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Greenhouse gas emissions and pollutant removal in treatment wetlands with ornamental plants under subtropical conditions

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ABSTRACT

Methane (CH_4) and nitrous oxide (N_2O) emissions, and pollutant removal were investigated in constructed wetland (CW) mesocosms planted with the ornamental plant *Zantedeschia aethiopica* to treat polluted river water. We used two types of CWs, surface flow (SF) and subsurface flow (SSF), and two plant densities, high density HD (32 plants m^{-2}) and low density LD (16 plants m^{-2}). We also compared CH_4 and N_2O emissions in zones planted with macrophytes (*Typha* sp and *Cyperus papyrus*) versus zones planted with *Zantedeschia aethiopica* in a pilot scaled CW treating municipal wastewater. In the mesocosms, average CH_4 emissions were significantly higher in SFCW (436 ± 32 and 518 ± 46 mg m^{-2} d^{-1}). than SSFCW (319 ± 65 and 210 ± 74 mg m^{-2} d^{-1}), and plant density did not affect such emissions. SSFCW showed higher ammonia and nitrate removal efficiencies than SFCW and also showed higher N_2O emissions (17 ± 3 and 23 ± 5 mg m^{-2} d^{-1}). Phosphate removal efficiencies were significantly higher in SFCW than SSFCW. In the pilot scale CW, no nitrous oxide emissions were observed and average CH_4 emission ($11{,}000 \pm 930$ mg m^{-2} d^{-2}) was higher in the zones near the outflow planted with *Zantedeschia aethiopica* than in the zones near the inflow planted with *Typha sp* (4500 ± 800 mg m^{-2} d^{-2}) and *Cyperus papyrus* (5500 ± 600 mg m^{-2} d^{-2}), although TOC was higher in the zones near the inflow. We concluded that substrate and water flow are important factors controlling greenhouse gas emissions in CW and the amount of *Zantedeschia aethiopica* plants did not influence the emissions. Differences in methane emissions in the zones planted with native wetland plants in comparison with zones planted with *Zantedeschia aethiopica* might indicate that methane production and consumption in CW is influenced differently by the ornamental plants than by native wetland plants.

1. Introduction

Constructed wetlands CW are designed to treat wastewater using the same natural processes that occur in natural wetlands but in a controlled manner. They provide an excellent alternative to conventional wastewater treatment such as active sludge systems, because constructed wetlands are low in cost and maintenance, offer good performance, and provide a natural appearance to the residents. Removal of organic matter in treatment wetlands is mediated by several microbial reactions such as aerobic respiration, denitrification, sulphate reduction, fermentation processes and methanogenesis (García et al., 2005). The products of some of these reactions include greenhouse gases such as methane (CH_4), carbon dioxide (CO_2) and nitrous oxide (N_2O), which are released to the atmosphere. Greenhouse gases contribute to the radiative forcing in the atmosphere and consequently affect Climate Change, thus, their quantification in CW needs to be addressed before a greater implementation of this technology. The utilization of ornamental plants in CW is a topic that has been investigated for the last 13 years in several countries especially near the tropics (Belmont and Metcalfe, 2003; Zhang et al., 2006; Konnerup et al., 2009; Calheiros et al., 2015; Zurita et al., 2006, 2009, 2016). In México the strategy of using ornamental plants in constructed wetlands has been proposed to facilitate the introduction of this technology in small communities. Flowers produced in the constructed wetlands can be commercialized by the community as an economical incentive in exchange for providing maintenance to the treatment wetlands (Hernández, 2016). The majority of studies regarding the use of ornamental plants have been focused on the treatment efficiency and plant growth (Konnerup et al., 2009; Méndez-Mendoza et al., 2015; Saumya et al., 2015). However, little is known about the effects of ornamental plants on the biogeochemical process that occur in constructed wetlands. The objective of this study was

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to investigate greenhouse gas GHG emissions in different types of CW with ornamental plants at different scales. We investigated the effect of water flow, substrate type and plant density on GHG emission, and pollutant removal in CW mesocosms with ornamental plants to treat polluted river water. We also compared GHG emissions in areas with native wetland plants versus zones planted with ornamental plants; in a pilot scaled subsurface constructed wetland, for treating municipal wastewater. Our hypotheses were: (1) surface flow CW mesocosms with soil would have more anaerobic conditions than subsurface flow CW with gravel, therefore higher methane emissions. (2) High plant density would provide more oxygen to the substrate, decreasing methane emissions. (3) In the pilot scale treatment wetland; our hypothesis was that areas with ornamental plants would have lower GHG because they were near the outflow and therefore would have less nutrient availability, as compared to areas with native wetlands plants near the inflow.

2. Material and methods

2.1. Study sites

This study was conducted in the central part of Veracruz State in Southeastern Mexico. The CW mesocosms were in a glass greenhouse (without temperature or humidity control) at the botanical garden "Francisco Javier Clavijero" in Xalapa city (96° 56′ 24″ W 19° 30′54″ N) at 1560 m AMSL. Weather in the region is humid subtropical with an annual precipitation of 1509.1 mm and an annual average temperature of 18° C. CW mesocosms were supplied with water from the Sordo River. This river is a third order stream that originates in a tropical mountain rainforest upstream from the botanical garden; downstream, it joins the Pixquiac River and finally it merges to La Antigua River which flows into the Gulf of Mexico.

The pilot scale treatment wetland was constructed in the community of Pinoltepec municipality, of Emiliano Zapata, Veracruz (96° 45′ 18″ W 19° 26′ 45″ N) at 780 AMSL. Weather in the region is humid tropical with an annual precipitation of 2779.1 mm and annual average temperature of 25.2° C. The pilot treatment wetland was supplied with settled municipal wastewater. Population in Pinoltepec is 649 inhabitants and has 168 residences.

2.1.1. Mesocosm units

The experimental mesocosms consisted of cells built using fiber glass (1.5 m length, 0.25 m wide and 0.6 m depth). Four cells were set up for free surface flow wetland SFCW mesocosm using upland soil (C = 13.8%, TN = 0.93%, $N\text{-}NO_3$ = 83.28 mg Kg^{-1}, pH = 5.8) as substrate (0.4 m deep, free water surface flow column of 10 cm), and four cells for subsurface flow wetland SSFCW mesocosm using volcanic gravel as substrate (0.04 m diameter, 0.5 m depth, water flow 10 cm below surface). Two cells of each type of flow were planted with *Zantedeschia aethiopica* at low density (16 plants m^{-2}) and two cells with high density (32 plants m^{-2} plants). Mesocosms were supplied with water from the Sordo River, which receives untreated urban wastewater from Xalapa city. River water was pumped into a 500 L distribution tank and continuously discharged into each mesocosm trough a PVC pipe. Water flow rate was adjusted for each cell to have a Hydraulic Retention Time (HRT) of 3 days (Fig. 1).

2.1.2. Pilot scale treatment wetland

The treatment wetland consisted of two parallel concrete cells (20 m length, 1 m wide and 0.6 m depth) with subsurface water flow (volcanic gravel 0.05 m diameter, 0.5 m depth, water flow 10 cm below surface). Both cells were planted with the same array of vegetation and received the same flow of wastewater. Vegetation in the cells were distributed from the inflow to the outflow as follows: 0–5 m *Typha* sp, 5–12 m *Cyperus papyrus*, 12–20 m *Zantedeschia aethiopica*. This arrangement was established to enhance flower production of *Zantedeschia aethiopica*; since previous studies demonstrated that a high nutrient load stimulated the growth of *Zantedeschia aethiopica,* but no flower production (unpublished data). On the other hand, wetland plant species such as *Typha sp* and *Cyperus papyrus*, are tolerant to high nutrient loads, therefore they were planted near the inflow where nutrient concentration was higher. Wastewater flow rates were adjusted for each cell to have a Hydraulic Retention Time (HRT) of 40 h.

2.1.3. Sampling and analytical methods

Water samples (200 ml) were taken from the influent and effluent of each CW mesocosm. Influent samples were taken beyond the distribution tank and from each individual hose that fed river water to the mesocosms and, effluent samples were taken at the exit of each cell. Water sampling was performed twice a week from May to November.

In the pilot scale treatment wetland, water samples (200 ml) were also taken from influent and effluent of each cell every other week, from June to October. Additionally, PVC wells were installed next to the gas sampling chamber and water samples from these wells were taken each time that GHG were measured.

The samples were analyzed for Chemical Oxygen Demand (COD), ammonia nitrogen ($N\text{-}NH_3$), nitrate ($N\text{-}NO_3{}^{-1}$), orthophosphate ($P\text{-}PO_4{}^{3-}$), Total Phosphorus (TP), Total Nitrogen (TN), Total Organic Carbon, Total Solids (TS) and Total Suspended Solids (TSS). COD was measured using the oxidation of $K_2Cr_2O_7$ micro-method (APHA, 1998); $N\text{-}NH_3$ was analyzed by the Nessler method; Total Nitrogen TN was analyzed by Kjeldahl method (APHA, 1998); $P\text{-}PO_4$ were quantified using the ascorbic acid method according to Sandell and Onish (1978); Total Phosphorus was analyzed by persulfate digestion followed by ascorbic acid method; $N\text{-}NO_3$ were quantified with the salicylic acid method, according to Rofarge and Jonson (1983). All these colorimetric analyses were performed using a UV–vis Jenway-Genova spectrophotometer (Jenway-Essex, UK). Total Organic Carbon in water was analyzed in a Total Organic Carbon analyzer (Torch, Teledyne Tekmar). TSS and TS were analyzed by gravimetric methods (APHA, 1988)

2.1.4. Gas flux measurements

In the mesocosms, gas fluxes were measured twice a month from June to November 2012, and in the pilot scale treatment wetland, from July to October 2013. In both cases the closed chamber technique was used for the measurement of greenhouse gas emissions (Hernández and Mitch, 2006; Altor and Mitsch, 2008). In the mescosms, chambers consist of a permanent base and a removable cover. The base was a PVC pipe (0.40 m height, 0.05 m ID) with a plastic collar to create a water seal with the cover. They were inserted permanently 0.12 m into the wetland substrate. The cover was 0.10 m height × 0.075 m ID and had a gas sampling port and thermometer. Two chambers were installed in each wetland mesocosm, one chamber was placed near the water inlet and one near the outlet.

In the pilot scale treatment wetland, the chamber bases were a PVC pipe (0.25 m height, 0.10 m ID) with a cover (0.10 m height x 0.30 m ID). Chambers were placed in both cells, at 3, 9 and 15 m from inflow to outflow in *Thypha sp*, *Cyperus papyrus* and *Zantedeschia aethiopica* vegetation zones respectively.

When the gas fluxes were measured, the cover was placed on top and sealed to the base using water in the collar. Internal gas samples were collected from the chamber every 5 min, during a 40-min period by using a syringe fitted with a Luer stopcock. Gas samples were stored into 10 ml vials previously vacuum evacuated and kept at 4 °C until their analysis (within three days after they were collected). The gas samples were analyzed for their CH_4 and N_2O