1.3-6 (<https://cran.r-project.org/web/packages/rworldmap/>), “ggplot2” version 3.2.1 (<https://cran.r-project.org/web/packages/ggplot2/>) and “ggmap” version 3.0.0 (<https://cran.r-project.org/web/packages/ggmap/>). Detailed map of the southern part of Vietnam displayed was queried from the Google Maps (Map data©2017 Google) using the function ‘get_map’ in the ‘ggmap’ R package

Table 1 Description of the in situ measurement sites in South Vietnam (FAO 1993; Nguyen 2000; Tran and Barzen 2016)

Study site	Da Lat-Bidoup	Tram Chim	Can Gio
Ecosystem	Montane evergreen broadleaf rain forest	Lowland freshwater forested swamp	Mangroves
Measurement sites	Mountain forest	<i>Melaleuca</i> rice field	<i>Avicennia</i> , <i>Rhizophora</i> typhoon-disturbed gap
Elevation (m)	1500	1–2	1–2
Climate type	Tropical monsoon in montane area	Tropical monsoon	Tropical monsoon
Annual mean air temperature (°C)	18	27	27.6
Annual mean relative air humidity (%)	85	82	80
Mean total annual precipitation (mm)	1857	1400	1336
Coordinates of the measurement sites	12.172624° N, 108.697346° E	10.718262° N, 105.500842° E 10.748335° N, 105.515893° E	10.385794° N, 106.885788° E 10.385703° N, 106.885595° E 10.386737° N, 106.885089° E

Dong Province: The measurement site is located on the Langbian Plateau which is a part of the Central Highlands of Vietnam (Fig. 1; Table 1). The forest is dominated by species of the *Fagaceae* and *Lauraceae* families, including *Castanopsis indica*, *Lithocarpus* spp., *Quercus* spp., *Cinnamomum* spp. and *Litsea* spp., and mixed with

coniferous species, such as *Pinus dalatensis*, *Calocedrus macrolepis*, *Fokienia hodginsii* and *Podocarpus imbricatus* (Tordoff et al. 2004). This forest type represents a pristine natural habitat of the much larger Southern Annamites montane rain forests in Laos and Vietnam (Queiroz et al. 2013).

Melaleuca forest

The Tram Chim *Melaleuca* flooded forest in the Tram Chim National Park, Dong Thap Province of the Mekong Delta (Fig. 1; Table 1). Tram Chim National Park is one of the last remnants of the Plain of Reeds, which was once a vast freshwater floodplain of the Mekong River, covering an area of approximately one million hectares in Cambodia and Vietnam (Tran and Barzen 2016). Efflux gas measurement was carried out in an adult *Melaleuca cajuputi* forest stand and on its adjacent open water surface (*Melaleuca* stagnant water). The land inside the Tram Chim National Park had been left inundated (0.3–0.7 m) by closing all water gates since June 2016 because of concerns about repetition of severe drought like that recorded in 2016.

Rice field

Efflux gas measurement was carried out one week after rice seeding in the Tram Chim National Park buffer zone experiencing shallow flooding with water 0.03 m deep (Fig. 1; Table 1).

Avicennia, Rhizophora and typhoon-disturbed gap

The measurement sites *Avicennia*, *Rhizophora* and typhoon-disturbed gap include different habitats such as a 30 years old planted *Rhizophora apiculata* forest stand, natural *Avicennia alba* stand along a tidal creek and a typhoon-disturbed gap (bare land) with some regenerating mangrove seedlings, where there had also been a planted forest until it was destroyed by the typhoon Durian in December 2006. These habitats are located in the Can Gio Mangrove forest, which is the main part of the Can Gio UNESCO Biosphere Reserve in the coastal zone district of Ho Chi Minh City, a low-lying delta of the Sai Gon-Dong Nai rivers (Fig. 1; Table 1). The Can Gio area once supported natural mangrove forest but almost all of it was destroyed by herbicides during the Second Indochina War (1954–1975). Between 1978 and 1986, the area was reforested with *Rhizophora apiculata*. The reforestation effort has been successful in getting the forest cover back and promoting natural regeneration of whole mangrove ecosystems (Tordoff et al. 2004). Current area of mangroves decreased in the south-eastern part of the Mekong River Delta in Vietnam mainly due to expansion of aquaculture farms (Hong et al. 2019).

Soil structure and properties

The soils were different in the ecosystems studied. Coarse structure was found in the mountain rain forest soil where the percentage content of sand particles was the highest out of all analysed soils (33–37%) across the soil profile to

0–0.6 m depth. Soils from the other ecosystems contained less than 22% of sand particles (8.2–21.6%). The highest percentage content of clay particles was found in the soil of the *Rhizophora* site (52%) and in the soil of the rice field (50.1%). The percentage content of silt in the soils was within the range of 24.0–49.6% and complemented that of fine particles, also including clay, which was up to 80–90%.

Soil acidity, i.e., pH (H₂O), ranged between 4.07 and 5.80 in the soil profiles. The lowest soil pH was recorded in the rice field and the highest was in the *Rhizophora* soil profile.

The highest percentage contents of soil organic carbon (about 6%) were determined in the top layer (0–5 cm) of the mountain rain forest soil and in the lower layer (19–60 cm) of the rice-field soil. The lowest organic carbon percentage content (<2%) was found in the lower soil layer (20–60 cm) of the mountain rain forest soil.

The nitrogen percentage content was highest in the topsoil layers of all soil profiles (0.213–0.536%). The highest phosphorus percentage content was recorded in the topsoil (0–19 cm) of the rice field (0.179%). The other soil layers contained phosphorus within the range of 0.041–0.072% except the soil at the typhoon-disturbed gap site, with 0.141% of phosphorus in the 12–60 cm soil layer.

Different contents of nitrogen and carbon resulted in different ratios between these two elements (Fig. 2). The lowest carbon to nitrogen ratio (C:N) was found at the typhoon-gap site where it was about 10 below 0.1 m depth and 18 in the topsoil. These different C:N ratios are caused by different contents of carbon in different soil layers while nitrogen content was similar in the upper and lower soil layers. The highest C:N ratio (19) was found in the lower soil layers at the *Avicennia* site. Apparent change of the C:N ratio with soil depth was found in the typhoon-disturbed gap profile.

Chamber measurements

Gas fluxes were measured using two types of chambers designed for soil and tree stem fluxes. The soil gas fluxes were measured at 5, 7 and 10 positions and those in water were at 3 positions from the stagnant water surface, according to the ecosystem investigated. Each soil chamber has a cylindrical shape with 18.9 cm inner diameter and 3.167 L volume. At each individual measurement position and 1 day before the measurements, a PVC collar was installed into the soil at about 5–10 cm depth, depending on current conditions. Stem fluxes (3–5 individual tree stems) were measured in tree-stem chambers of a plastic block shape (plan 0.097 m × 0.065 m) and volume of 0.470 L.

One day before the measurements, the stem chambers were fixed to the tree stems at 0.40 m (mangroves) and 1.10 m heights (mountain rain forest) with a plastics tape and sealed with silicone. The opening top part of each stem chamber was closed during the measurements by a sealed

Fig. 2 Distribution of belowground organic carbon percentage content in soil dry mass at the sites studied (Mountain rain forest, Rice field, *Avicennia*, *Rhizophora* and typhoon-disturbed gap sites) except

Melaleuca stagnant water site. Full lines—percentage content of organic carbon, dashed green lines—C:N ratio

plastic cover with mechanical locks. Both the soil-chamber and tree-stem chamber measurements were taken during daytime ebb tides, when the ground was only incompletely inundated.

The CH_4 and CO_2 flux measurements as such were carried out using a non-steady state closed soil/stem chamber system (Matson and Harriss 1995). Changing concentrations of CH_4 and CO_2 inside the closed chambers were measured at one-second intervals with a fast methane analyser GGA-30p (Los Gatos Research Inc., CA, USA). For the subsequent data processing of one-second, the raw data were used with vapour dilution correction (Butenhoff and Khalil 2002).

Redox potential measurements

Redox potential (E_H) was measured using platinum electrodes and a reference electrode (Ag/AgCl) together with the multimeter Multi340i (WTW, Germany). The electrodes were inserted in the surface soil profile at the depth of about 3–4 cm. The final E_H values were corrected relative to the normal H electrode by adding +200 mV (van Bochove et al. 2002).

Data processing

Calculation of the gas fluxes is based on the slope of the linear regression of gas concentration in a chamber's headspace against time (period of 4–5 min), taking into account the chamber volume (3.167 L) and surface area occupied by the chamber (0.02806 m²). Calculations of the gas fluxes also include their adaptation to the current air temperature and ambient air pressure (Juszczak et al. 2012). The final flux calculation was checked in terms of temporal linearity of gas concentration changes inside a close chamber during the measurements, using the adjusted correlation coefficient (R^2). Gas fluxes with $R^2 > 0.80$ are assumed to be correct flux estimates (Juszczak et al. 2012). The calculated fluxes were tested for their normal distribution using the Shapiro–Wilks test (Zar 2010). Homogeneity of the respective variances was tested using the Bartlett test (Zar 2010). The distribution of the primary data differed significantly from normality ($P < 0.01$) and their variances were not homogeneous according to the Bartlett test ($P < 0.01$). Based on these facts, the differences between the soil fluxes of CH_4 and CO_2 measured in different ecosystems were tested using

the nonparametric Kruskal–Wallis test with the possibility of multiple comparison between groups (Hollander et al. 2014). Statistical analyses were done using the R statistical software (Chambers 2008) version 3.4.2 with the following packages: “pgirmess” (<http://cran.r-project.org/web/packages/pgirmess/>) and “e1071” (<https://cran.r-project.org/web/packages/e1071/>). Relationships between the CO₂ and CH₄ fluxes were evaluated using the Spearman correlation coefficient (Best and Roberts 1975).

Results

Conditions during gas flux measurements

Measurements were taken during the transition period between the dry and rainy monsoon seasons. The lowest air and soil temperatures were recorded in the mountain rain forest at the Da Lat-Bidoup site. Average and median values of the air temperatures were very close to each other, being 20.7 °C and 20.9 °C, respectively. Average and median values of soil temperature were 18.0 °C and 18.5 °C, respectively (Table 2). In the other ecosystems studied, the average air temperatures were between 29.1 and 31.0 °C. Average soil temperatures were somewhat lower: between 27.9 and 29.6 °C and were very close to the median values.

The redox potential (E_H) measured in the ecosystems investigated, except the mountain rain forest, was mostly negative, an exception being the typhoon-disturbed gap within mangroves (Can Gio site). At this site, average E_H was positive: 161.8 mV (median 169.0 mV). In the other ecosystems, E_H was negative with values as low as about –527 mV in the *Rhizophora* mangroves. In the rest of the ecosystems, E_H was not lower than –201.6 mV (*Avicennia*). The least negative E_H was measured in the rice field (Tram Chim site): –116.4 mV on average (median –72.0 mV).

Water conductivity differed distinctly between the mangrove sites (*Avicennia*, *Rhizophora* and typhoon-disturbed gap) and freshwaters ecosystems represented by the rice field and the site with stagnant shallow water below the *Melaleuca* forest canopy. In the mangroves, the conductivity of interstitial water was within the range of 88.3–112.9 mS cm^{–1} (Table 2). The mangrove sites were influenced by both saline sea water and fresh river water creating brackish conditions in the soil. At the site with stagnant shallow water under *Melaleuca* forest canopy and in the rice field, the water conductivity was significantly lower about 0.633 mS cm^{–1} and 0.698 mS cm^{–1} respectively (Table 2). This conductivity characterizes freshwater contained in the respective soils.

Soil methane fluxes

The recorded CH₄ fluxes from soils and stagnant water of different ecosystems varied within a wide range (Fig. 3). In the mountain rain forest (Da Lat-Bidoup site), the CH₄ fluxes from the soil were negative, which means consumption (oxidation) of CH₄ in the forest soil. The consumption rate of CH₄ was from –0.3 to –0.8 mg CH₄–C m^{–2} day^{–1}. Here, in comparison with CH₄ fluxes recorded at the other measurement sites, the rate of CH₄ consumption (negative flux) was 10 times as low as the minimum negative fluxes and 1000 times as low as the maximum positive fluxes. The consumption of CH₄ was slightly negatively skewed (skewness = –0.124).

The highest positive fluxes of CH₄ recorded were those from the stagnant shallow water under *Melaleuca* forest canopy (Tram Chim site). In this case, the range of CH₄ emissions was from 356.7 to 784.2 mg CH₄–C m^{–2} day^{–1}. The mean of recorded CH₄ fluxes was higher than their median value, and the distribution of these fluxes was positively skewed (skewness = 0.378). Soil fluxes of CH₄ measured in

Table 2 Actual conditions on the sites where the fluxes of CH₄ and CO₂ were measured

Sites	Da Lat-Bidoup	Can Gio (mangroves)			Tram Chim	
Parameters/ecosystems	Mountain rain forest	<i>Avicennia</i>	<i>Rhizophora</i>	Typhoon-disturbed gap	Rice field	<i>Melaleuca</i> stagnant water
Air temperature (°C)	20.7 (20.9)	29.9 (30.2)	29.4 (30.0)	29.9 (30.0)	29.1 (29.2)	31.0 (31.1)
Soil temperature (°C)	18.0 (18.5)	27.9 (28.0)	28.5 (28.0)	29.6 (29.3)	28.8 (28.7)	28.3 (28.4)
Redox potential (mV) ^a	not measured	–201.6 (–165.0)	–527.0 (–252.0)	161.8 (169.0)	–116.4 (–72.0)	–152.8 (–112.5)
Electrical conductivity (25 °C; mS cm ^{–1})	0.633	88.9	112.9	88.3	0.698	0.145

The means and medians in brackets are indicated

^aThe redox potential was corrected relative to the normal H electrode by adding +200 mV (van Bochove et al. 2002)

Fig. 3 Fluxes of carbon in the forms of CH₄ and CO₂ from the soils of different ecosystems and stagnant shallow water under *Melaleuca* forest canopy. Shown are the means (small open boxes), median values of the second quartile (thick black lines), upper and lower quartile

(boxes with 50% of measured data) and error bars with the upper and lower extreme values indicated. Statistically significant differences between the sites are indicated by different letters

the other ecosystems ranged from -0.064 to $7.27 \text{ mg CH}_4\text{-C m}^{-2} \text{ day}^{-1}$, with almost all the fluxes being positive. Exceptionally weak negative fluxes (consumption of CH₄) were recorded, on two occasions, in the *Rhizophora* forest and in the typhoon-disturbed gap (both are mangrove sites). Distributions of these fluxes were almost all positively skewed while they were only slightly negatively skewed (-0.016) in the typhoon-disturbed gap mangrove site.

The widest fluctuation of CH₄ fluxes was recorded at the *Melaleuca* and *Avicennia* mangrove site, where the fluxes varied between 365.7 and $784.2 \text{ mg CH}_4\text{-C m}^{-2} \text{ day}^{-1}$ and 0.07 to $7.27 \text{ mg CH}_4\text{-C m}^{-2} \text{ day}^{-1}$ respectively. These fluxes were positively skewed (skewness = 1.057). Extreme skewness was calculated for fluxes at the *Rhizophora* mangrove site (skewness = 2.201). This situation shows a significantly shifted mean which was much higher than the median value. At this site, we took several measurements of very high flux rates (up to $19.4 \text{ mg CH}_4\text{-C m}^{-2} \text{ day}^{-1}$). The range of fluxes prevailing at the *Rhizophora* mangrove

site was 0.21 to $0.89 \text{ mg CH}_4\text{-C m}^{-2} \text{ day}^{-1}$. A very narrow range of CH₄ fluxes (-0.07 to $0.71 \text{ mg CH}_4\text{-C m}^{-2} \text{ day}^{-1}$) was recorded at the typhoon-disturbed gap mangrove site with an only very slightly negative skewness (-0.016), i.e., with an almost unskewed and nearly symmetrical distribution.

Statistical differences among rice field (Tram Chim site), *Avicennia*, *Rhizophora* and typhoon-disturbed gap mangrove sites were tested without sites mountain rain forest (Da Lat-Bidoup site) and *Melaleuca* stagnant water. Separately statistical testing enables to distinguish the differences among the selected sites. Statistically significant differences were found only between the typhoon-disturbed gap mangrove and *Avicennia* soils (Chi-square = 10.65 ; $df = 3$; $P \text{ value} = 0.01$, Fig. 3). Soil fluxes of CH₄ at the *Avicennia* mangrove site were not significantly different from those recorded in the rice field and *Rhizophora* mangrove site.

Soil carbon dioxide fluxes

The CO₂ fluxes from the soils recorded in the investigated ecosystems and stagnant shallow water under *Melaleuca* forest canopy were positive except only one negative value close to zero, recorded at the *Avicennia* mangrove site when the water level was 2.5 cm above soil surface. The overall range of CO₂ fluxes measured at all the sites was -0.016 to $16.529 \text{ g CO}_2\text{-C m}^{-2} \text{ day}^{-1}$. At the *Avicennia* mangrove site, the CO₂ fluxes fluctuated more widely than at the other measurement sites (Fig. 3). For example, a very narrow range of CO₂ fluxes was recorded in stagnant water of the *Melaleuca* forest (Tram Chim site), namely from 0.51 to $0.75 \text{ g CO}_2\text{-C m}^{-2} \text{ day}^{-1}$. A few higher flux rates were recorded in the typhoon gap of the mangrove site, their range being from 0.24 to $1.24 \text{ g CO}_2\text{-C m}^{-2} \text{ day}^{-1}$. Faster fluxes were recorded in the rice field (Tram Chim site), within the range of 0.94 to $2.43 \text{ g CO}_2\text{-C m}^{-2} \text{ day}^{-1}$. Fluxes from the sites rice field, *Rhizophora*, typhoon gap in mangroves and stagnant water of *Melaleuca* forest were similar and statistically significantly different from fluxes assessed at the mountain rain forest (Da Lat-Bidoup site) and *Avicennia* mangrove sites (Chi-squared = 45.76; df = 5; P value < 0.01). Almost all distributions of CO₂ fluxes were skewed positively. This is evident from the shift of the means to higher values, mainly in fluxes from the *Avicennia* site with the highest skewness (1.567). In this case, we recorded quite high CO₂ fluxes of 8.01 and $16.529 \text{ g CO}_2\text{-C m}^{-2} \text{ day}^{-1}$ as the maximum values. Other positively skewed fluxes of CO₂ were recorded in the mountain rain forest (skewness = 1.262). The rest of the measured fluxes had skewness values below 1. Namely the distributions of CO₂ fluxes from the rice field were very close to symmetrical distribution (skewness = 0.037). The skewness of the remaining fluxes was 0.519, 0.911 and 0.277 for the *Rhizophora*, typhoon gap in mangroves and stagnant water of the *Melaleuca* site, respectively.

Relationship between CH₄ and CO₂ soil fluxes

Relationship between the fluxes of carbon in the forms of CO₂ and CH₄ presented as medians shows that the ratio between the two gases broadly varied across the ecosystems. An analysis of the recorded data shows that no clearly visible relationship exists between the CO₂ and CH₄ fluxes recorded in different ecosystems. Very similar ratios between both gases were recorded at the rice field and the *Rhizophora* sites (Fig. 4).

Fluxes of CO₂ were slightly higher but statistically insignificant at the *Rhizophora* mangrove site than in the rice field and vice versa: CH₄ fluxes were slightly higher but statistically insignificant in the rice field than in *Rhizophora*. Measurements of CH₄ fluxes from these sites were similar also

to those from the typhoon-disturbed gap in mangroves site, but under very low CO₂ fluxes. The highest CO₂ flux rate was recorded along with negative CH₄ fluxes (consumption) only in the soil of the mountain rain forest (Da Lat-Bidoup site). High CO₂ fluxes were recorded at the *Avicennia* mangrove site, but along with quite high fluxes of CH₄. The highest CH₄ fluxes together with low CO₂ fluxes were recorded in open water of the *Melaleuca* forest.

The correlations between the fluxes of CO₂ and CH₄ analyzed individually for each site was statistically almost non-significant, but for two exceptions: the *Avicennia* and *Rhizophora* mangrove sites. In these two cases, the two fluxes were mutually positively correlated. The highest positive correlation was found at the *Avicennia* mangrove site ($R_{\text{Sperman's}} = 0.896$, P value < 0.001). A weaker statistically significant correlation was found at the *Rhizophora* mangrove site ($R_{\text{Sperman's}} = 0.732$, P value < 0.01).

At both sites, we recorded relevant clear signs of CO₂ fluxes together with fluxes of CH₄. The relationship between CO₂ and CH₄ fluxes can be easily characterized by statistically significant slopes of a simple linear model without intercept. The calculated slopes were 0.484 (P value < 0.001) and 0.785 (P value < 0.05) for the *Avicennia* and *Rhizophora* mangrove sites, respectively. Higher value of slope in the case of *Rhizophora* relates to a narrow range of fluxes of both gases recorded there, in comparison with their more variable fluxes recorded at the *Avicennia* mangrove site.

Fluxes of CH₄ and CO₂ from tree stems

Fluxes of CH₄ and CO₂ were measured individually on the tree stems of different dominant tree plant species: *Avicennia alba*, *Rhizophora apiculata*, *Melaleuca cajuputi* and mountain rain forest trees (*Manglietia chevalierii* and *Castanopsis ceratocantha*). Estimated age of these trees was more than 20–30 years. The breast diameters were 0.40 m and 0.56 m for *Avicennia alba* and *Rhizophora apiculata*, respectively. The measured tree of *Melaleuca cajuputi* had the breast diameter of 0.20 m and the trees measured in the mountain rain forest had the breast diameter of 0.30 m. The recorded fluxes of both gases varied quite broadly (Fig. 5). The highest fluxes of CH₄ were recorded for the stems of *Melaleuca cajuputi* (*Melaleuca* forest site). Positive fluxes were characterized by minimum and maximum values of 8.01 and $262.1 \text{ mg CH}_4\text{-C m}^{-2} \text{ day}^{-1}$, respectively. The distribution of these fluxes was positively skewed (skewness = 1.335) and their median ($37.5 \text{ mg CH}_4\text{-C m}^{-2} \text{ day}^{-1}$) markedly differed from their mean value ($69.8 \text{ mg CH}_4\text{-C m}^{-2} \text{ day}^{-1}$). High CH₄ fluxes from the stems of *Melaleuca* are followed by the fluxes from the stems of both *Avicennia alba* (*Avicennia* site) and *Rhizophora apiculata* (*Rhizophora* site). The *Avicennia alba* stems released more CH₄ than those of *Rhizophora apiculata*. The range of these fluxes was from

Fig. 4 Relations between fluxes in the form of CO_2 and CH_4 from soil surface, stagnant shallow water under *Melaleuca* canopy and tree stems (green points) Me=*Melaleuca cajuputi*, Av=*Avicennia alba*, Rh=*Rhizophora apiculata*, Mo=*Manglietia chevalierii* and *Castan-*

opsis ceratocantha. Medians (black boxes and green circles) and the ranges of the first and the third quartiles are presented, respectively, as vertical and horizontal lines across the medians (color figure online)

0.25 to 1.16 $\text{mg CH}_4\text{-C m}^{-2} \text{ day}^{-1}$ and their distribution was positively skewed (skewness = 0.633). More positively skewed distribution of CH_4 fluxes was recorded for the *Rhizophora apiculata* stems (skewness = 1.484). This skewness was most positive of all distributions of the measured fluxes. The range of the recorded CH_4 fluxes was 0.041–0.900 $\text{mg CH}_4\text{-C m}^{-2} \text{ day}^{-1}$. The lowest skewness (0.538) was calculated for measurements in the mountain rain forest. The range of the gas-flux measurements as such recorded in the mountain rain forest was very narrow and their median and mean values were 0.090 and 0.165 $\text{mg CH}_4\text{-C m}^{-2} \text{ day}^{-1}$, respectively. Statistically significantly differing fluxes from the stems were found in the mountain rain forest as compared with the *Avicennia* mangrove and *Melaleuca* forest sites. Stem fluxes measured at the *Rhizophora* site were similar to those recorded at the *Avicennia* and mountain rain forest sites. Fluxes of CH_4 measured at the *Melaleuca* site were similar to those at the *Avicennia* site. This similarity was, however, close to a statistically significant difference according to the Kruskal Wallis test (observed difference = 15.00 versus critical difference = 15.19 on the 0.05 probability level).

Fluxes of CO_2 varied from close to zero to 5.06 $\text{g CO}_2\text{-C m}^{-2} \text{ day}^{-1}$. The highest fluxes were recorded from the tree stems of *Avicennia alba*, within the range from 0.90 to 5.06 $\text{g CO}_2\text{-C m}^{-2} \text{ day}^{-1}$. The distribution of these fluxes was slightly positively skewed (skewness = 0.205). The lowest CO_2 fluxes, calculated from two measurements, resulted in assessment of negative fluxes from the stems of trees (*Manglietia chevalierii* and *Castanopsis ceratocantha*) in the mountain rain forest, where their range was –0.13 to 0.33 $\text{g CO}_2\text{-C m}^{-2} \text{ day}^{-1}$. The distribution of these fluxes was negatively skewed (skewness = –0.445) and the calculated mean flux (0.14 $\text{g CO}_2\text{-C m}^{-2} \text{ day}^{-1}$) was lower than the median flux value (0.16 $\text{g CO}_2\text{-C m}^{-2} \text{ day}^{-1}$). Similar fluxes of CO_2 were measured from the stems of *Rhizophora apiculata* and *Melaleuca cajuputi*. This similarity was statistically significant. The distributions of both fluxes were positively skewed but the distribution of data on fluxes from the stems of *Melaleuca cajuputi* was very positively asymmetric (skewness = 1.165). The median value of these fluxes was distinctly lower (0.53 $\text{g CO}_2\text{-C m}^{-2} \text{ day}^{-1}$) than their mean value (1.04 $\text{g CO}_2\text{-C m}^{-2} \text{ day}^{-1}$). Statistically significant differences were found between *Avicennia alba* stems

Fig. 5 Fluxes of carbon in CH₄ and CO₂ forms from the stems of different tree species. Mountain rain forest = (*Manglietia chevalieri*, *Castanopsis ceratocantha*), *Avicennia*=*Avicennia alba*, *Rhizophora*=*Rhizophora apiculata*, *Melaleuca*=*Melaleuca cajuputi*. Means (open small boxes), medians of the second quartile (thick

black lines), upper and lower quartile (boxes with 50% of measured data) and error bars with upper and lower extreme values are shown. Statistically significant differences between the sites are marked by different letters

and the rest of the measured stems of different trees (Fig. 5). The fluxes measured from the stems of *Melaleuca cajuputi* also differed from fluxes from the stems of the mountain rain forest tree species and from those of *Avicennia alba* (Mangrove).

Comparison of gas fluxes from the soils, stagnant water and tree stems

In most cases, the fluxes of CH₄ and CO₂ were higher from the soils and stagnant water, except for only one case in the mountain rain forest where negative flux (consumption) of CH₄ was recorded (Fig. 6). Median flux of CH₄ from the tree stems was positive and very close to zero (0.003 mg CH₄–C m⁻² day⁻¹). Although the gas fluxes were higher from the soils and from shallow stagnant water (*Melaleuca* site), we found statistically significant differences only in some cases.

Most of the CH₄ fluxes were statistically significantly (P value < 0.01) higher from the soils and stagnant water (*Melaleuca* site), for the *Rhizophora* site where the difference was non-significant (P value > 0.05). The greatest difference was found for the stagnant shallow water at the *Melaleuca* site, where the final difference between the median and mean values was between 387.4 and 509.4 mg CH₄–C m⁻² day⁻¹, respectively. The CO₂ fluxes differed less, and we found two statistically non-significant differences at the *Avicennia* (P value = 0.07) and *Melaleuca* sites (P value = 0.86). At the *Melaleuca* site, the CO₂ fluxes were similarly the lowest among the measurement sites, together with the measurements of fluxes from tree stems in the mountain rain forest (Fig. 6). Statistically significant differences between fluxes from the soils and those from the tree stems were found in *Rhizophora* and at the mountain rain forest sites. In this forest, the difference between medians and averages was

Fig. 6 Comparison of carbon fluxes in CH₄ and CO₂ forms (medians are presented) from the soils and stagnant shallow water under *Melaleuca* forest canopy (black boxes) with the same fluxes from stems of different species of trees (white boxes). Rain mountain forest = soil and *Manglietia chevalierii*, *Castanopsis ceratocantha* tree stems;

Avicennia = soil and *Avicennia albatree* stems; *Rhizophora* = soil and *Rhizophora apiculata* tree stems; *Melaleuca* = soil and *Melaleuca cajuputi* tree stems. Statistically significant differences between the stem and soil fluxes are indicated by the P value level

the highest (difference 3.78 and 3.91 g CO₂-C m⁻² day⁻¹, respectively) among the measurement sites. General view of the context of CH₄ and CO₂ fluxes from the soils and the tree stems is summarized in Fig. 4. It is evident from the graph that wetland plants (trees in our case) show quite high fluctuations in releasing CH₄ if this gas is formed in the soil. Fluxes of CO₂ fluctuated less widely in comparison with CH₄ fluxes and the widest fluctuation was recorded in *Melaleuca cajuputi* tree stems. In this case, the median soil fluxes and tree-stems fluxes of CO₂ were very similar.

Discussion

Rates and dynamics of soil CH₄ and CO₂ fluxes usually depend also on the soil type, stand composition, and both current and long-term conditions in the soil profile (Munera and Wollum 1977; Xu et al. 2004; Lopes de Gerenyu

et al. 2015; Ben-Noah and Friedman 2018). Prevailing soil conditions (e.g., aeration, moisture content, amount of soil organic matter and availability of nutrients) determine carbon (CO₂) balance of a whole ecosystem (Luyssaert et al. 2007) and thereby also long-term carbon pools stored as soil organic matter (SOM) (Post et al. 1982). The mountain rain forest site (Da Lat-Bidoup) belongs to ecosystems with quite a low content of SOM mainly in deeper soil layers. The SOM content decreased rapidly below the depth of 5 cm, despite a relatively high SOM content in the near-surface soil layer. SOM is a complex of organic compounds serving as respiratory substrate which is “aerobically breathed”, i.e., decomposed first to simpler compounds and eventually mostly to the final CO₂. Low content of SOM in the soil of the mountain rain forest probably reflects an intensive SOM turnover by microbial activity (Wang et al. 2017). The SOM is mineralized also by soil fauna activities, because termite mounds are common around the Da Lat-Bidoup and Cat

Tien National Park (Lopes de Gerenyu et al. 2015). CO₂ fluxes measured in Da Lat-Bidoup tropical mountain rain forest correspond with in situ measurements from other forests with tropical or subtropical climate (Inubushi et al. 2003; Melling et al. 2005; Shvaleyeva et al. 2011) and also with measurements from forests growing under cooler climatic conditions (Bond-Lamberty and Thomson 2010).

Soil fluxes of CO₂ demonstrate an intense oxidation of SOM under aerobic conditions while those of CH₄ demonstrate “anaerobically breathed” SOM, i.e., partly decomposed under anaerobic conditions usually detected in water-saturated soils (Richardson and Vepraskas 2001; Mer and Roger 2001). CH₄ fluxes from the mountain rain forest soil were significantly negative (Fig. 3). Negative flux of CH₄ means consumption of atmospheric CH₄ by the forest soil. The rate of CH₄ consumption by the mountain rain forest soil recorded at the Da Lat-Bidoup site is similar to rates measured in situ in tropical forests (Ishizuka et al. 2002; Butterbach-Bahl et al. 2004; Itoh et al. 2012) and also under different climatic conditions, e.g., temperate ones (Crill 1991; Castro et al. 1995; Chan et al. 2005; Dušek et al. 2018). The CH₄ consumption is also in agreement with the soil methanotrophy model MeMo v1.0 (Murguía-Flores et al. 2018). Distinctive consumption of CH₄ (negative fluxes) was not recorded at the other sites included in this study.

The highest positive fluxes of CH₄ were recorded in stagnant shallow water under *Melaleuca* forest canopy in the Tram Chim National Park. The free water surface released 100 times more CH₄ in comparison with the other mangrove forest sites. The *Melaleuca* forest site is flooded and the level of flooding is artificially maintained by the National park management. The resulting conditions were stable at least for two years and have induced strictly anaerobic reduced conditions facilitating CH₄ production (Mer and Roger 2001) in the flooded soil profile. The dominant tree *Melaleuca cajuputi* is a flooding-tolerant amphibious species (Yamanoshita et al. 2001) whose seedlings can grow under submergence for a long time (Tanaka et al. 2011).

During our measurements in *Melaleuca* forest site we never saw bubbles rising up from the bottom soil through the water. But during manipulation with a chamber outside of the measurement sites, we recorded some gas bubbles moving upwards from the bottom soil. Ebullition of CH₄ is often recorded, mainly in wetlands with free water surface (Strack and Waddington 2008) or in rice paddies (Green 2013). Our measurements were conducted at a stable water level and stable hydrostatic and air pressures. Under these conditions, ebullition was usually a non-significant component of CH₄ fluxes (Matson and Harriss 1995). Importance of the ebullition for CH₄ fluxes usually increases if the water level significantly fluctuates [e.g., in the Amazon River floodplain (Bartlett et al. 1990)]. CH₄ released in bubbles from the bottom soil is only incompletely oxidized while passing through

the water column (0.5 m) and the majority of CH₄ in bubbles is emitted from the water surface to the atmosphere.

High fluxes of CH₄ from free water surface in the *Melaleuca* forest connect with high fluxes of CH₄ from the stems of adult *Melaleuca cajuputi* trees. The root system of *Melaleuca* trees takes up CH₄ partially together with water (Reay et al. 2010), or CH₄ can penetrate into the trees via their gas-permeable aerenchyma tissues (Colmer 2003). CH₄ taken up by roots escapes from the tree mainly via the stems or other aboveground tree parts (branches, leaves). Tree stems are connected to the ambient atmosphere, where the background CH₄ concentration is usually less than 2 ppm (1.869 ppm on a global average, WMO Greenhouse Gas Bulletin 2019). But the CH₄ concentration inside plant's aerenchyma tissues can be temporarily higher due to increase of concentration during dark (night) period when the aerenchyma tissues is poorly ventilated (Dušek et al. unpublished data). The gradient of CH₄ concentration between the atmosphere and tree tissues resulted in positive fluxes of CH₄ out from the tree stems to the atmosphere. These tree-stem fluxes of CH₄ represent the largest non-ebullitive fluxes from wetlands (Pangala et al. 2017). Fluxes of CH₄ from the tree stems are part of the gas exchange system of a whole tree, including the fluxes of CO₂, N₂O and biogenic volatile organic compounds (Guenther et al. 1994; Kuhn et al. 2004; Bao et al. 2008). Large emissions from Amazon floodplain trees are close to the CH₄ budget of this ecosystem (Pangala et al. 2017). Fluxes of CO₂ from the tree stems of *Melaleuca cajuputi* were variable and low, similar to tree stems fluxes in the mountain rain forest (*Castanopsis ceratocantha* and *Maglietia chevalierii* trees). Low tree-stem fluxes of CO₂ and variable positive/negative fluxes of CH₄ relate to the mountain rain forest as an intact broad-leaved forest in which the age of some trees is hundreds of years. Large gas fluxes from stems of the lowland wetland trees, with CH₄ as an important component, were observed among the measured trees: *Melaleuca*, *Rhizophora* and *Avicennia*. Apparently, the flood-tolerant amphibious trees show significantly different pair comparisons of gas fluxes from tree stems and soil respiration (distance between tree species—green circles, and corresponding soil—dark squares in Fig. 4). This fact and a record of relatively widely fluctuating CH₄ flux (Fig. 5) reflect the different capability of internal conductive systems of those tree species to facilitate upward escape of soil CH₄ to the atmosphere. Furthermore, this response of trees to hydroperiods with upward escape of CH₄ is probably an inherited trait of floodplain trees, as it was repeatedly observed in the Borneo wetlands and Amazon basin (Pangala et al. 2017).

Lower and more variable CH₄ fluxes from the soil than those from shallow stagnant water under the *Melaleuca* forest canopy were measured in the mangrove forest, especially at the *Avicennia* site (stand of *Avicennia alba*). At the other

mangrove sites (*Rhizophora* and typhoon gap), the soil CH₄ fluxes were less variable and lower. Fluxes of CH₄ from the soil below *Rhizophora* trees were similar to soil CH₄ fluxes measured at the rice field site. These dynamics of CH₄ fluxes from the mangrove sites probably relate to regular semidiurnal tidal inundation.

The *Avicennia* site is located close to a tidal creek that supports water exchange during flood periods that last longer than those occurring at the distant *Rhizophora* and typhoon gap sites. At the *Avicennia* site, the carbon fluxes in both forms (CO₂ and CH₄) fluctuated within a wider range than those recorded at the *Rhizophora* and typhoon gap sites. A recent study (Diele et al. 2013) taken at another place in the Can Gio mangrove demonstrated that the values of redox potential along the soil profile below the *Avicennia* canopy was relatively higher than that below the *Rhizophora* canopy. Less negative Eh values along the soil profile recorded at the *Avicennia* site are most probably caused by the occurrence of pneumatophores, which facilitate root aeration and the rise of surrounding soil redox potentials (McKee 1993). Specific conditions in mangrove soils modify the partitioning of metals after their deposition and partially prevent release of these metals to the environment (Thanh-Nho et al. 2019).

The typhoon-disturbed gap site was formed by mangroves ruined after the Durian typhoon landfall (December 2006). Mangroves are naturally disturbed by tsunamis, floods and cyclones (Chen et al. 2014; Hogarth 2015). Declined earlier original mangrove forests have become a source of carbon and nutrients in the rhizosphere of mangrove soils. Important in this case are activities of litter-feeding sesamid crabs (*Grapsidae*) which probably depend on the availability of woody debris on the ground of the gaps. Their ecosystem-engineering activities may be reduced in the gaps in comparison with those in adjacent intact mangroves (Diele et al. 2013; Filser et al. 2016). Consequently, the soil respiration (CO₂ fluxes) was significantly lower at the typhoon gap site than that at the *Avicennia* and *Rhizophora* sites. Organic matter decay in mangrove soils is a continuous process. In mangrove soils, the content of carbon in particulate form is about 2.2% (median) and varies widely from 0.1 to 40% (Kristensen et al. 2008; Alongi 2012). At our study sites, the average percentage content of particulate carbon was higher than its median and was below 3% in deeper soil layers only at the typhoon-disturbed gap site. Particulate carbon does not represent all the soil carbon.

Mangrove forests are unique in that they accumulate carbon in tree biomass, especially in belowground tree parts (roots) and the majority (75–95%) of tree carbon stored belowground is contained in the biomass of dead rather than active live roots (Donato et al. 2011; Alongi 2012; Banerjee et al. 2020). The carbon stored in living or dead roots in mangrove soils is crucial for proper functioning of mangrove ecosystems and relates to the variability of CO₂ fluxes

from the soils. The expected smaller amount of live roots at the typhoon-disturbed gap site resulted in lower CO₂ fluxes from the soil. Approximately half of all CO₂ assimilated by intact mangrove forests are returned to the atmosphere via above- and belowground respiration (Alongi 2012). Fluxes of CO₂ and CH₄ from the rice field site are quite similar to fluxes from the Mangrove site as well as the fluxes of CO₂ from stagnant shallow water under the *Melaleuca* forest canopy. This similarity between the rice field site and the *Melaleuca* site also explains their belonging to the same unit of acid sulphate soils (soil profile C8 at Tram Chim park (Nguyen 1993), Soil map in the Atlas delivered by the National program on integrated investigation for the Mekong River Delta, code 60-02 and 60B). Significantly different hydroperiods occurring at these sites induce a large variability in soil respiration.

In general, rice cultivation is an anthropogenic manipulation with carbon fluxes, including carbon uptake (photosynthesis), fixation (biomass, rice grain), emission (respiration) and carbon transfer to different pools (rice grain, soil) (Bhattacharyya et al. 2014). Rice varieties have different specific physiological characteristics which affect the variability of CH₄ emissions (Guo and Zhou 2007). Fluxes of CH₄ vary within a quite wide range, e.g., 13.1 to 492.7 mg CH₄-C m⁻² day⁻¹ (Cai et al. 2007). Oo et al. (2013) reported an average range of CH₄ fluxes from 15.8 to 91.8 mg CH₄-C m⁻² day⁻¹. These fluxes are different also at different growth stages of current varieties of rice. Rice seedling have poorly developed root systems, which cannot ventilate the topsoil as effectively as a fully development root system. The root system of rice is relatively shallow and 95% of it is found at the top 0–0.2 m depth of the soil profile (Yoshida et al. 1982). The gas fluxes measured initially at the rice field site were low, and we expected their increase with the rice growth to a peak at 50 days (from the rice sowing in our case). According to measurements of gas flux in rice fields in south China, the methane flux from submerged paddy soil may increase a few times to its peak value within the period from transplantation of rice seedlings to their flowering stage (panicle formation or drainage of paddy field) (Khalil et al. 1998; Zhang et al. 2016). The rate of this flux is, however, variable in accordance with soil temperature, soil type and its redox condition.

Conclusions

The fluxes of CH₄ and CO₂ from different ecosystems of South Vietnam: intact mountain rain forest, rice field, *Melaleuca* forest and from different sites in mangroves (*Avicennia*, *Rhizophora* and typhoon gap) included measurements of gas fluxes from the soil and from tree stems. The gas fluxes characterized both actual and long-term

conditions and individual specificity of these ecosystems. Based on the obtained results, we can confirm the hypothesis that high flux of CH_4 occurs mainly in water-saturated soils. The highest fluxes of CH_4 were recorded in the *Melaleuca* forest and at the mangroves sites. The fluxes from stagnant shallow water under *Melaleuca* canopy were accompanied by higher fluxes of CH_4 from *Melaleuca* tree stems. However, we recorded quite a high flux of CO_2 at the *Avicennia* and *Rhizophora* mangrove site. As we assumed, the prevailing gas fluxes and their ratios significantly reflect both actual and long-term hydrological conditions resulting in either anaerobic or aerobic conditions in the soil profile. We found that fluxes of both gases were higher from the soil than from the tree stems. In some cases, the difference between fluxes from the tree stems and the soil was statistically highly significant. The last hypothesis assumes possible negative flux of CH_4 , i.e., into the soil. We can confirm that a low negative flux (consumption) of CH_4 was detected in the mountain rain forest, as we assumed. While fluxes of CH_4 from tree stems varied within a very narrow range close to zero, our findings highlight quite high differences in CH_4 and CO_2 emissions not only between terrestrial and wetland ecosystems but also among different types of wetland ecosystems. Covering different types of (wetland) ecosystems by the in situ measurements is fundamental base for measurements at higher levels such as aerial and satellite gas fluxes observations. We think that in the future will be necessary to cover ecosystems including man-made ecosystems by in situ measurements either short-term measuring campaign or long-term continuous measurements.

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Author contributions JD designed the study, carried out the field measurements, analysed the data and wrote the manuscript; VNX carried out the field measurements and wrote the descriptions of the measurement sites; TXL carried out the field measurements, contributed to writing the manuscript and reviewed the manuscript; MP carried out the field measurements and reviewed the manuscript.

Data availability The datasets from in situ measurements of the current study are available from the corresponding author on request.

Compliance with ethical standards

Conflict of interest The authors declare no competing financial interests.

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