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CO_2 production in anthropogenic *Chinampas* soils in Mexico City

La producción de CO_2 en suelos antropogénicos de Chinampas en la Ciudad de México
A produção de CO_2 em solos antropogénicos de Chinampas na cidade do México

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ABSTRACT

We studied microbial-associated C_2 production in anthropogenic *chinampas* soils. The soils were constructed by the accumulation of materials such as organic matter and loamy lacustrine sediments in Pre-Hispanic cultures in Mexico. To study the temperature sensitivity of C_2 production related to soil depth, moisture and oxygen availability, soil samples were collected at depths of 0-7, 7-18, 18-30, 30-40 and 40-50 cm. The soil samples were incubated under aerobic and anaerobic conditions at controlled temperatures (-5, 0, 5, 10, 20, 30 °C) and soil moistures of 10, 30, 60 and 90% water-filled pore space. For all the soil depths, incubation temperatures and soil moistures, the mean rate of aerobic CO_2 production was 58.0 mg CO_2 kg^{-1} d^{-1} and that of anaerobic CO_2 production 31.2 mg CO_2 kg^{-1} d^{-1}, with the highest rate found in the soil samples collected at a depth of 0-7 cm. A decrease in soil organic carbon content inhibited CO_2 production more under anaerobic than aerobic conditions. The dependence of aerobic CO_2 production on soil moisture increased at what constituted both unusually high and low temperatures for the study area. Since the response of CO_2 production to temperature was lower under anaerobic than aerobic conditions, the increase in soil moisture content led to a decrease in the temperature sensitivity of CO_2 production. The response of microbial activity to other factors may be modified under what constitutes the limiting conditions for any of the factors considered, as follows: (i) when anaerobiosis increases in the soil, the limiting effect of substrate availability on microbial activity increases; (ii) the CO_2 production rate becomes more dependent on soil moisture under temperature stress; (iii) the sensitivity of CO_2 production to temperature is highest under drought stress.

RESUMEN

En este trabajo estudiamos la producción de CO_2 asociada a la actividad de los microorganismos en suelos antropogénicos de chinampa, construidos por las culturas Pre-Hispánicas en México mediante la acumulación de materia orgánica, sedimentos lacustres limosos o por diferentes materiales utilizados para consolidarlos en islotes separados por un sistema de canales. Se tomaron muestras de suelo a las profundidades de 0-7, 7-18, 18-30, 30-40 y 40-50 cm para evaluar la sensibilidad a la temperatura de la producción de CO_2 y su variación en relación con la profundidad del suelo, la humedad y la disponibilidad de oxígeno. Se incubaron en condiciones aerobias y anaerobias a temperatura controlada (-5, 0, 5, 10, 20 y 30 °C) y a humedad controlada de 10, 30, 60 y 90% de las condiciones de saturación en agua del espacio poroso del suelo. Para todas las profundidades del suelo, tempe-

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raturas de incubación y humedad del suelo, la velocidad promedio de producción de CO_2 fue de 58.0 mg CO_2 kg^{-1} d^{-1} en condiciones aerobias y de 31.2 mg CO_2 kg^{-1} d^{-1} en condiciones anaerobias, obteniéndose la mayor producción de CO_2 en las muestras de suelo de la capa de 0-7 cm de profundidad. La disminución en el contenido de carbono orgánico del suelo inhibió la producción de CO_2 asociada a la actividad de los microorganismos del suelo con mayor intensidad bajo condiciones anaerobias que aerobias. A temperaturas inusualmente bajas o altas para el área de estudio, la dependencia de la producción aerobia de CO_2 con respecto a la humedad del suelo aumentó. Puesto que la respuesta de la producción de CO_2 a la temperatura fue menor bajo condiciones anaerobias que aerobias, el aumento en el contenido de humedad del suelo condujo a la disminución de la sensibilidad a la temperatura de la producción del CO_2. En condiciones limitantes de cualquier factor, la respuesta de la actividad microbiana a otros factores puede modificarse como se muestra a continuación: (i) el aumento de la anaerobiosis en el suelo aumenta el efecto limitante de la disponibilidad de sustrato sobre la actividad microbiana; (ii) bajo estrés de temperatura, la velocidad de producción de CO_2 se hace mas dependiente de la humedad del suelo; (iii) bajo el estrés de sequía, la sensibilidad de la producción de CO_2 a la temperatura es máxima.

RESUMO

Este trabalho estuda a produção de CO_2 associada à actividade de microrganismos em solos de Chinampa antropogénica, construídos por culturas Pre-Hispânicas do México através da acumulação de matéria orgânica, sedimentos lacustres limosos ou diferentes materiais usados para a sua consolidação, em ilhotas separadas por um sistema de canais. Colheram-se amostras de terra às profundidades de 0-7, 7-18, 18-30, 30-40 y 40-50 cm para avaliar a sensibilidade da produção de CO_2 à temperatura e a sua variação em função da profundidade do solo, da humidade e disponibilidade de oxigénio. As amostras de terra foram incubadas em condições aeróbias e anaeróbias a temperatura controlada (- 5, 0, 5, 10, 20 e 30 °C) e humidade controlada a 10, 30, 60 e 90% das condições de saturação de água no solo. Para todas as profundidades do solo, temperaturas de incubação e teores de humidade, a velocidade média da produção de CO_2 foi de 58,0 mg CO_2 kg^{-1} d^{-1} em condições aeróbias e 31,2 mg CO_2 kg^{-1} d^{-1}, em condições anaeróbias, tendo-se obtido a maior produção de CO_2 nas amostras de solo colhidas na camada de 0-7 cm de profundidade. A diminuição do teor de carbono orgânico do solo inibiu a produção de CO_2 associada à actividade dos microrganismos no solo com maior intensidade em condições anaeróbias do que em condições aeróbias. Para a área de estudo, e para valores de temperatura anormalmente altos ou baixos aumentou a dependência da produção aeróbia de CO_2 com a humidade do solo. Uma vez que a resposta da produção de CO_2 à temperatura foi menor em condições anaeróbias do que aeróbias, o aumento do teor de humidade do solo conduziu a uma diminuição da sensibilidade à temperatura da produção de CO_2. Sob condições limite de qualquer um dos factores, a resposta da actividade microbiana aos outros factores pode ser modificada conforme se refere a seguir: (i) o aumento de anaerobiose no solo aumenta o efeito limitante da disponibilidade do substrato sobre a actividade microbiana; (ii) em condições stress de temperatura, a velocidade da produção de CO_2 torna-se mais dependente da humidade do solo; (iii) em condições stress de seca, é máxima a sensibilidade à temperatura da produção de CO_2.

KEY WORDS
Temperature sensitivity, soil moisture, organic carbon content, aerobic-anaerobic conditions

PALABRAS CLAVE
Sensibilidad a la temperatura, humedad del suelo, contenido en carbono orgánico, condiciones aerobias y anaerobias

PALAVRAS-CHAVE
Sensibilidade à temperatura, humidade, carbono orgânico, condições aeróbias e anaeróbias

1. Introduction

There are large spatial and temporal variabilities in the rates of soil CO_2 production, caused by a wide range of environmental biotic and abiotic factors and the great diversity of soil types (Baggs 2006; Lee et al. 2006). The existing data show that CO_2 emissions strongly depend on the taxonomic soil group, with studies covering almost all the groups of mineral and organic soils in the world (Batjes 2006). However, for some endemic soil groups such as anthropogenic agricultural soils the data on CO_2 production are still insufficient. One inadequately studied soil is the anthropogenic *chinampas* soil of Mexico City. Pre-Hispanic cultures in Mexico developed a specific technology for cultivating wetlands around the lakes in the Valley of Mexico. They constructed elevated fields for agricultural production (Ezcurra 1990) called "chinampas" (a word of *Nahuatl* origin: *chinamitl* – "straw bed", and *pan* – "over"). The fields were created by the accumulation of materials such as organic matter and loamy lacustrine sediments which were consolidated into islands separated by a system of channels. (Jiménez-Osornio and Gomes-Pompa 1987; Ramos-Bello et al. 2011).

Since temperature is one of the most important environmental factors affecting respiratory processes on a physiological scale, the dependence of soil respiration (soil CO_2 efflux) on temperature is often used to model future carbon cycle scenarios within the context of global climatic change (Subke and Bahn 2010). One of the most common measures of the temperature sensitivity of CO_2 efflux in soils is the coefficient Q_{10}, which is defined as the increase in the respiration rate per 10 °C increase in temperature. The sensitivity of soil respiration to temperature (Q_{10}) in each ecosystem is an essential factor for the prediction of the interaction between soil carbon and global warming (Hashimoto 2005), but Q_{10} varies between ecosystems (Wang and Fang 2009) and within a temperature range (Vanhala et al. 2008; Chen et al. 2010). The sensitivity of soil respiration to temperature depends on vegetation activity (Wang et al. 2010), soil depth (Karhu et al. 2010), and the quality of soil organic matter (Conant et al. 2008; Vanhala et al. 2008; Briones et al. 2010).

We hypothesized that changes in aerobic conditions, soil water, and organic matter content could also affect the temperature sensitivity of CO_2 production in soils. The aim of this work was to study microbial-associated CO_2 production; the response of this process to temperature; and the variation in temperature sensitivity of the CO_2 efflux (Q_{10}) associated with soil moisture and oxygen availability in anthropogenic *chinampas* soils.

2. Material and Methods

Study sites

Soil samples were collected at the grassland site located in the Xochimilco Ecological Park in Mexico City, 2 200 m above mean sea level. The climate of the study area is temperate subhumid, according to the classification of Köppen, modified by García (1973). The area is characterized by a dry season from November to March and a rainy season from April to October. The mean annual precipitation was 686.1 mm for the 1996-2009 period, according to 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 anthropogenic soil 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 (Ramos-Bello et al. 2011). Since the research was done in the Ecological Park, the soils were not cultivated and did not receive manure or other organic fertilizers. In general terms, the morphology of the *chinampas* soils resembles that of deep organic soils (Histosols), but the organic matter content is lower (García et al. 1994). The *chinampas* soils have a homogeneous dark-coloured profile, with minor variations in organic matter content and texture that are difficult to distinguish in the field. High salinity and sodicity of groundwater and soils have been reported for the area (Ramos-Bello et al. 2011). According to our data, the mean annual soil temperature was 15 °C, ranging from 6 °C to 24 °C at a depth of 5 cm during the year 2009 (unpublished results). The mean soil temperature was 16.0 °C in the warmest season from March to September and that was 14.1 °C in the coldest season from November to February. The mean soil moisture content at a depth of 0-5 cm was 45% of water-filled pore space (WFPS) in 2009, with minimum values of 30% WFPS from November to January, and maximum values of 85% WFPS from June to August. The mean soil moisture content at a depth of 5-15 cm was 60% WFPS, with minimum and maximum values of 35% and 80% WFPS respectively (unpublished results). The vegetation varies with the seasons: in the dry period the dominant species are bristly ox-tongue (*Picris echioides* L.) and greater plantain (*Plantago major* L.), and in the rainy season the vegetation is represented mainly by rushes (*Juncus spp.*), dropseed (*Sporobolus pyramidatus* (Lam) Hitchc.) and common reed (*Phragmites australis* (Cav) Trin. ex. Stend.).

Soil chemical and physical analyses

Soil samples for chemical analysis were collected from soil sub-horizons of a soil profile at depths of 0-7, 7-18, 18-30, 30-40 and 40-50 cm, and analyzed by the routine methods for soil chemical and physical analysis (Van Reeuwijk 2002). In each soil sample pH was determined by a glass-calomel combination electrode pH meter method (H_2O extraction with a soil:solution ratio 1:5) and organic C by wet oxidation with a mixture of potassium dichromate and concentrated sulphuric acid. Moisture content and bulk density of selected samples were determined by the cylinder method: core samples were collected by cylinders of known volume, and then weighed before and after drying at 105 °C for 24 h. The total porosity of soils was calculated using the values obtained for bulk density and true density of the soil samples.

CO_2 production rates measurements

To measure the CO_2 production rates, 500-800 g soil samples were collected every two weeks from February to May 2009 from the same profile and from the same depths as the samples collected for soil chemical and physical analysis. The soil samples were transported to the laboratory in plastic bags, and air-dried indoors for three days at a temperature of about 20 °C to approximately 10% WFPS. Roots and stones were removed manually from the samples. For the study of the effect of soil moisture on gas production, each soil sample was divided into four parts. The soil moisture of the replicate samples was adjusted to either 10, 30, 60 or 90% WFPS with distilled oxygen-free water. Aerobic incubation was conducted by placing portions of 7 g of soil into 125-ml Erlenmeyer flasks, aired for 10 min and then sealed with screw cap and silicon septa (Corning System, USA). Anaerobic conditions were created by placing sub-samples of 2 g into 20 ml vessels and sealing with a septa and metal cap. The vessels were then vacuum-pumped and filled with N_2. The procedure was repeated five times within 10 minutes. The sub-samples were incubated at -5, 5, 10, 20, 30 °C under aerobic conditions and at 0, 10, 20, 30 °C under anaerobic conditions in a growth chamber (Precision GSA 815, PerkinElmer, USA) for 20 h. Each combination of incubation temperature and soil moisture was replicated 6 times. The headspace of each flask and vessel was sampled with a gas-tight 100 μL syringe (Hamilton Company) and analyzed with a gas chromatograph (HP Agilent, 6890 GC System, GMI, USA) with the temperature of the column at 35 °C, the temperature of the detector at 300 °C and N_2 as carrier gas. Soil moisture content of each soil sub-sample was measured by drying at 105 °C for 24 h. Soil CO_2 production was calculated on a dry weight basis according to Sey et al. (2008).

The sensitivity of CO_2 production to temperature was evaluated by using the coefficient Q_{10}, the factor representing the production rate change over a temperature shift by 10 °C. Q_{10} can be expressed as:

$$Q_{10} = (A\, e^{k(T+10)}) / A\, e^{kT} = e^{10k}$$

where *A* and *k* are constants, and *T* is the soil temperature (˚C) (Hashimoto 2005).

Statistical analyses

Statistical analyses were conducted using the standard statistical software package SAS (SAS Institute, Cary, NC, USA) and differences were considered significant at $P < 0.05$. Data were expressed as means with standard deviations. The significant differences in the CO_2 production rate and Q_{10} among five soil depths and among four soil water contents for both aerobic and anaerobic conditions were assessed by conducting ANOVA and T-tests. Regression slope significances were used to assess the response of the CO_2 production rates to the incubation temperature and soil organic carbon content within both aerobic and anaerobic incubations.

3. Results

Soil characteristics

The morphology of the profile was relatively uniform. Minor differences in colour, root density, texture and compaction allowed for division of the 50 cm topsoil into four layers. We designated these layers as A1, A2, A3 and A4, with A denoting superficial humus-enriched horizon and the numbers indicating sub-horizons which were distinguished by the layered morphology of the horizon. This layered morphology is typical for *chinampas* soils and it is believed to be the result of anthropogenic accumulation of excavated lacustrine sediments on the surface rather than of pedogenetic processes. The colour of the whole profile was black when moist (10YR 2/1), and varied from grey (10YR 5/1) in the A3 sub-horizon to dark grey (10YR 4/1) in A1, A2 and A4 sub-horizons when dry. The texture varied from silty loam to clay. All the layers were soft and friable. The structure was weak subangular blocky. The highest root density was found in the A1 sub-horizon and decreased sharply with depth. The organic matter content was high throughout the topsoil (**Table 1**). The vertical distribution of organic carbon was irregular. The bulk density was low in all soil layers, the lowest value being detected in the superficial layer. The true density was relatively uniform in all soil horizons, and the bulk density varied due to differences in the porosity. The soil reaction was alkaline, indicating strong influence of sodium carbonate and exchangeable sodium (Ramos-Bello et al. 2001).

Table 1. Selected soil physical and chemical properties of the topsoil sub-horizons of the chinampas soil from the Xochimilco area

Topsoil sub-horizon	Depth (cm)	C (g kg^{-1})	Bulk density (g cm^{-3})	Porosity (%)	pH_{H2O} 1:5
A1	0-7	148.2	0.29	86.7	8.4
A2	7-18	66.3	0.63	71.5	8.3
A3	18-30	27.3	0.78	63.1	8.6
A4	30-50	68.3	0.72	64.3	8.2

CO_2 production

For all the soil depths, incubation temperatures and soil moistures the mean rates of CO_2 production were 58.0 and 31.2 mg CO_2 kg^{-1} d^{-1} in aerobic and anaerobic conditions respectively, with the highest CO_2 production found in the 0-7 cm layer (**Figure 1**). On average, CO_2 production in anaerobic conditions was 36% of that under aerobic conditions. In the samples from the upper soil layer, the proportion of anaerobic to aerobic gas production was about 50%, which is known to be typical for organic soils (Moore and Dalva 1997). In the soil samples taken at the depth of 18-30 cm the proportion of anaerobic to aerobic production was less than 12%, and in the deeper soil samples it was 36% on average.

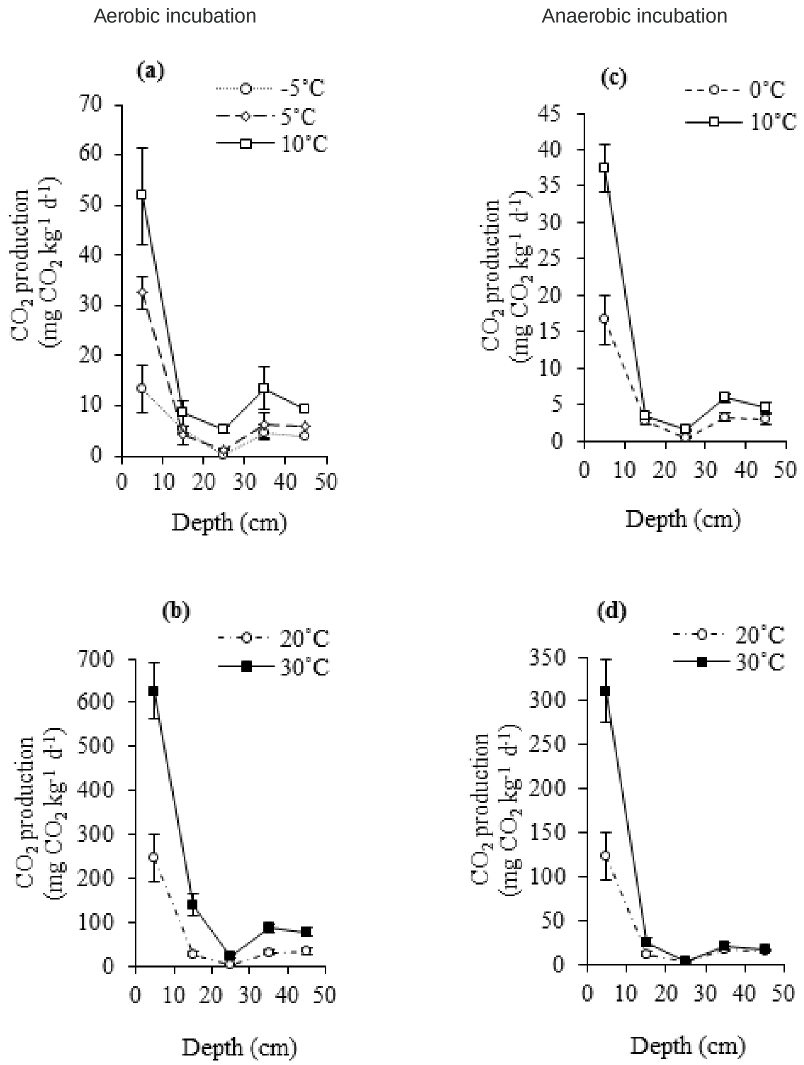

Figure 1. The CO_2 production rate connected with soil depth under aerobic (a, b) and anaerobic (c, d) conditions at different incubation temperatures. Every value of CO_2 production is the average at the soil moisture range of 10-90% of water-filled pore space (WFPS). Error bars indicate the standard deviation (n = 24).

For all the temperatures there was no significant difference (P > 0.05) between the CO_2 production rate in the samples being collected at the depths of 30-40 and 40-50 cm, because these layers were located within the same soil sub-horizon A4 (30-50 cm, **Table 1**). Therefore, to examine the response of CO_2 production to temperature in the soil from the sub-horizon A4 we combined all data related to the soil depths of 30-40 cm and 40-50 cm. At 20 °C both aerobic and anaerobic CO_2 production increased with the increase in organic carbon in the soil (**Figure 2**). The same relationship was found for all incubation temperatures (data not shown). Due to the small variability of soil pH within the soil profile we could not find any dependence of CO_2 production on soil alkalinity.

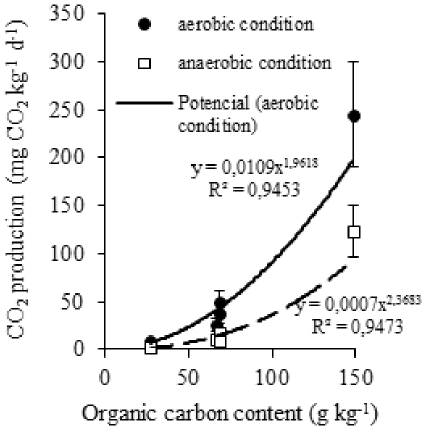

Figure 2. Relationship between CO_2 production and soil organic carbon content under aerobic and anaerobic conditions at 20 °C of temperature. Every value of CO_2 production is the average at the soil moisture range of 10-90% WFPS. Error bars indicate the standard deviation (n = 24).

The soil moisture clearly affected the CO_2 production rate in the soil samples incubated under both aerobic and anaerobic conditions, as can be shown for the samples being collected at the depth of 0-7 cm (**Figure 3**). The minimum CO_2 production rate was found under soil moisture values of 10% WFPS for both aerobic and anaerobic conditions. The difference between the aerobic CO_2 production rate in the soil incubated at 30 and 60% WFPS was not statistically significant (P > 0.05) at temperatures of 10 and 20 °C (**Figure 3a, b**). At temperatures of -5, 5 and 30 °C, the aerobic CO_2 production rate was significantly higher (P < 0.05) in the soil incubated at 60% WFPS than at 30% WFPS. This tendency was found for the soil samples collected at all depths (data not shown). We found no significant difference (P > 0.05) between aerobic and anaerobic CO_2 production in the soil samples incubated at 90% WFPS.

In all the soil samples, CO_2 production exponentially increased with an increase in temperature under both aerobic and anaerobic conditions (**Figure 4**). The mean Q_{10} values of aerobic and anaerobic CO_2 production are shown in **Table 2**. The Q_{10} values of CO_2 production decreased with the increase of the soil moisture content for the soil samples from all the depths incubated under aerobic conditions (**Figure 5**), but not for those incubated under anaerobic ones (data not shown).

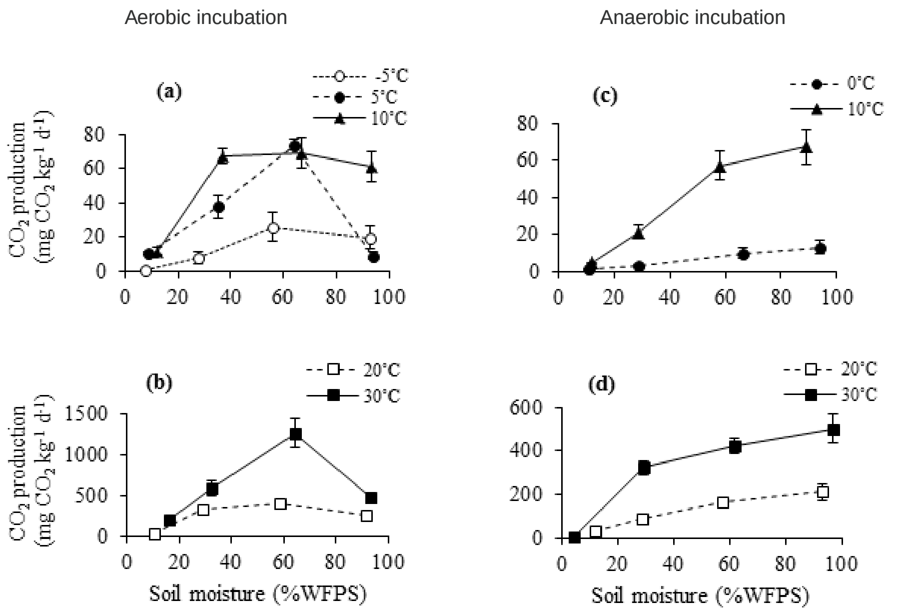

Figura 3. Relationship between CO_2 production and soil water content (water-filled pore space, WFPS) for the soil samples collected at a depth of 0-7 cm and incubated at different temperatures under aerobic (a, b) and anaerobic (c, d) conditions. Error bars indicate the standard deviation (n = 6).

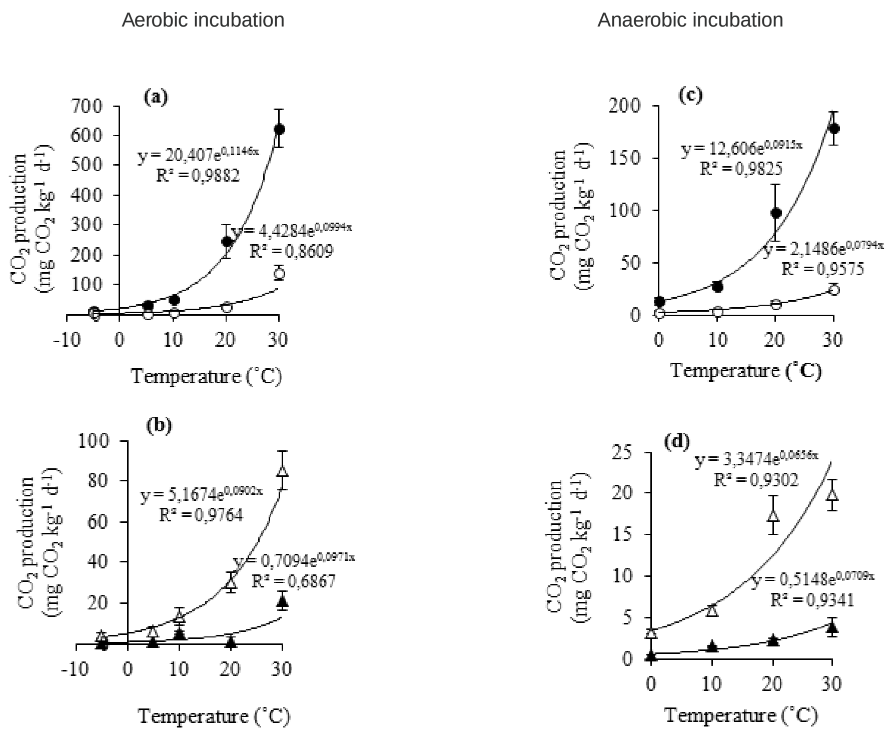

Figura 4. Relationship between CO_2 production and soil temperature. Plots show CO_2 production in the soil samples being collected at depths of 0-7 cm (filled circles), 7-18 cm (open circles), 18-30 cm (filled triangles) and 30-50 cm (open triangles), incubated under aerobic (a, b) and anaerobic (c, d) conditions. Every value of CO_2 production is the average at the soil moisture range of 10-90% WFPS. Error bars indicate the standard deviation (n = 24).

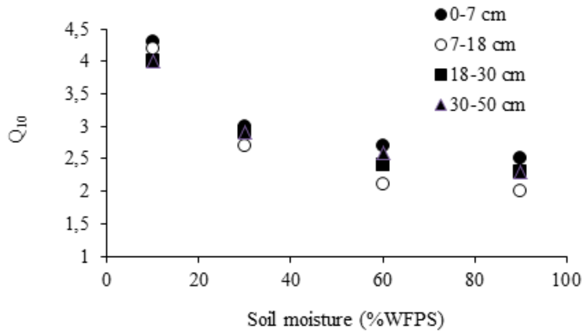

Figura 5. The temperature sensitivity (Q_{10}) of aerobic CO_2 production connected with soil moisture in soil samples collected at depths of 0-7, 7-18, 18-30 and 30-50 cm.

Table 2. The mean Q_{10} values of aerobic and anaerobic CO_2 production in the chinampas soil from the Xochimilco area

Depth (cm)	Aerobic condition	Anaerobic condition
0-7	3.1	2.5
7-18	2.7	2.2
18-30	2.9	2.0
30-50	2.5	1.9

4. Discussion

The *chinampas* Terric Anthrosols under study are wetland soils rich in organic matter, with properties and behavior between the mineral upland soils and the organic Histosols. The CO_2 production rate in the studied soil corresponds to the values obtained for excessively humid mineral soils (Leifeld and Fuhrer 2005; Sey et al. 2008) and for organic soils from drained swamps (Moore and Dalva 1997). The values obtained in our study were less than those recorded for peat soils from bogs and swamps (Moore and Dalva 1997; Briones et al. 2010), and greater than those values reported for most mineral soils (Fließbach et al. 1994; Fang and Moncrieff 2005; Silva et al. 2008; Wichern and Joergensen 2009).

The results of this study are in agreement with the conclusions of other authors (Moore and Dalva 1997; Fang and Moncrieff 2005; Hachimoto and Komatsu 2006) in the sense that most microbial respiration occurs in the surficial soil layer and decreases rapidly with depth. A positive correlation between soil organic matter content and microbial activity (Rila et al. 2003; Dhull et al. 2004) together with a general tendency for a decrease in organic matter concentration with depth (Jobbágy and Jackson 2000) cause the largest amount of CO_2 to be produced in the surface layer and a decrease in gas production with depth (Fang and Moncrieff 2005). In the soils under study, the variation in CO_2 production with depth matches the vertical distribution of the organic matter in the soil horizon. However, the relationship between CO_2 production and the organic matter at different depths may not necessarily be directly related to the total content but rather to the organic matter fractions present.

Previous studies showed that the CO_2 emission rate was higher for soil organic matter rich in labile components received from fresh plant residues (e.g Leifeld and Fuhrer 2005). Our data seem to be in agreement with these studies, because the upper sub-horizon in our profile had the highest income of fresh plant debris.

The results of this study indicated that the microbial-associated CO_2 production decreased under oxygen deficient soil conditions, and that this decrease was more pronounced when the soil organic matter content was low. Due to anaerobiosis, CO_2 production decreased twice in the upper soil sub-horizon with high organic matter concentration and more than eight times in the layers poor in organic carbon. Decreased organic matter, therefore, inhibited microbial activity and associated CO_2 production in the soil, an effect more noticeable under anaerobic than aerobic conditions. An explanation for this may be that when the oxygen content in the soil limits microbial activity, a microbial community becomes more dependent on the soil organic matter content.

The results (**Figure 3**) showed that for temperatures from 10 to 20 ^{o}C, aerobic CO_2 production did not depend on soil moisture in the 30 to 60% WFPS range. At temperatures below 10 ^{o}C and above 20 ^{o}C the change in soil moisture from 30 to 60% WFPS gradually increased the CO_2 production rate; the maximum production corresponded to 60% WFPS, which is in agreement with previously reported data (Aon et al. 2001). Under the natural conditions of chinampas soils the temperature mainly varied in the range of 10-20 ^{o}C (unpublished results). Our results showed that in this temperature range the microbial community can maintain a stable high activity level within the 30-60% WFPS soil moisture content range. This may be because microorganisms are adapted to the range of natural temperatures, and cannot easily adjust their metabolism to the alternating water content at unusually high and low soil temperatures for the study area. At unusually high and low temperatures, therefore, microbial activity and corresponding microbial-associated aerobic CO_2 production increase gradually with increasing soil moisture content up to 60% WFPS. It is likely that the microbial community becomes more dependent on soil water content under inclement temperature conditions.

In this study the Q_{10} values varied in the range of 1.8-4.3 depending on soil horizon, soil moisture and redox potential. Lenton and Huntingford (2003) reported a mean Q_{10} of CO2 production of 2.5 with a variation range of 0.8-12.9. In our study, the mean Q_{10} values for the whole range of soil depths, soil moistures and temperatures was 2.8 for the experiments under aerobic conditions and 2.1 under anaerobic conditions. In contrast to one earlier study (Leifeld and Fuhrer 2005) we found the highest Q_{10} value in the superficial sub-horizon, which showed also the highest CO_2 production rate. The authors above stated that the highest Q_{10} values were related to the oldest recalcitrant fraction of the soil organic matter usually found in deeper soil horizons. Previous studies on organic matter composition in *chinampas* soils (García et al. 1994; Reyes-Ortigoza and García-Calderón 2004) showed that unlike natural soils, the upper soil layer of *chinampas* soils had an exceptionally high proportion of recalcitrant humus, similar to that of deep (more than 1 m) soil horizons. Since the upper layer of *chinampas* soils was formed from excavated organic-rich lacustrine sediments, it has two different substrate pools: one consists of old recalcitrant organic matter of sedimentary origin and the other of recently decomposed and incorporated plant debris. Consequently, the upper layer of the studied soil exhibits properties typical both for surface horizons with the highest amount of fresh labile organic matter, and for deep horizons with the highest content of recalcitrant humus fractions.

In contrast to a recent finding (Craine and Gelderman 2011), in our study the Q_{10} values decreased with increasing soil moisture. When the soil water content increases, the soil pores fill with water causing anaerobic microbial metabolism. The results of our study showed that the Q_{10} of anaerobic CO_2 production was lower than that of aerobic production. Thus, the increase in soil moisture and the corresponding decrease in oxygen availability caused the lowering of the sensitivity of soil microbial respiration to temperature. The fact that this sensitivity decreased while the CO_2 production rate tended to increase with the increase in soil moisture is in agreement with the finding of Leifeld and Fuhrer (2005) showing that Q_{10} values were negatively related to CO_2 production.

5. Conclusions

Our study analyzed the influence of multiple factors (soil temperature and moisture, oxygen availability and organic carbon content) on the CO_2 production rate and its response to temperature. The results showed that under the limiting condition of any factor the response of the microbial activity to other factors is modified: 1) when anaerobiosis increases in the soil the limiting effect of the substrate availability on microbial activity increases, 2) CO_2 production becomes increasingly dependent on soil moisture under temperature stress (unusually low and high soil temperature), 3) temperature sensitivity of CO_2 production is the highest under drought stress (about 10% WFPS).

Taken the results together, it is likely that, if some factor limits microbial activity and microbial-associated CO_2 production in the soil, the impact of other affecting factors, especially that of temperature, may be increased.

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