



Temperature response of ex-situ greenhouse gas emissions from tropical peatlands: Interactions between forest type and peat moisture conditions

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ARTICLE INFO

Handling Editor: Jan Willem Van Groenigen

Keywords:

Climate change

Carbon dioxide

Methane

Peatland

Moisture status

Temperature response

Tropical

ABSTRACT

Climate warming is likely to increase carbon dioxide (CO₂) and methane (CH₄) emissions from tropical wetlands by stimulating microbial activity, but the magnitude of temperature response of these CO₂ and CH₄ emissions, as well as variation in temperature response among forest types, is poorly understood. This limits the accuracy of predictions of future ecosystem feedbacks on the climate system, which is a serious knowledge gap as these tropical wetland ecosystems represent a very large source of greenhouse gas emissions (e.g. two-thirds of CH₄ emissions from natural wetlands are estimated to be from tropical systems). In this study, we experimentally manipulated temperatures and moisture conditions in peat collected from different forest types in lowland neotropical peatlands in Panama and measured how this impacted ex-situ CO₂ and CH₄ emissions. The greatest temperature response was found for anaerobic CH₄ production ($Q_{10} = 6.8$), and CH₄ consumption (mesic conditions, $Q_{10} = 2.7$), while CO₂ production showed a weaker temperature response ($Q_{10} < 2$) across the three moisture treatments. The greatest temperature response of CO₂ production was found under flooded oxic conditions. Net emissions of CO₂ and CH₄ were greatest from palm forest under all moisture treatments. Furthermore, the temperature response of CH₄ emissions differed among dominant vegetation types with the strongest response at palm forest sites where fluxes increased from 42 ± 25 to 2166 ± 842 ng CH₄ g⁻¹ h⁻¹ as temperatures were raised from 20 to 35 °C. We conclude that CH₄ fluxes are likely to be more strongly impacted by higher temperatures than CO₂ fluxes but that responses may differ substantially among forest types. Such differences in temperature response among forest types (e.g. palm vs evergreen broad leaved forest types) need to be considered when predicting ecosystem greenhouse gas responses under future climate change scenarios.

1. Introduction

Global atmospheric methane (CH₄) and carbon dioxide (CO₂) concentrations are increasing as a consequence of human activities such as fossil fuel burning and land use change (IPCC, 2013). The resulting climatic changes may further increase greenhouse gas (GHG) emissions from terrestrial biomes, creating a positive feedback loop resulting in additional climate warming; however, such feedbacks will differ among ecosystems. Wetlands are important components of the global carbon cycle and exchange large quantities of CH₄ and CO₂; indeed, they are recognised as the largest individual natural source of atmospheric CH₄, a potent GHG (e.g. Lelieveld, 1998; Bridgman et al., 2013; IPCC, 2013).

Two thirds of wetland CH₄ emissions are estimated to originate from natural tropical ecosystems in Southeast Asia, Africa and the Neotropics (Melton et al., 2013). These wetlands are also large emitters of CO₂,

estimated at 4540 ± 1480 Tg CO₂ year⁻¹ (Sjögersten et al., 2014). Furthermore, tropical peatlands acts as globally important stores of carbon (C) (Page et al., 2011). The CO₂ and CH₄ emissions of tropical peatlands are regulated by water table/redox state (Jauhiainen et al., 2005; Hoyos-Santillán, 2014), quantity and quality of litter inputs (Wright et al., 2011; Sjögersten et al., 2014; Hoyos-Santillán et al., 2015) and temperature (Hirano et al., 2009). However, despite the significance of tropical wetlands in the global carbon cycle, the temperature response of GHG emissions from tropical peatlands is largely unknown (see Hirano et al., 2009), limiting our ability to predict climate change responses of their CO₂ and CH₄ emissions despite their high emissive potential (Bridgman et al., 2013).

This is a critical knowledge gap as we do not know if the wealth of data exploring temperature responses of CH₄ and CO₂ fluxes from higher latitude ecosystems can be transferred to tropical systems. It is

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for example plausible that tropical wetland microbial communities are adapted to higher temperatures, rendering them less sensitive to elevated temperatures than those in higher latitudes. Alternatively, differences in soil organic matter chemistry between high and low latitude wetlands may result in substantial differences in the temperature response of decomposition and release of GHGs (Lloyd and Taylor, 1994; Bosatta and Ågren, 1999; Fierer et al., 2005).

Tropical peatlands are under threat from climate change, which could substantially affect their water balance, and resultant CO₂ and CH₄ emissions (Furukawa et al., 2005; Li et al., 2007; Hooijer et al., 2010; Laiho, 2006; IPCC, 2013). With regards to climate change, current predictions indicate air temperatures in the neotropics and Southeast Asia will be 3–4 °C higher by 2100 and 5–7 °C higher by 2200 (IPCC, 2013). To date precipitation changes in the Amazon region have been associated with wetter wet seasons and drier dry season but there are no strong overall trends for the region (Almeida et al., 2017). In the future precipitation in the neotropics is predicted to decrease by ca. 10% by 2100 (ca. 350 mm less per year) and by 20–40% by 2200 (up to 1400 mm less per year) under the Intergovernmental Panel on Climate Change (IPCC) scenario RCP 8.5 (IPCC, 2013) although, model predictions of changes in precipitation patterns are more uncertain than the temperature predictions and patterns varies between inland and coastal areas (Chao et al., 2008; Oueslati et al., 2016). Together these changes are predicted to result in drier soils (IPCC, 2013). Increased temperature can be expected to increase microbial decomposition rates directly (Hirano et al., 2009), while lower water tables could result in large increases in soil CO₂ losses to the atmosphere and reduced CH₄ emissions (Jauhiainen et al., 2005; Couwenberg et al., 2010).

The “carbon-quality temperature hypothesis” postulates that the temperature sensitivity of decomposition processes increases with the complexity (recalcitrance) of soil organic matter, because larger activation energies are required for its catabolism under aerobic conditions (Lloyd and Taylor, 1994; Bosatta and Ågren, 1999; Fierer et al., 2005). In the context of tropical peatlands, this would suggest that climate change could result in decomposition of recalcitrant organic matter as temperatures increase. Furthermore, it is plausible that the dominance of palms and evergreen broad leaved trees in tropical peatlands result in substantially different soil organic matter chemistry (Hoyos-Santillán et al., 2015) compared to higher latitude wetlands where peat formation is often driven by graminoid and moss litter inputs (Turetsky et al., 2014) which is likely to affect the temperature response of peat decomposition. For example, recalcitrant lignin and long chain fatty acids from wood and evergreen leaf litter inputs, respectively, represent a large component of litter inputs in tropical peatlands (Sjögersten et al., 2014). According to the carbon-quality temperature hypothesis this would suggest that soil organic matter in tropical peatland may be more responsive to elevated temperature than higher latitude ecosystems.

Water logging and anaerobic conditions have been shown to affect the temperature response of C mineralisation strongly: CH₄ production in both subtropical and high latitude wetlands appears to be more sensitive to temperature than either aerobic or anaerobic CO₂ production (Dunfield et al., 1993; van Hulzen et al., 1999; Inglett et al., 2012; Treat et al., 2014). When comparing the relative impact of temperature on CH₄ production and oxidation, CH₄ oxidation does not appear to increase with temperature as rapidly as CH₄ production (Dunfield et al., 1993; Inglett et al., 2012), so higher temperatures may increase net CH₄ emissions. It is important to consider temperature response in the context of moisture status as soils are predicted to come drier in the tropics in response to climate change as there are strong links between moisture conditions/water tables position and GHG emissions (Jauhiainen et al., 2005; Couwenberg et al., 2010).

The aim of this study is therefore to investigate how increasing peat temperatures and changes in moisture levels of neotropical peatlands may interact to control ex situ CO₂ and CH₄ emissions. To achieve this we ran controlled experiments with peat from lowland neotropical peatlands to determine the temperature responses for ex situ CO₂ and

CH₄ fluxes under both aerobic and anaerobic conditions. The experiment consisted of incubating peat at a range of temperatures and moisture states. As these peatlands are heterogeneous with regards to vegetation and soil nutrient status (Troxler, 2007; Sjögersten et al., 2011) we investigated the impact of moisture and temperature treatments on CO₂ and CH₄ emissions from peat samples extracted from four forest types commonly found in peatlands in the neotropics (Phillips et al., 1997; Nahlik and Mitsch, 2011; Roucoux et al., 2013): palm, mixed, hardwood and stunted forest.

2. Methods

2.1. Study area

The San San Pond Sak wetland complex is a 164 km² mosaic of freshwater and marine-influenced wetlands in Bocas del Toro Province on the Caribbean coast of western Panama (Cohen and Stack, 1996). Recognised internationally as a largely pristine wetland of special scientific interest (Ramsar site #611), San San Pond Sak includes the significant 80 km² Changuinola peat deposit, an ombrotrophic domed peatland to the south east of Changuinola river (Phillips et al., 1997). The oldest deposits in the Changuinola peatland are estimated to have been formed 4000–4500 years ago and are > 8 m deep in the central areas (Phillips et al., 1997). Peat at the edges of the peatland is younger and ca. 2 m deep.

Seven distinct phasic plant communities cover the peatland (Phillips et al., 1997). Starting from the periphery, these communities have been designated as (i) *Rhizophora mangle* mangrove swamp, (ii) mixed back mangrove swamp, (iii) *Raphia taedigera* palm forest swamp, (iv) mixed forest swamp (consisting of both palm and evergreen broadleaved hardwood trees), (v) *Camposperma panamensis* forest swamp, (vi) sawgrass/stunted forest swamp and (vii) *Myrica-Cyrilla* bog-plain. In this study we focused on (iii) to (vi) of these phasic communities as these represent the dominant forest types in the peatland. For simplicity we denote these as palm forest, mixed forest, hardwood forest, and stunted forest throughout the paper. The forest is mainly unaffected by human activities although occasional small scale selective logging is evident in areas close to the coast and rivers. Nutrient levels in the peat and plant tissue vary greatly among vegetation communities and are generally low in the interior and higher towards the edge of the peatland (Troxler, 2007; Sjögersten et al., 2011). The low nutrient content in the interior is reflected by reduced microbial activity, with higher microbial biomass C:N and C:P ratios and up-regulation of the activity of extracellular enzymes involved in nutrient acquisition (Sjögersten et al., 2011; Cheesman et al., 2012). Furthermore, in situ (i.e. measurement in the field) CO₂ and CH₄ fluxes along this vegetation transect did not appear to reflect peat nutrient availability (Wright et al., 2013), while laboratory incubations (ex situ) of drained surface peat samples show lower CO₂ production in substrates from the interior than sites closer to the edge of the peatland (Sjögersten et al., 2011).

A weather station in the nearby town of Bocas del Toro, Isla Colon, ca. 10 km from the peatland, shows the area has a mean annual temperature of 25.9 °C with low intra-annual variability, and recorded a mean annual precipitation of 3092 mm between 2003 and 2011 (Hoyos-Santillán et al., 2015). Rainfall is continuous throughout the year with no pronounced dry season, although there are two distinct periods of lower rainfall (February–March and September–October). Water tables in these peatlands are dynamic and mainly fluctuate around ± 0.2 m from the surface, with water tables increasing rapidly after intense rainfall events and dropping to or below the surface in between rainfall events (Wright et al., 2013; S. Sjögersten, pers. obs.). During occasional, prolonged dry (i.e. no rainfall) periods, the water table can drop as low as –40 cm (Hoyos-Santillán, 2014). Conversely, high rainfall events can cause the water tables to rise above the peat surface (normally no more than ca. 10–20 cm). Mean peat temperature 10 cm below the surface is ca. 25 °C and shows little intra-annual

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