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Research article

Carbon sequestration and surface energy balance measurement using eddy covariance technique for mangrove forest under influence of treated domestic wastewater, Phetchaburi province, Thailand

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Abstract

Importance of the work: There is a growing demand for the quantification of carbon sequestration.

Objectives: To quantify the flux movement of carbon dioxide within the King's Royally Initiated Laem Phak Bia Environmental Research and Development (LERD) Project in Phetchaburi province, Thailand in a natural mangrove forest receiving treated domestic wastewater.

Materials & Methods: The initial study used the eddy covariance technique to quantify the carbon dioxide fluxes within the study location.

Results: The mangrove forest served as a carbon sink, sequestering an estimated 19.94 tCO_2/ha/yr. However, during the day, the forest's role as a secondary treatment system led to the release of CO_2 into the atmosphere due to the absence of photosynthetically active radiation at nighttime. However, this research also investigated the surface energy balance based on the calculation of the closure gap of the latent, sensible and ground heat fluxes, which equaled 0.62, indicating that the energy use in the mangrove canopy closely resembled that of a natural forest.

Main finding: Understanding the CO_2 flux in the treated mangrove forest contributed to the expanding body of research on the "Blue Carbon" dynamics in mangrove forests.

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Introduction

Mangrove forests are a type of wetland forest that occupies the intertidal zone and is located around tropical and sub-tropical latitudes (Chamberlain et al., 2021). Given the current deforestation rates, it is estimated that the annual loss of the mangrove forest is less than 2% annually (Gandhi and Jones, 2019). This decline is primarily attributed to human settlement and the growing demands for shrimps and other coastal-related activities. To encourage mangrove reforestation globally, there has been emphasis of understanding the mangrove ecosystem with the introduction of the term "Blue Carbon" in the early 2000s (Friess, 2023) Studies have shown that despite mangrove forests accounting for just 1–2% of the world's total forested areas, they play a substantial role in sequestering CO_2 from the atmosphere (Charles, 2020). In quantifying the amount of CO_2, it is crucial to measure the CO_2 flux between forests and the atmosphere, to help in better understanding the climate system, which also involves referencing specific steps in the process. One of the most applied methods is eddy covariance (EC) which represents the most direct approach for gauging the CO_2 exchange rate. This method uses micrometeorological conditions to express rates on various timescales (Baldocchi, 2003). In mangrove forests, the relationship between CO_2 flux and carbon sequestration is based on the effects of mangroves that leverage differences in vapor deficit between the atmosphere and the forest ecosystem.

The primary objectives of this study were the utilization of the EC system for an initial evaluation of CO_2 flux movement and the surface energy balance within the mangroves ecosystem of the King's Royally Initiated Laem Phak Bia Environmental Research and Development (LERD) Project in Thailand. In particular, this site study had the dual roles of considering the forest not only as a natural environment but also as a secondary treatment system complementing the oxidation pond system for the treatment of municipal wastewater through "nature-by-nature: processes.

Materials and Methods

Study area

This study was conducted in the mangrove forest within the LERD project in Phetchaburi province, Thailand (UTM 1442725N; 617774E). This forest also serves as a secondary treatment system in conjunction with the oxidation pond system to treat domestic wastewater from the nearby Phetchaburi municipality. The LERD mangrove forest area covers approximately 500 ha and is dominated by three main species of mangroves: *Avicennia marina*, *Rhizophora mucronata* and *R. apiculata*. On this site, the mangrove system has acted as a natural mechanism to treat domestic wastewater from the Phetchaburi municipality. The forest stand is aged approximately 30 yr with mean values (±SD) for the diameter at breast height over bark of 33.32±11.2 cm, the height of 7.97±2.2 m and the density of 1.32±0.3 tree/m^2 (Maskulrath et al., 2022). The mangrove tidal system floods the forest floor approximately 18 d/mt to water depth of 0.5–1.0 m (Jitthaisong et al., 2012). The measurement site was located at the center of the LERD Project area. This placement was the initial step in applying the eddy covariance system as it allowed the measurements to encompass the footprint of the forest area. This site also accommodated the Mangrove Climate Tower. Thus, conducting longitudinal measurements (in years) at this site would provide the most accurate estimates, given a displacement height of 5.0 m and average roughness (Z_0) of 0.3, for the overall productivity of the mangrove forest.

Eddy covariance flux tower

Micrometeorological and trace gas (CO_2) measurements were conducted at a 10 m above the mangroves forest in the LERD Project using a three-dimensional (3D) sonic anemometer, (CSAT-3; Campbell Scientific Inc.; Logan, UT, USA) to measure wind velocity components (u_x, u_y, u_z). Furthermore, sonic temperature (T) was recorded using an open path infrared gas analyzer system (IRGA; Campbell Scientific Inc.; Logan, UT, USA) to gauge the fluxes of carbon dioxide and water vapor.

The sonic anemometer and IRGASON provided raw data that was captured through an analyzer interface unit (EC 100; maker and location) at a frequency of 10 Hz. Data were collected for 30 d consecutively (1–30 September 2022) at half-hourly intervals. The additional environmental variables were measured above the canopy at intervals of 0.1 s and recorded in a data logger (CR3000; Campbell Scientific Inc. Logan, UT, USA). Measurements were made of net radiation (CNR4; Kipp and Zonen; Delft, the Netherlands) and incoming photosynthetic active radiation (PAR SQ110; Apogee Instruments; Logan, UT, USA) installed at 10 m above the forest floor (Fig. 1).

Table 1 Summary of measured parameters

Parameter	Instrument	Units
Carbon dioxide flux (CO_2 flux)	Three-dimensional (3D) sonic anemometer, CSAT-3 (IRGASON)	µmol/m^2/s
Latent (evapotranspiration) and sensible heat	Three-dimensional (3D) sonic anemometer, CSAT-3 (IRGASON)	W/m^2
Photosynthesis photons flux density (PPFD)	PAR SQ110 (Apogee Instruments)	µmol/m^2/s
Soil heat flux	HFP01SC-L	W/m^2
	Self-calibrating soil heat flux plate	
Soil moisture	CS655	dS/m
	12 cm soil moisture and temperature sensor	°C

Fig. 1 Study site canopy view and forest tower in natural mangrove forest

Data processing

The half-hourly computed flux data, following standard corrections, exhibited occasional spikes due to instrument errors. Thus, a continuous averaging method was implemented in the gap-filling process for missing or filtered data because of the relatively small dataset, spanning only 30 d of sampling. This involved applying the block average method to the covariance over intervals of 30 min or longer (Kaimal et al., 1989). Furthermore, the calculation of the standard deviation for the CO_2 flux was factored in to capture flux changes corresponding to diurnal variations during the measurement period. Data were presented as an average for 24 hr to produce an overall estimate for the site.

Flux footprint

The model advanced by Kljun et al. (2004) was used to estimate the footprint which accounted for 90% of the total turbulent flux computations. This model took into the consideration the surface friction velocity (average± SD = 0.27±0.11 m/s), which reflected the influence of tidal changes during the study period, with the highest recorded tidal depth being less than 50 cm. In addition, various parameters (the standard deviation of the vertical velocity at the receptor, receptor height, planetary boundary layer height, horizontal distance from the receptor location and the footprint function) were considered. These parameters contributed to a dimensionless footprint function and a dimensionless distance. Additionally, the function incorporated the boundary-layer stabilities ranging from strongly convective to strongly (z/L) stable (27.1%), neutral (29.2%) and unstable (43.7%).

This study showed that all the footprint originated from the mangroves. The average radius of the footprint was approximately 400 m with the details of the actual footprint described in Fig. 2. During the flux measurement period (1–30 September 2022), it became apparent that the northeast wind influenced the flux direction. This was evident from the fetch of the footprint, which predominantly originated from this direction (Fig. 2).

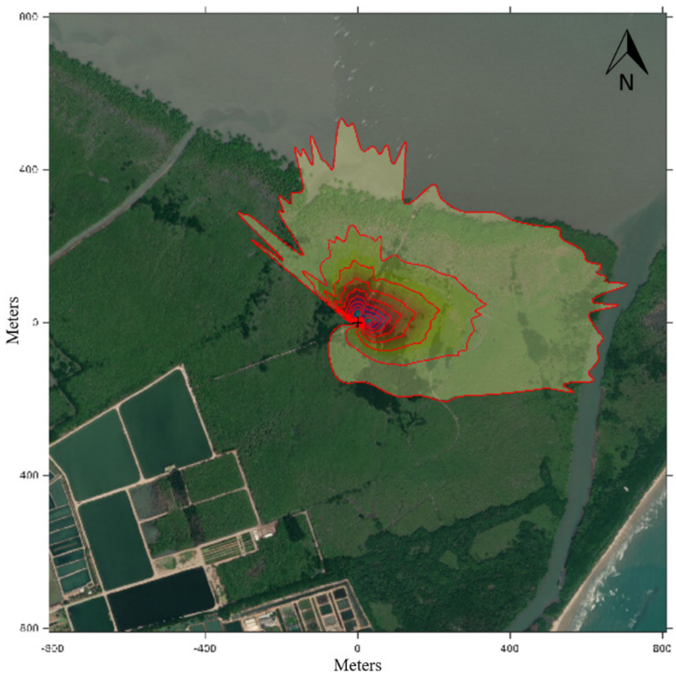

Fig. 2 Flux footprint of mangrove forest measurement site, where red contours indicate the steps of 10% to 90% (Kljun et al., 2004)

Results and Discussion

Carbon flux and sequestration

Fig. 3 shows the daily 30 min average values of CO_2 sequestration (CO_2 Flux (Fc)) across the mangrove canopy. The 24 hr average was applied to account for data spikes and outliers in the daily averages. At the same time, standard deviation calculations were utilized for the carbon flux. As illustrated in Fig. 3, the negative flux of Fc represents net sequestration (sink) by the mangrove ecosystem, with positive values indicating a net loss (source) of CO_2 to the atmosphere and respiration suggesting the net release of CO_2 from the ecosystem to the atmosphere.

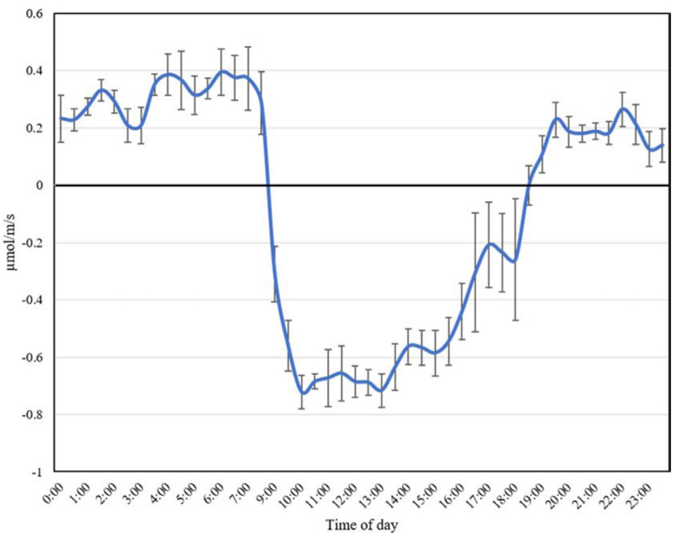

Fig. 3 Average diurnal CO_2 flux over mangrove forest, with error bars indicating SD

Analysis of the flux data revealed variations in ecosystem respiration, particularly during nighttime, when positive CO_2 flux was observed. Throughout the study period, the daily 30 min data illustrated CO_2 sequestration estimates ranging from 0.39 to -0.79 µmol/m/s. The nighttime values were in the range 0.2–0.4 µmol/m/s. whereas CO_2 flux from photosynthesis during the day (negative CO_2 flux) reached its peak at -0.79 µmol/m/s.

At this specific site, it was observed that during nighttime, CO_2 release due to soil respiration was significantly higher than that of other natural mangroves forest at levels lower than 0.2 µmol/m^2/s. This was attributed to the fact that this mangrove forest served as a secondary treatment for domestic wastewater from which higher amounts of nutrients were released into the forest (Maskulrath et al., 2022).

Taking into consideration photosynthetic radiation on cloudy or rainy days, Fig. 4 depicts the relationship between the CO_2 flux and the photosynthesis flux density, with a coefficient of determination (R^2) value of 0.79, indicating a strong connection between photosynthesis and CO_2 sequestration in the mangrove area.

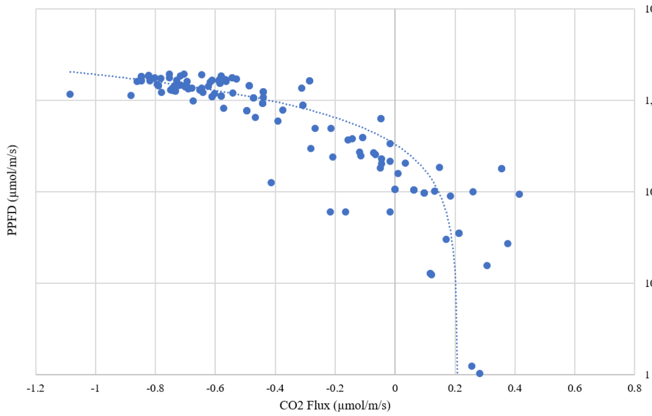

Fig. 4 Relationship between photosynthesis photons flux density (PPFD) and CO_2 flux within mangrove forest study area, where R^2 = coefficient of determination

Based on the calculations, the average carbon dioxide flux, integrated over a 24 hr average from the area under the curve in Fig. 3, the estimated CO_2 sequestration in the mangrove forest at the study site was 19.94 tCO_2/ha/yr. Compared to sequestration rates in other mangrove forests, the current study site had lower sequestration capacity (Rodda et al., 2022). On close examination, it was found that the influence of domestic wastewater was a key factor in the release of CO_2 into the atmosphere (Rodda et al., 2016). The underlying rationale for this observation was due to the forest's other role as a treatment system for domestic wastewater. Through this process, soil bacteria digest organic matter, resulting in direct CO_2 emission.

Heat fluxes and energy balance

The average net radiation (Rn) during 24 hr was 169 W/m^2 during the study period. The majority of this energy could be partitioned into sensible heat flux (H) and latent heat flux (LE). In this study, both H and LE showed a linear relationship with net radiation, reaching their peaks between 1200 and 1400 hours. This might have been related to fluctuation in the air and water vapor contents at the site (Fig. 5). Furthermore, it was observed that LE was greater than H during the measurement period due to ample water availability from rain events, which were triggered by the strong influence of evapotranspiration (2.71 mm/d) from mangrove forests. This contrasted sharply with the urban environment measured at Kasetsart University, Bangkok, Thailand, where the evapotranspiration calculated from latent heat (ET) was 2.33–1.17 mm/d. This observation was confirmed by the dichotomy in land use between a forested area and an urban zone, with the latter heavily influenced by anthropogenic structures as the predominant land cover.

The closure of the surface energy offered insight into the performance of the eddy covariance measurement system. In principle, Rn is the sum of LE, H and G. Since the canopy heat storage (S) was expected to uniform based on the age, height, density and diameter of the mangrove trees and canopy, the surface energy balance was determined using Equation 1:

$$Rn - G = H + LE \quad (1)$$

where Rn is the net radiation, G is the ground heat, H is the sensible heat and LE is the latent heat.

Fig. 6 depicts energy closure at the study site, showing the R^2 value of 88 percent. This indicated that approximately 88 percent of the available energy was explained by the 30-minute fluxes within the current mangrove ecosystem. When compared to a mangroves natural site, a closure value of 0.62 was found to be prevalent, where studies had found that the closure gaps in other forested areas fell into these typical ranges (Jin et al., 2022). It was suggested that a perfect closure would require long-term measurement, and any imbalance in the ratio are often caused by factors such as sensor accuracy, data processing, underestimations of advection due to the homogenous terrain and in some cases anthropogenic heat flux input. Additionally, it was important to note that the measurement duration was still in its initial phase, and the storage terms (S) were not yet fully accounted for.

In terms of their potential as a carbon sink, the natural mangroves at the study site, which additionally functioned as a secondary treatment system of domestic wastewater, had demonstrated capacity at sequestrating carbon. This was supported by the eddy covariance system which showed an overall negative flux during the measurement period. However, the quantification of the CO_2 flux still needed to be further verified over a longer measurement period. Consequently, the current study marked the initial phase of carbon research at the study site.

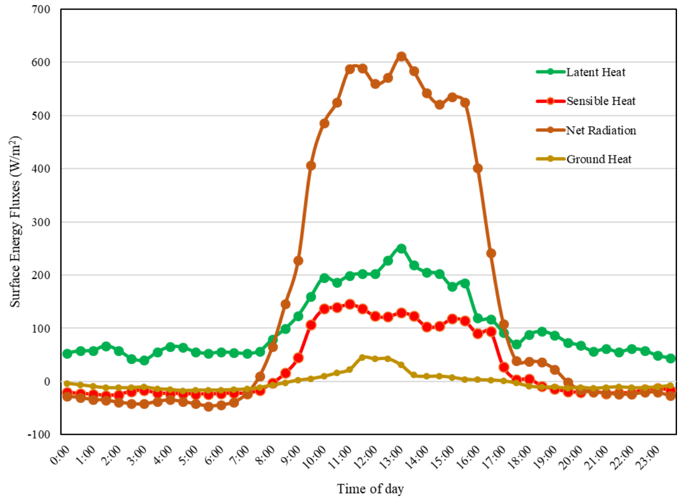

Fig. 5 Average diurnal variation of fluxes in monthly mean net radiation, sensible heat, latent heat and ground heat

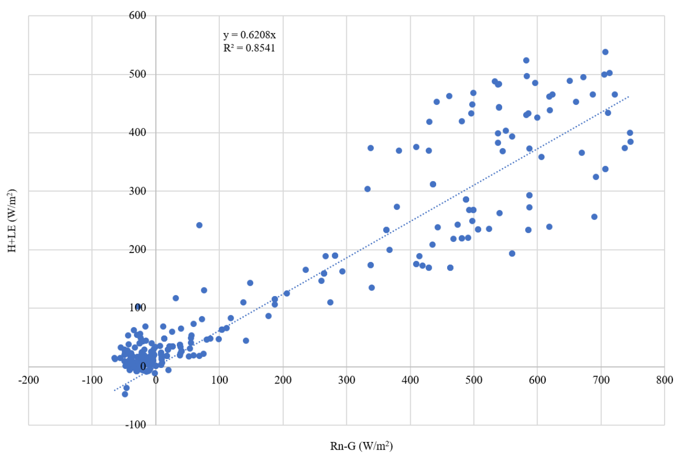

Fig. 6 Energy balance closure analysis for half-hourly measurement (LE +H) versus (Rn -G), where Rn is the net radiation, G is the ground heat, H is the sensible heat and LE is the latent heat

Conflict of Interest

The authors declare that there are no conflicts of interest.

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