Analysis of carbon sink effects for saline constructed wetlands vegetated with mangroves to treat mariculture wastewater and sewage
Lei Yang and Chung-Shin Yuan

ABSTRACT

In this study, two saline mangrove artificial wetlands, Datang Saline Constructed Wetland (DSCW) created for treating mariculture wastewater and sewage, vegetated with *Avicennia marina*, and Mangrove Wetland Park (MWP) created for mangrove conservation, vegetated with *Rhizophora stylosa*, were selected for assessment of carbon sequestration and carbon budget based on measuring greenhouse gas (GHG) emissions and net primary productivities. The average GHG flux and net carbon sequestration flux as carbon dioxide equivalent (CO₂ eq.) were measured. The results showed that the GHG flux emitted from DSCW and MWP were 2,128 and 2,148 g CO₂ eq./m²-yr, respectively, while the flux of net sequestered carbon was 2,909 and 3,178 g CO₂ eq./m²-yr, respectively, which achieved carbon budget values of -676 and -230 g CO₂ eq./m²-yr, respectively, exhibiting carbon source effects. Some amounts of N₂O, with a high global warming potential of 265, emitted from both artificial wetland systems might cause high GHG flux as CO₂ eq. emitted from the wetland systems. It was concluded that both the nitrogenous contents and environmental conditions suitable for microbial production of N₂O might be the main factors to change the wetland systems from carbon sinks to carbon sources.

Key words | carbon sequestration, carbon sink effect, greenhouse gas emissions, mangroves, mariculture wastewater, saline artificial wetlands

INTRODUCTION

The three main greenhouse gases (GHGs), carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O), emitting into the atmosphere from either natural or anthropogenic sources may cause global warming, extreme weather and drastic climate change, which attracts global attention on this worldwide environmental issue. According to the 2007 Report of the Intergovernmental Panel on Climate Change (IPCC 2007), natural wetlands emit yearly 20–39% of global CH₄ emissions through methanogenesis occurring in the wetland sediments (Dalal et al. 2008). In addition, in wetland systems CO₂ can be generated through catabolism by different species of organisms, while N₂O production may occur under aerobic (nitrification) and anoxic (denitrification) conditions (Pihlatie 2007). Although natural wetlands can release GHGs, the ecosystems are still functioning as carbon sinks due to their great sequestration and storing ability of carbon. It was reported that wetlands occupy only 2–6% of the earth’s land surface, yet contain a large portion of the carbons stored in the terrestrial reservoirs (Mander et al. 2014). However, for constructed wetlands (CWs) treating wastewater, more GHGs may be emitted due to the amounts of organic pollutants and nitrogenous nutrients coming into the CWs (Brix et al. 2013; Anderson & Mitsch 2006). Hence, it is necessary to learn if wastewater treatment types of CWs are either carbon sources or carbon sinks after calculating their carbon budget balances. Although the GHG N₂O emitted from wetlands is not related to the carbon budget balance directly, N₂O has a global warming potential (GWP) 265 times higher than that of CO₂ (IPCC 2014). Although the amounts of N₂O emitted from wetland systems are not a direct output for evaluating the C budget in wetland systems,
N₂O may be transferred to CO₂ equivalent (CO₂ eq.) by multiplying its mass by its GWP value of 265, which can then be used to calculate the C budget. The calculated results are possibly valuable references for assessing the carbon sink effect or ability in wetland systems.

It was reported that coastal saline wetlands (mangrove swamp, salt marsh, and seagrass bed), known as ‘blue carbon’ sources, exhibited better carbon sink effects than inland freshwater wetlands due to high salinity and sulfate contents in seawater, which can depress methane fermentation and shows competition of the sulfate reducing process against denitrification, causing decreasing emission of CH₄ and N₂O, respectively (Bouillon et al. 2008; Krithika et al. 2008; Chen et al. 2012). Among the three types of saline wetlands, it was reported that mangrove swamp wetlands could sequester greater amounts of carbon, with a value of about 2,300 t CO₂ eq./ha, to decrease the larger amounts of GHGs released into atmosphere (Murray et al. 2011).

Although natural mangrove wetlands can sequester and store large amounts of carbon, and thus present significant carbon sink effects, for saline mangrove type of CWs treating wastewater their carbon sink ability is still not yet confirmed. Like freshwater CWs, saline CWs might become carbon sources due to high organic and nitrogenous contents in wastewater. There are a few studies that have investigated blue carbon sink effects for saline mangrove types of CW used for wastewater treatment.

Thus, in this study, a saline type of CW (SCW) vegetated with mangroves, receiving mixing mariculture wastewater and sewage, and a saline wetland park designed for mangrove conservation with slightly polluted tidal seawater from a coastal lagoon as its influent were selected for investigating and comparing these two salty artificial wetland systems to learn if they presented either carbon sink or carbon source effects, through the calculating results of carbon budget balances by measuring the GHGs emissions and net primary productivities (NPPs) in these two artificial SCWs.

**MATERIALS AND METHODS**

**Sampling sites location**

Dapong Bay is a coastal lagoon located in the southwest of Taiwan with only one entrance exchanging seawater with the outer oceanic area. The lagoon is surrounded by many seawater fish (grouper) ponds, into which the mariculture wastewater was discharged. Thus, to prevent pollution to the lagoon, five SCWs around the lagoon were built to interrupt the wastewater for treatment as shown in Figure 1. In this study, the Datang SCW (DSCW) among the five was selected as the studying site, while the Mangrove Wetland Park (MWP), which is a wetland park, not for wastewater treatment but mangrove conservation, built on the lakeside...
of Dapong Bay, was also selected as a comparison site. The DSCW was vegetated mainly with a black mangrove species, *Avicennia marina*, and used to treat a mixture of mariculture wastewater and sewage, while in the MWP, the mangrove species *Rhizophora stylosa* was planted mainly, and the sea-water was exchanged from Dapong Bay by tidal currents through the outlet of the park. The DSCW is located in the northeast of the National Scenic Area of Dapong Bay in southern Taiwan as illustrated in Figure 2. It is constructed for functions of both an ecological detention pond and a natural wastewater treatment system. In the rainy seasons, the wetland can exert its detention function, while, in the drought seasons, it treats domestic sewage and mariculture wastewater from nearby residential communities and seawater fish ponds. The area of DSCW is approximately 6 ha, and has two inlets located at the east and west sides of the wetland, respectively. Each of the inflows then flows through a sedimentation tank, a subsurface filtration tank (the filter media consisting of waste bricks, concrete blocks, and oyster shell), a marsh area, a wading pool, ecological land, and a deep water zone as outlet. The treated wastewater is finally discharged into the coastal lagoon of Dapong Bay as a receiving water. The MWP is located in the northwest of Dapong Bay with an area of 7 ha separated into two parts by mangrove forest islands. The plant sampling and GHG monitoring sites for DSCW and MWP are shown in Figure 2.

**Field measurement of greenhouse gases**

The DSCW is mainly divided into three reservoirs including a water intake zone, intermediate treatment zone, and deep water outlet zone. The three types of GHGs of CO2, CH4, and N2O were monitored continuously at the monitoring sites shown in Figure 2. A floating chamber, which was designed by the research fellows of this study, with the height of 1 m and basal dimensions of 0.45 m × 0.45 m, was suspended over the surface of the CW. A Teflon sampling tube was connected at the top of the floating chamber, from which the air samples were pumped to an infrared GHG analyzer (Teledyne Analytical Instruments, Series 7600), based on the principle of integrated non-dispersive infrared (NDIR) absorption. The air samples were then tested *in situ* for monitoring their on-line concentrations of CO2, CH4, and N2O. In each GHG monitoring and sampling site, the GHGs emitted from the wetland could then be collected and analyzed every 5 minutes inside the chamber for 24 hours in different seasons. The assessments of variations of amounts of GHGs emitted from the wetland systems among different seasons were conducted by analysis of variance (ANOVA). The *in situ* GHGs monitoring system is illustrated in Figure 3. However, such a GHG analyzer has the minimum detection concentrations of 0–20, 0–500, and 0–200 ppm for CO2, CH4, and N2O, respectively, while the maximum monitoring concentrations of CO2, CH4, and N2O were all 0–100 vol% (Yang et al. 2017).

The *in situ* GHG monitoring system includes a transparent floating chamber, a rotameter, a dust filter, a diffusion dryer, and an air sampling pump. Air samples were completely mixed in the headspace of the floating chamber to reduce the potential airflow disturbances during the GHG sampling periods. The previous studies of the research
team of this study showed that continuous monitoring of GHGs could record more accurately GHG emissions than intermittent monitoring for random samplings. Consequently, the continuous monitoring data of GHG emissions could be used precisely for estimating the GHG emission fluxes over the wetland.

The emission fluxes of the GHGs CO₂, CH₄, and N₂O from the saline mangrove CW were determined from the amounts of air samples drawn from the floating chamber to a continuous GHG analyzer under the principle of NDIR absorption spectrometry for GHG analysis. The uptake/emission fluxes of GHGs were then determined by the changes of GHG concentrations inside the chamber headspace over time in the same manner as those from the in-situ on-line GHG monitoring system.

**Carbon budget calculations**

The amounts of CO₂, CH₄, and N₂O emissions can be calculated by Equation (1):

\[
F_{\text{gas}} = H \times \Delta C / \Delta t \times M / V \times [273 / (273 + T)] \times 365 \text{(day/yr)}
\]

where \( F_{\text{gas}} (F_{\text{CO₂}}, F_{\text{CH₄}}, \text{or} F_{\text{N₂O}}) \) is the GHG flux emission for CO₂, CH₄, or N₂O (g/m²·yr), respectively; \( H \) is the height of chamber (1.2 m); \( \Delta C / \Delta t \) is the daily average change of volume concentrations of CO₂, CH₄, or N₂O emitted in the floating chamber; \( M \) is the molecular weight of CO₂, CH₄, or N₂O (g/mole); \( V \) is the volume per mole of GHGs at standard temperature and pressure (0 °C, 1 atm), equal to 22.4 L/mole; \( T \) is the temperature of GHGs (°C). The concentration of each GHG emitted from the wetlands was calculated by deducting the background concentration of CO₂, CH₄, and N₂O, measured as 395 ppm, 1.85 ppm, and 0.32 ppm, respectively, from the respective GHG concentration monitored inside the chamber.

The three \( F_{\text{gas}} \) values could then be unified by converting them to CO₂ eq. using the GWP values for these three GHGs, and calculating the total GHGs flux as \( F_{\text{GHGs}} \) as shown in the following equation:

\[
F_{\text{GHGs,CO₂ eq.}} (g \text{ CO₂ eq./m²·yr}) = F_{\text{CO₂}} \times \text{GWP}_{\text{CO₂}} + F_{\text{CH₄}} \times \text{GWP}_{\text{CH₄}} + F_{\text{N₂O}} \times \text{GWP}_{\text{N₂O}}
\]

where \( F_{\text{GHGs,CO₂ eq.}} \) is the total GHGs flux expressed as CO₂ eq.; the values of \( \text{GWP}_{\text{CO₂}}, \text{GWP}_{\text{CH₄}}, \) and \( \text{GWP}_{\text{N₂O}} \) are 1, 28, and 265, respectively (IPCC 2014).

The NPP of mangroves in the wetlands could be calculated by the amounts of litter falls, which were collected for each sampling point by three 42 cm diameter round plastic baskets with nylon mesh inside put at a height that is not submerged by tidal water. After 2 months, the amounts of litter falls collected in three repetitions were weighed and averaged, and litter falls flux \( (L_{\text{NPP}}) \) was then calculated. According to the studies in Taiwan (Chen 2014; Li 2015), litter falls were 45.33% and 44.13% of total net primary productivity \( (F_{\text{NPP}}) \) for *Avicennia marina* and *Kandelia obovata*, respectively, in the coastal mangrove wetlands of Taiwan. Thus, it was assumed that the average value of litter/net primary productivities \( (L_{\text{NPP}}/F_{\text{NPP}}) \) ratio is 45%, which would be used to calculate the amounts of net carbon sequestered and stored in the wetlands as in the following three equations:

\[
L_{\text{NPP}} = \frac{\sum_{s=1}^{n} LWs_s}{A_{\text{trap}} \times C_f}
\]

\[
L_{\text{NPP}} = \frac{\sum_{r} (L_{\text{NPP}} \times a_r)}{a_r}
\]

\[
F_{\text{NPP}} = \frac{L_{\text{NPP}}}{0.45}
\]

where \( r \) is the sampling site number; \( L_{\text{NPP}} \) is the annual average net primary productivity of litter in sampling site \( r \) (g C/m²·yr); \( s \) is the order number of a year for sampling \( n \) times; \( (LWs)_s \) is the dry weight of litter for sampling number \( s \) in sampling site \( r \), which is an average value in a collecting basket (g dry materials/trap); \( A_{\text{trap}} \) is the area of collecting basket (m²/trap); \( C_f \) is the carbon weight ratio of dry litter (g C/g dried materials); \( F_{\text{NPP}} \) is the total net

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**Figure 3** | Schematic diagram of GHGs monitoring facilities and instrument.
primary productivity of mangroves (g C/m²-yr), which is the input of carbon sequestered and stored in the wetland systems.

The value of $F_{\text{NPP}}$ is approximately equal to the total carbon input ($F_{\text{carbon input}}$) to the wetland systems. It was reported that about 35% of $F_{\text{NPP}}$ was the total output of carbon ($F_{\text{export}}$) in the form of detritus, and dissolved and particulate organic carbons existing in water leaving the wetland systems (Chen 2014; Li 2015). In addition, the three $F_{\text{GHGs}}$ were also the output for calculating the carbon budget of wetland systems. Hence, the total carbon output ($F_{\text{carbon output}}$) expressed as CO₂ eq. from the wetland systems is calculated by Equation (4):

$$F_{\text{carbon output}} (\text{g CO₂ eq}/m²/yr) = F_{\text{GHGs CO₂ eq}} + F_{\text{export}} \times (44/12) \quad (4)$$

### Carbon sequestration and carbon budget assessments

To assess the flux amounts of carbon sequestered in wetland systems, the values can be calculated by the following Equation (5):

$$F_{\text{carbon sequestration}} (gC/m²-yr) = F_{\text{NPP}} - F_{\text{export}} - F_{\text{CO₂}} - F_{\text{CH₄}} \quad (5)$$

in which $F_{\text{CO₂}}$ and $F_{\text{CH₄}}$ are the flux amounts of CO₂ and CH₄ emitted from the wetlands expressed as C. To assess the wetland systems as carbon sink or source, the flux of carbon budget balances ($F_{\text{carbon budget}}$) expressed as CO₂ eq. should be calculated first by the following Equation (6):

$$F_{\text{carbon budget}} (\text{gCO₂ eq}/m²/yr) = F_{\text{NPP}} (≈ F_{\text{carbon input}}) \times (44/12) - F_{\text{carbon output}} \quad (6)$$

in which $F_{\text{carbon output}}$ was determined by Equation (4). If the calculated value is positive, the wetland system exhibits a carbon sink effect, while a negative number indicates a carbon source effect.

### RESULTS AND DISCUSSION

#### Seasonal variations of greenhouse gas emissions

In this study, a continuous monitoring system to sample and measure GHGs emitted from DSCW and MWP was developed and employed. The seasonal variations of GHG emissions in different artificial wetland systems are illustrated in Figures 4–6. According to Figure 4, although the results of continuous monitoring of CO₂ concentration released from different measuring sites in both DSCW (D1–D3) and MWP (R1 and R2) showed that the average CO₂ emission concentration monitored in winter (455.29 ppm) was larger than that in spring (448.36 ppm), and then in fall (447.82 ppm), according to ANOVA analytical results it still showed no significant difference ($p > 0.05$) among the three seasons. For CH₄ emission concentrations in different measuring sites of DSCW and MWP, as seen in Figure 5, it was found that the average CH₄ emission concentrations in different seasons were in the order of fall (22.48 ppm) > spring (5.21 ppm) ≈ winter (5.13 ppm). From the atmospheric...
temperature point of view, the average temperature in the fall sampling period was 27.2 °C, while the average temperature during the winter and spring sampling periods was 22.6 °C and 21.5 °C, respectively. It is inferred that the CH₄ emission concentrations in the artificial wetland systems are related to atmospheric temperature. The reason might be the significant effects of atmospheric temperature on microbial methanogenesis, producing more CH₄, but lesser effects of CO₂-producing respiration of most organisms in wetlands. The monitored results of average concentrations of N₂O emitted are shown in Figure 6. As seen in this figure, it was found that N₂O emission concentrations in different seasons were in the order of fall (2.26 ppm) > spring (1.61 ppm) > winter (1.2 ppm). Like CH₄, N₂O emissions were also significantly greater in fall than in both winter and spring, while the N₂O emission concentrations in winter and spring were not much different. From the atmospheric temperature point of view, the factor of average temperature for different seasons still presents significant effects, affecting microbial activities of denitrification. It was concluded that the N₂O concentrations emitted from these two artificial wetland systems were also related to the atmospheric temperature.

GHGs emissions expressed as carbon dioxide equivalent

Since the total amounts of GHGs emitted from the saline CW were of concern for assessing the greenhouse effect, the amounts of CO₂ eq. emitted from the saline CW were further calculated. First of all, the GHGs emission fluxes from the saline CW were determined according to the GHG concentrations measured in the floating chamber and covering surface area of the chamber. The background concentrations of CO₂, CH₄, and N₂O in the atmosphere were 394.5 ppm, 1.85 ppm, and 0.32 ppm, respectively (Liu et al. 2010). As shown in Table 1, extracting the background concentrations of the three types of GHGs, the emission fluxes of CO₂, CH₄, and N₂O were then calculated to be 226 g CO₂/m²-yr, 15.2 g CH₄/m²-yr, and 5.57 g N₂O/m²-yr, respectively, in DSCW system, while for MWP system, the values were calculated to be 164 g CO₂/m²-yr, 24.0 g CH₄/m²-yr, and 4.95 g N₂O/m²-yr, respectively.

To transform the amounts of the three GHGs to CO₂ eq., the GWP for these three types of GHGs measured over a specified timescale (generally, 100 years) should be learned (Shine et al. 2005). The data of CO₂ eq. can reflect the time-integrated radiative forcing of a quantity of emissions or a rate of greenhouse gas emissions to the atmosphere rather than the instantaneous value of the radiative forcing of the stock (i.e. concentration) of GHGs in the atmosphere described by CO₂ eq. As mentioned previously, the GWPs of CO₂, CH₄, and N₂O are 1, 28, and 265, respectively (IPCC 2014), based on which the calculation results of CO₂ eq. for the three types of greenhouse gases of CO₂, CH₄, and N₂O emitted from the artificial wetlands of DSCW and MWP are also shown in Table 1. As seen in the table, the emission flux of CO₂ equivalent for all three GHGs (FGHGs CO₂ eq.) was 2,128 g CO₂ eq./m²-yr in DSCW system, while the value was calculated to be 2,148 g CO₂ eq./m²-yr in MWP system. The area of DSCW is about 6 ha; thus the total amounts of GHGs emission from the wetland system expressed by CO₂ eq. were calculated to be 128 tons CO₂ eq./yr in DSCW system, while in MWP system with total area of 7 ha, the annual emission amounts of total GHGs was calculated to be 150 tons CO₂ eq./yr. However, the amounts of GHGs emitted from the sewage treatment plants in Taiwan ranged between 9,000 and 36,000 tons CO₂ eq./yr (HK Drainage Services Department 2012), which were larger than those emitted from CW systems. Thus, if those sewage treatment plants were substituted by building CWs for sewage treatment, the total amounts of GHGs emission might be reduced.

Assessment of carbon sequestrations and budgets

The calculation results of NPP flux (F_NPP) and organic carbon exported flux (F_export) in these two artificial wetland systems (DSCW and MWP) are shown in Figures 7 and 8.
respectively. According to these two figures, the flux of NPP for the mangrove in DSCW system was calculated based on the values of mangrove litter falls measured on sites by Equation (3) shown previously, while the value of organic carbon flux out of the artificial wetland systems (Fexport) was estimated according to the FNPP values. It was reported that about 35% of FNPP was the Fexport in the form of detritus, and dissolved and particulate organic carbons existing in water leaving the wetland systems mentioned previously (Chen 2014; Li 2015). As seen in Figures 7 and 8, the value of FNPP was calculated to be 609 g C/m²/year for DSCW system, while calculated results was 804 g C/m²/year for MWP system, which implied that the vegetative condition performed better for the MWP system functioning as mangrove conservation than for the DSCW system functioning as wastewater treatment.

According to Figures 7 and 8, the flux amounts of carbon sequestered and carbon budget balances are calculated based on Equations (4) and (5), and summarized in Table 1. As seen in this table, the flux amounts of carbon sequestered in the artificial wetlands of DSCW and MWP were calculated to be 323 and 460 g C/m²·yr, respectively.

It was concluded that the created wetland type of artificial wetland used for mangrove conservation exhibited higher carbon sequestration ability than the treatment type of CW for wastewater treatment. This might be due to better conditions for vegetation and water quality existing in the created wetland park than in the constructed treatment wetland, resulting in larger NPP and less CO₂ and CH₄ emissions in the wetland park (804 and 77 g C/m²·yr, respectively) than those in the treatment CW (609 and 77 g C/m²·yr, respectively) as shown in Table 1. Hence, the total amounts of carbon sequestered and stored in the saline artificial wetland systems of DSCW and MWP in this study are calculated to be 36.5 and 56.3 tons C/year, respectively.

After transferring the organic carbon exported and the emissions of CO₂, CH₄ and N₂O into CO₂ eq. by GWPs and adding those values together, the carbon output flux (Fcarbon output) expressed as g CO₂ eq./m²·yr from the wetland systems was then obtained, which could be used to calculate the carbon budgets and to assess if the wetland systems were carbon sinks or sources by using Equations (5) and (6). Further, it would show whether the wetland systems

Table 1 | Calculation results of assessment of carbon sequestrations and budgets in the two artificial wetland systems in this study

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mangrove Wetland Park (MWP)</th>
<th>Datang Saline Constructed Wetland (DSCW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dominant mangrove species</td>
<td>Rhizophora stylosa</td>
<td>Avicennia marina</td>
</tr>
<tr>
<td>LNPP (g C/m²·yr)</td>
<td>362</td>
<td>274</td>
</tr>
<tr>
<td>FNPP (≈ Fcarbon input) (g C/m²·yr)</td>
<td>804&lt;sup&gt;a&lt;/sup&gt;</td>
<td>609&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>(g CO₂ eq./m²·yr)</td>
<td>2,948</td>
<td>2,233</td>
</tr>
<tr>
<td>Fexport (g C/m²·yr)</td>
<td>281&lt;sup&gt;b&lt;/sup&gt;</td>
<td>213&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>(g CO₂ eq./m²·yr)</td>
<td>1,030</td>
<td>781</td>
</tr>
<tr>
<td>FCΟ₂ (g C/m²·yr)</td>
<td>45</td>
<td>62</td>
</tr>
<tr>
<td>(g CO₂ eq./m²·yr)</td>
<td>164</td>
<td>226</td>
</tr>
<tr>
<td>FCΗ₄ (g CH₄/m²·yr)</td>
<td>24.0</td>
<td>15.2</td>
</tr>
<tr>
<td>(g CO₂ eq./m²·yr)</td>
<td>672</td>
<td>426</td>
</tr>
<tr>
<td>FN₂Ο₂ (g N₂Ο₂/m²·yr)</td>
<td>4.95</td>
<td>5.57</td>
</tr>
<tr>
<td>(g CO₂ eq./m²·yr)</td>
<td>1,312</td>
<td>1,476</td>
</tr>
<tr>
<td>FGHGs CO₂ eq. = FCΟ₂ × GWPCO₂ + FCΗ₄ × GWPCH₄ + FN₂Ο₂ × GWPN₂Ο₂ (g CO₂ eq./m²·yr)</td>
<td>2,148&lt;sup&gt;c&lt;/sup&gt;</td>
<td>2,128&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td>FSequestration = FNPP − Fexport − FCΟ₂ − FCΗ₄ (g C/m²·yr)</td>
<td>460</td>
<td>323</td>
</tr>
<tr>
<td>Fcarbon output = FGHGs CO₂ eq. + Fexport (g CO₂ eq./m²·yr)</td>
<td>3,178</td>
<td>2,909</td>
</tr>
<tr>
<td>Fcarbon budget = FNPP (≈ Fcarbon input) − Fcarbon output (g CO₂ eq./m²·yr)</td>
<td>−230</td>
<td>−676</td>
</tr>
</tbody>
</table>

<sup>a</sup>LNPP (litter fall) ≈ 45% FNPP.<br><sup>b</sup>35%FNPP ≈ Fexport (≈ Fdetritus + FDOC + FPOC, dissolved organic carbon: POC, particulate organic carbon).<br><sup>c</sup>The values of GWP for CO₂, CH₄, and N₂O are 1, 28, and 265, respectively, to calculate CO₂ eq. (FGHGs CO₂ eq. = FCO₂ + 28FCH₄ + 265FN₂Ο₂) (IPCC 2014).
depress or enhance the greenhouse effects. According to the calculation results as shown in Table 1, it was learned that both of the artificial wetland systems of DSCW and MWP in this study presented negative carbon budget values, which meant that both wetland systems were carbon sources, and thus exhibited enhanced GHG effects, showing contrary results to natural wetlands mentioned previously in the ‘Introduction’. This might be due to the nitrogen contents in both artificial wetlands in this study, into which polluted lagoon seawater and mariculture...
wastewater/sewage were discharged, respectively. Large amounts of nitrogenous nutrients in influent flowing into the wetland systems might result in large amounts of N₂O (with GWP value as high as 265) generated and emitted out of the systems, contributing higher carbon sources and then enhancing greenhouse effects. Further study is required to analyze the relationship between water quality and GHG emissions in CW systems.

CONCLUSIONS

In this study, it was found that the GHGs of CO₂, CH₄, and N₂O were indeed emitted from the saline artificial wetland systems of DSCW and MWP vegetated with mangroves. For carbon sequestration ability, it was concluded that the saline MWP receiving lagoon seawater as its influent performed better than the saline mangrove CW treating mariculture wastewater and sewage (DSCW). However, according to the calculated results of carbon budget balance, both DSCW and MWP systems showed negative values, which meant they were carbon sources for greenhouse effects. The cause might be the quite large amounts of N₂O, with high GWP value of 265, emitted from the wetland systems, which might be due to excessive nitrogen loads into the wetland systems from either the wastewater as influent to the CWs, or nitrogen contents inside the wetland sediments. Further studies on monitoring water quality and sediment content, especially for nitrogen in CWs, and then on their relationships to GHG emissions, especially for N₂O, are suggested in the future.

ACKNOWLEDGEMENTS

This study was performed under the auspices of Ministry of Science and Technology (MOST) of Taiwan under the Research Project MOST 104-2221-E-110-004. The authors would like to express their sincere appreciation for its financial support to accomplish this study.

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First received 8 November 2018; accepted in revised form 12 April 2019. Available online 22 April 2019