

# Carbon balance in tropical freshwater wetlands on the coastal plain of the Gulf of Mexico

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## ABSTRACT

### Carbon balance in tropical freshwater wetlands on the coastal plain of the Gulf of Mexico

Wetlands play an important role as carbon stores; however, these ecosystems also contribute to the emission of greenhouse gases (GHG). In this study, we compared the carbon balance (CB) in coastal freshwater marshes and swamps. We use three different methods, which are described in the literature. The first is based upon the CB basis (Carbon-emission subtracted to Carbon-sequestration), without considering the global warming potential (GWP) of GHG. The second method is a CB considering the GWP, and the third method estimated the wetland function as carbon sink or source, by using a dynamic model with different horizon times (20, 100 and 500 years). With the first method, the studied wetland soils functioned as carbon sinks. Using the second method, the carbon in the form of GHG was up to 5 times more than sequestered carbon, however, the methodology does not consider the dynamics of gases in the atmosphere. By using a dynamic model that integrates productivity, plant respiration, the half-life of the gases and soil carbon emitted as methane, it was found that these ecosystems are net sinks carbon at horizon times of 500 years. This outlines a need to conserve and restore wetlands, and demonstrates the wetlands role as carbon sinks without concerning that they are sources of GHGs.

**Key words:** freshwater, swamps, marshes, carbon sequestration, carbon emissions, and carbon dynamic model

## RESUMEN

### Balance de carbono en humedales tropicales de agua dulce de la planicie costera del Golfo de México

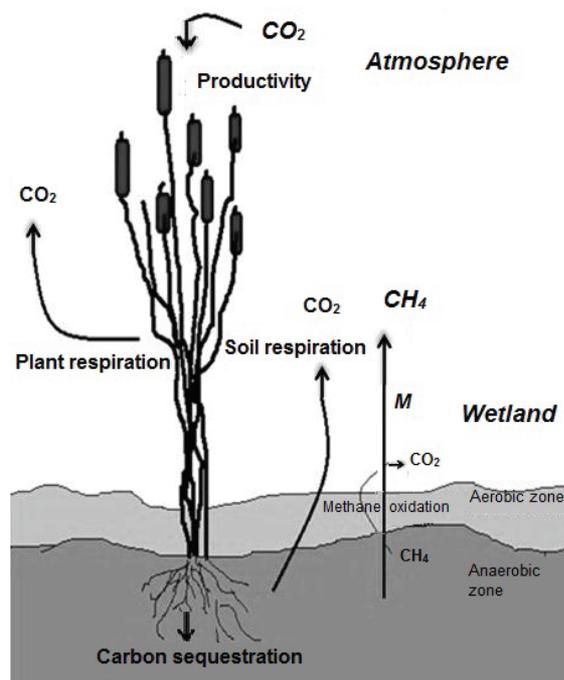
Los humedales juegan un papel importante en como almacenadores de carbono. Sin embargo, estos ecosistemas también contribuyen a las emisiones de gases de efecto invernadero (GHG). En este estudio, se comparó el balance de carbono (CB) en humedales herbáceos y arbóreos costeros de agua dulce. Se usaron tres métodos, descritos en la literatura. El primer método de CB se basó en el carbono emitido restado a carbono almacenado, sin considerar el potencial de calentamiento global (GWP) de GHG. El Segundo método de CB consideró el GWP, y el tercer método estimó la función del humedal como sumidero o fuente de carbono, usando un modelo dinámico con diferentes horizontes de tiempo (20, 100 y 500 años). Con el primer método, el suelo de humedales estudiados funcionó como sumidero de carbono. Usando el segundo método, el carbono en forma de GHG fue hasta 5 veces mayor que el carbono almacenado; sin embargo, la metodología no considera la dinámica de gases en la atmósfera. Usando un modelo dinámico que integra productividad, respiración de las plantas, vida media de los gases en la atmósfera y carbono del suelo emitido como metano, se encontró que estos ecosistemas son sumideros netos de carbono a un horizonte de tiempo de 500 años. Lo anterior refiere a la necesidad de conservar y restaurar humedales, y demostrar el papel de los humedales como sumideros de carbono, sin preocuparse de que estos sean fuentes de GHGs.

**Palabras clave:** humedales arbóreos de agua dulce, humedales herbáceos, almacenamiento de carbono, emisiones de carbono, modelo dinámico de carbono

## INTRODUCTION

Wetlands are transitional zones between terrestrial and aquatic ecosystems that include small lakes, floodplains, and flooded areas with trees (swamps) and herbaceous (marshes) vegetation (Cox, 2002; Mitsch & Gosselink, 2015). Wetland ecosystems provide many services such as decreased flood damage, improved water quality, protection of fish and wildlife habitat, and play an important role in carbon cycling (Kayranli *et al.*, 2009; Mitsch & Gosselink, 2015). Wetland soils are considered to be potentially large carbon pools (Pant *et al.*, 2003; Marín-Muñiz *et al.*, 2014). However, they may also be a significant source of greenhouse gases (Nahlik & Mitsch, 2011; Marín-Muñiz *et al.*, 2015). The role of wetlands in the carbon cycle is complex to understand, considering the variety of wetlands that exist on the planet, the type of vegetation present in these ecosystems, and the environmental and hydrogeomorphic features. The net function of wetlands within the carbon cycle has rarely been studied, and therefore, minimally understood. In wetlands, atmospheric carbon is fixed in plants through photosynthesis, then, when senescence occurs, the plant residues fall on flooded or waterlogged soils. These residues are then slowly decomposed under anaerobic conditions; thereby carbon is stored or sequestered in the soil (Pant *et al.*, 2003; Kayranli *et al.*, 2009). On the other hand, wetlands are considered a source for emitting greenhouse gases because of the same anaerobic conditions that enhance carbon sequestration, also favor the production of methane and nitrous oxide (Sjögersten *et al.*, 2014). Many studies have overestimated the functioning of the ecosystem service of carbon sequestration in wetland soils, because they do not consider the amount of carbon in the form of GHG that is released to the atmosphere (Webb, 2002; Brevik & Homburg, 2004; Ceron-Breton *et al.*, 2010). In contrast, there are studies that only report GHG emissions, where it is concluded that wetlands act as sources of carbon, but they do not estimate the amount of carbon that such ecosystems had stored (Nahlik & Mitsch, 2011; Sun *et al.*, 2013a; Sun *et al.*, 2013b). There are some studies that quantify both, carbon stored and GHG emissions

in wetlands soils, but less studies report the carbon balance and even less studies report such function in tropical wetland sites with field data (Brix *et al.*, 2001; Mitsch *et al.*, 2013; Waletzko & Mitsch, 2013; Sjögersten *et al.*, 2014). To know the carbon balance in wetlands, some studies (Mittra *et al.*, 2005; Mitsch & Gosselink, 2007) have based the calculations on converting the methane emissions to carbon dioxide equivalents taking into account the global warming potential (GWP) of this gas, then the carbon dioxide is converted to carbon. Whiting & Chanton (2001) reported a model for carbon balance in wetlands that considered two important factors. The first factor is the ratio of CH<sub>4</sub> emissions to CO<sub>2</sub> uptake (mole/mole) for the ecosystem which provides an index of the ecosystem's greenhouse gas exchange balance (carbon) with the atmosphere. The second factor compares the relative potential of GHG's to absorb infrared radiation in the atmosphere, with an index termed GWP; such index incorporates direct radioactive effects, the lifetime of the gases in the atmosphere, and indirect effects caused by chemical feedbacks (Lelieveld *et al.*, 1998). The GWP has been used like a standard value of 25:1 by the international panel of climatic change (IPCC, 2007) for comparing the methane and carbon dioxide over a period of 100 years. For longer periods (100-500 years), dynamic models have been developed in which the carbon fixed by plants reflected in productivity and respiration (soil and plant), carbon sequestered in the soil, and the carbon released as methane are involved (Fig. 1) (Whiting & Chanton, 2001; Mitsch *et al.*, 2013). In the tropical regions there are many studies on wetland carbon sequestration (Marín-Muñiz *et al.*, 2011; Cerón-Bretón *et al.*, 2010; Adame *et al.*, 2013; Thorhaugh *et al.*, 2018). However, there is little information on the carbon balance in freshwater wetlands by using field data. In the present study, we aimed to calculate the carbon balance in tropical freshwater wetlands by using three different methods. These methods use data for carbon sequestration (Marín-Muñiz *et al.*, 2014), and GHG (CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O), sampled in natural wetlands of the coastal plain of the Gulf of Mexico (Marín-Muñiz *et al.*, 2015), according to the CO<sub>2</sub> equivalent of each gas.



**Figure 1.** Conceptual model of carbon budget in a wetland and its carbon exchanges with the atmosphere. Carbon sequestration; M) methane emission; productivity; plant respiration; soil respiration. *Modelo conceptual de almacenamiento de carbono en un humedal y su intercambio con la atmósfera. Secuestro de carbono; M) emisión de metano; productividad; respiración de la planta; respiración del suelo.*

## MATERIALS AND METHODS

### Study sites

Carbon sequestration and carbon emitted in the form of greenhouse gases in the soil were measured experimentally in three freshwater marshes (wetlands dominated by grasses, sedges and other non-woody species) and three freshwater swamps (forested wetland containing woody plants –trees and shrubs-) in the coastal plain of the Gulf of Mexico, in the state of Veracruz. The sampled sites included wetlands of Estero Dulce, Tecolutla, Laguna Chica, Vega de Alatorre and Boquilla de Oro, Alto Lucero (Table 1). In each site, one swamp and one marsh wetland types were established (Fig. 2). The study sites experience similar climatic conditions (see details on the characterization of sites in Marín-Muñiz *et al.* (2014)).

### Field and laboratory methods

**Carbon sequestration.** In each study site, both in the swamp and marshes three sampling points (1 m<sup>2</sup>) were established. At each point, four soil profiles (depth 0.80 m x 0.05 m in diameter) were taken and sectioned at 2 cm, three profiles mixed for carbon content and one used to analyze bulk densi-

**Table 1.** Description of the characteristic of the studied wetlands. *Descripción de las características de los humedales estudiados.*

Study site	Location	Wetland type	Specie plants	Geomorphology <sup>a</sup>
Estero Dulce, Tecolutla	20°17'53"N 96°52'19"W	Swamps	<i>Pachira aquatica</i> Aubl.	Estuarine
		Marshes	<i>Thalia geniculata</i> L., <i>Cyperus giganteus</i> Vahl., and <i>Echinochloa pyramidalis</i> (Lam.).	
Laguna Chica, Vega de Alatorre	20°05'48"N 96°41'24"W	Swamps	<i>Pachira aquatica</i> Aubl, <i>Hippocratea celastroides</i> Kunth, <i>Rhabdadenia biflora</i> (Jacq.) Müll. Arg. and <i>Dalbergia brownei</i> (Jacq.) Schinz.	Perilacustrine
		Marshes	<i>Cyperus giganteus</i> and <i>Typha domingensis</i> Pers.	
Boquilla de Oro, Alto Lucero	19°49'47"N, 96°26'59"W	Swamps	<i>Ficus insipida</i> and <i>Pleurantho dendron lindenii</i> (Turcz.) Sleumer.	Depresional
		Marshes	<i>Pontederia sagittata</i> , and <i>Cyperus</i> spp. mixed with <i>Acrostichum</i> spp.	

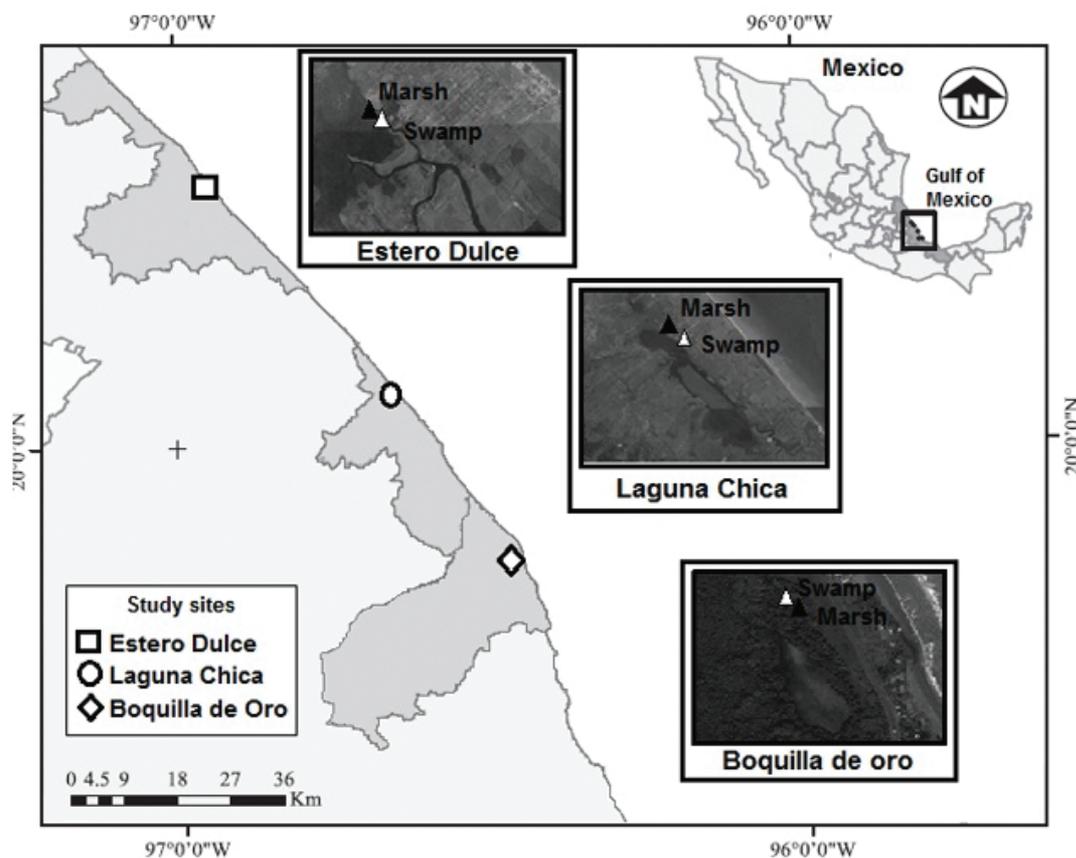
ty (BD). Knowing the volume of soil samples for BD ( $19.6 \text{ cm}^3$ ), these samples were dried ( $105^\circ\text{C}$ ) until they reached constant weight (CW); the values for each 2 cm profile were used according to formula:  $\text{BD} (\text{g}/\text{cm}^3) = \text{CW}/19.6 \text{ cm}^3$ .

Organic Carbon (OC) was obtained by analyzing the percentage of organic matter content (% OM). 2 g of dried mixed composed soil samples were dried up ( $105^\circ\text{C}$ ) to CW, then they were calcinated to  $450^\circ\text{C}$  by 4 hours. Organic matter was calculated by using the following formula:  $\% \text{ OM} = (\text{CW } 105^\circ\text{C} - \text{CW } 450^\circ\text{C}) / \text{CW } 105^\circ\text{C}$ . % OC was calculated as a portion of OM by using the conversion coefficient of 0.58 (Van Bemmelen factor; Wang *et al.*, 2003).

The annual accretion rate (A) of soil was determined by the method of artificial marker horizontal. Three accretion plots ( $0.25 \text{ m}^2$ ) were estab-

lished in each wetland in this study, placing areas with green glitter and areas with blue sand inside each plot as markers, one year after, vertical corers ( $\sim 0.10\text{-}0.25 \text{ m}$ ) in each plot with different markers were subtracted by using three different techniques (cryogenic coring device with liquid  $\text{CO}_2$ , corer with a Russian peat borer and a horizontal freezing corer; Marín-Muñiz *et al.* (2014)). Taking the vertical corer, the centimeters of soil over the horizontal marker indicated the annual accretion rate (cm/yr). Due to the accretion was not statistically different by using any of the techniques, data were averaged for each type of wetland. The rate of carbon sequestered was calculated by using the following formula:  $\text{C (accumulation rate of carbon)} = A \times \text{BD} \times \text{OC} (\text{g m}^{-2} \text{ yr}^{-1})$ .

GHG emissions. GHGs were measured by the closed chamber method, which has widely been



**Figure 2.** Location of the study sites in the coastal plain of the Gulf of Mexico. *Ubicación del sitio de estudio en la planicie costera del Golfo de México.*

used in studies *in situ* (Hernandez & Mitsch, 2006; Marín-Muñiz *et al.*, 2015; Hernández *et al.*, 2018; Windham-Myers *et al.*, 2018). The measurements were bimonthly from April, 2010 to February, 2012 for CH<sub>4</sub> and N<sub>2</sub>O, and during the last year for CO<sub>2</sub> and grouped according to the type of wetland in the same study sites, where the rate of carbon sequestration (Fig. 2) was measured. The closed chamber consisted of two parts: a base and a removable cap, each one was made of polyvinyl chloride (PVC) pipe (0.15 m diameter). Four bases (0.30 m high and inserted approximately 5 cm into the wetland soils) were permanently installed in each wetland site. The base had an open bottom and a collar, 5 cm from the top. The removable cap includes a gray butyl sampling port and an alcohol-type thermometer on the top. Every time gas fluxes were measured, the cover was set on the base collar, and the water was added to ensure a gas-tight seal between the base and the cap. Chambers were closed, and every 5 minutes, internal gas samples were taken for the next 45 minutes, and the internal temperature was registered. Gas samples (25 ml) were taken by using 60 ml propylene syringes (TERUMO), and having a one-way stopcock (Lieur). Gas samples were injected through rubber septa into pre-evacuated 20 ml glass vials. All samples were taken between 10:00 h and 16:00 h (local time) and were analyzed within 72 h after collection.

Gas concentrations were quantified and analyzed by a gas chromatograph (Perkin Elmer Claruss 5000) equipped with a flame ionization detector (FID) for CH<sub>4</sub> and a methanizer to detect CO<sub>2</sub> and electron capture detector (ECD) for N<sub>2</sub>O. All the analyzed individual gas values (ppm CH<sub>4</sub>, N<sub>2</sub>O and CO<sub>2</sub>) were corrected by using the ideal gases law:  $m = c \times (P \times M / R \times T)$ , where  $m$  is the methane concentration by weight (gCH<sub>4</sub> m<sup>-3</sup>),  $c$  the methane concentration by volume (ppmv = 10<sup>-6</sup> cm<sup>3</sup> = cm<sup>3</sup>/m<sup>3</sup>),  $P$  the atmospheric pressure (assume 1 atm),  $M$  the molecular weight of gas (m/mol),  $R$  the Universal Gas constant (82.0575 (atm-cm<sup>3</sup>)/(mol-K)), and  $T$  the absolute temperature (K) of the chamber at the time of each sample. Corrected gas concentrations were converted to gas flux rates  $F_c$  (mg m<sup>2</sup> d<sup>-1</sup>) by using data of the change in gas concentration over the enclosure period  $dc/dt$

(mg m<sup>3</sup> min<sup>-1</sup>), the chamber volume  $V$  (m<sup>3</sup>), and the base chamber soil-surface area  $A$  (m<sup>2</sup>) as follows:  $F_c = ((dc/dt) * (V/A)) * 1440$ . For each chamber measurement, gas sample concentrations were plotted versus sample time. Linear regressions were performed on each flux rate in Microsoft Excel™ to determine linearity of flux. Results were included only if  $R^2$  was greater than 0.85.

### Carbon balance calculations

We used three different methods to investigate the carbon balance according to previous studies:

Method 1. This is a method which is based on the net balance calculation proposed by Mitsch *et al.*, (2013), where the carbon emitted in forms of methane and carbon dioxide was subtracted from the carbon sequestered in the soil according to this formula: ECA1 (Exchange of carbon with the atmosphere; Kg C m<sup>-2</sup> y<sup>-1</sup>) =  $C_{seq.} - C_{emi.}$ . Where,  $C_{seq.}$  is the carbon sequestered in the soil (Kg C m<sup>-2</sup> y<sup>-1</sup>),  $C_{emi.}$  is the carbon emitted to the atmosphere (Kg C m<sup>-2</sup> y<sup>-1</sup>), considering C-CH<sub>4</sub> and C-CO<sub>2</sub>.

Method 2: This balance includes the carbon sequestered and the greenhouse gas emissions on a molecular basis, considering the global warming potential of greenhouse gases (Mitra *et al.*, 2005; Mitsch & Gosselink, 2007). In this method, the carbon emission included CH<sub>4</sub> and N<sub>2</sub>O by using a GWP of 25 for CH<sub>4</sub> and 298 for N<sub>2</sub>O, values established as GWP, based in last inform of the intergovernmental panel on climate change (IPCC, 2007). Such method does not involve the lifetime of gases. The balance for this method was obtained according to this formula: ECA2 (Exchange of carbon with the atmosphere; Kg C m<sup>-2</sup> y<sup>-1</sup>) = Carbon balance:  $C_{seq.} (Kg C m^{-2} y^{-1}) - [[CH_4 \times GWP \times (12 \text{ kg C}/44 \text{ kg CO}_2)] + [N_2O \times GWP \times (12 \text{ kg C}/44 \text{ kg CO}_2)]] (Kg C m^{-2} y^{-1})$ . Where,  $C_{seq.}$  is the carbon sequestered in the soil (Kg C m<sup>-2</sup> y<sup>-1</sup>), GWP is the global warming potential of greenhouse gases. In both methods, 1 and 2, there is absence of carbon accumulated in vegetation, there is only reference to carbon sequestration in soil.

Method 3: This approximation was made by using a model developed by Whiting & Chanton (2001) and estimates the role of wetlands as sinks

or source of carbon in various time horizons. This model uses a GWP for CH<sub>4</sub> of 21.8, 7.6 and 2.5, to time horizons of 20, 100 and 500 years, respectively. The reduction of GWP for methane while increase the time is due to the extended lifetime of CO<sub>2</sub> in the atmosphere relative to CH<sub>4</sub> (Bridgham *et al.*, 2014). This model is the relationship between the GWP of methane, expressed as CO<sub>2</sub> equivalents, and the molar ratio of CH<sub>4</sub> emitted to CO<sub>2</sub> taken up (CH<sub>4</sub>/CO<sub>2</sub>) by a wetland. The net ecosystem production encompassing the productivity, plant respiration, and soil community microorganism respiration. CH<sub>4</sub>/CO<sub>2</sub> is the molar ratio of CH<sub>4</sub> emitted to CO<sub>2</sub> taken up. The results of the model are represented in a graphic, where in the x-axis is the CH<sub>4</sub>/CO<sub>2</sub> ratio and the GWP of methane in the y-axis. The graphic includes a compensation line that indicates that greenhouse potential uptake of CO<sub>2</sub> is offset by the emission of CH<sub>4</sub> [GWP<sub>methane</sub> × (CH<sub>4</sub>/CO<sub>2</sub>) = 1]. The area below the compensation point is called sink region and the values that are above the line indicate that they are a source of carbon. The uptake CO<sub>2</sub> was calculated according to this formula: Uptake CO<sub>2</sub> (mol m<sup>-2</sup> y<sup>-1</sup>) = [(FNC)\*(44/12)]/44, where, FNC (Fixed net carbon; g C m<sup>-2</sup> y<sup>-1</sup>) = (AP + RP) – (R<sub>soil</sub> + R<sub>plant</sub>), where: AP = (Above productivity; g C m<sup>-2</sup> y<sup>-1</sup>) was calculated by obtaining the 44 % of carbon content (found in plant residues of the freshwater wetlands in the study area; Hernández, 2010) of above biomass in marshes (obtained according to previous studies in similar sites of the coastal plain of Veracruz, 1.84 kg biomass m<sup>-2</sup> y<sup>-1</sup>; unpublished data) or swamps (we used previous data obtained from the swamps in study, 1.75 kg litterfall m<sup>-2</sup> y<sup>-1</sup>; Infante *et al.*, 2011). RP =

(Root productivity; g C m<sup>-2</sup> y<sup>-1</sup>) this was calculated by using the ratio of productivity (above/root) (1:2) reported in the literature in marshes (Scarton *et al.*, 1998; Asaeda *et al.*, 2005) and swamps (Briggs, 1977; Giraldo, 2005). R<sub>soil</sub> (Respiration soil) was the data of CO<sub>2</sub> measured in the wetland soil of this study. R<sub>plant</sub> (Respiration plant) was obtained by knowing the value of 21 % of aerial productivity (Neubauer *et al.*, 2000).

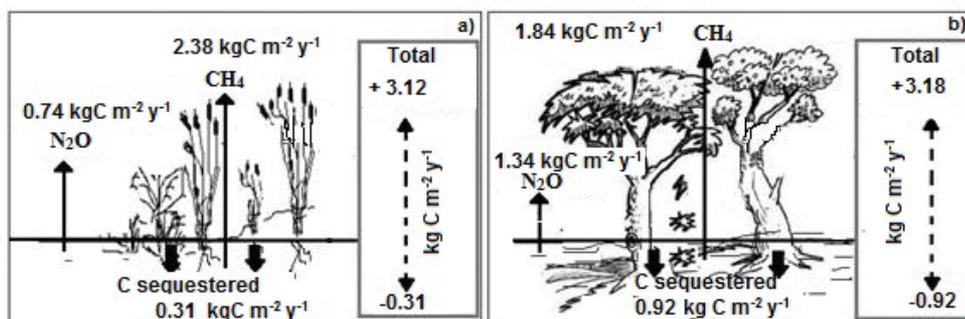
## RESULTS

Using method 1, i.e. based only on carbon, the six tropical wetlands sequestered carbon in a range 0.29 to 1.17 kg C m<sup>-2</sup> y<sup>-1</sup> in the soil, with an average of carbon sequestration of 0.31 ± 0.08 and 0.92 ± 0.12 kg C m<sup>-2</sup> y<sup>-1</sup> in marshes and swamps, respectively (Table 2). The swamps soils sequestered 66.3 % more carbon than marsh soils, showing mean differences statistically significant (*P* = 0.030). When we compared on a molecular basis, without considering the GWP (Table 2) carbon sequestered in the soil marshes (0.31 ± 0.08 kg C m<sup>-2</sup> y<sup>-1</sup>) and soil swamps (0.92 ± 0.12 kg C m<sup>-2</sup> y<sup>-1</sup>) were approximately 1.5 and 5 times more carbon than the carbon liberated to the atmosphere like methane (0.238 ± 0.06 and 0.184 ± 0.05 kg C m<sup>-2</sup> y<sup>-1</sup> in marsh and swamp soils, respectively, without statistical differences within mean data). Ratios of CO<sub>2</sub>:CH<sub>4</sub> were lower to the GWP with respect to carbon dioxide (25:1), in marshes (3.1:1) and swamps (2.7:1) (Table 2).

The second method considers the GWP, for this reason, GHG emissions were converted to CO<sub>2</sub> equivalents. The C-CH<sub>4</sub> emissions oscillated from 1.09 to 2.87 kg C m<sup>-2</sup> y<sup>-1</sup>, with average value

**Table 2.** Carbon balance in the wetlands in study, considering carbon sequestration, methane emissions, and ratios of CO<sub>2</sub>/CH<sub>4</sub>. Balance de carbono en los humedales de estudio, considerando secuestro de carbono, emisiones de metano y tasas de CO<sub>2</sub>/CH<sub>4</sub>.

Wetland type	CS, Carbon sequestration (gC m <sup>-2</sup> y <sup>-1</sup> )	CE, Methane emissions (gC m <sup>-2</sup> y <sup>-1</sup> )	Net C exchange (gC m <sup>-2</sup> y <sup>-1</sup> )	CS/CE	Carbon dioxide sequestration (g CO <sub>2</sub> m <sup>-2</sup> y <sup>-1</sup> )	Methane emissions (gCH <sub>4</sub> m <sup>-2</sup> y <sup>-1</sup> )	CO <sub>2</sub> :CH <sub>4</sub> ratio
Marshes	-310	+238	-72	1.30:1	1116	316.54	3.5:1
Swamps	-920	+184	-736	5:1	3312	1223.6	2.7:1



**Figure 3.** Scheme carbon sequestered and emitted of  $N_2O$  and  $CH_4$  gases (a: marsh, b: swamp) according to their GWP. The upward arrows indicate positive signals and broadcast. Arrows down and negative signs indicate carbon sequestration. *Esquema de carbono secuestrado y emitido de gases de  $N_2O$  y  $CH_4$  (a: humedales herbáceos, b: humedales arbóreos). Las flechas hacia arriba y signos positivos indican emisiones. Las flechas hacia abajo y signos negativos indican secuestro o almacenamiento.*

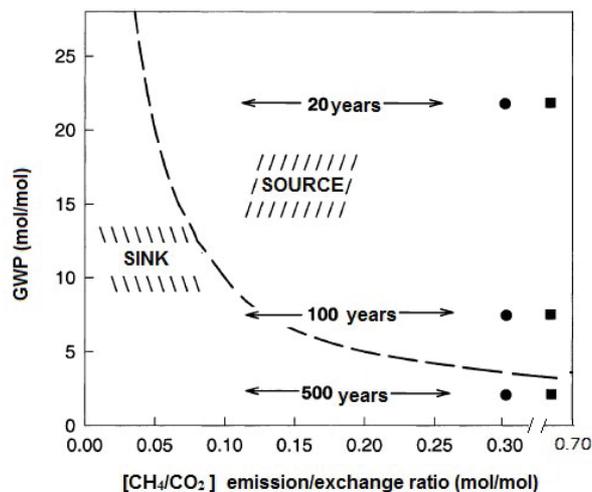
**Table 3.** Biomass, productivity, soil and plant respiration, net carbon, and exchange annual of  $CH_4$  and  $CO_2$  in tropical freshwater wetlands in study. *Biomasa, productividad, respiración de suelo y vegetación, carbono neto e intercambio anual de  $CH_4$  y  $CO_2$  en los humedales tropicales de agua dulce de estudio.*

Wetland type	Above Biomass ( $g\ m^{-2}y^{-1}$ )	Productivity		Respiration			Fixed net C	C- $CH_4$ emission	$CH_4$	$CO_2$	$CH_4/CO_2$	Compensation point
		Aerial <sup>1</sup>	Root <sup>2</sup>	Soil <sup>3</sup>	Plant <sup>4</sup>	Total						
Marsh	0.00184	809.6	1619.2	1868.8	170.02	390	238	19.8	32.5	0.61	0.59	
Swamp	0.00205*	902.0	1804.0	1985.6	192.57	528	184	15.33	44.0	0.35	1.9	

\*1.75 kg litterfall  $m^{-2} y^{-1}$  (Infante *et al.*, 2011) plus 17 % for obtaining the total aerial biomass (Brown, 1981). <sup>1</sup>PA: Biomass x (44 % C) according to Hernández (2010); <sup>2</sup>PR: root productivity x 2; <sup>3</sup>R<sub>soil</sub>:  $CO_2$  emission; <sup>4</sup>R<sub>plant</sub>: 21 % of above productivity (Neubauer *et al.*, 2000).

of  $2.38 \pm 1.6\ kg\ C\ m^{-2}\ y^{-1}$  in the marshes and  $1.84 \pm 1.2\ kg\ C\ m^{-2}\ y^{-1}$  in the swamps (Fig. 3). For  $N_2O$ , the emission in  $CO_2$  equivalents oscillated from 0 to  $2.3\ kg\ C\ m^{-2}\ y^{-1}$ , observing 45 % more  $N_2O$  emissions in swamps ( $1.34 \pm 1.4\ kg\ C\ m^{-2}\ y^{-1}$ ) than marshes ( $0.74 \pm 1.8\ kg\ C\ m^{-2}\ y^{-1}$ ), but without significant differences ( $P = 0.025$ ). The total carbon emitted in marshes ( $3.12\ kg\ C\ m^{-2}\ y^{-1}$ ) and swamps ( $3.18\ kg\ C\ m^{-2}\ y^{-1}$ ) was higher than carbon sequestered in the marsh ( $0.31 \pm 0.08\ kg\ C\ m^{-2}\ y^{-1}$ ) and swamp soil ( $0.92 \pm 0.12\ kg\ C\ m^{-2}\ y^{-1}$ ). The carbon emitted to the atmosphere was 10 times higher than the carbon sequestered in the marshes and 3.5 times higher in the swamps.

The third method uses a dynamic model of carbon balance in various horizon times. The ratio of  $CH_4/CO_2$  in the marshes were 0.61 and 0.35 for swamps (Table 3); these values were plotted in the graphic model (Fig. 4) proposed by Whiting and Chanton (2001). Considering a short time horizon ( $GWP_{methane}$ : 21.8) calculated for a period of integration of 20 years, it appears that marshes and swamps act like sources of greenhouse gases (Fig. 4, circles and squares). When we consider a long-time horizon (100 years), the GWP used is 7.6, in such period, again it was observed that both wetland types act like sources of greenhouse gases (Fig. 4, circles and squares).



**Figure 4.** The annual  $\text{CH}_4/\text{CO}_2$  exchange ratio for table 3, expressed on the model presented by Whiting and Chanton, 2001. The circles and squares represent the freshwater swamps and marshes, respectively, over 20, 100 and 500 year time horizons. *Intercambio anual de  $\text{CH}_4/\text{CO}_2$  para la tabla 3, expresado sobre el modelo presentado por Whiting and Chanton, 2001. Los círculos y cuadros representan los humedales herbáceos y arbóreos de agua dulce, respectivamente, sobre horizontes de tiempo de 20, 100 y 500 años.*

On the other hand, considering an extended time horizon (500 years), where the GWP used is 2.6, the function of studied freshwater wetland is like carbon sinks (Fig. 4, circles and squares). Every wetland has a balance point between the equivalents of  $\text{CO}_2$  sequestered and  $\text{CH}_4$  emitted, and is expressed like compensation point (Table 3).

## DISCUSSION

In wetlands, the GHG emissions and the soil carbon sequestration are natural processes influenced by the environmental conditions, and differences in the plant communities (Dalal *et al.*, 2008; Marín-Muñiz *et al.*, 2014). Methane emissions found in these tropical wetlands are lower than those reported in temperate and subtropical regions (Sun *et al.*, 2013a; Mitsch *et al.*, 2013b; Sjögersten *et al.*, 2014; Zhang *et al.*, 2017), also, the carbon stored in these same wetland soils have been reported with values higher than in wetland soils from other regions (Campos *et al.*, 2011; Marín-Muñiz *et al.*, 2014). This was attrib-

uted to the high productivity in the tropical wetlands compared with temperate wetlands (Pant *et al.*, 2003; Chimmer & Ewel, 2005). In Mexico, the coastal zone located in Veracruz is one of the most vulnerable to climate change (Martínez *et al.*, 2011). While the climate change effect on wetlands is uncertain, several scenarios have shown to be a threat to the wetland areas and the associated species (Root *et al.*, 2003; Hulme, 2005; Erwin, 2009). It is also significant that wetlands also emit GHG (Altor & Mitsch, 2006; Dalal *et al.*, 2008; Nahlik & Mitsch, 2011). However, little research about the net carbon balance in tropical wetlands is involved in the global carbon budgets, so the tropical ecosystems are underrepresented in the scientific literature compared to temperate ones.

The carbon stored in the soil of the studied wetlands was up to 5 times less than the carbon being emitted into the atmosphere, considering the first method. With the same type of calculation, Mitra *et al.* (2005) using values of methane and carbon from different wetland around the world, reported  $1.5 \text{ t C ha}^{-1}$  production of methane and carbon equivalent and  $1.4 \text{ t C ha}^{-1}$  of carbon sequestered which suggested minimal impact of wetlands on climate change. On the other hand, in created wetlands in Ohio, Mitsch & Gosselink, (2007) reported that wetland soils stored more carbon than those emitted in the form of  $\text{C-CH}_4$ . In both of these studies, nitrous oxide emissions were not considered, contrary to our study that included it. When compared on a molecular basis, regardless of the GWP, the ratio of  $\text{CH}_4:\text{CO}_2$  was lower than the global warming potential (25:1) in the two wetlands types (marshes and swamps). Similar to this study, by using the same methodology, Mitsch *et al.*, (2013) found ratios of  $\text{CH}_4:\text{CO}_2$  with values < to 25:1, for natural tropical wetlands of Costa Rica, Botswana and Ohio. However, a ratio of 50:1 of carbon sequestrations/carbon dioxide to methane emitted was observed in a created wetland in Ohio. When we use method 2, it is necessary to know the GWP of GHG; our results showed higher carbon emitted than sequestered. However, this methodology does not involve the global climate change context, nor the complete carbon cycle in wetlands, because it did not assume the

half-life of gases and the carbon accumulated in vegetation is omitted.

In the atmosphere, the GWP is dynamic and not static, because 25:1 for CH<sub>4</sub>, and 298:1 for N<sub>2</sub>O change with respect to time, for that reason, the carbon balance with method 2 resulted overestimated. Therefore, the approximation of the dynamic model at different time horizons is a more appropriate methodology for assessing carbon exchange in wetlands. According to the model used with method 3, we demonstrate that wetlands are carbon sinks when considering the half-life of methane in the atmosphere, and with time horizons of more than 500 years, the function as a sink in wetlands is clear. Mitsch *et al.*, (2013) developed a dynamic simulation model of carbon fluxes and found that methane emissions measured in temperate and tropical wetlands are negligible within 300 years compared to carbon sequestration in wetlands. However, Neubauer (2014) for the same sites studied by Mitsch *et al.* (2013), reported that the methane emissions become unimportant from 61 to 14,049 years, a value considerable longer than the 300 years timeframe reported by Mitsch *et al.* (2013). The differences are a result of an inappropriate use of GWP in the dynamic simulation model, pointed out by the author in relation to the reported by Mitsch *et al.* (2013). Similarly, Bridgham *et al.* (2014) commented that the dynamic model used is flawed in double counting the atmospheric decay of methane and incorporating a single 100 years CH<sub>4</sub> GWP. They also argued that Mitsch *et al.* (2013) used a small number of sites (7) and unrealistically high soil C sequestration rates. It is important to mention the difficulty to obtain specific carbon sequestration data because the accretion rates change according the climatic seasons and involve changes in allochthonous and autochthonous carbon. Radiometric analyses (ie. <sup>137</sup>Cs or <sup>210</sup>Pb techniques) only include the measurements for roughly the past 50-100 years. Yu (2012) estimated a net carbon balance of 10 g C m<sup>-2</sup> y<sup>-1</sup> for 33 boreal peatland sites over the last millennium considering <sup>14</sup>C dates, and long-term decomposition rates. In our study we used artificial horizon markers to measure short-term accretion which might overestimate the accretion rates. However, in the same wetland soils Marin-Muñiz

*et al.* (2014) showed that carbon stocks were also high, indicating that these tropical freshwater wetlands in the southern Gulf of Mexico are an important carbon sink for the planet.

The results obtained by using the three methods in this study are approximations of carbon balances in tropical freshwater wetlands. Sjögersten *et al.* (2014) described that tropical wetland ecosystems are not included in Earth system models because there is a remarkable lack of data on the carbon balance in tropical ecosystems, therefore, the results of this study could be important data for making predictions about the future earth's climate and promote the conservation of wetlands. Whiting and Chanton (2001), developed the model used in the method 3 and by using boreal, temperate and subtropical wetland data, so they found that considering a horizon time of 500 years, wetlands acting like carbon sinks, would be ceasing the GHG emissions to the atmosphere. Opposite to our findings, Bridgham *et al.* (2006), by using a carbon balance (sum of carbon soil and plant sequestration and oxidation), in different types of North American wetlands found that wetlands could be a constant source of carbon or maybe be a zero balance between carbon emitted in methane form and carbon sequestered. The same authors describe that exists an uncertainty (close to 100 %) in the results of carbon emissions and sequestration, due to the lack of a data base on accretions rates in the soil and the use of factor conversions for the reported data.

Coletti *et al.* (2011) developed a minimalistic carbon cycling model, showing that results on carbon storage pool and net metabolism are related with parameters such as respiration, photosynthesis and microbial respiration. They also argue that the model provides a first step to explain how changing patterns of rainfall, temperate and evapo-transpiration can change the carbon retention and efficiency of wetlands. Their study also suggests that such effects need more depth of analysis for new studies. We consider that their results are relevant for establishing a standard methodology to calculate the carbon balance in wetland ecosystems.

Although the close chamber technique for measuring GHGs emissions had been widely

used in wetlands (Mitsch *et al.*, 2013; Wilson *et al.*, 2016; Hernández *et al.*, 2018; Windham-Myers *et al.*, 2018), Camacho *et al.* (2017), reported that methane emission by ebullition processes cannot be accurately estimated by close chamber techniques, situation that needs to be analyzed for standard methods in future studies. Other authors (Chaichana, 2018; Wali, 2018) had compared the advantages and disadvantages in the use of close chamber and Eddy covariance techniques, indicating that selection of the best method depends on some cases in the resources available, landscape type and objectives. The possibility of using both methods for a better understanding of methane emissions is the ideal scenario, but there are not always the resources to do it.

According to the results of this study, we consider that it is erroneous referring to wetlands as contributors to global warming by previous studies (Altor & Mitsch, 2006; Nahlik & Mitsch 2011; Sun *et al.*, 2013b). We think that such erroneous conclusion is a result of the short time scale of most gas exchange studies in wetlands. The studied wetlands are carbon sinks, and thus mitigating global warming if they are assessed by long time horizons (> 100 years), therefore, it is important to protect and restore the existing wetlands. Besides the carbon sink function, other multiple ecosystem services provided by wetlands would continue in the future if they are protected. Further, carbon balance studies should be directed in wetlands in other parts of the tropics by using models and considering different time frames.

## CONCLUSIONS

Carbon balance data in tropical wetlands are scarce, despite the fact that tropical latitudes contain large areas of these ecosystems. The obtained carbon balances showed that a dynamic model that includes productivity, respiration of plant and soil, carbon sequestration, gas fluxes, the half-life of the gases in different time horizons, result in a more comprehensive option for estimating the carbon balance in wetlands. With this model, we found that the studied wetlands should be considered as sinks of carbon in horizon times higher than 100 years, while in horizon time's ≤

100 years are considered as net sources of carbon. Despite the methodological limitations of the GWP consideration, another important finding of the study is that methane emissions in this type of wetland can significantly modulate its mitigating function (changes from sink to source when warming potential is considered). The data reported here, are the first for Mexican wetlands and should be incorporated into global climate change models. Additional studies of carbon balance in tropical wetlands are necessary for a better understanding on how they differ from carbon balance in wetlands from other regions.

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