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Soils act as sinks or sources of CH_4 depending on air-filled porosity in sclerophyllous ecosystems in semiarid central Chile

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ABSTRACT

Carbon dioxide (CO_2) and methane (CH_4) are greenhouse gases (GHG), which sustained increase in the atmosphere contribute to global warming and climate change. The GHG fluxes of soils are strongly controlled by water content, temperature, plant and microbial communities and soil management. The Chilean sclerophyllous ecosystem is a global biodiversity hotspot historically and increasingly threatened by human activity. The aim of this study was to compare soil CH_4 (and CO_2) fluxes, under prevailing aerobic (dry hot summer) versus presumed partial anaerobic (wet winter) conditions, across a disturbance gradient in sclerophyllous ecosystems of central semiarid Chile. The CO_2 fluxes were measured with an infrared gas analyzer (IRGA) while CH_4 fluxes by gas chromatography using closed soil chambers. Soils were sources of CO_2 ($\sim 3.35\ \mu mol\ CO_2\ m^{-2}\ s^{-1}$) drastically changing with vegetation and seasons. Soils were generally sinks of CH_4 in summer ($\sim -3.75\ nmol\ CH_4\ m^{-2}\ s^{-1}$) and sources in winter ($\sim +4.12\ nmol\ CH_4\ m^{-2}\ s^{-1}$), which was mainly explained by air filled porosity. Modelled values showed that soils of the severely-disturbed *A. caven* savannah was overall a CH_4 source ($0.86\ g\ CH_4\ m^{-2}\ year^{-1}$), while the strongly-disturbed thorn scrub ($-0.56\ g\ CH_4\ m^{-2}\ year^{-1}$) and the moderately-disturbed sclerophyllous forest ($-2.68\ g\ CH_4\ m^{-2}\ year^{-1}$) were sinks. Hence protecting sclerophyllous forests and restoring disturbed ecosystems may contribute to mitigate anthropogenic CH_4 emissions.

1. Introduction

Greenhouse gases (GHG) maintain the temperature in the Earth's atmosphere, since they have the capacity to absorb radiation and reemit it as heat and also as radiation that is absorbed by the land. Increases in GHG concentration, as a result of anthropogenic activities, are responsible for the current global warming (IPCC, 2013). This effect has been accentuated by human activity with increasing emissions mainly as carbon dioxide (CO_2) and methane (CH_4). Atmospheric CO_2 concentrations are approximately 408 ppm, while CH_4 near 1.86 ppm (NOAA, 2018), although, CH_4 is about 23 times more efficient in heat capture than CO_2 (Chapin et al., 2012; Lechat et al., 2016).

Soil respiration releases a large portion of carbon fixed by photosynthesis partially regulating net ecosystem productivity, and hence global and regional carbon cycles (Luo and Zhou, 2006). Soil CO_2 effluxes are strongly controlled by water content (Balogh et al., 2011; Moyano et al., 2012; Cueva et al., 2015) and temperature (Balogh et al., 2011; Lellei-Kovács et al., 2011; Cueva et al., 2015), increasing exponentially with soil temperature in the absence of soil moisture limitations (Lloyd and Taylor, 1994; Guidolotti et al., 2013). When water limited, the CO_2 efflux increases with soil water content steadily until a threshold is reached (e.g. 20%) to even out thereafter (Luo and Zhou, 2006; Guidolotti et al., 2013).

The soil CH_4 fluxes are the result of two microbial processes: methanogenesis (CH_4 microbial production) in anaerobic conditions, and methanotrophy (CH_4 microbial consumption) under aerobic conditions (Chan and Parkin, 2001b; Dutaur and Verchot, 2007; Serrano-Silva et al. 2014). Water-saturated systems (such as wetlands) are sources of CH_4, whereas unsaturated soils (such as uplands) are CH_4 sinks (Warner et al., 2017). Methanogenesis (CH_4 soil emission) is strictly driven by archaea in anaerobic conditions, whereas methanotrophy (CH_4 soil uptake) is regulated by methanotrophic and nitrifying bacteria under aerobic conditions (Savi et al., 2016). Soils can act as sources and sinks for CH_4, depending on their air/water conditions (Chan and Parkin, 2001a). When soil water content is low, the air-filled porosity is high and therefore CH_4 diffusivity increases, favoring methanotrophy and hence CH_4 consumption (Epron et al., 2016, Fest et al., 2015). Soil CH_4 consumption can therefore be controlled by soil bulk density (Del Grosso et al., 2000; Fest et al., 2015), soil volumetric water content (Fest et al., 2015; Epron et al., 2016) and gas diffusivity (as measured by air filled porosity or water filled pore space) (Del Grosso et al., 2000; Dutaur and Verchot, 2007; Dalal and Allen, 2008; Fest et al., 2015;

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Epron et al., 2016). In contrast, methanogenesis and hence soil CH_4 emissions may occur in anaerobic soil pockets as a result of high soil bulk density and high volumetric water content decreasing air filled porosity and gas diffusivity (Dutaur and Verchot, 2007). In spite of the above, soil CH_4 exchange and its spatial variability is not fully understood, probably associated to the spatial and temporal variation of methanotrophic and methanogenic microbial activity (Christiansen et al., 2016).

The sclerophyllous scrubs and forests are the most common vegetation in Central Chile, where a semiarid mediterranean climate with a dry warm summer and cold rainy winter occur. These ecosystems exhibit a great diversity of plants due to the climate transition and hilly terrain (Gajardo, 1994; Luebert and Pliscoff, 2006); which is probably enhanced by a long history of degradation by cultivation, cattle grazing, fire and firewood extraction (Armesto et al., 2007; Bown et al. 2014).

The aim of this study was to compare soil CH_4 fluxes across a vegetation disturbance gradient of sclerophyllous scrubs and forests of Central Chile during a hot dry summer versus a mild wet winter. Also we aimed to better understand the environmental drivers controlling CH_4 fluxes. We hypothesized that soils will act as CH_4 sinks during the hot dry summer; where aerobic conditions prevailed, while as CH_4 sources during the mild wet winter when anaerobic conditions may arise.

2. Material and methods

2.1. Study site

The study was carried out in the National Reserve 'Roblería del Cobre de Loncha' (34° 08′ S, 71°03′ W), located in the Coastal Range, approximately 80 km southwest of the city of Santiago in central Chile. The physiography of the National Reserve watershed (5870 ha) is formed by non-continuous peaks cut by deep ravines and valleys, which largely determined the location of historical human settlement (UNDP, 2011). Parent materials are typically granitic, granodioritic and volcanic rocks (ODEPA, 1968; SERNAGEOMIN, 1982). The climate is Mediterranean, dry and semi-arid, with a mean annual precipitation of 503 mm, water deficit of 956 mm and mean annual temperature of 14.9 °C. Summer droughts extend for 6–8 months typically from October to April (CONAF, 2008).

The natural flora of the site is dominated by the tree sclerophyllous species *Cryptocarya alba* (Mol.) Looser. (Lauraceae), *Quillaja saponaria* Mol. (Quillajaceae), *Lithraea caustica* (Mol.) Hook. et Arn. (Anacardiaceae) and *Peumus boldus* Mol. (Monimiaceae), the invasive small N-fixing tree legume *Acacia caven* (Mol.) Mol. (Fabaceae) and the shrub species *Colliguaja odorifera* Mol. (Euphorbiaceae) and *Retanilla trinervia* (Gillies et Hook.) Hook. et Arn. (Rhamnaceae). These tree and shrub species are typical of the sclerophyllous forest, thorn scrub and *A. caven* savanna of Central Chile (Gajardo, 1994; Luebert and Pliscoff, 2006; Armesto et al., 2007).

The studied site was located in a toe slope in a north-aspect position. Soils developed from colluvial materials that belong to the coarse-loamy, mixed, thermic Typic Xerochrepts family (Soil Survey Staff, 1999) and locally associated with the Quilamuta Series (CIREN, 1996). Soil textures varied from loamy clay in the more disturbed sites to loamy sand in the less disturbed sites. Nine 25 × 25 m plots (625 m^2) were distributed equally across three clearly distinct vegetation types, henceforth identified as A, B and C (Fig. 1, Table 1), in increasing order of disturbance. Perennial cover decreased and species composition drastically changed from A to C. Plots ranged in altitude between 300 and 800 m above the sea level. The A condition, the least disturbed among A, B and C; is a second growth-coppice dominated by the tree species *C. alba*, *Q. saponaria* and *L. caustica*, with a tree cover ~50–75% and a leaf area index (LAI) ~3.26 $m^2 \times m^{-2}$. The strongly disturbed thorn scrub (B) has a sparse tree cover of sclerophyllous species (< 15%), notably *Q. saponaria* (up to 16 m in height) but also *C. alba*, *L. caustica* and *A. caven*, with medium shrub cover (~50%) of primarily *C. odorifera* and the thorny *R. trinervia* of less than 4 m in height (LAI ~ 2.86 $m^2 \times m^{-2}$, both shrub and tree cover). The severely-disturbed *A. caven* savanna (C) is a xerophytic open woodland dominated by the invasive leguminous tree *A. caven* (LAI ~ 0.12 $m^2 \times m^{-2}$) with emerging infrequent sclerophyllous trees of *Q. saponaria*, *C. alba* and *L. caustica*, with a dense herbaceous annual cover composed primarily of European annual herbs and grasses (e.g., slender wild oat, *Avena barbata* Pott ex Link) that are typically associated with grazing pastures (Armesto et al., 2007).

2.2. Soil CO_2 and CH_4 fluxes

Soil CO_2 and CH_4 fluxes were measured in the nine selected plots, three from each vegetation cover i.e. A, B and C. In each plot, measurements were also segregated by species cover. In the moderately-disturbed A situation, measurements were taken under *C. alba*, *L. caustica* and *Q. saponaria*. In the strongly-disturbed B condition, measurements were taken under *Q. saponaria*, *R. trinervia* and *C. odorifera*. In the severely-disturbed C condition, measurements were taken under the N-fixing leguminous *A. caven*, under the pasture, and under *Q. saponaria*. Therefore there were 3 vegetation covers × 3 plots per vegetation cover × 3 species cover per plot × 3 replicates per species cover × 2 seasons, which yielded 182 measurements.

Measurements were performed on rainless days between 10 am and 5 pm on the following dates: January 10–20, 2017 (summer) and June 5–July 12, 2017 (winter). Ninety one soil collars made of polyvinyl chloride (100 mm inner diameter and 50 mm length) were inserted into the soil across vegetation and species covers in September 2016. Soil CO_2 efflux (R_s) was measured in all collars within each plot using a closed chamber (100 mm inner diameter, Model SRC-1, PP Systems, Amesbury, MA, USA) connected to an infrared gas analyzer (Model EGM-4, PP Systems, Amesbury, MA, USA). Soil temperature (T_s) was measured simultaneously to R_s to a depth of 10 cm using a digital thermometer (PDT550, UEi, USA). Soil samples were taken to a depth of 20 cm around each collar to determine the soil gravimetric water content (θ_g). The bulk density (ρ_b) was determined using the parafin-sealed clod method (Blake, 1965). The volumetric water content (θ_v) was calculated as:

$$\theta_v = \rho_b \times \theta_g \quad (1)$$

Volumetric water content was converted into absolute air-filled porosity (AFP, $m^3\ m^{-3}$) knowing the bulk soil density (ρ_b) and the density of the solid phase (ρ_s) with the equation (Epron et al., 2016):

$$AFP = (1-\rho_b/\rho_s)-\theta_v \quad (2)$$

Soil particle density (ρ_s) was determined using the pycnometer method (Flint and Flint, 2002). This method is based on the displacement of water by solid particles (Archimedes method). The displacement of water was determined at 20 °C, by using 50 ml standard pycnometer flasks, which were partially filled with de-aired distilled water and then completed with 10 g (oven-dry basis) of soil. The particle density was then calculated as the ratio between the mass of the soil and the displaced volume of water.

Measurements of soil CH_4 fluxes were taken immediately after measuring soil CO_2 fluxes in each collar. To estimate soil CH_4 fluxes (F_{CH4}) we used a closed chamber made out of polyvinyl chloride (100 mm inner diameter, 200 mm length, with a stopcock on top). Gas samples were extracted from the static chambers using a plastic syringe (25 ml) and injected into pre-evacuated 12 ml vials (Exetainers, Labco Ltd., UK). CH_4 concentrations were determined by gas chromatography at the Soils Laboratory of Universidad de Concepción, Chillán, Chile. Blanks of CH_4 concentration were taken from the atmosphere and from the empty chamber three times per day as controls.

In an initial trial to know the time the chamber should be closed before extracting the 25 ml air aliquot, the CH_4 concentration was