Soil contribution to CO$_2$ fluxes in Chinampa ecosystems, Mexico

**ABSTRACT**

Since soil CO$_2$ flux is a key component of ecosystem carbon balance, quantifying its contribution to the ecosystem carbon flux and understanding the factors that underlie its temporal variation is crucial for a better comprehension of ecosystem carbon dynamics under climate change and for optimal ecosystem use and management. Our objectives were to quantify the contributions of total soil CO$_2$ efflux ($F_S$) to ecosystem respiration ($R_E$) and heterotrophic soil CO$_2$ efflux ($F_H$) to $F_S$ in two chinampa ecosystems with different natural grass covers. We also aimed to identify the main environmental drivers of seasonal variability of these contributions. The CO$_2$ fluxes were measured on each site about every 14 days from September 2008 to August 2009 in the Xochimilco Ecological Park in Mexico City using dark chamber techniques. For two studied sites, $R_E$, $F_S$ and $F_H$ were estimated on average as 94.1 ± 8.5, 34.7 ± 3.5 and 16.5 ± 1.7 (± S.E.) mg C-CO$_2$ m$^{-2}$ h$^{-1}$, respectively. On average over the study period and sites, the annual cumulative $R_E$, $F_S$ and $F_H$ fluxes were 824 ± 74, 304 ± 31 and 145 ± 15 g C m$^{-2}$ year, respectively. The $R_E$, $F_S$ and $F_H$ varied between the winter and summer seasons; this variation was explained mostly by seasonal variations of soil temperature, soil water content and shoot plant biomass. Temperature sensitivity of CO$_2$ fluxes depended on vegetation type and plant growth differences among the sites and decreased in the following order: $R_E > R_s > R_H$. The contribution of $F_S$ to $R_E$ and $F_H$ to $F_S$ for the two studied sites and period averaged about 38% and 50%, respectively regardless of the site vegetation type, but the degree of $F_S/R_E$ and $F_H/F_S$ variability depended on the differences in seasonal dynamics of plant cover. The contribution of $F_H$ to $F_S$ varied from 37% in summer to 73% in winter at the site without a seasonal shift in dominant plant species, but $F_H/F_S$ was close to constant during the year at the site with a seasonal change in dominant plant species. During the cold period, the contribution of $F_H$ to $F_S$ increased following plant growth decrease. The linear regression analysis showed that plant biomass was the dominant factor controlling the seasonal variation of $F_H/F_S$ ratios, whereas the plant biomass dynamic followed the dynamics of soil water content, water table depth, and soil temperature. Our results suggest that seasonal variation of soil contribution to total fluxes from the chinampa ecosystem is locally differentiated. These differences were related to differences in seasonal dynamics of cover productivity which has been associated with localization of soil water content. This finding has important implications for assessing the contribution of the chinampa ecosystem to the global carbon budget.

**RESUMEN**

Dado que el flujo de CO$_2$ del suelo es un componente clave del balance de carbono del ecosistema, la cuantificación de su contribución a las pérdidas de carbono del ecosistema y la comprensión de los factores que subyacen a la variación temporal de la magnitud de los flujos es crucial para una mejor comprensión de la dinámica del carbono del ecosistema conforme a los cambios climáticos y para planificar el uso y la gestión óptima de los ecosistemas. Nuestros objetivos fueron cuantificar la contribución del flujo de CO$_2$ total del suelo ($F_S$) a la respiración del ecosistema ($R_E$) y el flujo de CO$_2$ heterótrofo del suelo ($F_H$) con respecto a $F_S$ en dos ecosistemas de chinampa con cobertura de
as contribuições do fluxo total de CO2 do solo (FS) para a respiração do ecossistema (RE) e do fluxo heterotrófico temporal são cruciais para uma melhor compreensão da dinâmica do carbono no ecossistema no âmbito das alterações da sua contribuição para o fluxo de carbono no ecossistema e a compreensão dos fatores subjacentes à sua variação RE, FS e FH foram, respetivamente, 94,1 ± 8,5, 34,7 ± 3,5 e 16,5 ± 1,7 (± S.E.) mg C-CO2 m-2 h-1. Os fluxos de CO2 foram medidos em cada local cada 14 dias de setembro de 2008 a agosto de 2009 no Parque Ecológico Xochimilco de la Ciudad de México, usando la técnica de câmaras obscuras. Em média, para os dois sítios estudados, RE, FS e FH no estação de verão e inverno de RE, FS e FH se explicou principalmente por variações estationais de temperatura do solo, conteúdo de água no solo e biomassa de brotos das plantas. A sensibilidade da temperatura dos fluxos de CO2 depende do tipo de vegetação e de variações estacionais do conteúdo de água no solo, a profundidade do manto freático e a temperatura do solo. Nosso resultados sugerem que a variação estacional da contribuição do solo para os fluxos totais do ecossistema chinampa localmente diminui. Dessa forma, compararam as diferenças estacionais de produção da vegetação que se associou com a localização do conteúdo de água no solo. Este hallazgo pode ter implicações importantes para avaliar a contribuição do ecossistema chinampa al conteúdo global de carbono.

RESUMO

Dado que o fluxo de CO2 do solo é um componente chave do balanço de carbono nos ecossistemas, a quantificação da sua contribuição para o fluxo de carbono no ecossistema e a compreensão dos fatores subjacentes à sua variação temporal são cruciais para uma melhor compreensão da dinâmica do carbono no ecossistema. Os nossos objetivos foram quantificar as contribuições do fluxo total de CO2 do solo (FT) para a respiração do ecossistema (RE) e do fluxo heterotrófico de CO2 do solo (FH) relativamente a FS em dois ecossistemas com diferentes coberturas naturais de pastagem. Também se pretendeu identificar os principais fatores da variabilidade sazonal dessas contribuições.

Os fluxos de CO2 foram medidas em cada local cada 14 dias de setembro de 2008 a agosto de 2009 no Parque Ecológico Xochimilco na cidade de México usando técnicas de câmara escura. Em média, para os dois sítios estudados, RE, FS e FH foram, respetivamente, 94,1 ± 8,5, 34,7 ± 3,5 e 16,5 ± 1,7 (± S.E.) mg C-CO2 m-2 h-1. Os fluxos anuais cumulativos de RE, FS e FH durante o período de estudo e nos dois sítios foram em média, respectivamente, 824 ± 74, 304 ± 31 e 145 ± 15 g C m-2 por ano. A variação entre as estações de verão e inverno de RE, FS e FH explicou-se, principalmente, pela variação sazonal da temperatura do solo, conteúdo de água no solo e biomassa da parte aérea das plantas. A sensibilidade à temperatura dos fluxos de CO2 depende do tipo de vegetação e das diferenças no crescimento das plantas entre os sítios e diminuiu de corda com a ordem seguinte: RE > RS > RH. A contribuição de FS para RE e FH para FS para os dois sítios e período estudo, foi em média de cerca de 38% e 50%, respetivamente, independentemente da vegetação do local; o grau de variabilidade de FH/FS, enquanto a dinâmica de biomassa das plantas seguiu a dinâmica do conteúdo de água no solo, a profundidade do manto freático, a temperatura do solo. Nosso resultados sugerem que a variação sazonal da contribuição do solo para os fluxos totais do ecossistema chinampa se diferencia localmente. Estas diferenças estão relacionadas com as diferenças na dinâmica sazonal da produtividade da vegetação que está associada à localização do conteúdo de água do solo. Este resultado tem implicações importantes para avaliar a contribuição do ecossistema chinampa para o conteúdo global de carbono.

KEYWORDS

Ecosystem respiration, total soil CO2 efflux, heterotrophic soil CO2 efflux.

PALABRAS-CHAVE

Respiración del ecosistema, flujo total de CO2 del suelo, flujo heterotrófico de CO2 del suelo.

PALAVRAS-CHAVE

Respiración del ecosistema, flujo total de CO2 del suelo, flujo heterotrófico de CO2 del suelo.
1. Introduction

Ecosystem respiration ($R_e$) including aboveground plant respiration and total soil CO$_2$ flux ($F_S$) is commonly regarded as the most critical component determining large-scale spatial and temporal variation in ecosystem net carbon balance (Grogan and Jonasson 2005). For characterizing spatial and temporal variability in ecosystem carbon balance and for correct prediction of carbon cycling and sequestration under changing climatic conditions, the controlling factors, component fluxes and their contribution to $R_e$ should be well understood (Kuzyakov and Cheng 2001). The heterotrophic soil CO$_2$ flux ($F_H$) (i.e. the decomposition of soil organic matter by the soil microbial community) and autotrophic root respiration are the main contributors to soil CO$_2$ production and consequently, to $F_S$ (Kuzyakov and Cheng 2001). For grasslands, the contribution of $F_H$ to $F_S$ was reported to range between 40 and 70% (Subke et al. 2006). Considerable variations of the contributions might be connected with large differences among site types and vegetation characteristics (Xavier et al. 2019; Santos et al. 2019). Climate may drive variation of CO$_2$ fluxes on seasonal and annual time scales (Martin and Bolstad 2005). Since autotrophic and heterotrophic respirations have a differential response to environmental drivers such as temperature, moisture and substrate supply (Hartley et al. 2006; López et al. 2018; Santos et al. 2019) or water table depth (Juszczak et al. 2013), high temporal variability of contributions of each flux component to the ecosystem flux can be expected. Furthermore, root respiration exhibits greater seasonality than heterotrophic respiration (Widén and Majdi 2001) and the seasonal variation of plant biomass could increase temporal variability of the contribution of CO$_2$ flux components to $R_e$.

$R_e$ and $F_S$ are widely documented to depend on temperature (Lloyd and Taylor 1994; Alm et al. 1997; Almagro et al. 2009; Mahecha et al. 2010; López et al. 2018; Silva et al. 2019). The temperature sensitivity is expressed as $Q_{10}$, which is the rate of respiration increase as a consequence of increasing the temperature by 10 ºC. The $Q_{10}$ values of autotrophic and heterotrophic respiration varies widely with environmental conditions and terrestrial ecosystem types (Atkin et al. 2005; Ikkonen et al. 2012a). On an annual time scale, the $Q_{10}$ values could be affected by climatic factors such as temperature (VanHala et al. 2008), soil water content (Ikkonen et al. 2012a), or plant activity (Wang et al. 2010). The differences in temperature sensitivities and their responses to varying external drivers could be partly responsible for temporal variability of the contribution of different components to ecosystem fluxes.

Chinampas are unique anthropogenic wetland ecosystems used for agriculture in the Valley of Mexico since pre-Hispanic times. Chinampas were made by hand from the wetland around the lakes in the Valley of Mexico by forming raised fields separated by a system of canals (Jiménez-Osorio and Gómez-Pompa 1987; Blanco-Jarvio et al. 2011). The fields constructed by the accumulation of lacustrine organic loamy sediments were typically characterized by exceptionally high yields (Jiménez-Osorio et al. 1995). In pre-Hispanic times this intensive agricultural system used for growing foodstuffs occupied large areas, but to date, the chinampa land area has been greatly reduced due to the expansion of Mexico City. A part of the remaining chinampas was reserved in Xochimilco Ecological Park to restore these unique ecosystems without soil cultivation and fertilization but with the development of native vegetation.

Although many studies focused on greenhouse gas production and emission from soil of the Valley of Mexico (Beltrán-Hernández et al. 2007; Silva et al. 2008; Dendooven et al. 2010; Dendooven et al. 2012a, b), little is known about temporal dynamic of CO$_2$ fluxes from chinampas soils (Ortiz-Cornejo et al. 2015) and no information concerning soil contribution to chinampa ecosystem fluxes are available. We hypothesized that the magnitude of the $F_S$ contribution to the total chinampa flux varies depending on soil water and temperature regime as well as the seasonal dynamic of plant cover. The objective of the study was to evaluate the contribution of $F_H$ to $R_e$ and $F_{A}$ to $F_S$, their seasonal variability and dependence on driving factors in chinampa ecosystems.
2. Material and Methods

2.1. Study sites

We studied two chinampas ecosystems within the Xochimilco municipality of Mexico City, DF, at the geographical coordinates 19°17’45” N and 99°05’34” W and at the altitude of 2240 m above sea level (Figure 1). The climate of the study area is temperate subhumid. The area is characterized by an alternation of the dry season from November to March and the rainy season from April to October. The mean annual precipitation for the 1996-2009 period was 686.1 mm, according to the data of the Escuela Nacional Preparatoria meteorological station, Plantel 1 “Gabino Barreda” UNAM (Xochimilco, Mexico City, D.F.) located close to the sampling site. The mean air temperature was 17 °C with a minimum of 13.5 °C in January and a maximum of 19.3 °C in July as reported by the same meteorological station. The soil of chinampas was classified by its origin as Terric Anthrosol (IUSS Working Group WRB 2006) because the surficial layers of the soil were known to be constructed of excavated lacustrine sediments. The soil texture varied from silty loam to clay and the morphology of the soil profile is relatively uniform and the horizons are hardly distinguishable (Ramos-Bello et al. 2011). The morphology of chinampa’s soils resembles that of deep organic soils (Histosols), but the organic matter content is lower (García et al. 1994). High salinity and sodicity of groundwater and soils have been reported for the area (Ramos-Bello et al. 2011). The pH of the chinampas soils, as was reported by N. Ortiz-Cornejo et al. (2015), is alkaline with total N ranges from 5.9 to 6.2 g kg\(^{-1}\) and organic carbon content equals 28.4 t ha\(^{-1}\) at the 20-40 cm depth. High organic matter content throughout the topsoil and irregular vertical distribution of organic carbon and bulk density has been reported for the chinampas area (Ikkonen et al. 2012b).

Two study sites were located in the Xochimilco Ecological Park in Mexico City (Figure 1). The uniqueness of this area is connected with the peculiarity of anthropogenic chinampas soils through a specific agricultural practice referred to the Pre-Hispanic period. The distance between the study sites did not exceed 100 m, but they varied in groundwater table depth and dominant plant species composition. The vegetative community of first study site (S1) was dominated by rushes (*Juncus* spp.) and broadleaf cattail (*Typha latifolia* L.). The plant cover of the second site (S2) varied between the seasons: in the dry period the dominant species were bristly oxtongue (*Picris echioides* L.) and greater plantain (*Plantago major* L.), and in the rainy season the vegetation was represented mainly by rushes (*Juncus* spp.) and common reed (*Phragmites australis* (Cav) Trin. ex. Stend.). Single specimens of seashore saltgrass (*Distichlis spicata* L.) were found on both sites. The highest root density was found in the layer of 0-7 cm depth, but it decreased sharply with the depth (Ikkonen et al. 2012a).

![Figure 1. Location of the study sites in the Xochimilco Ecological Park in Mexico City, Mexico.](image-url)
2.2. CO₂ flux measurements

The $R_{e}$, $F_{s}$ and $F_{h}$ fluxes were measured using static chamber techniques (Alm et al. 1997) every two-three weeks from September 2008 to August 2009. The measurements were performed between 8:00 and 12:00. All chambers were opaque in order to prevent photosynthesis and ensure that only respiration was measured. For ecosystem respiration measurements four stainless steel collars (length × width × height = 40 cm × 30 cm × 10 cm) were inserted into the soil six months prior to the first flux measurement. Locations for collars were selected using the presence of photosynthesizing plants as the main criterion. A steel removable chamber 40 cm × 30 cm × 50 cm (length × width × height) in size was placed and sealed over the collars using water for capsulation of chamber air during each flux campaign. An internal electric fan was used to homogenize air temperature and humidity within the chamber. An aluminum cover was added outside of the chamber to reduce the impact of direct irradiative heating during sampling. The measurement of $F_{s}$ flux was made with four replicate cylindrical chambers (diameter × height = 10 cm × 15 cm) directly inserted into the soil, about 5 cm below the surface. The locations for the cylindrical chambers were selected between individual plants without their presence inside the chambers. In order to collect the data on $F_{h}$, the same cylindrical chambers were inserted into the soil of surface section fenced off by PVC tubes that were inserted 30 cm into the soil six months prior to the measurements. The sections for $F_{s}$ measurements contained plant litter but did not include photosynthesizing plants and the sections for $F_{h}$ measurements did not include plant roots.

The headspace gas samples were collected through a sampling port to 20 ml vessels (Corning System, USA) using a double-sided needle every 10 min from 0 to 30 min. The vessels were vacuum sealed with a rubber stopper and metal cap. All air samples were transported to a laboratory and analyzed within 24 h following gas collection. The CO₂ molar fraction were recorded by HP Agilent 6890 GC System gas chromatographer (GMI, USA) with a Poropac-Q column (35 °C of column’s temperature and 300 °C of detector’s temperature; argon was used as carrier gas). The flux was calculated by estimating the slope of the increase in CO₂ molar fraction in the chamber, adjusted for air temperature and pressure.

2.3. Environmental measurements and shoot plant biomass

Air temperatures, air pressure and water table depth (WTD) were recorded on each sampling occasion immediately after the flux measurements. The ambient air temperature, atmospheric pressure and humidity were simultaneously registered with a weather station (Crosse Technology, USA). Soil temperatures at 5-cm depth in the organic soil layer were recorded using a portable temperature probe (WIKA, USA) immediately after the flux measurements at both S1 and S2 sites and at 30-min intervals using a 5TM sensor with an E50-series data logger (Decagon, USA) at the S1 site from September 2008 to August 2009. The soil water content at 5-10 cm depth was determined gravimetrically in four replicates by oven drying the samples at 105 °C for 24 h. WTD was measured in soil profile pits.

Shoot biomass was measured four times during the flux measuring period in 2008-2009: September 18, November 18, January 27, and April 13 for Site 1 and September 4, November 18, January 27, and April 13 for Site 2. We quantified shoot plant biomass by clipping green vegetation and litter within four randomly located 20 × 20 cm plots outside permanently designated locations for CO₂ flux measurement. The clipped material was separated into plant species and total litter, dried at 105 °C and weighed after drying.

2.4. Statistical analysis

The C-CO₂ flux results are presented as means ± SE. We defined the proportion of soil respiration ($F_{s}$) in the total ecosystem respiration ($R_{e}$) as a percentage $F_{s}/R_{e}$ and the proportion of heterotrophic respiration ($F_{h}$) in total soil respiration as a percentage $F_{h}/F_{s}$. Data were tested for normality and homogeneity of variance using the Chi-Square test and Levene’s test in Statistica (v.8.0.550.0, StatSoft, Inc). Differences of means between the two
studied sites were tested with one-way ANOVA followed the least significance difference (LSD) test. The correlation coefficients were calculated to examine the relationships between $R_E$, $F_S$, $F_H$, $F_S/R_E$, $F_H/F_S$, soil temperature, soil water content, water table depth and shoot biomass. The statistical significance was judged at the 5% probability level and the statistical analyses were performed using Statistica (v.8.0.550.0, StatSoft, Inc). The sensitivities of CO2 fluxes to variations in soil temperature were calculated in the form of $Q_{10}$ values according to Meyer et al. (2018). Annual cumulative C-CO2 fluxes were defined using mean flux values for the measuring period.

3. Results

3.1. Environmental variables and shoot plant biomass

According to the data of the “Gabino Barreda” meteorological station, the total precipitation from September 2008 to August 2009 was close to 450 mm, which was lower than the mean annual value for the same period (Figure 2A). During the dry season (from October to April) the area received only 10% of the total precipitation. At both sites WTD followed precipitation pattern, but the temporal variations in WTD were much higher at S2 than at S1 (Figure 2B, Table 1). WTD at S1 remained only a few cms below the surface throughout the measuring period. WTD was nearly 10 cm deeper at S2 compared with S1 for the August-February period and more than 30 cm deeper at the end of the dry season (February-April). From May to August, WTD trends showed only small differences between the study sites. Following the patterns of precipitation, soil water content was high from May to September and low from October to April at both sites, but the values were 1.5-2.5 times higher at S1 (Figure 2C). The lowest soil water content values were recorded from November to April and the highest ones immediately after the beginning of the May to August rainy season. Mean soil temperature at 5 cm depth did not differ significantly between S1 and S2 sites (Table 1). During the study period, the mean annual soil temperature was about 15.0 °C (Figure 2D).

| Parameter                  | S1        | S2        |
|----------------------------|-----------|-----------|
| Soil water content, %       | 322 ± 24a | 145 ± 22a |
| WTD, cm                    | 17.7 ± 1.9a | 27.4 ± 3.4a |
| Soil temperature, °C        | 14.8 ± 0.6a | 16.1 ± 0.5a |
| Total shoot biomass, g m⁻²  | 406 ± 151a | 705 ± 107a |
| $R_E$, mg C-CO₂ m⁻² h⁻¹     | 78.0 ± 13.1a | 108.1 ± 10.3a |
| $F_S$, mg C-CO₂ m⁻² h⁻¹     | 28.0 ± 5.4a | 40.5 ± 4.3a |
| $F_H$, mg C-CO₂ m⁻² h⁻¹     | 13.0 ± 2.9a | 19.6 ± 1.8a |
| $F_S/R_E$, %               | 36.7 ± 3.0a | 39.4 ± 3.2a |
| $F_H/F_S$, %               | 50.0 ± 5.6a | 50.1 ± 1.7a |

| Winter season               |           |           |
| $F_S/R_E$, %               | 42.9 ± 3.6a | 36.1 ± 3.4a |
| $F_H/F_S$, %               | 72.6 ± 4.6a | 50.7 ± 1.6a |

| Summer season               |           |           |
| $F_S/R_E$, %               | 32.2 ± 1.6a | 36.1 ± 3.4a |
| $F_H/F_S$, %               | 36.8 ± 2.6a | 49.8 ± 1.8a |

WTD – water table depth, $R_E$ – ecosystem respiration, $F_S$ – total soil CO₂ flux, $F_H$ – heterotrophic soil CO₂ flux, $F_S/R_E$, $F_H/F_S$ – contribution of $F_S$ to $R_E$, $F_S/F_H$ – contribution of $F_S$ to $F_H$. Means followed by different letters in the same line are significantly different (LSD test). N = 76 and 85 (Soil temperature, $R_E$, $R_F$, $R_H$) 19 and 22 (Soil water content, WTD, $F_S/R_E$, $F_H/F_S$), 16 and 16 (Total shoot biomass) for S1 and S2, respectively.
Figure 2. Precipitation (A), water table depth (WTD) (B), soil water content within 5-10 cm depth (C) and daily mean soil temperature at 5-cm depth (D) during the study period at the S1 and S2 sites.
The shoot plant biomass differed between the study sites (Figure 3, Table 1). The site S2, where the water table was lower during winter, had higher total plant biomass and litter than S1. In the rainy summer season, the S2 vegetation was dominated by rushes and common reed, and in winter it was replaced mainly by bristly oxtongue and seashore saltgrass. This replacement was connected with the lowering of WTD. For the S1 site, the seasonal change of dominant plant species was not observed. The decreases of shoot plant biomass started in November at both sites, but at the S2 site it quickly recovered due to active growth of the winter period vegetation (‘dry season type’). Unlike the S1 site, litter mass of S2 was high during the winter and close to zero during the summer. The decomposition rate of S1 litter was slow probably because WTD remained only a few cm below the surface during the measurement period. The results indicated significant positive relations between total shoot biomass and soil water content and a negative relation between biomass and WTD in S1. For the S2 site, shoot plant biomass was positively related to soil water content and temperature (Table 2).

3.2. Seasonal variation in CO₂ fluxes

The mean C-CO₂ fluxes for the measuring period are shown in Table 1. Although $R_e$, $F_s$ and $F_H$ were
higher at the S2 than at the S1 site, no significant differences in mean seasonal fluxes were found among the sites \((P > 0.05)\). Regardless of the flux and vegetation type, all the \(CO_2\) fluxes exhibited a pronounced seasonal variation with the lowest values during the cold period from November to February and the highest values during the warm period (Figure 4), indicating the strong positive correlation of the flux with the temperature (Table 2). After the winter period, when the \(R_e\) values were minimal, an increase of \(R_e\) was recorded at the S2 earlier than at the S1. The results did not indicate a significant relationship between \(F_s\) or \(F_h\) and soil water content or WTD \((P > 0.05)\) especially at the S1 site characterized by low seasonal variability of WTD. The annual cumulative \(R_e\), \(F_s\) and \(F_h\) fluxes were higher by about 30% at the S2 than at the S1 (Table 2). For

Table 2. Statistical data \((P\) value, \(R^2)\) indicating relationships between measured \(CO_2\) fluxes, \(F_s/R_e\), \(F_h/F_s\) and environmental variables at the S1 and S2 sites of chinampa ecosystem

| Variable          | S1   |       | S2   |       |
|-------------------|------|-------|------|-------|
| \(R_e\)           |      |       |      |       |
| Soil water content| < 0.001 | 0.63 | < 0.001 | 0.41 |
| WTD               | 0.028 | -0.09 | 0.285 | 0.02 |
| Soil temperature  | < 0.001 | 0.59 | 0.112 | 0.04 |
| Total shoot biomass| 0.002 | 0.18 | < 0.001 | 0.18 |
| \(F_s\)           |      |       |      |       |
| Soil water content| < 0.001 | 0.49 | 0.002 | 0.21 |
| WTD               | 0.440 | -0.01 | < 0.001 | 0.36 |
| Soil temperature  | < 0.001 | 0.49 | 0.001 | 0.17 |
| Total shoot biomass| 0.616 | 0.00 | < 0.001 | 0.30 |
| \(F_h\)           |      |       |      |       |
| Soil water content| 0.239 | 0.04 | < 0.001 | 0.34 |
| WTD               | 0.470 | 0.01 | 0.680 | 0.00 |
| Soil temperature  | < 0.001 | 0.46 | 0.020 | 0.09 |
| Total shoot biomass| 0.206 | -0.03 | < 0.001 | 0.30 |
| \(F_s/R_e\)       |      |       |      |       |
| Soil water content| < 0.001 | -0.26 | 0.030 | -0.10 |
| WTD               | 0.002 | 0.17 | 0.224 | 0.02 |
| Soil temperature  | 0.704 | -0.00 | 0.006 | 0.12 |
| Total shoot biomass| < 0.001 | -0.41 | 0.154 | 0.03 |
| \(F_h/F_s\)       |      |       |      |       |
| Soil water content| < 0.001 | -0.48 | < 0.001 | 0.28 |
| WTD               | < 0.001 | 0.56 | 0.003 | -0.13 |
| Soil temperature  | 0.031 | -0.09 | 0.081 | -0.05 |
| Total shoot biomass| < 0.001 | -0.85 | 0.917 | 0.00 |

WTD – water table depth, \(R_e\) – ecosystem respiration, \(F_s\) – total soil \(CO_2\) flux, \(F_h\) – heterotrophic soil \(CO_2\) flux, \(F_s/R_e\) – contribution of \(F_s\) to \(R_e\), \(F_h/F_s\) – contribution of \(F_h\) to \(F_s\). N = 76 (S1) and 85 (S2).
the site S1, the annual cumulative $R_E$, $F_S$ and $F_H$ fluxes were $683 \pm 109$, $246 \pm 47$ and $114 \pm 25$ C m$^{-2}$ year, respectively, and for the S2 site, these parameters were $947 \pm 85$, $355 \pm 36$ and $172 \pm 15$ C m$^{-2}$ year, respectively.

3.3. Seasonal variation in the contribution of $F_S$ to $R_E$ and $F_H$ to $F_S$

The contribution of $F_S$ to $R_E$ or $F_H$ to $F_S$ did not differ significantly between the study sites ($P > 0.05$), however, the $F_H/R_E$ and $F_H/F_S$ values of the S1 site, in contrast to the S2, showed a significant difference.
A trend that varied between seasons (Figure 5). While the daily $F_s/R_e$ and $F_i/F_s$ values in the S2 were close to the means for the measuring period, they were lower than the mean values during the warm season and higher than ones during the cold season in the S1 (Table 1).

3.4. Environmental factors controlling CO$_2$ fluxes

The variations in CO$_2$ fluxes in the chinampas area were clearly associated with the variations of all measured independent parameters: soil water content and temperature, WTD, and plant biomass (Table 2). However, the degree of influence of environmental variables and biomass on the CO$_2$ fluxes differed depending on flux and vegetation type. The regression analysis of the results of the S1 site indicated that $R_e$ was significantly positively correlated with soil water content and soil temperature, whereas at the S2 site the variation in $R_e$ was explained by the dependence on soil water content alone. A positive correlation of $R_e$ with total shoot biomass was found for both study sites. Whereas soil respiration at the S1 could be explained by the relationships with soil water content and temperature, for the S2 the $F_s$ flux was mostly affected by WTD and plant biomass.
biomass. The $F_n$ variation was explained by soil temperature alone at the S1 and by the combined influence of soil water content, soil temperature and shoot biomass at the S2. Total shoot biomass had the strongest negative effect on $F_n/F_h$ and $F_n/F_r$ at the S1, but not at the S2. Soil water content was negatively related with $F_n/F_h$ at the S1 and positively related with $F_n/F_r$ at the S2. A combined effect of soil water content, WTD and soil temperature on total shoot biomass was found for both study sites.

4. Discussion

This study was carried out to partition the components of ecosystem respiration and their individual responses to environmental factors, such as temperature, soil water content, and vegetation type in the chinampa ecosystem. The mean and annual cumulative CO$_2$ flux observed in this study (Table 1) were lower than respective values shown for a broad range of grassland ecosystems (Wang and Fang 2009; Hu et al. 2016). Low soil CO$_2$ fluxes can be explained by a high salt content in soils in the Valley of Mexico (Dendooven et al. 2010), where the chinampa area is located. The bottom sediments of the former lake Texcoco located in the center of the Valley of Mexico were enriched with pyroclastic deposits. Weathering of the volcanic ash resulted in the release of sodium, and, consequently, in the sodicity of the lake and soils formed later in the exposed lacustrine sediments when the lake Texcoco was drained in the 17th century (Luna-Guido et al. 2000). In the soils of the former lake of Texcoco the pH values can range from 9.8 to 11.7 and electrolytic conductivities in saturation extracts vary from 22 to 150 dS m$^{-2}$ (Beltrán-Hernández et al. 2007). Excessive amounts of salts result in poor soil structure and inhibit biological processes (Dendooven et al. 2010), The production of CO$_2$ decreases with increased electrolytic conductivity (Beltrán-Hernández et al. 2007), which depends on salt concentration and thus high salinity and sodicity of soils reported for the chinampa area (Ramos-Bello et al. 2011) might be one of the reasons for the low soil CO$_2$ fluxes observed in this study. Moreover, high soil water content especially can be at least partly responsible for the depressed CO$_2$ fluxes in the chinampas area due to the limitation of O$_2$ diffusion into the soil and, thus, aerobic decomposition of organic carbon (Almagro et al. 1997). In our study a significant positive soil water content effect was generally observed for all sites (Table 2). The soil water content explained about 40-60% of the variability of $R_n$ and 20-50% of the variability of $F_n$, with the effect especially well marked at the S1 site. It should be noted that WTD had less impact on CO$_2$ fluxes than soil water content, but in general, the CO$_2$ fluxes decreased with increased WTD at the S1 and increased with decreased WTD at the S2.

Temperature is commonly shown to be the major driver of ecosystem or soil CO$_2$ fluxes, as temperature rise can stimulate biological activity resulting in increased gas fluxes (Silvola et al. 1996). In agreement with a number of previous reports (Silvola et al. 1996; Hu et al. 2016) we also found that CO$_2$ fluxes in the chinampa ecosystem show a positive relationship with soil temperature explaining about 50-60% of flux variations at the S1 site, but much less at the S2 (Table 2). For the chinampa ecosystem, the temperature sensitivity of all types of CO$_2$ fluxes, especially for $R_n$, were higher at the S1 site than at the S2 site (Table 3), which can be due to the differences in the seasonal dynamics of plant cover. The vegetation cover of the S2, in contrast to the S1, varies between seasons (Figure 3), changing from ‘wet season type’ to ‘dry season type’ in November. During the dry period, while the green shoot biomass of the S1 is close to zero, bristly oxtongue and greater plantain plants actively grow at the S2 thereby increasing not only $R_n$, but also $F_n$ via root and rhizosphere respiration and $F_h$ via the rhizosphere priming effect (Kuzyakov and Cheng 2001). The dry and cold periods are closely related to each other in the study area, thus the development of new vegetation cover under low temperature could modify temperature sensitivity of CO$_2$ fluxes and cause a decline in annual $Q_{10}$ values at the S2 (Table 3). This is consistent with the statement of Song et al. (2014) that temperature sensitivity of $R_n$ reflects the ecosystem’s structure and related biotic and abiotic factors that can closely interact with each other. Temperature sensitivity of soil CO$_2$ fluxes can be modulated by soil water content (Almagro et al. 2009). In our case,
soil water content influenced the temperature sensitivity of CO$_2$ fluxes via the shift of dominant plants during the year. Thus, seasonal vegetation trend effects on the temperature response of $R_\text{E}$, $F_\text{S}$, and $F_\text{H}$ should not be ignored for a correct prediction of CO$_2$ fluxes under climatic changes.

The mean values of the contributions of $F_\text{S}$ to $R_\text{E}$ for the studied chinampa sites are significantly lower than those reported in the literature (Zobitz et al. 2008). Due to low values of $F_\text{S}$, presumably caused by high salts content in soils and consequent low microbiological activity, $F_\text{S}$ was not the main contributor to $R_\text{E}$ at both sites of chinampa ecosystem. Recent studies demonstrated that the $F_\text{S}$ contribution to $R_\text{E}$ and $F_\text{H}$ contribution to $F_\text{S}$ can vary between seasons with a large proportion of soil microbial respiration during the winter period (Zobitz et al. 2008). The component contribution variability could be due to seasonal variation in microbial community composition and plant physiological and growth processes (Grogan and Jonasson 2005). Moreover, above- and belowground vegetation parts or microbial biomass could differ in their respiration response to changes in environmental factors (Hartley et al. 2006), causing variability in the contribution of components to soil and ecosystem CO$_2$ fluxes. The two studied sites of chinampa ecosystem were different in their seasonal trend of the $F_\text{S}/R_\text{E}$ and $F_\text{H}/F_\text{S}$ ratios (Figure 5). In contrast to the S1 site, at the S2 site, the mean contribution of $F_\text{S}$ to $R_\text{E}$ and $F_\text{H}$ to $F_\text{S}$ did not vary significantly between the winter and summer seasons (Table 1) despite the correlation with the soil water content or temperature (Table 2). We assume that the seasonal shift in the abundance of dominant species and active plant growth during the winter period caused an increase in the contribution of autotrophic respiration to winter CO$_2$ fluxes and a decrease in variability of the $F_\text{S}/R_\text{E}$ and $F_\text{H}/F_\text{S}$ ratios at the S2. At the S1, where plant growth was depressed during the cold season, the contribution of $F_\text{S}$ to $R_\text{E}$ and $F_\text{H}$ to $F_\text{S}$ was higher in winter and lower in summer (Table 1). This confirms the fact that changes in the relative contributions of individual component fluxes to $R_\text{E}$ are regulated by a shift in plant internal allocation of recently fixed plant-associated carbon in an ecosystem (Grogan and Jonasson 2005). The linear regression results showed that plant biomass was the dominant factor controlling the seasonal variation of $F_\text{H}/F_\text{S}$ ratios at the S1 (Table 2), wherein plant biomass dynamics followed the dynamics of soil water content, WTD and soil temperature. During the winter period with low soil temperature and soil water content, the contribution of heterotrophic respiration to soil respiration increased following plant growth depression at the S1. In addition, the winter increase in the $F_\text{H}/F_\text{S}$ ratios at the S1 appeared to be the result of lower temperature sensitivity of heterotrophic compared to autotrophic respiration (Table 3).

Table 3. Q$_{10}$ values of measured CO$_2$ fluxes at the S1 and S2 sites of chinampa ecosystem

| CO$_2$ flux | S1 | S2 |
|-------------|----|----|
| $R_\text{E}$ | 3.0 | 0.9 |
| $F_\text{S}$ | 2.4 | 1.6 |
| $F_\text{H}$ | 1.8 | 1.4 |

$R_\text{E}$ – ecosystem respiration, $F_\text{S}$ – total soil CO$_2$ flux, $F_\text{H}$ – heterotrophic soil CO$_2$ flux. N = 76 (S1) and 85 (S2).
5. Conclusions

The studied chinampa ecosystem sites with different vegetation characteristics demonstrated that $R_E$, $F_S$ and $F_H$ were lower than those reported for most grasslands. This presumably could be caused by the high salinity and sodicity of chinampa soils. Despite their low values, $R_E$, $F_S$ and $F_H$ showed seasonal variations followed by variations in shoot biomass, soil water content and temperature, whereas temperature sensitivity of CO$_2$ fluxes reflected the vegetation-type and plant growth differences among the sites. The seasonal variation of soil contribution to total CO$_2$ fluxes was locally differentiated for the chinampa ecosystem. These differences were related to differences in seasonal dynamics of cover productivity which has been associated with localization of soil water content. The variability of the contributions of $F_S$ to $R_E$ and $F_H$ to $F_S$ was clearly expressed at the site without a seasonal change of plant dominant species, while the component contribution did not vary between the seasons at the site where the plant dominants of ‘dry season type’ and ‘wet season type’ changed. This confirms the fact that soil contribution to CO$_2$ fluxes may depend on the vegetation type and seasonal dynamics of the plant cover. Further studies are needed to improve management of the chinampas area in Mexico in order to reduce their carbon losses. These ecosystems contain huge amounts of organic carbon, which may be released to the atmosphere in the case of their improper use. In this respect, the research should be focused on the balance of carbon in the chinampas under different land uses and management practices, and on the response of these ecosystems to the global climatic change.

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