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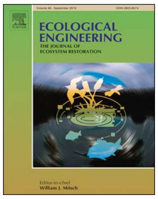

Methane emissions from mangrove soils in hydrologically disturbed and reference mangrove tidal creeks in southwest Florida

Alvaro Cabezas[a], W.J. Mitsch[a,*], Conor MacDonnell[a,b], Li Zhang[a], Franciszek Bydałek[a,c], Ana Lasso[a,d]

[a] Everglades Wetland Research Park, Florida Gulf Coast University, Naples, FL, USA
[b] Soil and Water Sciences Department, University of Florida, Gainesville, FL, USA
[c] The Faculty of Civil Engineering, Architecture and Environmental Engineering, University of Zielona Góra, Zielona Góra, Poland
[d] Univerisdad Autonoma de Occidente, Jamundi, Cali, Colombia

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ABSTRACT

Studies have suggested that some mangrove soils might contribute to wetland methane (CH_4) production and emissions, especially when the mangroves are disturbed. CH_4 emissions were measured seasonally from nine locations on two mangrove creeks on Naples Bay in southwest Florida, USA. One of the tidal creeks has been impacted in the past few decades with alteration of upstream watersheds and freshwater inflows; the other creek was an un-impacted reference tidal creek. Our study sites were established along a longitudinal gradient (distance to the creeḱs mouth) with different plant communities and freshwater influences, which were further evaluated by measurements during the dry and wet seasons. CH_4 emission measurements were also performed during the flood and ebb tides ($n = 6$) to incorporate the influence of water level fluctuations on CH_4 emissions. Additionally, hydroperiods and soil pore water electrical conductivity (EC) as a measure of salinity were measured along the study creeks. Our study showed very small, if not negligible, CH_4 emissions from mangrove soils in this southwest Florida location at all sampling locations and sampling times. Despite our collecting over 1900 methane samples from methane emission chambers, most analyses of rates of change in the chambers showed no methane emissions. Seasonal averages ranged from 0.24 to 1.68 mg CH_4-C m^{-2} d^{-1} (annual average of 0.32 g CH_4-C m^{-2} y^{-1}). Ironically, the lowest methane emissions were at the end (December–January) of a typical wet season of daily rainfall and were highest in the dry season (March–April) when freshwater inputs from watersheds and precipitation were negligible. Water level fluctuations, freshwater inputs, and plant species composition did not play a significant role in CH_4 emissions. There appeared to be a slight pattern of methane emissions versus air temperature but the relationship was not linear. Combining our results with carbon sequestration rates in a companion study suggested that mangroves in southwest Florida are clearly net sinks of both carbon and radiative forcing and therefore beneficial for mitigating climate warming.

1. Introduction

Vegetated coastal wetlands, including mangrove forests, salt marshes, and seagrass beds, play a critical role in global carbon (C) sequestration. Carbon sequestration rates in tropical/subtropical wetlands, including coastal mangroves and salt marshes, have been recently summarized to be in the range of 150–250 g-C m^{-2} yr^{-1} (Mitsch and Gosselink, 2015; Mitsch, 2016). Carbon accumulated by these ecosystems has been defined as “blue carbon” because of these significant rates and lack of mitigating methane measurements that frequently occur in freshwater wetlands (McLeod et al., 2011; Vaidyanathan, 2011; Mitsch, 2016). Duarte and Cebrian (1996) recognized the importance of this blue carbon within the ocean C cycle, which was formerly overlooked due to the limited extent of marine vegetation, which covers less than 2% of the ocean surface. However, blue carbon is estimated to represent 10–15% of the total organic carbon burial in marine environments (Duarte et al., 2005). Carbon burial in mangroves is estimated to be ~18.4 Tg C yr^{-1} (FAO, 2003; Bouillon et al., 2008) given mangroves occupy 138,000–170,000 km^2 worldwide (Mitsch and Gosselink, 2015). Due to long-term mangrove forest C storage capacity, conservation and restoration of mangroves represent cost-effective tools to reduce the net effects of greenhouse gas (GHG) emissions and a means to abate climate change (Donato et al., 2011).

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[*] Corresponding author.
E-mail address: wmitsch@fgcu.edu (W.J. Mitsch).

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Mangroves are one of the most effective radiative sinks (Mitsch et al., 2013) due to low emissions of CH_4, a powerful GHG. Consequently, mangrove soils are generally considered to be a minor contributor to CH_4 production and emissions on a global scale (Harris et al., 1998; Alongi et al., 2000, 2001). Our knowledge of the factors controlling CH_4 production and emissions in mangrove environments is limited and relies primarily on a few recent studies (Kristensen et al., 2008a,b). King (1984) showed sulfate-reducing and CH_4 -producing bacteria competed for the same substrates (H_2/CO_2, acetate), with sulfate reducers being better competitors. Therefore, the high sulfate availability in coastal ecosystems from saline water leads to low CH_4 production rates. Additionally, aerobic and/or anaerobic CH_4 oxidation at near-surface sediments can slow down atmospheric CH_4 emissions. Lee et al. (2008) observed contemporary sulfate reduction and CH_4 production occurred due to the presence of non-competitive substrates, and pristine mangrove communities were described to occasionally act as CH_4 sources (Purvaja et al., 2000; Kreuzwieser et al., 2003; Dalal and Allen, 2008). Mangrove support structures, e.g., prop roots and pneumatophores and/or bubbles, can facilitate soil CH_4 emissions by providing bypasses of CH_4 oxidation. Allen et al. (2007, 2011) showed that CH_4 emissions from pristine mangrove soils were characterized by high diurnal, seasonal, and spatial variability. This heterogeneity can be promoted by water level fluctuations, freshwater inputs, and plant species composition, amongst other factors (Kreuzwieser et al., 2003; Barnes et al., 2006; Kristensen et al., 2008a,b). Elevated water levels impede oxygen diffusion to mangrove soils, whereas freshwater input decreases sulfate availability. Therefore, both factors could influence CH_4 production in mangrove soils. In addition, plant community composition can determine the amount and composition of autochthonous organic matter input, i.e., labile organic matter availability, influencing CH_4 production.

Over the past 50 years, approximately one-third of the world's mangrove forests have been lost due to clearing for urbanization, agriculture, aquaculture, and other uses; overharvesting; river course alterations; pollution; climate change; and indirect losses from overfishing and coral reef destruction (Alongi, 2002). A promising instrument to encourage mangrove conservation and restoration worldwide is payment for ecosystems services (PES), e.g., the financing provided to mangrove owners for mangrove soils serving as net radiative sinks. A limited understanding of CH_4 emissions from mangrove soils complicates the application of mangrove restoration as a PES instrument (Alongi, 2011).

In our study, we estimated CH_4 emissions from mangrove forest soils on two tidal creeks with different degrees of urban impacts, evaluating the influence of water level fluctuations, freshwater input, and mangrove plant community structure. The objectives of the study were as follows:

a) provide reliable and seasonal CH_4 emission estimates for subtropical mangrove forest soils in southwest Florida in disturbed and reference conditions; and
b) gain insights on the factors promoting spatial and temporal variability in CH_4 emissions from mangrove soils.

2. Materials and methods

2.1. Study area and sampling design

The study was conducted in Naples Bay (26° 5′ N, 81° 47′ W, Fig. 1), a semi-diurnal, micro-tidal (0.7–1.2 m water level variation), shallow (< 7 m) estuary (Lynch et al., 1989; Marchio et al., 2016; MacDonnell et al., 2017), located in southwest Florida. The climate is warm temperate to subtropical, with an average annual temperature of 23.6 °C (Lynch et al., 1989). Precipitation in southwest Florida is seasonally dependent, occurring predominately from May to October; 60–65% of the annual 1346 mm yr^{-1} of precipitation occurs from June through September (Twilley et al., 1986). Naples Bay is located within the Gordon River/Pass system, which empties the urban Naples watershed.

Naples Bay is predominately a sand-dominated system, though remnants of oyster beds supply the estuary with calcareous shell materials. Prior to urbanization, sea grass beds and oyster bars were distributed throughout Naples Bay. Because of changes to the hydrodynamic character of the bay through dredging, channelization, and compartmentalization of water flows, the bay has largely lost its natural estuarine characteristics. A significant percent of the coastal fringing mangrove communities along Naples Bay have been converted to human-dominated residential developments (Marchio et al., 2016; MacDonnell et al., 2017; Marois and Mitsch, 2017). Loss of 53% mangroves, 62% forested upland, and 76% coastal scrub in the watershed was already described a decade ago by the South Florida Water Management District (2007). The northern portion of Naples Bay is highly urbanized, while the southern region of the bay and its connection to Dollar Bay are relatively unaltered; Rookery Bay National Estuarine Preserve protects most of Dollar Bay.

Two mangrove creeks (Hamilton Avenue Creek (HA); and Susan Creek (SC)) were selected as sample sites within Naples Bay (Fig. 1). Tidal fluctuations dominate the hydroperiods at both creeks, due to the lack of any significant barrier between the bay and creeks. Urban development dominates the lower reaches of the watershed draining into Hamilton Avenue creek. As a result, it is likely that tidal flow paths and freshwater input have been significantly modified for this creek. Marois and Mitsch (2017) recently concluded that the mangrove forest and a restored brackish marsh that were once hydrologically connected to Naples Bay by Hamilton Avenue Creek are now mostly isolated from marine flows and "water level and salinity in these areas indicate that there is little tidal influence on these areas through the surface water." Marois and Mitsch (2017) developed a restoration plan, based on historical flow conditions, of deepening and widening Hamilton Avenue Creek to increase both tidal fluxes and freshwater inflows from uplands. They demonstrated with a hydraulic model how the mangrove system could be hydrologically restored while protecting upstream users from salinity intrusion. The watershed draining into our reference Susan's Creek (SC) remains in place and natural, leading to more seasonal freshwater input.

Sampling sites (HA, n = 4, HA1–HA4); (SC, n = 5, SC1–SC5) were established at mangrove swamps adjacent to the creeks (Fig. 1) following a longitudinal gradient. The objective of longitudinal transects at sampling sites was to reflect different mangrove plant community structure and different influences of freshwater input. It is assumed that the influence of tidal, saline water will be higher at plots located closer to the creek mouth, whereas freshwater inputs will have more importance at sites located far from the creek mouth. Most sampling sites coincided with those used by Marchio et al. (2016) for a companion carbon sequestration investigation.

2.2. Mangrove community structure

Mangrove plant community structure characterization was performed at every sampling site but SC3. Rectangular plots were chosen because the shape was most suitable to the elongated forest patches. The plots were placed perpendicular to the creek. Plot dimensions varied proportionally to tree height, which captured maximum variability without over-sampling. The long axis of each plot was at least twice the height of the dominant trees, i.e., the mean height of the two tallest trees. The short axis was long enough to establish a plot area = dominant height^2. Each plot area ranged from 25 to 100 m^2. Every stem in the plot was recorded for species and diameter at breast height (DBH).

2.3. Hydroperiod and salinity

The hydroperiod was characterized by comparing water level