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GREENHOUSE GAS EMISSIONS FROM A CHINAMPA SOIL OR FLOATING GARDENS IN MEXICO

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ABSTRACT

Agriculture in chinampas or 'floating gardens', is still found on the south of Mexico City, it is a high yield pre-Columbian cultivation system, which has soils enriched with organic matter. The objective of this research was to determine the greenhouse gas (GHG) emissions from a chinampa soil cultivated with amaranth (*Amaranthus hypochondriacus* L.), maize (*Zea mays* L.) or uncultivated. The soil was characterized and fluxes of GHG (CO_2, N_2O and CH_4) were monitored for one year. The chinampa soil was alkaline saline with an organic C content that ranged from 21.7 t/ha in the 0-20 cm layer of the soil cultivated with amaranth to 28.4 t/ha in the 20-40 cm layer of the uncultivated soil. The cumulative GHG emissions (kg CO_2-equivalents/ha/y) were 395, 376 and 258 for N_2O, and 44, 30 and 26 for CH_4 in the uncultivated, amaranth cultivated and maize cultivated soil, respectively. No significant effect of cultivated crop or soil characteristics on GHG emissions over one year was found. In general, N_2O contributed 91 % and CH_4 9 % to the global warming potential of the GHG. The organic C was high and distributed equally over the soil profile, because it is an anthropic soil.

Palabras clave: GEI, flujos de dióxido de carbono, metano y óxido nitroso, potencial de calentamiento global, secuestro de carbono

RESUMEN

La agricultura en chinampas o "jardines flotantes", todavía la podemos encontrar al sur de la Ciudad de México, este es un sistema de cultivo de alto rendimiento pre-colombino con suelos ricos en materia orgánica. El objetivo de esta investigación fue determinar la emisión de gases de efecto invernadero (GEI) del suelo de chinampas cultivadas con amaranto (*Amaranthus hypochondriacus* L.), maíz (*Zea mays* L.) y sin cultivo. Se caracterizó el suelo y se monitorearon los flujos de gases de efecto invernadero (CO_2, N_2O y CH_4) durante un año. El suelo de la chinampa fue salino alcalino con un contenido de

C orgánico que varió de 21.7 t/ha en la capa de 0-20 cm del suelo cultivado con amaranto a 28.4 t/ha en la capa de 20-40 cm del suelo sin cultivar. Las emisiones de gases de efecto invernadero acumuladas (kg de CO_2 equivalente/ha/año) fueron 395, 376 y 258 para el N_2O y 44, 30 y 26 para el CH_4, en el suelo sin cultivo, en el cultivado con amaranto y en el cultivado con maíz, respectivamente. No se encontró un efecto significativo del cultivo o de las características del suelo sobre las emisiones de gases de efecto invernadero durante un año. En general, el N_2O aportó el 91 % y el CH_4 aportó el 9 % del potencial de calentamiento global de los GEI. El C orgánico fue elevado y se distribuye por igual en el perfil del suelo, debido a que es un suelo antrópico.

INTRODUCTION

In Mexico, Xochimilco´s chinampas are also known as floating gardens, they are high yield agricultural systems since pre-Columbian times. They are a system of small plots (500-1000 m^2) surrounded by channels (Morehart and Frederick 2014). Swamps were reclaimed by digging channels by hand, creating small plots, chinampas are typically narrow, around 4 m wide, but may extend in length up to 400-900 m (Arco and Abrams 2006). Lake sediment was added constantly to the gardens and trees were planted at the borders to strengthen them and to protect the banks from erosion (Leszczynska-Borys and Borys 2010, Morehart 2012). An intensive agricultural system that provided food to Tenochtitlan the whole year was created. Currently, flowers, maize (*Zea mays* L.), vegetables and amaranth (*Amaranthus hypochondriacus* L.) are still cultivated there in a more or less traditional way, although more and more modern techniques with extensive use of inorganic fertilizers, pesticides and herbicides prevail (Clauzel 2009).

The main contribution to anthropic GHG emissions after the burning of fossil fuels is from agricultural soils. Agriculture contributes up to 30 % of the anthropic GHG emissions that drive climate change (Smith and Gregory 2013). Agricultural activities are responsible for approximately 50 % of the global atmospheric CH_4 emissions and agricultural soils for 75 % of the global N_2O (Wang *et al.* 2012). Management practices, such as irrigation, tillage, cropping system, and N fertilization, can alter soil GHG emissions substantially. The GHG are produced as a result of some microbial processes in the soil, but the flux between soil and the atmosphere depends largely on physical factors and soil conditions (Sanford *et al.* 2012).

If the GHG emission occurs in conventional agricultural soils, then it would be expected higher emission from a chinampa soil due to the content of organic matter and humidity that could affect the GHG emission. However, no information exists about how chinampas contribute to global GHG emissions, so the objectives of this research were to characterize a chinampas soil, to monitor the GHG fluxes (CO_2, CH_4 and N_2O) for one year from an uncultivated soil and two cultivated soils with maize and amaranth (these two plants were used due to their food and farm importance in the chinampas zone), and also to calculate the global warming potential (GWP) emitted from these systems.

MATERIAL AND METHODS

Experimental site

The experimental site is located to the south of Mexico City in Xochimilco (19º 16’ 27.05’’ N, 99º 05’ 33’’ W) at an altitude of 2240 masl. The climate is temperate with precipitation 600-1000 mm/year mostly from June to October. Mean annual temperature is 16 ºC. The soils of the chinampas are of anthropic origin.

Recently, the remaining chinampas are fertilized with low-grade sewage and many of the channels have become stagnant and contaminated with garbage and domestic waste runoff. Increasingly, insecticides and chemical fertilizers are being used to cultivate new and “improved” plant varieties (Chapin 1988).

Experimental design

Three plots (6.5 × 28 m) covered mostly with grasses were cultivated with maize, amaranth or left fallow to monitor GHG. A systematic sampling was performed similarly in each plot. Maize and amaranth were planted on beds 40 cm wide with a 60 cm spacing between the rows on July 8th 2012 and then harvested in January 2013. The crops were unfertilized and no herbicides or pesticides were applied. Weeds were removed when required and during the dry season, from September 2012 to January 2013 (harvest), once a week, 1.2 L of water from the channel was used to irrigate each plant. The plots with grass were left undisturbed and served as control.

Greenhouse gas emissions

CO_2, CH_4 and N_2O fluxes were monitored simultaneously from February 1st 2012 to January 28th 2013. Three chambers (25 cm length × 20 cm, internal diameter) were placed in the three plots of each treatment. They were designed as reported by Parkin *et al.* (2003) with a coated top and a sampling port fitted with a butyl rubber stopper. The chambers were inserted 5 cm into the soil. Gas sampling was done between 10:00 and 12:00 h. The covers were placed on the chambers and sealed airtight with Teflon tape. A 15 cm^3 air sample was collected from the PVC chamber at 0, 20, 40 and 60 min after it was closed. The gas in the headspace was mixed by flushing 5 times with the air inside the chamber followed by gas collection for analysis. The 15 cm^3 air sample was injected into 15 cm^3 evacuated vials closed with a butyl rubber stopper and sealed with an aluminium cap pending analysis.

The headspace of the vials was analyzed for CO_2, CH_4 and N_2O on two Agilent Technologies 4890D gas chromatographs (GC) according to Serrano-Silva *et al.* (2011).

Soil characterization

Each plot used to measure GHG fluxes was sampled by drilling 20 times the 0-20 cm layer. The soil samples from each plot were pooled (n = 9), sieved separately and characterized. The features measured to the soils were: pH, electrolytic conductivity (EC), water holding capacity (WHC), total N, organic C and soil texture, as described by Serrano-Silva *et al.* (2011).

Additionally, at the onset (February 2012) and end (January 2013) of the GHG monitoring, soil samples were taken from the 0-20, 20-40 and 40-60 cm layers in each plot to determine the total carbon (C_{tot}) and bulk density. Calculation of the net GWP was based on Robertson *et al.* (2000) and Thelen *et al.* (2010), taking into account soil C sequestration (Δ soil C GWP), emissions of GHG from the soil (soil N_2O flux + soil CH_4 flux), emissions of GHG from the fuel used for farming operations (which in this case were not used) (operation GHG flux) and the production of fertilizer and seeds (input GHG flux, were not used). The net GWP was calculated as:

Net GWP = Δ soil C GWP + soil N_2O flux + soil CH_4 flux + operation GHG flux + input GHG flux.

The overall GWP of the gasses emitted was calculated considering the GWP of 298 and 25 CO_2-equivalents for N_2O and CH_4, respectively (IPCC 2007).

Statistical analysis

Emissions of CO_2, CH_4 and N_2O were regressed on elapsed time, i.e. 0, 20, 40 and 60 min, using a linear model forced to pass through the origin, but allowing different slopes (production rates). The sample at time 0 accounted for the atmospheric CO_2, CH_4 and N_2O, and was subtracted from the measured values.

The C content in the 0-20, 20-40, 40-60 and 0-60 cm layers were subjected to a two-way analysis of variance using Proc GLM (SAS 1989) to test for a significant effect from layer, treatment and their interaction. Significant differences between treatments for CO_2, CH_4 and N_2O emission rates were determined using Proc Mixed considering repeated measurements (SAS 1989).

The total CO_2, N_2O and CH_4 emissions over the one-year period were calculated by linear interpolation of data points between each successive sampling event (Ussiri *et al.* 2009) and numerical integration of underlying area using the trapezoid rule (Whittaker and Robinson 1967).

RESULTS

Soil characteristics

The pH of the sandy clay loam soil was alkaline and EC ranged from 2.79 to 6.64 dS/m (**Table I**). The WHC of the soil ranged from 1888 to 2190 g/kg and total N from 5.92 to 6.17 g/kg, while the C_{tot} was considered high and ranged from 45.8 to 48.6 g/kg soil. None of the soil characteristics was significantly different between treatments.

Greenhouse gas emissions

The CO_2 emission did not show a clear pattern, but was higher by the end of 2012, and in the beginning of 2013 it ranged from 0.0012 to 6.0306 kg/ha/d (**Fig. 1a**). The emission of N_2O was considered low and ranged from -0.0065 to 0.0118 kg/ha/d (**Fig. 1b**). Sometimes negative values were obtained, i.e. reduction of N_2O was larger than its production. The emission of N_2O did not show large changes over time. The emission of CH_4 was low without a clear pattern (**Fig. 1c**). The flux of CH_4 ranged from –0.0249 to 0.0259 kg/ha/d and was mostly positive, so production prevailed over oxidation. The CO_2, N_2O and CH_4 emission rate was not affected significantly by treatment (**Table II**).

TABLE I. SOME PHYSICAL AND CHEMICAL CHARACTERISTICS OF CHINAMPA SOIL

Treatment	pH	EC[(1)]	WHC[(2)]	Total N	Organic C	Clay	Silt	Sand	USDA soil texture
		dS/m	g/kg						
Uncultivated	8.66 a	5.41 a	1888 a	5.95 a	45.8 a	316 a	185 a	499 a	Sandy clay loam
Amaranth	8.59 a	6.64 a	2126 a	5.92 a	48.0 a	316 a	199 a	485 a	Sandy clay loam
Maize	8.42 a	2.79 a	2190 a	6.17 a	48.6 a	299 a	216 a	485 a	Sandy clay loam
MSD[(3)]	0.56	4.27	362	0.28	6.6	51	28	61	
F value	0.61	2.88	2.61	0.03	0.70	0.51	1.02	0.89	
p value	0.558	0.088	0.106	0.969	0.514	0.608	0.433	0.383	

[(1)] EC: electrolytic conductivity; [(2)] WHC: water holding capacity; [(3)] MSD: Minimum significant difference ($p < 0.05$). Mean of three soil samples ($n = 3$). Values with the same letter are not significantly different between treatments (within the column) ($p < 0.05$). USDA: United States Department of Agriculture.

Global warming potential of the greenhouse gasses

The GWP of N_2O and that of CH_4 were similar in the different treatments and varied between 258 and 395, and between 26 and 44 kg CO_2-equivalents/ha/y, respectively (**Table III**). Consequently the GWP of the GHG was similar in the different treatments.

C content in the soil profile

The organic C content of the soils ranged from 21.7 t/ha in the 0-20 cm layer of soil cultivated with amaranth to 28.4 t/ha in the 20-40 cm layer of uncultivated soil (**Table IV**). Soil layer, treatment and their interaction had no significant effect on the soil C content.

DISCUSSION

Soil characteristics

Adverse effects of salinity and alkalinity on plants have been reported (Carrión *et al.* 2012). The high EC and pH found in the chinampas soil might inhibit growth of certain crops. The chinampas soil has a high organic matter content compared to arable soils of the regions, e.g. 7.2 g C/kg found in soil of Otumba (State of Mexico). Soils with high organic matter content do generally have a good fertility, and crop yields are high (Ball *et al.* 2007).

The constant application of sediment buries the organic material in the deeper soil layers. Consequently, the soil profile was organic rich, but with no clear gradient as normally found in arable soils (**Table IV**). The values found for C_{tot} in the 0-60 cm layer ranged from 73.9 in the maize cultivated soil to 81.7 t C/ha in the uncultivated soil, similar values have been reported in agricultural soils in the region. In the 0-60 cm layer of a conventional tilled soil with wheat and maize crop rotation and removal of residue in the valley of Mexico, the carbon content was 69.7 t C/ha (Dendooven *et al.* 2012).

Greenhouse gas emissions

Emissions of CO_2 were generally low in the first half of the year, but tended to increase towards the end of the year (**Fig. 1a**). During the dry season, i.e. mostly from November to May, channel water is used to irrigate the crops. The channel water is organic rich (Chavarría *et al.* 2010) and the mineralization of the applied organic material will increase CO_2 emissions.

Mineralization of the organic matter will provide nutrients for the crops, but this will also favour N_2O emissions, especially when an excess of mineralized N is present (Towprayoon *et al.* 2005). Additionally, frequent application of channel water will increase emissions of N_2O as the moisture content increases and denitrification is stimulated (Stewart *et al.* 2012). Cultivation of crops is also known to increase the emission of N_2O, as root exudates mineralization might stimulate denitrification (Kettunen *et al.* 2007).

In this study, N_2O emissions were generally low and occasionally even negative (**Fig. 1b**). Stewart *et al.* (2012) suggested that N_2O uptake can occur at relatively low soil moisture and temperature, and limited soil N. These conditions might be present in the chinampa soil, especially during dry spells in the rainy season.

In the chinampa soil, the CH_4 flux was mostly positive so the production of CH_4 was often larger than its oxidation. The high organic matter content (which stimulates microbial activity and oxygen consumption) and the regular irrigation with channel water, facilitate the creation of anaerobic microsites, and in consequence, methanogenesis.

CO_2, N_2O and CH_4 fluxes were not affected by crop. Management practices, such as irrigation, tillage

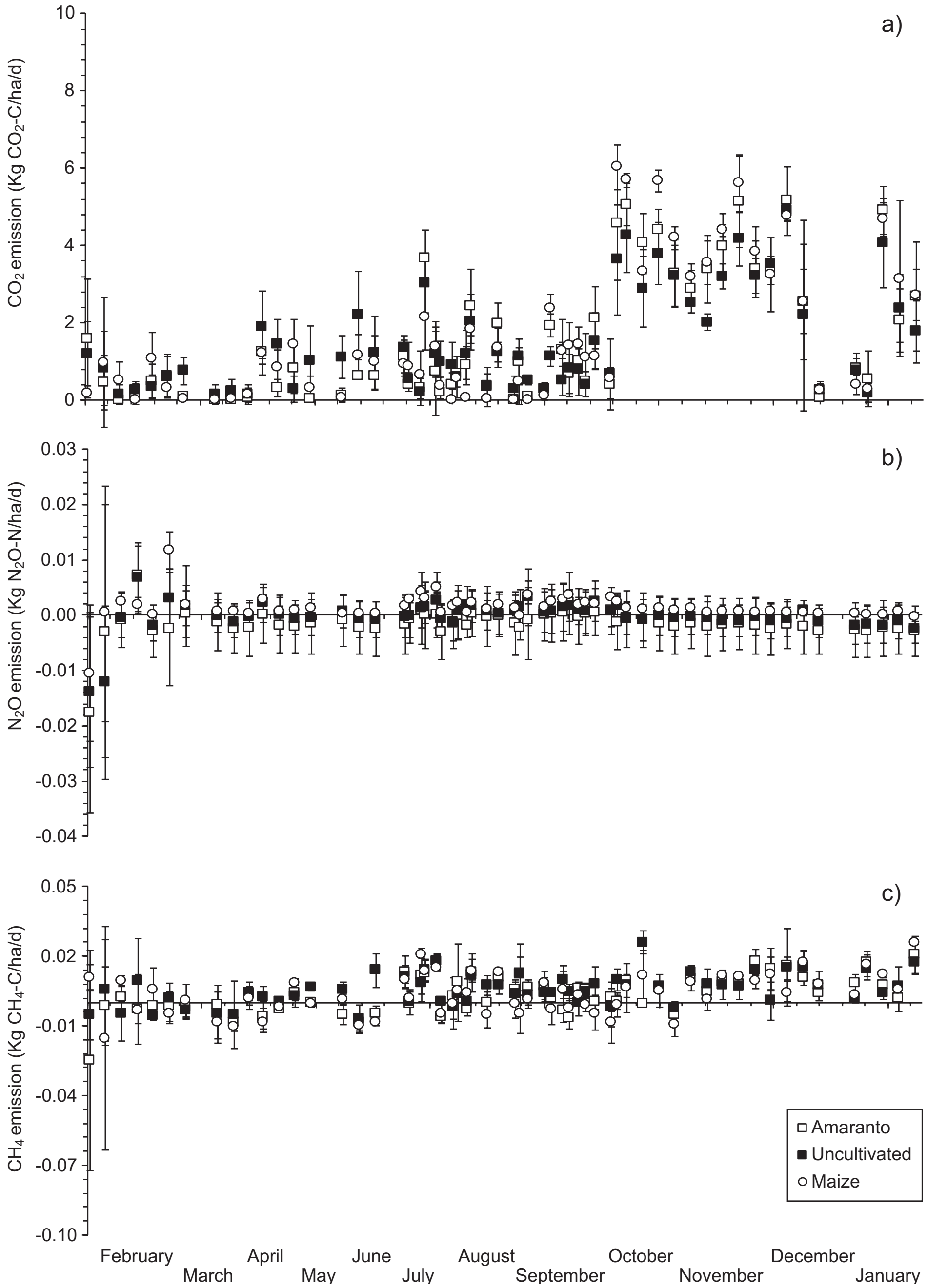

Fig. 1. Fluxes of a) CO_2 (kg CO_2-C/ha/d), b) N_2O (kg N_2O-N/ha/d), c) CH_4 (kg CH_4-C/ha/d) from chinampa soil cultivated with maize (○), amaranth (□) or uncultivated (■) monitored from February 1st 2012 to January 28th 2013.

and cropping system, as well as characteristics of the soils were similar in the study, so their effect on GHG emissions would be the same in the three treatments. The only different factor between treatments was the cultivated crop. It has to be considered, however, that crops-vegetables-flowers are regularly rotated in chinampa so it is very unlikely that crop will have an effect on GHG emissions.

Global warming potential of the greenhouse gases

N_2O contributed 91 % to the GWP of the GHG and CH_4 9 %. N_2O is often the most important GHG from agricultural systems (Wan *et al*. 2012). It is only in rice-cultivation that CH_4 emissions are often more important than N_2O emissions (Horwath 2011). Cultivation of maize or amaranth had no significant effect on the GWP of the GHG. From this study, it

TABLE II. MEAN CARBON DIOXIDE (CO_2), NITROUS OXIDE (N_2O) AND METHANE (CH_4) EMISSION RATES FROM CHINAMPA SOIL CULTIVATED WITH MAIZE (*Zea mays* L.), AMARANTH (*Amaranthus hypochondriacus* L.) OR UNCULTIVATED. MEASUREMENTS WERE REGISTERED BETWEEN FEBRUARY 1ST 2012 AND JANUARY 28TH 2013

Treatment	Emission		
	CO_2-C	N_2O-N	CH_4-C
	kg/ha/d		
Uncultivated	1.50 a	0.00175 A	0.00533 A
Amaranth	1.56 a	0.00202 A	0.00366 A
Maize	1.65 a	0.00169 A	0.00344 A
SEE(1)	0.08	0.00035	0.00166
F value	1.67	0.52	1.96
p value	0.2977	0.6565	0.2554

(1) SEE: Standard error of the estimate ($p < 0.05$). Values with the same capital letter are not significantly different between the treatments, i.e. the columns ($p < 0.05$)

TABLE III. CUMULATIVE EMISSIONS OF NITROUS OXIDE (N_2O) AND METHANE (CH_4) FROM CHINAMPA SOIL CULTIVATED WITH MAIZE (*Zea mays* L.), AMARANTH (*Amaranthus hypochondriacus* L.) OR UNCULTIVATED. MEASUREMENTS WERE DONE BETWEEN FEBRUARY 1ST 2012 AND JANUARY 28TH 2013

Global warming potential (GWP) of the greenhouse gases (GHG) emitted			
Treatment	N_2O(1)	CH_4(1)	GHG(2)
	kg CO_2 eq/ha/y		
Uncultivated	395 A	44 A	439 A
Amaranth	376 A	30 A	406 A
Maize	258 A	26 A	284 A
MSD(3)	336	19	328
F value	0.98	2.97	1.25
p value	0.1271	0.1271	0.4024

(1) The GWP of the gases emitted was calculated considering the CO_2-equivalent emission of 298 for N_2O and 25 for CH_4 (IPCC 2007), (2) the GWP of the GHG emitted; (3) MSD: Minimum significant difference ($p < 0.05$). Values with the same capital letter are not significantly different between the treatments, i.e. the columns ($p < 0.05$)

TABLE IV. TOTAL C CONTENT OF THE 0-20, 20-40, 40-60 AND 0-60 CM LAYER OF UNCULTIVATED CHINAMPA SOIL, OR SOIL CULTIVATED WITH MAIZE (*Zea mays* L.) OR AMARANTH (*Amaranthus hypochondriacus* L.)

Layer	Treatment			MSD(1)	F value	p value
	Uncultivated	Amaranth	Maize			
	t of C/ha					
0-20 cm	26.1 aA	21.7 aB	25.8 aA	3.5	6.64	0.0086
20-40 cm	28.4 aA	24.2 aA	23.5 aA	6.0	2.61	0.1067
40-60 cm	27.2 aA	28.0 aA	26.0 aA	9.0	0.18	0.8390
MSD	4.9	9.0	4.7			
F value	0.72	1.67	1.13			
P value	0.5034	0.2210	0.3481			
0-60 cm	81.7 A	75.3 A	73.9 A	16.7	0.84	0.4528

(1) MSD: Minimum significant difference ($p < 0.05$). Values with the same letter are not significantly different between the layers (within the column; $p < 0.05$), and values with the same capital letter are not significantly different between the treatments (within the rows; $p < 0.05$)

can be assumed that the crop will have little effect on the GWP of the GHG emissions.

The GWP of the GHG was approximately 400 kg CO_2-equivalents/ha/y in a conventional agricultural system (tillage, maize monoculture, residue removal) in the valley of Mexico City in the year 2008-2009 and 230 kg CO_2-equivalents/ha/y in 2009-2010 (Dendooven *et al*. 2012). The values reported in this study were similar to those found in the arable soil mentioned above.

CONCLUSIONS

It was found that chinampa soils are saline-alkaline, rich in nutrients and organic matter as a result of application of lake sediment and plant residues.

N_2O contributed 91 % and CH_4 9 % to the GWP of the GHG.

The GHG emissions were not affected significantly by cultivated crop or soil characteristics.

The organic C was equally distributed in the soil profile and large amounts of C were sequestered from the atmosphere.

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